TECHNISCHE UNIVERSITÄT MÜNCHEN

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Fish Protection and Downstream Migration at Hydropower Intakes: Investigation of Fish Behavior under Laboratory Conditions

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Abstract

Fish experiments with potamodromous species were conducted in the Laboratory of Hydraulic and Water Resources Engineering (VAO) of Technische Universität München (TUM) to investigate the fish behavior at the intake screen of innovative hydro power plant (HPP) concepts. The objective was to improve the knowledge concerning the fish protection at the turbine intake and the fish guidance to a downstream passage facility. The experiments were conducted for 24 hours at the scale one-to-one in an open air experimental channel supplied with water from the Isar River. Two concepts were investigated:

The first one consisted of an inclined screen to the horizontal to guide the fish to a surface bypass. Different inclinations (α = 20, 30, 45 and 70°), bar clearances (b_c = 20, 30 and 50 mm), fish species (barbel, chub, nase) and fish sizes (from 19 cm to 61 cm body length) were investigated. The fish were marked with passive integrated transponders (PIT) allowing a precise documentation of the fish passages. The factors affecting the downstream migration under laboratory conditions like the water temperature, the light conditions, the water turbidity and the phase of the moon were analysed. By means of statistical analysis, the influence of the screen inclination, bar clearance and fish length on the fish passage either through the screen or to the surface bypass was studied. A logistic regression enabled the development of a model to calculate the probability to pass through the screen or into the bypass in function of the screen configuration and the fish length. A low inclined screen with narrow bar clearance provided the best results for the fish protection and the fish guidance to the surface bypass at an approach velocity of 0.5 m/s.

The second concept investigated was the Hydro Shaft Power Plant recently developed at the TUM. The assumption that a horizontal screen with low approach velocities (max. 0.4 m/s toward the screen) would be advantageous for the fish protection was tested in the laboratory. Brown trout, barbel and chub with body width larger than the bar clearance (b_c =17.5 mm) were employed. The underwater video records revealed no impingement of the fish at the horizontal screen. The fish oriented themselves with the local effective flow direction. Moreover, the opening in the vertical gate on the weir side was used by fish to pass safely downstream. Therefore, the Hydro Shaft Power Plant provided promising results relating to fish protection and fish migration for fish larger than the bar clearance.

Keywords: Downstream migration, fish behavior, fish experiments, fish passage facilities, fish protection, hydraulic modelling, intake screens, potamodromous species

Kurzfassung

An der Versuchsanstalt Obernach (VAO) des Lehrstuhls für Wasserbau und Wasserwirtschaft der Technische Universität München (TUM) wurden Fischversuche mit potamodromen Arten durchgeführt, um das Fischverhalten am Einlauf von innovativen Wasserkraftwerkskonzepten zu untersuchen. Das Ziel war den Fischschutz am Wasserkraftwerkseinlauf und die Führung der Fische zur Fischabstiegspassage zu verbessern. Die jeweils 24-stündigen Versuche wurden in einem mit Isar Wasser gespeisten Kanal auf dem Freigelände der VAO im Maßstab 1:1 durchgeführt. Zwei Konzepte wurden untersucht:

Das erst Konzept bestand aus einem zur Sohle geneigten Rechen der die Fische zu einem Bypass an der Oberfläche führen sollte. Bei einer Anströmgeschwindigkeit von 0,5 m/s wurden verschiedene Neigungen des Rechens (α = 20, 30, 45 und 70 Grad), Stababstände (b_c = 20, 30 und 50 mm), Fischarten (Barbe, Aitel, Nase) und Fischlängen (von 19 cm bis 61 cm) untersucht. Die Fische wurden mit «passive integrated transponder» PIT-Sendern markiert, wodurch eine präzise Erfassung der Fischpassagen ermöglicht wurde. Faktoren die die Abwanderung unter Laborbedingungen beeinflussen, wie die Wassertemperatur, die Lichtverhältnisse, die Wassertrübung oder die Mondphase wurden damit analysiert. Durch eine statistische Auswertung der umfangreichen PIT-Daten wurde der Einfluss der Rechenneigung, des Stababstandes und der Fischlänge auf die Passage der Fische durch den Rechen beziehungsweise in den Bypass untersucht. Mittels logistischer Regression wurde ein Modell für die Berechnung der Wahrscheinlichkeit der Passage durch den Rechen oder in den Bypass in Abhängigkeit von der Rechenneigung, dem Stababstand und der Fischlänge entwickelt. Ein flach geneigter Rechen mit engem Stababstand erzielte die besten Ergebnisse für den Fischschutz und die Führung zum Bypass.

Das zweite untersuchte Konzept war das kürzlich an der TUM entwickelte Schachtkraftwerk. Es wurden Fischschutz und Fischabstieg an einem horizontalen Rechen mit niedriger Anströmgeschwindigkeit (max. 0.4 m/s) untersucht. Bachforelle, Barben und Aitel mit Körperdicken breiter der lichten Stabweite (b_c = 17.5 mm) wurden eingesetzt. Die Unterwasser-Videoaufnahme zeigte keinen Kontakt der Fische mit dem horizontalen Rechen. Die Fische orientierten sich mit der lokalen Strömungsrichtung. Die Öffnung im Verschluss wurde für eine gefahrlose Passage ins Unterwasser angenommen. Das Schachtkraftwerk zeigte somit vielversprechende Ergebnisse für den Fischschutz und die Fischabwanderung für nicht rechengängige Fische.

Schlüsselwörter: Einlaufrechen, Fischabwanderung, Fischpassage, Fischverhalten, Fischversuche, Fischschutz, hydraulische Modellierung, potamodromous Arten

Resumé

Afin d'étudier le comportement des poissons près des grilles de prise d'eau des centrales hydroélectriques, des expériences ont été réalisées avec des espèces potamodromes sur des concepts novateurs au laboratoire de génie hydraulique et d'aménagement des eaux (VAO) de la Technische Universität München (TUM). L'objectif était d'acquérir des connaissances concernant la protection des poissons à l'entrée de la turbine et leur guidage vers les ouvrages de dérivation lors de la dévalaison. Les expériences ont été réalisées à l'échelle 1 pendant 24 heures dans un canal en plein air alimenté en eau par la rivière Isar. Deux nouvelles approches ont été étudiées :

La première a consisté en un plan de grille incliné par rapport à l'horizontale afin de guider le poisson au sommet de la grille vers le dispositif de dévalaison. Les paramètres étudiés étaient l'inclinaison de la grille (α = 20, 30, 45 et 70°), l'espacement des barreaux (b_c = 20, 30 et 50 mm), les espèces de poissons (barbeaux, chevesnes, hotus) et leur longueur (de 19 cm à 61 cm). Grâce au marquage des poissons avec des transpondeurs passifs intégrés (PIT), le passage des poissons a été précisément documenté. Les facteurs qui pouvaient influencer la migration en aval ont été analysés : la température de l'eau, les conditions lumineuses, la turbidité de l'eau et la phase de la lune. Une régression logistique a permis le développement d'un modèle afin de calculer la probabilité de passer à travers la grille et d'aller vers la passe à poissons en fonction de l'inclinaison de la grille, de l'espacement des barreaux et de la longueur des poissons. Un plan de grille très incliné avec de faible espacements des barreaux a fourni les meilleurs résultats concernant la protection des poissons et leur guidage vers l'ouvrage de contournement à une vitesse d'approche de 0,5 m/s.

La seconde approche étudiée était la centrale hydroélectrique «en puits» développée à la TUM. L'hypothèse selon laquelle un plan de grille horizontal avec des vitesses d'approche faibles (max. 0,4 m/s) était avantageux pour la protection des poissons a été testé au laboratoire VAO. Truites, barbeaux et chevesnes avec une largeur de corps supérieure à l'espacement des barreaux (b_c = 17,5 mm) ont été étudiés. Les enregistrements vidéo n'ont pas révélé de plaquage des poissons à la grille horizontale. De plus, le passage dans la vanne dans le plan du barrage a été utilisé par les poissons pour passer en toute sécurité en aval. Ainsi la centrale hydroélectrique «en puits» a fourni des résultats prometteurs concernant la protection et la dévalaison de poissons de largeur supérieure à l'espacement des barreaux.

Mots-clés : Comportement des poissons, espèces potamodromes, expériences avec poissons, grille d'entrée, migration en aval, modélisation hydraulique, passe à poissons, protection des poissons

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Contents

1 Introduction

1.1 Background

Worldwide, countless hydraulic structures have been established in the rivers for various purposes like river regulation, hydro power usage, irrigation or river bed stabilization. These constructions seriously affect the river ecology and continuity. Especially, the migration of fish which is essential for most species during their life cycle is significantly interfered or completely obstructed. Fish populations are fragmented and consequently the genetic exchange between populations is reduced (IUCN 2013). Moreover, by altering the flow dynamics and the sediment transfers, the transverse structures in the rivers involve a habitat loss for the aquatic organisms (Bunn et al. 2002).

To maintain a sustainable fish population, a safe passage for migrating fish across stream barriers is essential. In the context of the European Union (EU) Water Framework Directive, the member states must restablish a good ecological status of all water bodies until 2027 (European Commission 2000). The free passage of the fish in the rivers is one of the major objectives. River restauration and fish passage facilities as for example bypass rivers, fishways or fish passes, have been developed since the early 20th century to minimize the environmental impact of weirs and dams (Katopodis et al. 2012b). At the beginning, most of the development focused on the salmonid species due to commercial interests. Nowadays, important efforts are made to develop efficient fishways for further species.

While there has been a significant progress in the design and implementation of fishways for upstream migration (ATV-DVWK 2010; Jungwirth et al. 1998), downstream fish passage remains difficult (ATV-DVWK 2005; Schmutz et al. 2013; Williams et al. 2012). The downstream migrating fish mostly follow the main stream and pass through the turbine if not prevented by special means. Fish injury and mortality occur depending on the hydro power plant (HPP) intake structure, the fish species, the fish size, the turbine type and the service condition. The principle of fish downstream facilities is to stop the fish before the turbine, to guide them to a bypass and finally to bring them downstream safely (Courret et al. 2008). The most approved method to prevent turbine passage is by using a physical barrier, i.e. a fine trash rack/screen. Whereas the downstream passage itself is rather manageable, the guidance to the bypass turns out to be the most challenging point. Some facilities show poor efficiency because fish cannot find the passage entrance and swim towards the turbine or are pressed at the screen after weakness and unsuccessful search (Ebel 2013). A targeted arrangement of the screen, the flow and the bypass entrance is required to achieve efficient fish protection. The concepts must feature respectable findability and attractiveness of the bypass entrance in order to provide a safe passage downstream.

The most direct and reliable method to develop and investigate such facilities is the observation of the fish. The investigation of fish behavior in migration installations in laboratory environment was developed during the last decade, involving the collaboration of engineers and biologists (Lehmann et al. 2012). This approach enables targeted test conditions, complete records of migration movements, competitive test series and parameter studies.

1.2 Objectives

At the laboratory of Hydraulic and Water Resources Engineering (VAO) of Technische Universität München (TUM), fish experiments were conducted in an open air channel. The objective was to investigate the fish behavior in front of the simulated intake screen of HPPs in order to evaluate and optimize fish protection and downstream migration facilities. Two concepts were tested.

The first one consisted of an inclined screen to the horizontal. The objectives were to:

- test the guidance to a surface bypass by varying the inclination of the screen,
- evaluate the influence of the bar clearance on the fish passage through the screen,
- improve the attractiveness of the passage entrance,
- provide an efficient and safe passage to the downstream.

The second concept investigated was the Hydro Shaft Power Plant recently developed at TUM. The objectives were to:

- investigate the fish behavior and test the fish protection at the horizontal screen,
- test the downstream passage facility.

While most of the research efforts were made for diadromous species like the eel and the salmon, less is known about the behavior of other species. Therefore, for both concepts, potamodromous species were employed to gather information concerning their migration and swimming behavior. Fish experiments to test fish passage facilities in a laboratory is a relatively new discipline. The experiments conducted in the VAO laboratory also aimed at gathering experience in order to improve the significance of such experiments.

1.3 Outline of the thesis

Subsequent to the introduction, five chapters structure the present work:

- Chapter 2 gives an overview of the state of the art concerning fish protection and fish downstream passage at HPPs.
- Chapter 3 describes a preliminary fish experiment to test its feasability at the VAO laboratory and to study the fish behavior in front of an inclined screen in a small experimental flume.
- Chapter 4 presents a fish experiment conducted at the scale one-to-one to investigate the influence of the screen inclination and the bar clearance on the fish passage through the screen and to the surface bypass.
- Chapter 5 concerns the fish protection and downstream passage at the TUM Hydro Shaft Power Plant concept.
- Chapter 6 summarises and discusses the results obtained from the fish experiments.

2 State of the art

2.1 Fish biology and ecology

2.1.1 Fish biology

Fish are aquatic vertebrate cold-blooded animals. They have fins and respire by passing water over gills. More than 30,000 species are inventoried composed of 3 classes: Jawless fish, cartilaginous fish and bony fish. The bony fish is the largest class of vertebrates counting 45 orders, over 435 families and 28,000 species worldwide. They are very diversified in their shape, size and habitat and occupy freshwater and marine environments. Most of the bony fish (90 %) are ovopartity; laying undeveloped eggs followed by external fertilization (Hart et al. 2008). The main life cycle stages are: Egg stage, larvae stage, fry stage, juvenile stage and adult stage. Figure 2.1 illustrates the life cycle of the brown trout showing its life stages and the corresponding habitats. The life span varies in function of the species, the size of the adult fish and the habitat.

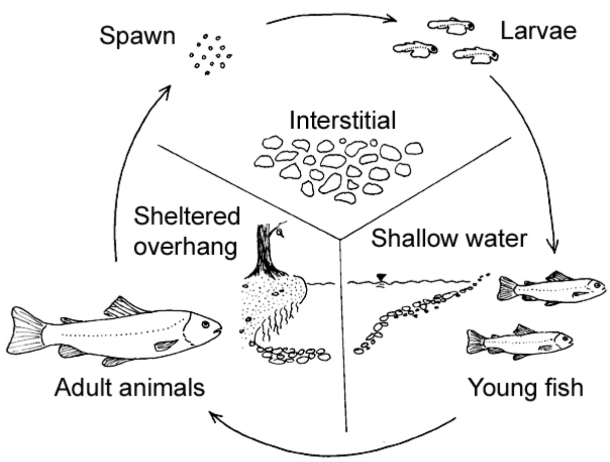


Figure 2.1 Life cycle of the brown trout (Bostelmann 2004)

2.1.2 Fish migration

Most of the fish are migrating in the river as well in the upstream as in the downstream direction (Ebel 2013). The migration distance and duration vary between the species and the life stages from some meters to more than thousand kilometers over a daily or annually period. The habitat preferences vary between the species and along the fish life in function of their food habits and swim capacities which implicate migration during their whole life. Moreover, fish migrate to spawn, find calm zone during flood events or warmer water during winter periods (Zitek et al. 2007). Fish migration is associated to three purposes (Lucas et al. 2001): Spawning, feeding and refuge as illustrated in figure 2.2. Related to the place the fish reproduce, either in seawater or in freshwater, different types of migration are distinguished by ichthyologists (Myers 1949) as described in figure 2.3. The present work focuses on the potamodromous species which stay in freshwater their whole life.

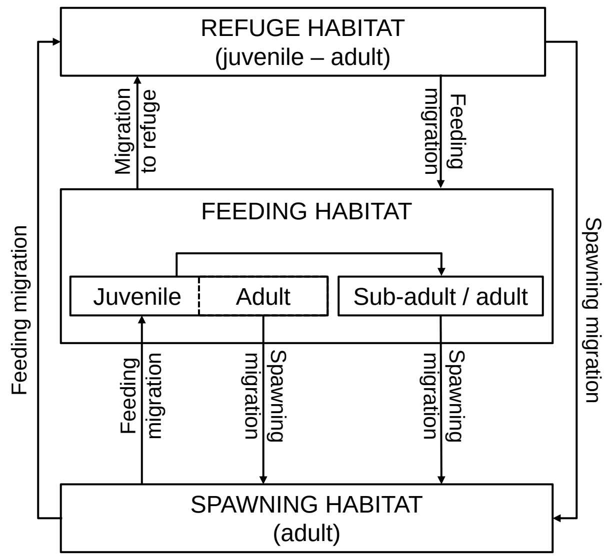


Figure 2.2 Scheme of functional types of migration (Lucas et al. 2001)

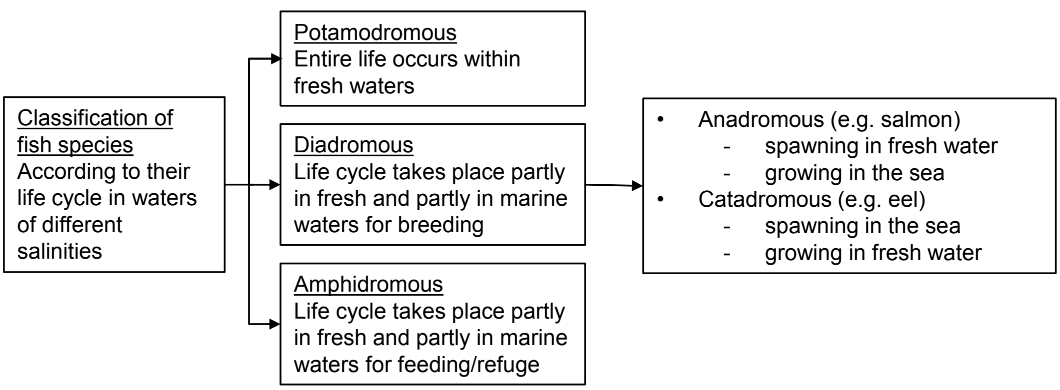


Figure 2.3 Type of fish migration (by Wang 2007)

2.1.3 Factors affecting the downstream migration

This thesis focuses on the downstream migration. Information concerning the upstream migration are available in ATV-DVWK 2010 for example. According to Baggerman 1962; Ebel 2013; Pavlov et al. 2008a; Schwevers 2000; Vøllestad et al. 1986; Zitek et al. 2004a,b, the factors affecting the downstream migration are:

- The season of the year: After the spawning season fish usually migrate downstream
- The water temperature and especially a water temperature increase or decrease
- The discharge: During high discharge fish drift with the flow to save energy
- The day length by affecting the hormone production
- The moon phase strongly influences the eel migration for example
- The water turbidity by reducing the visual capabilities of fish
- The time of the day (light, temperature)
- The atmospheric pressure

There are also interactions between these factors which could either stimulate or inhibit the downstream migration. The downstream migration of potamodromous species is not clearly synchronized. Therefore, it is difficult to delimit a period of migration (Schwevers 2000).

2.1.4 Swimming orientation and behavior

Fish have four sensory systems: Vision, chemoreception (olfaction and gustation), mechanoreception (hearing and lateral line) and electrical sense (sturgeons, lampreys). The sight of fish varies strongly between the species and the life stage. Adult fish have a better sight than the young ones. Species living in open water areas usually feature good vision. The sight is an important sense to avoid predators and to detect prey but also for the orientation in the river channel. Due to their inner ear and the lateral line along the body of the fish, fish are able to hear (see figure 2.4). The lateral line is present only in aquatic vertebrates and is composed of neuromasts sensitive to water velocity and acceleration (Bleckmann 1986). It is a very important organ allowing the detection of vibration at the water surface and in the water surrounding the fish caused by preys or predators. The lateral line is essential for the fish orientation to currents in the river and for schooling behavior.

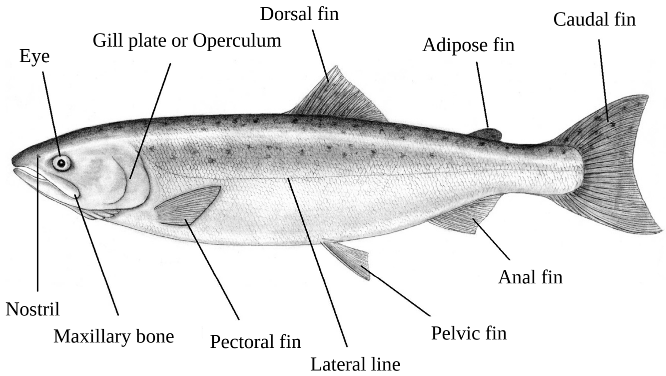


Figure 2.4 Fish anatomy with salmon as example (by K. Uldall - Ekamn)

The term rheotaxis, introduced by Lyon 1904, describes the behavioral orientation of the fish to the water current involving the lateral line (Montgomery et al. 1997). The orientation of the fish to the flow and the head against the current is defined as positive rheotaxis. When fish swim with the flow head downstream, it is a negative rheotaxis. Pavlov defined the rheoreaction as «the behavioral reaction of fish related to their life in the water current» (Pavlov et al. 2008b). There are three types of downstream migration (figure 2.5): Passive migration, active-passive migration and active migration. The passive migration concerns mostly the early life stages which cannot orient themselves to the flow. The effective speed of migration is equal to the flow velocity. By the active-passive migration, the fish speed of migration is lower than the flow velocity. The fish are aligned with the head against the flow. This type of migration occurs when the swimming ability is reduced due to cold water temperature for example. The active migration refers to fish which have the head towards the downstream and actively swim with the flow direction. Then, the speed of migration is higher than the flow velocity.

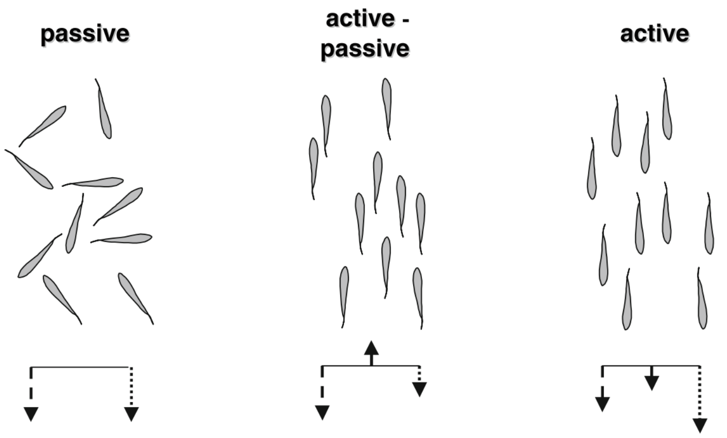


Figure 2.5 Patterns of downstream migration of young fish, dotted arrow: Speed of migration, dashed arrow: Flow velocity (Pavlov et al. 2008b)

2.1.5 Potamodromous species investigated

This section gives a short description concerning the ecology and habitat preferences of the four species used for the fish tests described in chapter 3, 4 and 5. The barbel, nase and chub belong to the cyprinidae family while the brown trout is a salmonidae. The brown trout lives in the upper trout region according to the river longitudinal zonation of Huet 1949. The nase, barbel and chub are common in the grayling and barbel region. The literature references for the following species descriptions are ATV-DVWK 2005; Ebel 2013; IUCN 2013; Unfer et al. 2003.

2.1.5.1 Barbel (*Barbus barbus*)

The barbel is a rheophilic species, which prefers relatively fast water compared with other cyprinid fish. The habitat preferences range from lowland reaches of clear and warm waters and medium to large rivers with fast currents and gravel bottom. They vary over their life cycle: The larvaes and juvenile fish live in lentic shallow environment with sand substrate and the young and adult fish in the deeper areas with faster velocities. The barbel is a typical bottom-oriented fish. Adults are encountered most active during dusk and dawn while larvae and juveniles are active during both day and night. The barbel is an indicator of anthropogenic disturbance: Their presence indicates fluvial habitat of relatively low disturbance concerning the water quality and the longitudinal connectivity. The barbel can be resident or mobile (from > 1 to > 30 km). There are considerable intra-population differences. Up to 300 km migration distances were recorded in the upstream and downstream direction. They are aggregative fish with a shoaling behavior. The barbel has cyclical migration patterns through the year with a tendency to move downstream in autumn and upstream in spring and early summer to spawn (from May to July). The downstream movements are often associated with flood events. The fish activity is synchronized with the light intensity and water temperature. The barbel prefers shelter and deep water especially during night-time.

Figure 2.6 Barbel (*Barbus barbus*) (by P.J. Dunbar)

2.1.5.2 Brown trout (*Salmo trutta*)

The early stages of brown trout prefer the shallow riffle areas with cobble substrate and moderate water velocities (20-50 cm/s). As the fish grow, they inhabit deeper stream areas with more cover and place. The spawning season depends on the photoperiod and the water temperature. It usually occurs in November and December. Brown trout prefer to spawn in fast-water sections of streams with gravel substrates. They show a territorial and solitary behavior. They are more active during the night and stay in shelter area during the day. Brown trout are considered as the most wary of all salmonids. They feed on aquatic and terrestrial insects, small fish and large crustaceans. The brown trout can migrate up to 120 km.

Figure 2.7 Brown trout (*Salmo trutta*) (by P.J. Dunbar)

2.1.5.3 Chub (*Squalius cephalus*)

The chub is a rheophilous freshwater fish widely distributed in Europe. They frequent lotic habitats from slow to moderate rivers with shallow water and coarse gravel. Chub prefer structured habitats such as wood, overhanging vegetation or riprap. When the temperature rises above 12°C between April and June, adult chub migrate to the upstream to spawn in fast-flowing water above gravel bottom. The larvae and juvenile chub stay in groups in shallow water while the adults are solitary and often stay under overhanging trees. They can live up to 15 years, females longer than males. Between 2-4 years the males reproduce for the first time, females at 4-6 years. Chub feed on small aquatic invertebrates (juvenile fish), plant material, insects and fish (adult fish). The migration distance is about 100 km in the upstream and 170 km in the downstream direction.

2.1.5.4 Nase (*Chondrostoma nasus*)

The nase live in medium to large size rivers with moderate to fast currents and rock or gravel bottom. They migrate upstream some tens of kilometers to spawn on shallow gravel bed in fast-flowing water in March-May when the temperature is close to 12°C. The early juvenile stages are benthic and live in shallow shoreline habitat. They move to faster current as they grow. In winter, the juveniles stay in backwaters or in cavities. The adults move in the lower parts of the river and form dense swarms. Small invertebrates constitute the food of the larvae and juveniles. The older fish feed on benthic diatoms and organic detritus from the substrate. Nase are indicators of good water quality. They live up to 12 years and become reproducible at 4-5 years. The nase are mobile and can migrate 140 km upstream and up to 440 km downstream.

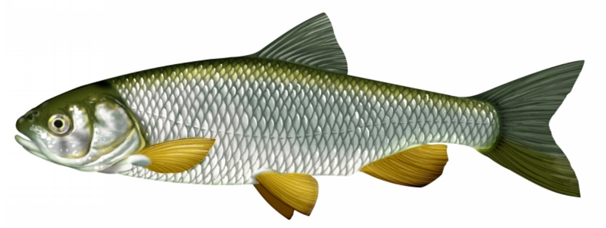


Figure 2.8 Chub (*Squalius cephalus*) (by P.J. Dunbar)

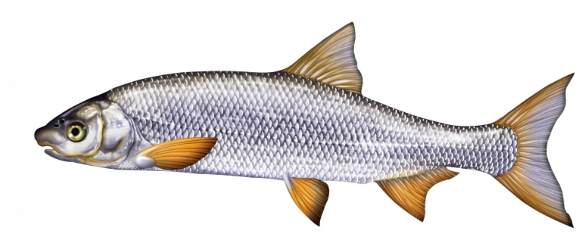


Figure 2.9 Nase (*Chondrostoma nasus*) (by P.J. Dunbar)

2.2 Impacts of hydraulic constructions on fish

There are about 7,500 HPPs in Germany producing 23.6 % of the renewable electric energy (BMU 2014). In addition, there are also numerous transverse structures e.g. in order to stabilize the river bed. All these hydraulic constructions have an impact on the river ecosystem and especially on the fish population. They delay or interrupt the fish passage and migration (ATV-DVWK 2005; Calles et al. 2009; Larinier 2008). Furthermore, they alter the flow regime and the sediment transport affecting the quality, quantity and accessibility of the fish habitat (Bunn et al. 2002; Cowx et al. 1998; Cushman 1985; Poff et al. 1997). Actually, the freshwater biodiversity declines worldwide due to humans activities (Dudgeon et al. 2006).

At the HPP itself, injury and mortality can occur at the turbine intake, during the passage through the turbine and/or in the tailwater. At the turbine intake, fish damages can happen due to fish impingement at the trash rack/screen which is installed upstream of the turbine. This concerns fish larger than the bar clearance. A combination of high flow velocities towards the screen and a fine screen induce high injuries for large fish since they are pressed against the screen without being able to pass through it (Hübner et al. 2011; Schneider et al. 2012). Under these conditions, the fish fight against the flow until exhaustion, are removed with the screen cleaning machine and/or submitted to predation. The screen surface and the bar profile can as well be a source of injury if they present rough surface or sharp edges.

During the passage through the turbine, the fish can endure strike, grinding and collision with the turbine blade. Moreover, the rapid decrease in pressure (Becker et al. 2003; Foye et al. 1965; Jacobson et al. 2012), cavitation, dissolved gas supersaturation (Abernethy et al. 2001; Weitkamp et al. 2003) and shear stress can conduct to internal lesions. The injury and mortality rates caused by the passage through the turbine depend on many factors (Davies 1988) like the turbine type, the turbine diameter, the rotational speed, the operating condition (Cramer et al. 1964), the size of the fish (Cada 1990) and the fish species (Holzner 2000). For example, Francis turbines show higher mortality rates than Kaplan turbines and the mortality rates increase with the fish length (see figure 2.10). Usually, the probability of injury increases with high turbine rotational speed and small turbine diameter. Several empirical and mathematical models were developed to estimate the fish mortality due to turbine passage (Ebel 2013; Larinier 2008; Montén 1985).

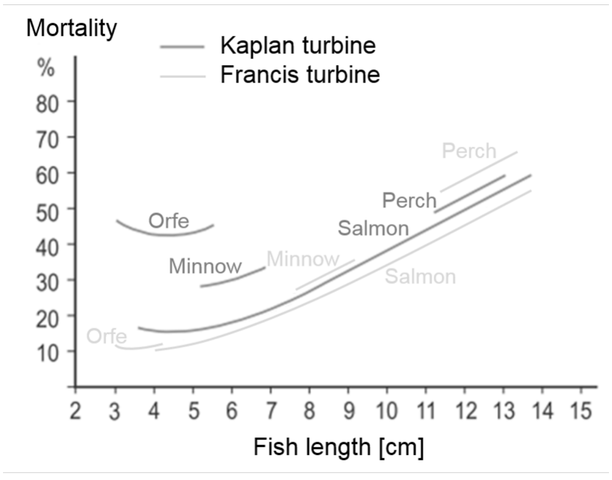


Figure 2.10 Fish turbine mortality rate in function of the species, the fish length and the turbine (0.6 m diameter) in laboratory test (Dumont et al. 2005; Montén 1985)

Finally in the tailwater, the fish are disoriented due to the passage through the turbine and feature an easy prey for predator birds or fish (Larinier et al. 2002). During flood events, the exceed discharge passes over the spillway allowing the fish a direct passage to the downstream. However, this passage is not totally safe for the fish. Actually the fish passing over the spillway endure high quantities of pressure fluctuation, dissolved oxygen, turbulence and energy dissipation which could also conduct to injury and death (Cuchet et al. 2012b).

The fish have to pass several HPPs during their migration in the river. This results in a cumulative effect on the final fish mortality rate. For example considering 5 % mortality at each HPP, after the passage of five HPPs the final fish mortality rate will be 23 % (Dumont et al. 2005; Larinier 2008; Norrgård et al. 2013).

2.3 Hydraulic engineering for the fish downstream migration

2.3.1 Introduction

Fish naturally migrate in the river in the upstream as well as in the downstream direction. Actually, the fish migrating downstream follow the main flow which, at a HPP, is usually directed towards the turbine intake. The fish can either be stopped at the screen protecting the turbine or pass through the screen into the turbine. Only in case of flood discharge, the passage over the spillway is possible.

Over the last decade, efforts have been made to reduce the fish injury and mortality at HPPs during the downstream migration and to enable the fish to pass safely to the tailwater. Fish downstream passage facilities have been developed in cooperation with civil engineers and biologists. Up to now, the monitorings of such facilities reveal very diverse results. In most of the cases, the downstream passage facilities do not provide a sufficient efficiency to protect fish and feature mortality rates which may endanger the fish populations.

The aims of downstream passage facilities are to avoid injury at the screen and during the turbine passage, to reduce the migration delay, to minimize the stress for the fish and the potential vulnerability to predation. The general principle of downstream passage facilities is (Courret et al. 2008):

- to stop the fish before they pass through the turbine,
- to guide the fish to the passage facility,
- and to bring the fish safely to the downstream of the HPP.

The second point is the most challenging. It is essential to guide the fish to the downstream passage entrance (also called bypass) very quickly to avoid exhaustion and finally impingement of the fish at the screen or the passage through the screen into the turbine.

The following parts describe some means to stop, guide and bring the fish safely to the downstream of the HPP. Moreover, some alternative approaches for safe fish downstream passage are presented.

2.3.2 Fish protection at HPPs

2.3.2.1 Conventional physical barriers

The most common way to prevent fish from passing through the turbine is by installing a screen. There is usually a trash rack at the turbine intake to avoid the input of wooden debris or trash which could affect the turbine. However, the common trash rack structures are originally not fine enough to avoid the passage of most fish. Therefore, a rather fine barrier, mostly denoted as screen or grid, is installed for fish protection. It consists of vertical or horizontal metal bars with additional structural elements. The bar profile can have different shapes, for example rectangular or rounded to reduce vibration and energy loss but also potential injury for fish. The free distance between two bars, where the flow and the fish can pass through, is called the bar clearance (b_c) or the bar spacing (see figure 2.11). At the majority of HPPs the screen serves as trash rack and fish barrier at the same time. In some cases an additional trash rack is installed upstream. The blockage of the trash rack and/or the screen by floating debris and sediment has to be accounted for by cleaning and flushing installations and service.

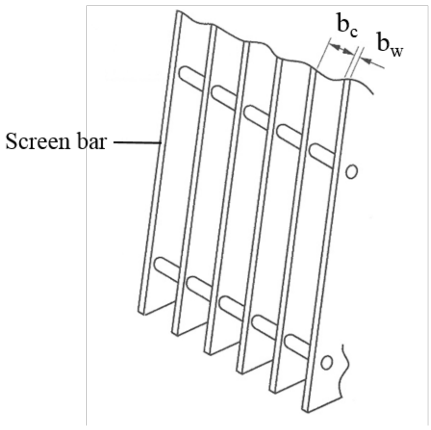


Figure 2.11 Screen with vertical bars, b_c: Bar clearance, b_w: Bar width (ATV-DVWK 2005)

To provide a mechanical barrier effect, i.e. to avoid the passage of the fish through the screen, the bar clearance has to be smaller than the fish body width. While a small bar clearance is required to protect the fish, it increases the energy loss (Ebel 2013) and the amount of floating debris stopped at the screen. Therefore, with regard to the facility efficiency and the cleaning efforts, the bar clearance should not be reduced too much. The maximum bar clearance which does provide sufficient fish protection has to be determined. The bar clearance can be selected by taking the target species of the fish region concerned. Höfer et al. 1996 developed a mathematical relation among the body length of brown trout and the maximum bar clearance necessary to avoid fish passage:

$$b_c = 0.101 \times L_{Browntrout} \tag{2.1}$$

where b_c is the bar clearance in millimeters (mm) and $L_{Browntrout}$ the fish length of the brown trout in millimeters (mm). This relation is considered as valid for salmonids and cyprinids (Schwevers 2004).

The relative fish body width is defined as follows:

$$W_{Fish,rel} = \frac{W_{Fish}}{L_{Fish}} \tag{2.2}$$

where W_{Fish} is the maximal fish width (cm), and L_{Fish} the fish length (cm). For most of the potamodromous species, the relative fish body width is between 0.09 and 0.13 (Ebel 2013). It is used to calculate the passability index P which is a relative dimension to estimate the fish passability through screens with vertical bars:

$$P = \frac{b_c}{W_{Fish,rel} \times L_{Fish}} \tag{2.3}$$

where b_c is the bar clearance in cm, $W_{Fish,rel}$ is the relative body fish width and L_{Fish} the fish length (cm). Two classes are defined:

- $P < 1$: The fish cannot physically pass through the bars
- $P > 1$: The fish can physically pass through the bars

The common recommend minimal bar clearance value is 20 mm (ATV-DVWK 2005; Dumont et al. 2005). However, it varies according to the authors, the country and the target fish species and size. For example Schwevers 2004 recommends 12 mm for salmonids. In the German federal State Hessen 15 mm are required. British regulations prescribe 10 mm. A bar clearance smaller than 10 mm is suggested to protect the smolts (Dumont et al. 2005). Larinier et al. 2002 recommend a bar clearance equivalent to 1/10 of the total length of salmonids to avoid the passage through the screen. Moreover, during experiments a bar clearance of 1/8 to 1/4 of the fish body length revealed a repulsing effect on fish. This behavioral effect was strongly depending on the hydrodynamic condition at the screen. With moderate velocities at the screen, a bar clearance between 1/7 and 1/8 was enough to prevent the fish from passing through the screen (Larinier et al. 2002). Similar results are presented in Hübner et al. 2011, showing that the passage through the screen is strongly depending on the fish species, the fish size, the bar clearance and the approach velocity at the screen. These experiments revealed that for an approach velocity of 0.5 m/s a bar clearance equal to the maximal fish body width can cause death injury.

2.3.2.2 Fish swimming capacity and velocity at the screen

A small bar clearance is necessary to prevent fish from a turbine passage, but it is not enough to protect them. The approach velocity at the screen is as well a very important factor which has to be considered to avoid any impingement of the fish against the screen (Hübner et al. 2011; Larinier et al. 2002).

Beamish 1978 classified the fish swimming speeds as burst, prolonged and sustained (see table 2.1). Burst speed corresponds to the maximal swimming speed that a fish can reach over short time about maximal 20 seconds, for example to capture prey. The prolonged speed can be attained from 20 seconds to 30 minutes, which leads to fatigue of the fish (Katopodis et al. 2012a). The sustained speed is low and can be performed indefinitely without fatigue. The velocity and the duration of these three classes vary among the species, the life cycle, the water temperature and the oxygen concentration (Tudorache et al. 2008).

Table 2.1 Classification of swimming speeds according to Katopodis et al. 2012a; Pavlov et al. 1989

Swimming speed	Dart or burst speed	Prolonged speed	Sustained or cruising speed
Duration	Max 20 sec.	Max 200 min.	Indefinitely
Used for	Capture prey, escape predators or negotiate difficult passage conditions	Avoid Obstacles	Migration, routine activities such as foraging and holding

The critical swimming speed (U_{crit}) is a subcategory of the prolonged speed and was defined by Brett 1967. It is a standard labor measurement to determine at which velocity the fish cannot keep its position anymore due to fatigue (Plaut 2001). Like represented in figure 2.12, the critical swimming speed of the fish varies with the species and the body length (ATV-DVWK 2005; Ebel 2013; Pavlov et al. 1989).

Different equations were developed to estimate the critical swimming speed (Ebel 2013; Larinier 2002) which also depends on the water temperature (Larinier 2002).

To prevent any fish impingement at the screen, the maximal approach velocity (V_A) should enable the fish to swim at the intake for a sufficient time to look for and find another passage. Therefore, the approach velocity should not be higher than the critical swimming speed. The flow distribution at the turbine intake should be as uniform as possible. The recommend maximal velocity is usually 0.5 m/s (Courret et al. 2008; Dumont et al. 2005). A way to reduce the velocity is by increasing the screen surface.

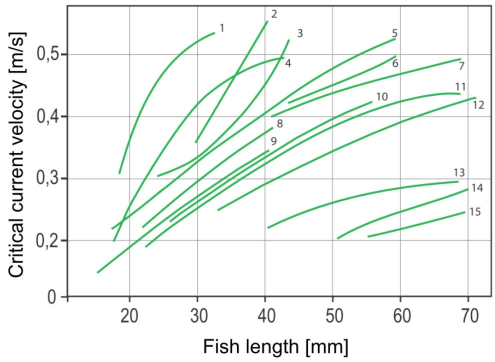


Figure 2.12 Critical current velocities (U_{crit}) for different species in function of the fish length: 1: *Albumus albumus*, 2: *Leucaspis delineates*, 3: *Rutilus rutilus caspius*, 4: *Carassius carassius*, 5: *Abramis ballerus*, 6: *Perca fluviatilis*, 7: *Vunba vimba*, 8: *Nemachilus barbatulus*, 9: *Cottus gobio*, 10: *Rhodeus sericeus*, 11: *Tinea tinea*, 12: *Cobitis taenia*, 13: *Acipenser guldenstada*, 14: *Huso huso*, 15: *Acipenser stettatus* (Pavlov et al. 1989)

2.3.2.3 Alternative physical barriers

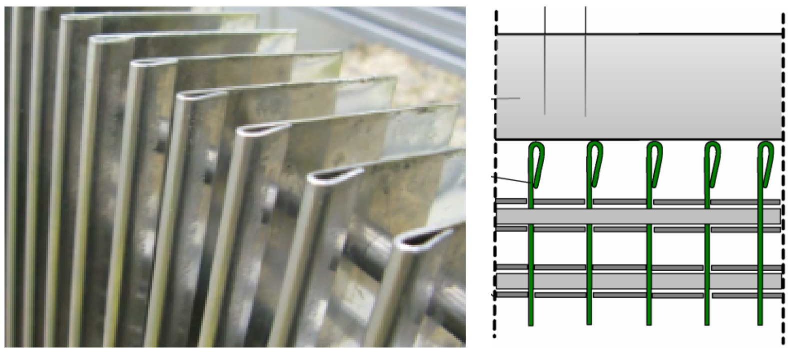
Beside the conventional vertical screen with vertical bars, alternative barriers were developed. Here is a short description of some of them.

The Opperman screen, also called fish friendly screen, was developed in order to improve the hydraulic situation and to reduce energy loss, cleaning efforts and fish injury. Since the energy loss at the screen is reduced, smaller bar clearances can be used to protect the fish. The screen consists of vertically folded bars (see figure 2.13). The round leading edge of the bar and the smooth surface induce smaller fish injury (Hassinger 2009).

Wedge wire screen are screens with a triangular bar profile reducing the fish passage (figure 2.14). The distance between the bars can be close to 1 mm. Moreover, the screen surface is smooth which reduce fish injury (ATV-DVWK 2005; Adam et al.

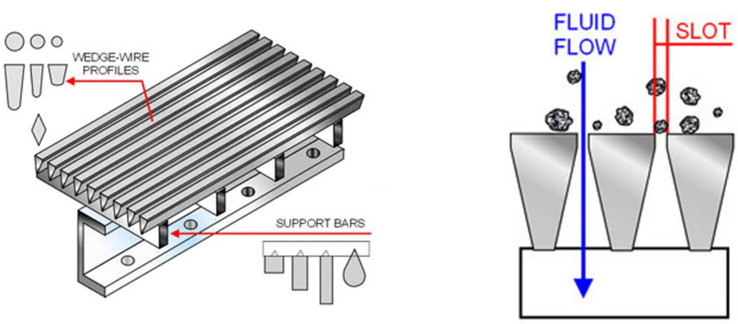
1999). As a disadvantage, energy losses at such screens are high compared with conventional screens (Dumont 2000).

An alternative to bar type screens are perforated plates. The size of the perforation can be adapted to prevent the passage of all fish life stages, including larvae stage. Different types exist: Stationary screens installed perpendicular or inclined to the flow, drum screens which are rotating to a horizontal axe to remove floating debris and traveling screens with a continuous rolling of the mesh (figure 2.15). These installations are considered as fish friendly since they avert fish passage due to the fine perforations (McLaren et al. 2000). Additionally, due to their smooth surface fish injury can be reduced. The drum screen and traveling screen can be equipped with fish buckets to transport the fish to the downstream. However, the perforated plates require high maintenance and operating cost to keep the screen clean (Jamieson et al. 2005).



(a) (b)

Figure 2.13 Opperman screen (Hassinger 2009)



(a) (b)

Figure 2.14 Wedge wire screen (Plastok®)

(a) (b) (c)

Figure 2.15 (a) stationary screen (River Design Group Inc.), (b) drum screen (Hydroscreen Co. LLC) and (c) traveling screen (LMS)

2.3.2.4 Behavioral barriers

Due to their vision, lateral line and ears, fish are very sensitive to their environment. The effect of artificial means like air bubbles curtains (Adam et al. 1999; Patrick et al. 1985), electrical fields (Travade et al. 2006), strobe and lighting systems (Hamel et al. 2008; Patrick et al. 1985), infrasound (Gosset et al. 1999; Popper et al. 1998) on the fish behavior were tested in laboratory and field investigations in order to develop a deterrent system repulsing the fish from the turbine intake. The main advantage is that these systems are not expensive and require low maintenance. However, the effects on fish are low and strongly vary by the species, the life stage and the physiological state (Hocutt 1980). Moreover, the environmental conditions have an influence on the efficiency of such behavioral barrier. The response of fish to an artificial stimuli is strongly dependent on factors, like the water turbidity, the water temperature, the sun light and the hydraulic conditions, which influence the sense and the reaction of fish. Up to now, the use of behavioral barriers alone is not enough to protect fish from passing the turbine (ATV-DVWK 2005). The hybrid combination of a behavioral barrier with a mechanical barrier might improve fish protection.

2.3.3 Fish guidance

A good findability of the migration corridor is essential to provide a good efficiency of the passage to the downstream. Several relevant aspects and developments to improve the fish guidance to the bypass entrance are presented in the following sections.

2.3.3.1 Position of the bypass entrance

In general, the bypass entrance should be located close to the screen plane where the fish tend to accumulate. Depending on the HPP configuration, several cases are possible. Figure 2.16 illustrates some examples from Larinier et al. 2002. When the power plant intake screen is angled to the flow, the bypass entrance should be placed at the downstream end of the screen. If the flow is coming perpendicular to the flow, two bypass entrances are recommended at both sides of the screen. Whenever a recirculating zone is present, the bypass entrance should be located close to it. The hydraulic condition at the bypass entrance also called the zone of influence is very important to enable an attraction of the fish and at the same time to avoid any repellent effect. Turbulent zones, hydraulic jumps and strong accelerations are repulsive for the fish and should be avoided (Enders et al. 2009; Haro et al. 1998). The flow going to the bypass should be as smooth as possible without any rapid changes and high velocity gradients (Kemp et al. 2008). A discharge between 2 to 10 % of the turbine discharge is recommended (Larinier et al. 2002). The velocity at the bypass entrance should be 1 to 2 times higher than the approach velocity at the screen with an absolute value from 0.3 m/s to 1.5 m/s (Ebel 2013).

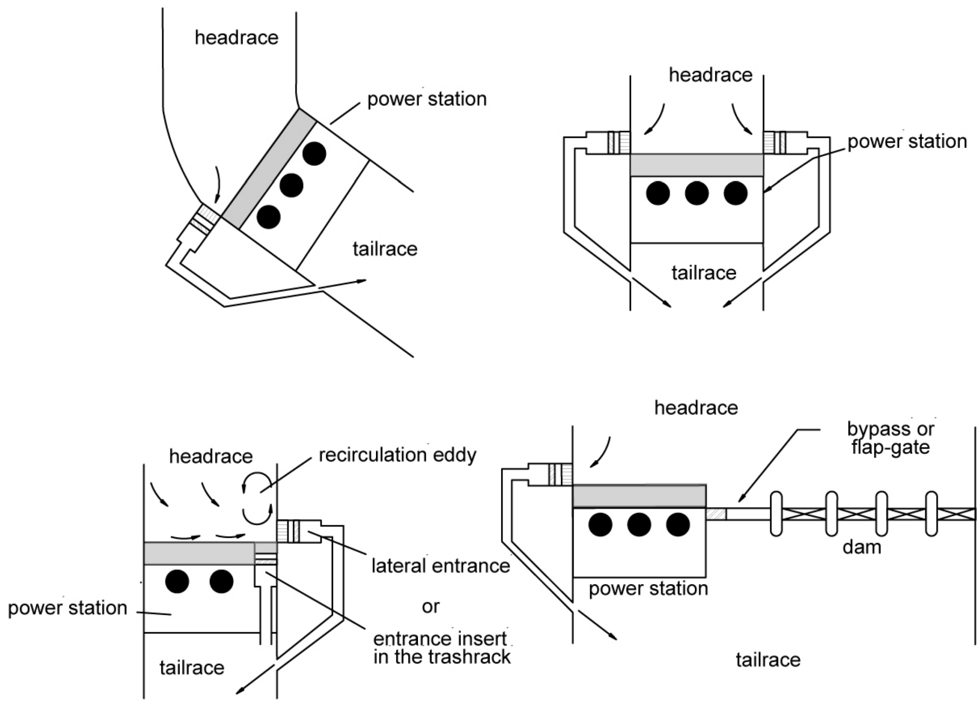


Figure 2.16 Examples of the bypass entrance location at hydroelectric plant intakes (Larinier et al. 2002)

2.3.3.2 Inclined and angled screen

One of the most promising ways to improve the fish guidance to the downstream passage entrance is by inclining the screen at the turbine intake to physically guide the fish. The screen can be either inclined to the horizontal (α) or angled to the flow (β) as illustrated in figure 2.17. The bypass entrance should be placed near the surface on the top of the inclined screen or respectively at the downstream end of the angled screen. The disadvantage of the inclined and angled configurations is that a bigger screen surface is required inducing higher costs. Moreover, by inclining the screen the head loss increases, especially for the angled screen. Several equations exist to calculate the effective head loss. They are summarized in Raynal et al. 2013a. An understanding of the relations between inclination/angle and guidance is required in order to design effective but economic facilities.

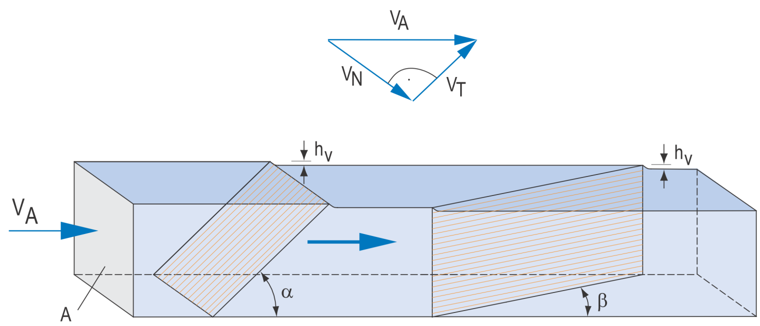


Figure 2.17 Velocities at the screen inclined to the horizontal and angled to the flow, V_A: Approach velocity, V_N: Normal velocity, V_T: Tangential or sweeping velocity (Dumont et al. 2005)

For the inclined and angled configuration, the approach velocity V_A can be characterized by two velocity vector components: The normal velocity V_N which is perpendicular to the screen surface and the sweeping velocity or tangential velocity V_T parallel to the screen. The normal velocity vector should not be higher that the critical swimming capacities of the target fish to avoid any impingement at the screen (Dumont et al. 2005). On the other side, the tangential velocity might guide the fish along the screen into the bypass. By inclining the screen, the normal velocity is reduced and the tangential velocity is increased according to the following formulas:

$$V_N = \sin\alpha \times V_A \qquad V_N = \sin\beta \times V_A \tag{2.4}$$

$$V_T = \cos\alpha \times V_A \qquad V_T = \cos\beta \times V_A \tag{2.5}$$

If α and β are equal to 45°, the normal and the tangential velocity components are identical. An angle smaller than 45° will increase the tangential velocity component and therefore the guidance of the fish. Courret et al. 2008 recommend a tangential component at least twice as large as the normal component to effectively guide the fish to the bypass.

Raynal et al. 2013a measured the velocity distribution at a screen inclined to the horizontal and angled to the flow by means of PIV (Particle Image Velocimetry) (Chatellier et al. 2011; Raynal et al. 2013b). The velocity map for the inclined screen is represented in figure 2.18. The study confirms that the inclination of the screen is the main factor influencing the tangential and normal components of the velocity. Moreover, the screen has to be very flat inclined (α = 25°) to provide the recommended tangential component two times higher than the normal velocity and thus to efficiently guide the fish (Raynal et al. 2013a).

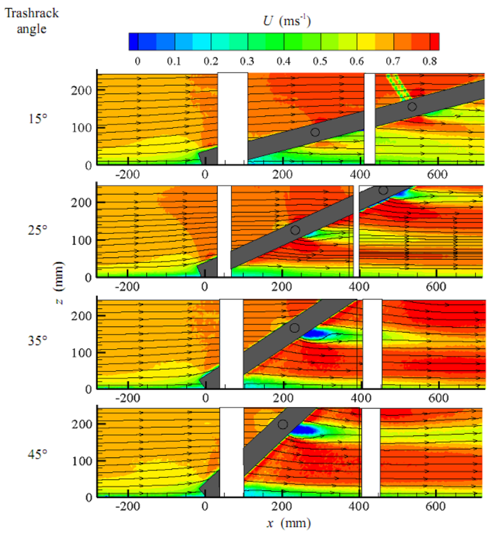


Figure 2.18 Velocity map (m/s) upstream and downstream of a trashrack inclined at different angles α = 15, 25, 35 and 45°, V_A = 0.67 m/s (Raynal et al. 2013a)

Field observations confirm the positive potential of the inclination of the trash rack. Even for inclined screens steeper than 25° the guidance to the bypass located at the surface is enhanced. For example in Sweden at the small HPP Ätrafor (Q_T = 72 m^3/s) in the Ätran River, by inclining the screen from 63 to 35° and reducing the bar clearance from 20 to 18 mm (figure 2.19), the passage efficiency to the surface bypass increased from 28 to more than 90 % (Calles et al. 2012). Similar measures were conducted at the Upper Finsjö HPP (Q_T = 14 m^3/s) in the Emån river, where the inclination was changed from 80 to 35° and the bar clearance from 20 to 18 mm (figure 2.20). The passage efficiency of the two surface bypasses increased from 33-66 to 84 % (Calles et al. 2009). The low-sloping racks give very promising results, also in respect of eel protection and migration (Calles et al. 2013).

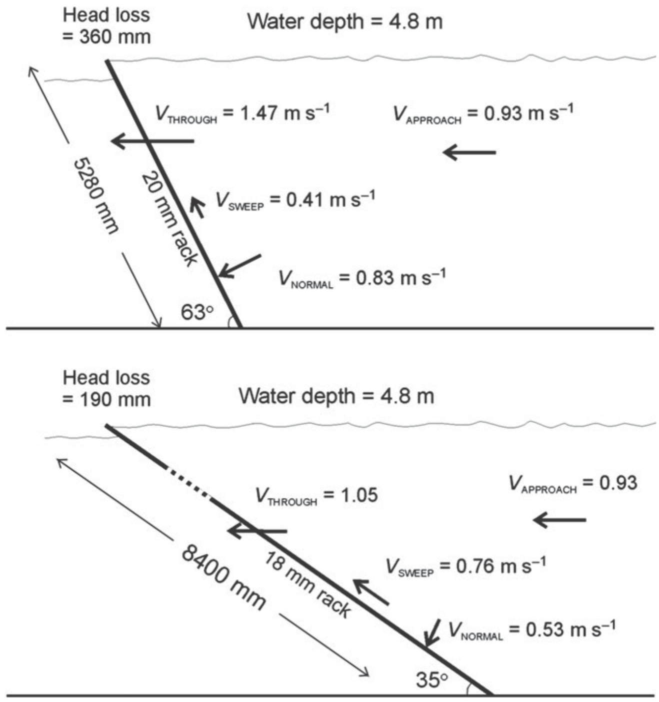


Figure 2.19 Old (top) and new racks (bottom) with velocity component at the Ätrafor hydroelectric plant in the Ätran river in Sweden (Calles et al. 2013)

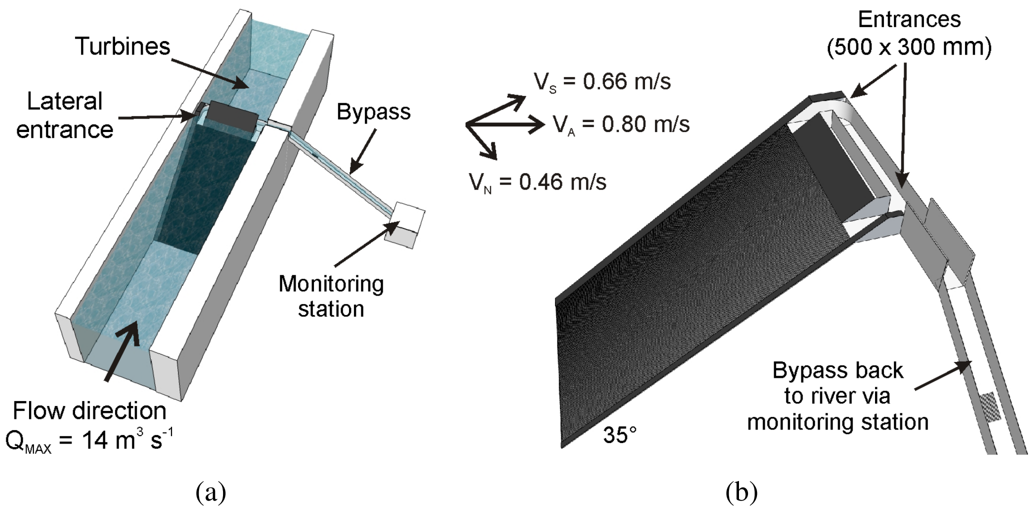


Figure 2.20 Upper Finsjö new rack and bypass in the Emån river in Sweden (Calles et al. 2009)

The angled configurations feature advantageous aspects as well. The angled screens usually have horizontal bars to facilitate the cleaning machine operation. The horizontal arrangement of the bars might also have a positive influence on fish protection. The movement of the fish might be less disturbed if they get between the horizontal bars. Furthermore, a larger bar clearance could be used compared with vertical bar arrangements for oval bodied fish (see figure 2.21).

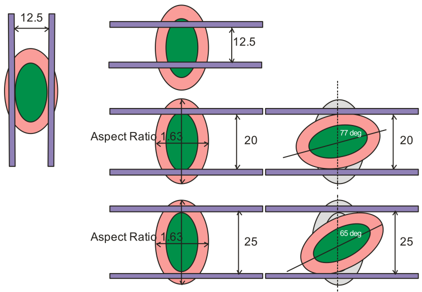
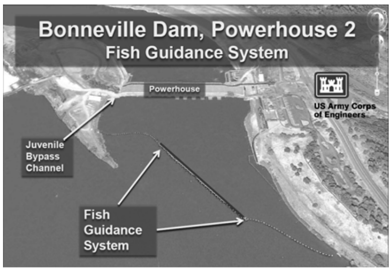


Figure 2.21 Vertical versus horizontal bar screens: Benefit for oval-bodied fish (Turnpenny 2011)

The angled screen arrangement might be especially suitable for those power plants which divert the current to the bay. At the VAO laboratory, a scaled physical model of such an arrangement was used to investigate and optimize the hydraulic conditions of an enhanced concept. To provide a good findability along the screen plane a surface channel (collection gallery) was constructed over a vertical screen plane. Several surface openings provided connections between the headwater and the collection gallery (Cuchet et al. 2010, 2011b). The concept is particularly adapted for young fish which swim near the surface like salmonids and is widely spread in the USA (Evans et al. 2008).

2.3.3.3 Floating barriers

One fish guidance system consists on a floating guidance barrier across the river channel before the turbine intake to avoid the turbine passage of the fish and to guide them to the bypass entrance. Since the barrier covers only the upper meters of the water depth, the floating barrier is specially adapted for surface oriented fish like juvenile salmonids for example. It is relatively economical, requires low maintenance and is flexible. This concept is spread at big power plants in the USA and the results vary among fish species, sizes and sites considered (Scott 2012). The design has to be adapted to the hydraulic conditions of each site to provide a good efficiency. At the Bonneville Dam the floating barrier is 3 meter deep and 213 m long. The bypass entrance is at the downstream end of the barrier (see figure 2.22).



(a)

(b)

Figure 2.22 Fish Guidance System (floating barrier) at the Bonneville Dam, Columbia River, Washington State, USA (Scott 2012)

2.3.3.4 Louvers

Louvers are similar to the floating barriers since they cross the channel and guide the fish to the bypass. But in contrary to the floating barrier, louvers are covering the whole water depth. Louvers consist of a diagonal structure crossing the channel with slats perpendicular or angled to the flow (see figure 2.23). Due to the orientation of the slats to the flow, turbulences are created near the slats which repulse the fish from the structure. Moreover, a strong tangential velocity compound is created which guides them along the louver to the downstream end where the bypass entrance is located (Bates et al. 1957; USBR 2006). Louvers can be considered as behavioral barrier since they provide hydrodynamic stimuli repellent for the fish. The spacing between the louver slats should be selected in function of the fish sizes and species considered. Fish test evaluations revealed that the guidance efficiency varies with the array angle of the louver structure, the slat spacing, the approach velocity, the fish species and the fish size (Amaral et al. 2001). A disadvantage of these structures is the high hydraulic loss generated by the special flow patterns near the barrier.

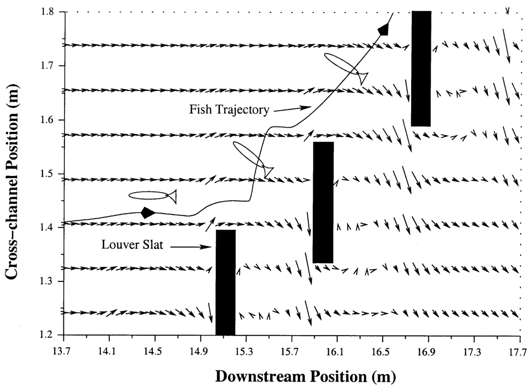


Figure 2.23 Simulated fish trajectory and superimposed flow vectors near the louvers with slats perpendicular to the flow (Haefner et al. 2002)

2.3.3.5 Non-physical guidance

As described in section 2.3.2.4, artificial means like air bubbles curtains, electrical fields, acoustic or lighting systems can also be used to guide the fish by attracting them to the entrance of the fish passage facility (Coutant 2001; Hocutt 1980). The results are strongly dependent on the species and life stages considered (Popper et al. 1998). Up to now, the behavioral guiding systems do not provide a good efficiency. However, the combination with a physical guidance system might improve the findability of the fish passage entrance (Larinier et al. 1991a,b).

2.3.4 Bypass design

As soon as the fish reach the downstream passage entrance, the transfer to the tailwater is usually provided by a so-called bypass which leads in the tailrace. The bypass can be an open channel or a pipe enabling a safe passage of the fish. However, a pipe entails more difficulties for maintenance. To avoid any turbulence or hydraulic jump at the entrance which can repulse the fish (Enders et al. 2009), the shape of the bypass entrance has to be optimized to provide smooth hydraulics. It is recommended to control the acceleration at the bypass entrance by means of an intermediate pool directly downstream of the entrance (Larinier et al. 2002). The whole bypass should have smooth surfaces and no sharp edges to avoid any fish injury. The recommended discharge in the bypass is 2 to 10 % of the turbine discharge (Larinier 2002).

The cross section of the entrance has to be large enough to enable an easy passage of bigger fish. Moreover, wood debris will also reach the entrance. For that reason the bypass entrance as well as the whole bypass channel has to be large enough to flush the wooden debris and prevent accumulation of floating matters. The dimension of the bypass should be adjusted to the fish species and fish size considered (Ebel 2013). A minimal bypass width from 0.4 to 0.6 m and water depth from 0.6 to 0.9 m is however required to enable a safe passage of the fish. Sharp curves of the bypass should be avoided to prevent fish injury. The velocity in the bypass should not be higher than 12 m/s (Travade et al. 1992).

The egress of the bypass can flow into the tailwater or into the fish upstream passage if present. The bypass should lead to a relatively calm hydraulic zone specially by avoiding the recirculating zones where the disoriented fish could be an easy prey for predator bird or fish (Ruggles et al. 1983). In case of an outflow from the bypass to the tailrace, a water cushion of 25 % of the water head and a minimal value of 0.9 m is required to avoid fish injury (ATV-DVWK 2005). To prevent any injury due to high concentration of dissolved gas, it is recommend to spread out the water jet (Larinier et al. 2002).

2.3.5 Special turbines

During the passage through the turbine, the fish are subject to pressure change, strike and collision with the turbine, high turbulence, cavitation, and shear force conducting to injury or death of the fish. Over the last decade, efforts have been made to reduce the fish injury by improving the turbine design. It mainly consists of reducing the turbine rotational speed, increasing the diameter of the runner and reducing the gaps of the turbine. These turbines are often called «fish friendly turbine». It should be noted that this term implies no standards at all and can be used by any turbine constructor. Some developments are established on scientific criteria for fish friendliness like the studies of the US Department of Energy (Odeh 1999).

The VLH turbine for Very Low Head was developed in France for a head range between 1.4 and 3.2 meters. The objective was to design a very efficient turbine for small heads, requiring less construction work at reasonable cost. The principle is to use a large turbine runner (3.55-5.6 m diameter) which includes a structure ensuring the whole function like the generator, a protection grid and a rotation trash rack cleaner (see figure 2.24a). Thanks to low turbine speeds (9-40 rotation/min) and low pressure changes, this turbine is considered fish friendly. Tests with fish revealed mortality rates for eels of 7.7 % and 3.1 % for salmons in the Millau site in France (Lagarrigue et al. 2008).

The Alden turbine was developed in the US to enable a safe passage of the fish by reducing shear, pressure and blade strike. The turbine has only three blades, low rotational speed and an efficiency of 94 % (figure 2.24b). It is adapted for water heads from 6 to 36 m. Tests with fish revealed a mortality rate below 2 % for fish smaller than 20 cm. The mortality rate for eel and sturgeon was below 1 % (aldenlab.com).

Most of the turbine producers are currently improving the turbine efficiency and design details in order to reduce fish injury and mortality (Voith, Anditz, Alstom). However, the modifications of common turbine designs are less promising to achieve actual fish friendliness.

2.3.6 New HPP concepts

New HPP concepts like the screw turbine, the moveable hydro-electric power plant (HEPP), the TUM Hydro Shaft Power Plant or the hydraulic pressure machine have been developed to achieve a better economic efficiency at low water heads and also to reduce the disturbance on the ecological connectivity of the river by enabling sediment transfer and fish passage.

The hydrodynamic screw turbines are adapted for heads from 1.5 m to 10 m (andritz.com). They consist of an Archimedean turbine installed in a 20 to 30° inclined channel (see figure 2.25a). The screw turbines have efficiency up to 92 % and a power capacity of up to 500 kW. As the rotational speed is very low (between 20 and 80/min), no fish protection is implemented but fish are meant to pass unharmed through the screw. Tests and monitorings to estimate the fish mortality were conducted and the results varied between 0 and 50.6 % (Ebel 2013; Edler et al. 2011; Schmalz 2011).

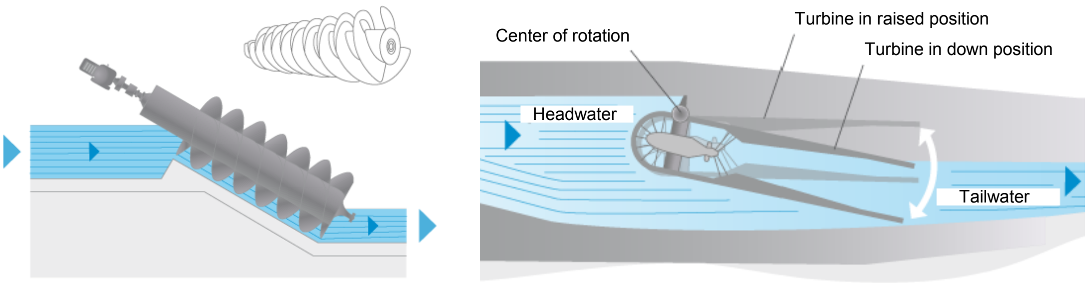
The moveable HEPP was developed by the Hydro-Energie Roth GmbH in Karlsruhe (Roth et al. 2002). It consists of a moveable steel component including a Kaplan turbine and which can be raised to achieve sediment transfer (see figure 2.25b). A fine (e.g. 15 mm) curved screen is installed for fish protection and the fish slide over the steel corpus to the tailwater. Raising the installation provides an additional migration corridor at the ground. The actual fish monitoring conducted revealed promising results concerning fish protection but so far imperfect downstream passage. Further monitorings with relevant discharges are required (Hoffmann et al. 2013; Schmid 2011).

The hydraulic pressure machine consists of a waterwheel design with blades and was developed for small water head difference between 0.1 and 1 m (Müller 2011) (see figure 2.26a). Thanks to large distances between the blades and a very low rotational speed of the device, low fish mortality is expected. Fish monitorings were conducted at a full scale model and at a real site in the river Iskar in Bulgaria. The results revealed zero mortality and an injury rate of 10 % (Uzunova et al. 2014).

The TUM Hydro Shaft Power Plant concept was developed at the Technische Universität München (Rutschmann et al. 2013). An underwater compact turbine is installed in a shaft with a horizontal screen for fish protection (see figure 2.26b). Openings in a vertical gate enable the fish downstream passage. With low velocities at the screen and small bar clearance, the concept aims to be fish friendly. The first fish investigation concerning fish protection and downstream passage is presented in chapter 5. Further fish investigations were conducted with small fish and weak swimmers to estimate the passage distribution between the turbine and the downstream passage facility. Turbine

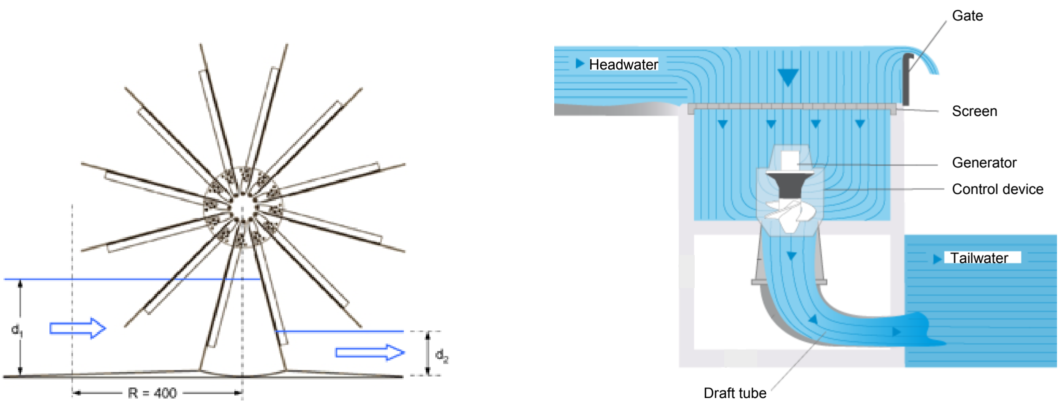
(a) (b)

Figure 2.24 (a) VLH turbine (vlh.com) and (b) Alden turbine (aldenlab.com)



(a) (b)

Figure 2.25 Hydrodynamic screw turbine (a) and moveable HEPP (b) (Bayerische Landeskraftwerke GmbH)



(a) (b)

Figure 2.26 (a) The hydraulic pressure machine (hylow.eu) and (b) the TUM Hydro Shaft Power Plant (Bayerische Landeskraftwerke GmbH) injuries and mortality rates were measured with a Kaplan turbine at the prototype facility in the VAO laboratory (Geiger et al. 2014).

2.4 Laboratory evaluations with fish

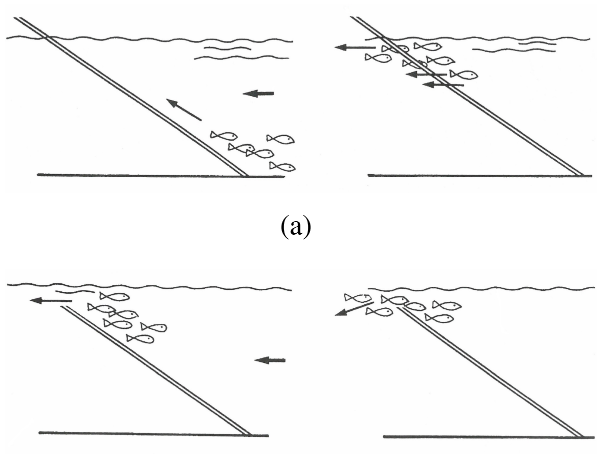
To test, improve or optimize fish passage facilities and fish protection systems, experiments with fish in laboratories are conducted to investigate the fish behavior under specific hydraulic conditions. This requires the knowledge of biologists and hydraulic engineers as well. In Germany, this new discipline is called «ethohydraulic» in reference to ethology and hydraulic (Lehmann et al. 2012; Lehmann 2013).

In comparison to field investigations, the fish tests under laboratory conditions i.e. controlled conditions enable the focus on one parameter after another to determine their influence on the fish behavior. Moreover, the laboratory fish experiments allow repetition of one test to confirm and improve the significance of the results obtained. The fish behavior can be documented by underwater video record.

Physical model tests are largely used to test the hydraulic conditions in fish passage facilities (Mader et al. 2011; Rajaratnam et al. 1986; Wang 2007). However, the introduction of fish in such models requires some adaptations. First of all, an authorisation to animal experiments can be necessary depending on the experiments conducted and the animal protection legislation of the country where they are executed. Moreover, to conduct fish experiments, adequate equipments are required like nets, grids or perforated plates to keep the fish in the flume without affecting the flow condition. Dip net and fish pool are likewise necessary to catch and hold the fish. Water parameters like water temperature, oxygen concentration or pH value have to be documented as they can influence the fish health and behavior. Moreover, to get reliable results it is essential to care about the model scale and document the hydraulic conditions. The flow condition in the experiment has to be identical to the one in the real fish passage facilities. The direct transferability of the results obtained in laboratory to nature is questionable and has to be implemented carefully. The investigations of fish behavior under simulate hydraulic situations enable to improve the knowledges concerning the fish behavior in relation to specific hydraulic conditions.

Already, many fish experiments for fish protection and downstream facilities were conducted and revealed new knowledges in Germany (Adam et al. 1999; Hassinger 2009; Hassinger et al. 2013; Hübner 2009; Hübner et al. 2011; Lehmann 2013), in Switzerland (Kriewitz et al. 2013), in England (Russon et al. 2010), in the USA (Amaral et al. 2001, 2005; Kynard et al. 2008; Lacey et al. 2012), in Canada (Enders et al. 2009; Katopodis et al. 2012a). Also in the VAO laboratory fish experiments were conducted and became a new research topic (Cuchet et al. 2009, 2011b; Geiger et al. 2012; Göhl 2004).

Several works are of special relevance for the present thesis. Already, in 1999 Adam et al. conducted fish tests to investigate the behavior of smolts in front of an inclined screen (α). The fish showed a positive rheotaxis and swam along the screen to the surface. An overflow of the screen strongly reduced the passage through the bars (see figure 2.27). Further studies of inclined screens were performed with eels (Hübner 2009; Russon et al. 2010) and fish from the bream zone (Hübner et al. 2011). The present thesis includes a profound study of fish protection at inclined screens concerning potamodromous fish from the trout and barbel zone.



(a)

(b)

Figure 2.27 Scheme representing the behavior of smolts at a 25° inclined screen without overflow (a) and with 15 cm overflow (b) (Adam et al. 1999)

3 Preliminary fish experiments at an inclined screen

3.1 Introduction

The main difficulty with regard to the design of fish downstream migration facilities is to achieve a good findability of the entrance to the fish pass. Otherwise, the fish have low probability to use the bypass, follow the main stream and pass through the turbine or are impinged at the screen. For these reasons, it is necessary to improve the attractiveness of the downstream migration facility entrance. One possibility might be to incline the screen at the turbine intake from the horizontal to shield the fish away from the turbine and lead them to a bypass at the surface. As described by Raynal et al. 2013a, the ratio between tangential velocity and normal velocity at the screen increases for a flat inclined screen. Thus, screens with low inclination angles should decrease impingement of fish at the screen and improve the guidance along the screen. An inclination lower than 25° is recommended by Courret et al. 2008. Actually these considerations are theoretically and exclusively based on hydraulic aspects, whereas the real reaction of the fish remains unclear. Therefore, the actual behavior of fish in front of an inclined screen should be investigated.

In the VAO laboratory, experiments with fish were conducted to study these issues. A preliminary test series was conducted in 2009 in a small experimental flume. It was followed by an enhanced large scale test series in 2010 which is described in chapter 4. The objectives of the preliminary tests were to gather experiences with fish experiments and to observe the fish behavior at the screen in order to reveal an eventual influence of the inclination on the fish guidance to the surface. The bar clearance of the screen was not accounted for in this test series. The experimental conditions have to be kept in mind when interpreting the test results. They cannot be directly transposed to real river sites. Nevertheless, they provided a first orientation and the initial point for further investigations.

3.2 Methodology

3.2.1 Fish collection and care

About 200 breeding brown trout (*Salmo trutta*) were supplied by the Chair of Aquatic Systems Biology (TUM). The fish were 10 months old and about 10 cm long. They were kept in circular pools with continuous water exchange and were not fed 24 hours before the test. Further 6 wild fish from a river close to the laboratory where temporarily kept in different pools. Their body length varied from 20 to 40 cm.

3.2.2 Experimental setup

The experiments were conducted in an open-air laboratory channel (see figure 3.1). The channel was 6 m long, 1.25 m wide, 0.47 m deep and supplied with water from the Isar River. The discharge was controlled by a gate valve with a maximal amount of 150 l/s. The water level in the flume could be adjusted with a gate at the downstream end of the flume. The velocity at the screen was measured with a propeller type current meter (Ott-propeller). Fine grids were installed at the upstream and downstream end of the experimental flume to keep the fish in the test zone. A fish net covered the whole flume to avoid fish escape, raptor attacks and input of leafs from the trees close to the experimental flume. The inclined screen was installed in the middle of the flume at the observation window. A screen bar clearance of 4 mm was chosen with regard to the fish width in order to avoid any passage through the screen. Four inclinations were investigated: α = 25, 35, 45 and 90° to the horizontal. The flattest screen inclination corresponded to 25°.

3.2.3 Experimental procedure

For all tests conducted, the discharge was 150 l/s and the water depth in the flume was 42 cm, which corresponded to a mean approach velocity at the screen close to 0.3 m/s. The screen was 5 cm overflowed on the whole flume width for each tested inclination. The fish pool was divided in 4 groups of 50 fish. In order to reduce any learning effects, each group was used only once within two weeks. The tests started with the introduction of 50 fish at the upstream side of the flume and ran for 48 hours. During the tests, the fish behavior could be observed and video recorded at the window. To avoid any disturbance of the fish by the light coming from the side, the observation window was most of the time covered with a board. Since the screen had a 4 mm bar clearance, the passage of fish downstream was possible only over the screen through the 5 cm overflow. After 48 hours the discharge was reduced and all fish were caught. The numbers of fish which stayed upstream of the screen and those which passed downstream were recorded. Three repetitions per inclination were performed. The climatic conditions like water temperature, weather and water turbidity were documented for each test.

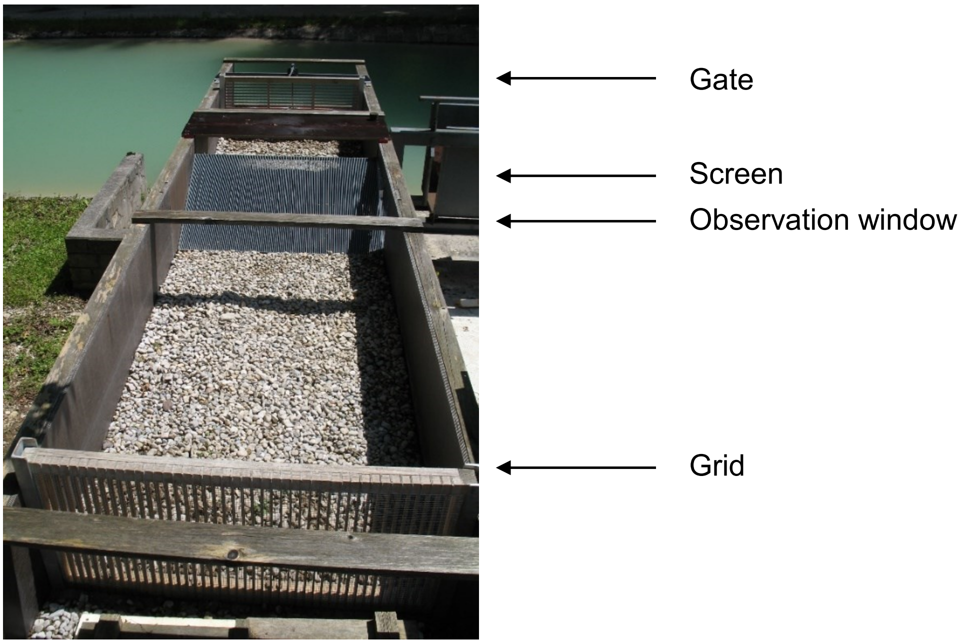


Figure 3.1 Experimental flume view from upstream

3.3 Results and discussion

3.3.1 Velocity at the screen

The approach velocity at the screen was measured for each inclination and showed values from 0.25 m/s on the middle of the screen to 0.3 m/s just before the top end of the screen. The small bar clearance (b_c = 4 mm) influenced the velocity distribution at the screen and explained the inhomogeneity. With a larger bar clearance, the velocity distribution along the inclined screen would not have varied so much between the middle and the top (Raynal et al. 2013a). The small bar clearance was chosen in order to identify those fish which passed over the screen by avoiding any fish passage through the screen. The narrow bar distance might also have improved the guidance of the fish to the surface in comparison to larger bar clearance.

3.3.2 Fish migration behavior in a laboratory flume

With an approach flow velocity of 0.3 m/s a positive rheotaxis could be observed. The small brown trout swam in swarm with the head against the flow. After the first test (α = 20°), all fish except one were caught upstream of the screen. Actually during that experiment no fish could be observed at the screen. They stayed in swarm at the upstream end of the test channel and did not approach the screen at all. Since the fish did not migrate downstream, the objective of the experiment could not be achieved.

A series of tests was conducted in order to stimulate the fish downstream migration. The resulting migration rates are summarized in figure 3.2. As described in Schwevers 2000, there are several parameters influencing downstream migration like the season of the year, the phase of the moon, water turbidity, river discharge fluctuation, light condition or water temperature variation. The only factor that could be easily control in the described experimental channel was the light condition. The second test was conducted with a board covering the screen and providing a dark zone in the screen area. Seven fish passed over the 20° inclined screen. The change in light conditions showed a positive effect on the fish migration downstream. It might be due to the low illumination and the protective function of the board covering the channel from eventual predation from the air. During the second test, the fish swam principally near the bottom covered with gravels where they seemed to look for refuge and food. To initiate fish movement, the gravels on the channel bottom were removed in test number three and only a smooth surface remained. No improvement in the downstream migration rate was observed. To make the upstream area even more repellent, the bottom was covered with a white surface in test number four. The screen area was further covered with a dark board to stimulate the passage over the screen. During this test, the water turbidity was very high which could as well have influenced the fish migration. Under these conditions half of the fish passed the screen. Since the water turbidity could not be controlled, another solution should be found to initiate migration. In test number five, a cage with two big brown trout was introduced in the upstream area. During this test the water was clear. Half of the fish passed over the screen. Face to the predator fish in the upstream area the small brown trout were encouraged to pass downstream.

Finally, the configuration of test number five was used for the test series concerning the investigation of the screen inclination. This setup included a white smooth bottom and a cage with two predator fish in the upstream area as well as a board covering the screen area (see figure 3.3).

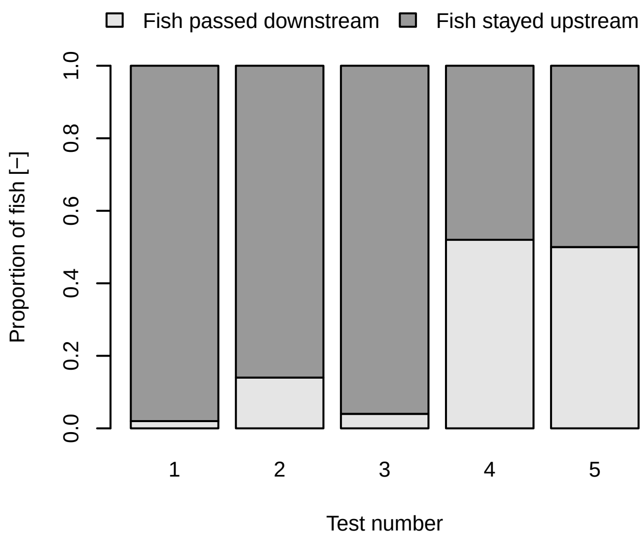


Figure 3.2 Observed migration rates during the optimization tests to initiate fish movement downstream with α = 25°

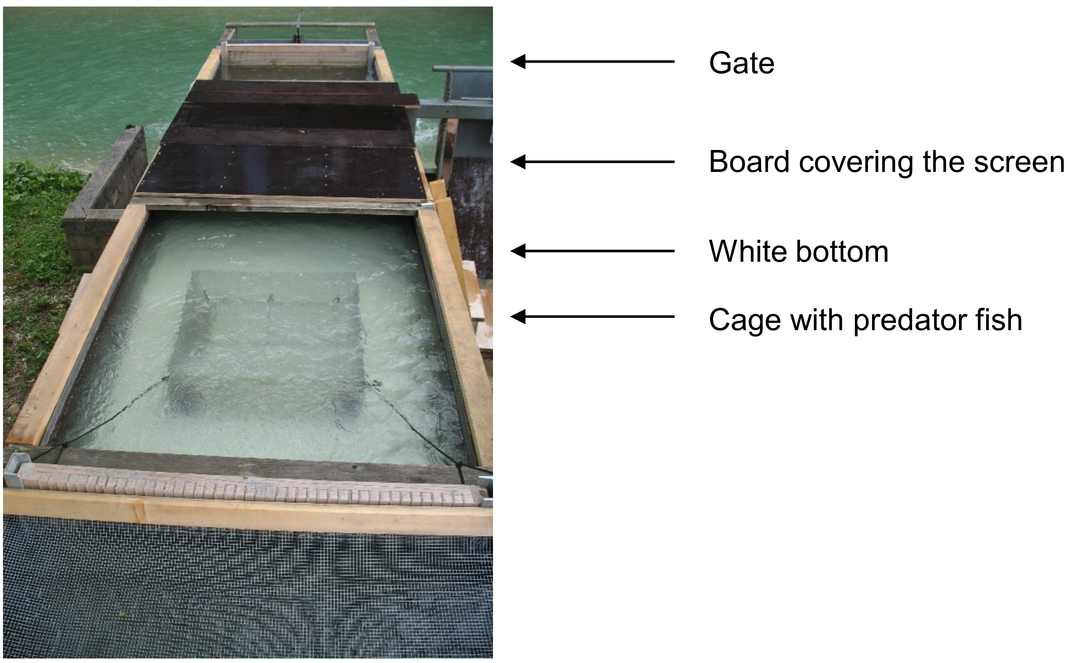


Figure 3.3 Experimental setup after optimization

3.3.3 Farm fish passage in function of the screen inclination

After the optimization of the channel to initiate fish movement downstream, the influence of the screen inclination on the fish passage could be investigated. It is evident that the experimental conditions were not optimal and that further parameters might have influenced the fish. Moreover, under these conditions the downstream migration was not natural. The presented results should be interpreted carefully. Nevertheless, the results provided a first idea of the fish behavior at an inclined screen. The experiments allowed gathering experiences with fish tests for subsequent projects in the VAO laboratory to investigate fish comportment.

Three repetitions per inclination were conducted with the configuration described before. The results obtained for the proportion of fish which passed over the screen in function of the inclination are presented in figure 3.4. The chances for the fish to pass downstream showed a slight tendency to decrease as the screen inclination increased: The fish had lower success to pass over a vertical screen than a low inclined screen. A vertical screen seemed to be repellent for fish and did not forward guidance to the surface.

In general, it could be observed that the fish avoided contact with the screen. However, for an inclination of 25° some fish were on the screen and let them drift to the top of the screen (figure 3.5). As the fish were at the downstream side of the screen, they had the possibility to swim back upstream by passing over the screen. It was quite unlikely but might interfere the results obtained.

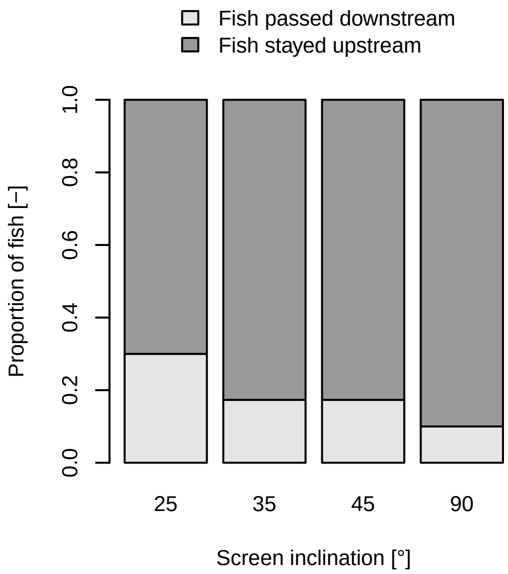


Figure 3.4 Passage of the farm fish to the downstream in function of the screen inclination

(a) $\alpha = 25°$

(b) $\alpha = 90°$

Figure 3.5 Brown trout at the 25° inclined screen (a) and at the vertical screen (b)

3.3.4 Wild fish passage in function of the screen inclination

Further tests were conducted with 6 wild brown trout from 20 cm to 40 cm body length. The objective was to examine if there was a difference in the behavior compared with the farm fish. The size difference was unfavorable for a direct comparison but had to be accepted with regard to the availability of fish. The cage with predator fish was removed and the wild fish introduced in the upstream area. After a few minutes the wild fish investigated the whole upstream area and were searching for a passage. The channel section seemed for them uncomfortable. Since the fish were very active the test duration was reduced to 5 hours. The results concerning the downstream passage in function of the inclination of the screen are illustrated in figure 3.6. Here again the tendency to pass downstream decreased as the inclination increased. A low inclined screen favoured the passage to the downstream and seemed to better guide the fish to the surface.

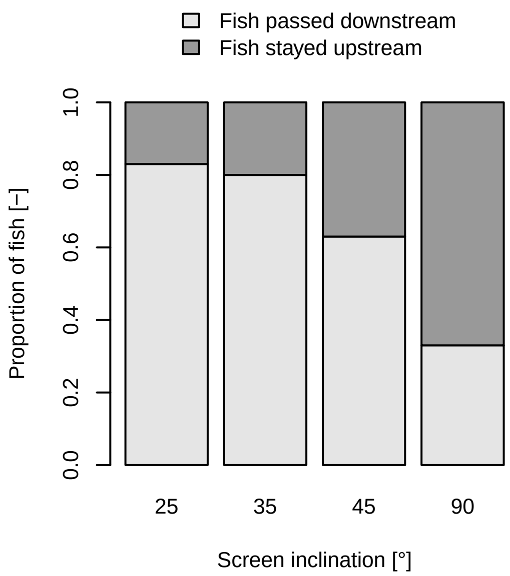


Figure 3.6 Passage of the wild fish to the downstream in function of the screen inclination

3.4 Conclusion

The preliminary tests aimed to gather experience with fish experiments in the VAO laboratory. The tests with small brown trout of farm origin showed that the migration downstream in the laboratory flume was not natural and had to be stimulated. By removing the gravels, covering the bottom with a white smooth surface in the upstream area and covering the screen area to provide a dark zone, it was possible to initiate downstream migration of the small fish. Moreover, a cage with predator fish was installed in the upstream area to improve the movement of the small brown trout. Four different inclinations were tested. The screen was 5 cm overflowed which allowed the passage downstream. A fine bar clearance of 4 mm was used to avoid any passage through the screen. The tests revealed that a low inclined screen allowed a better guidance of the fish to the surface. Similar conclusions were obtained for adult wild fish. In contrary to the farm fish, the wild fish showed a high swimming activity. A direct comparison was not possible since farm and wild fish had different body length.

The presented experiment provided a first approach of the fish behavior at a screen. The 4 mm screen bar clearance was used since it was the easiest way to differentiate the fish which passed over the screen or not, but it affected the hydraulic condition at the screen. A better solution to follow the fish passage is necessary. The use of predator fish to increase the migration induced the flight of fish which might have affected the actual behavior in front of the screen. Moreover, it was questionable whether the results of the fish experiments could be transferred to a larger scale. As the fish behavior is complex, further experiments in a bigger scale were required to confirm the observations. For further experiments in the VAO laboratory, it is recommended to prefer wild fish whenever possible.

4 Fish experiments at an inclined screen

4.1 Introduction

The following investigation was the chronological progression of the experiment described in chapter 3. The former fish experiments revealed that the inclination of the screen to the horizontal positively influenced the fish to swim to the surface. Furthermore experiments with fish on a one-to-one scale were conducted to get more detailed and reliable results. Three fish species were investigated in an outdoor channel at the VAO laboratory. By tagging the fish, detailed information on the fish passages was available. It enhances the knowledges concerning fish downstream migration activity of potamodromous species and their social behavior. The fish passage related to different screen configuration was recorded. This has allowed to precisely describe the influence of the screen inclination and the bar clearance on the fish passage through the screen and the guidance to the surface bypass. Finally, different configurations of the bypass were tested to develop an efficient passage downstream.

4.2 Methodology

4.2.1 Experimental Setup

The experiments were conducted in an open air lab flume. The rectangular concrete channel was 220 m long, 2 m deep and 2.48 m wide. It was supplied with water from the Isar River. The discharge could be regulated by a Rehbock flume gauge with a precision of $\pm$ 2 %. Over a length of 12 m the flume width was narrowed to 1.25 m in order to reduce the discharge necessary to get the intended approach velocity at the screen (figure 4.1a). The screen with rounded bar profile (40 mm x 10 mm) was installed in the narrow part of the channel. Four inclinations α = 20, 30, 45 and 70° to the horizontal and three bar clearances b_c = 20, 30 and 50 mm were tested (figure 4.1b). At the top of the screen a 3.25 m horizontal deck separated the flow towards the «turbine» and the flow towards the bypass. A vertical gate at the downstream end of the bypass allowed the regulation of the velocity and the water level in the bypass. Four different configurations of the bypass were tested (see part 4.2.4). About 20 m upstream and 10 m downstream of the inclined screen two grids with 1 cm mesh size were installed in order to keep the fish in the test section and stop floating debris or wild fish entering from upstream. A supplementary grid upstream of the test section was periodically cleaned from flotsam during the test to avoid a discharge reduction.

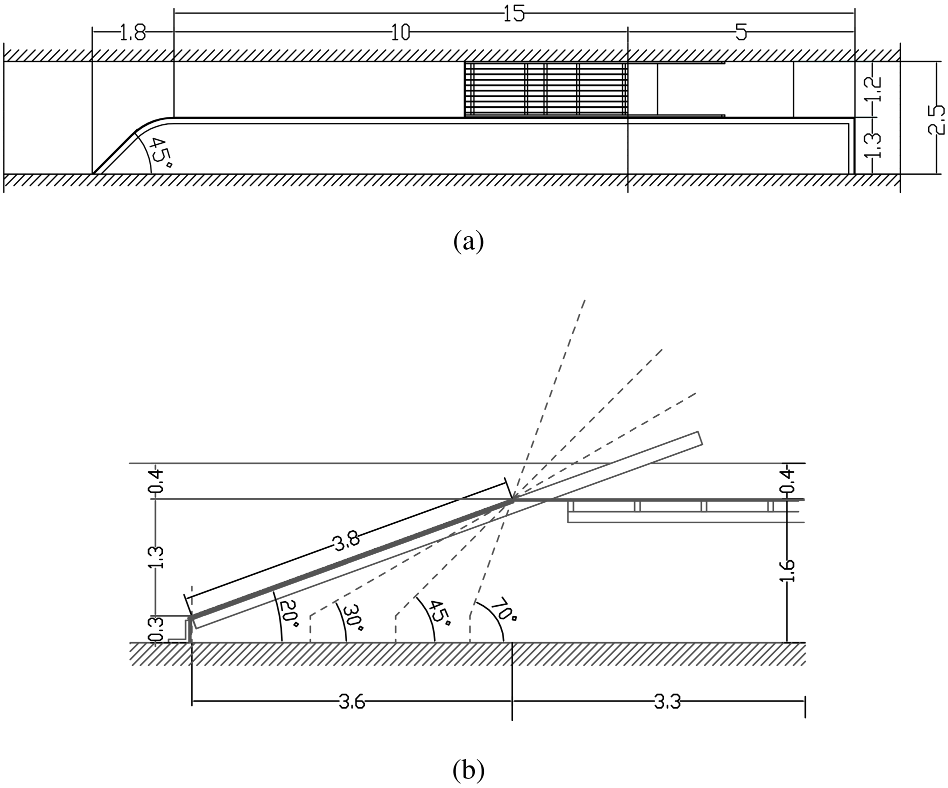


Figure 4.1 Plan view (a) and longitudinal section (b) of the experimental channel [m]

4.2.2 Fish collection and care

Three species were studied: Barbel (*Barbus barbus*), chub (*Squalius cephalus*) and nase (*Chondrostoma nasus*). They differ in their swimming behavior and habitat preferences and represent a major part of the ecological spectrum in the barbel region. Barbel and nase are typical bottom-dwelling species. Barbel prefer shelter and deep water especially during night-time, whereas nase rather select shallower and less structured bottom also during night-time. As a contrast, chub strongly prefer structured habitats such as wood, overhanging vegetation or riprap. A total of 63 barbel, 69 chub and 105 nase were caught in the Danube by EZB Consulting Office using electrofishing equipment. The fish size distribution is illustrated in figure 4.2. The fish width of all fish was measured at the end of the experiments series and is presented in figure 4.3. The relative body width (see equation 2.2) was $W_{barbel,rel} = 0.11$, $W_{chub,rel} = 0.12$ and $W_{nase,rel} = 0.10$. These values are consistent with literature (Ebel 2013). The physical fish passability P through the bars as described in equation 2.3 occurred consequently for a fish length smaller than 181 mm considering the barbel, 166 mm for the chub and 200 mm for the nase with 20 mm bar clearance.

The fish were held in two circular pools (2000 x 2000 x 700 mm) with a constant water supply from a spring and fresh water from the Isar River in order to adapt them to the water condition used during the tests. 50 fish per species with representative sizes of the available fish were kept in the first pool, while the rest of the fish were in the second pool as «reserve» fish. The pools were partially covered with boards to supply rest zones and totally covered with fine nets to avoid predation attack from outside and fish escape. Fish were fed in the pool. No food was supplied in the 12 hours period before the test began. The fish were handled by spoon nets and an adapted «fish barrow tank» was used to introduce them carefully in the test channel.

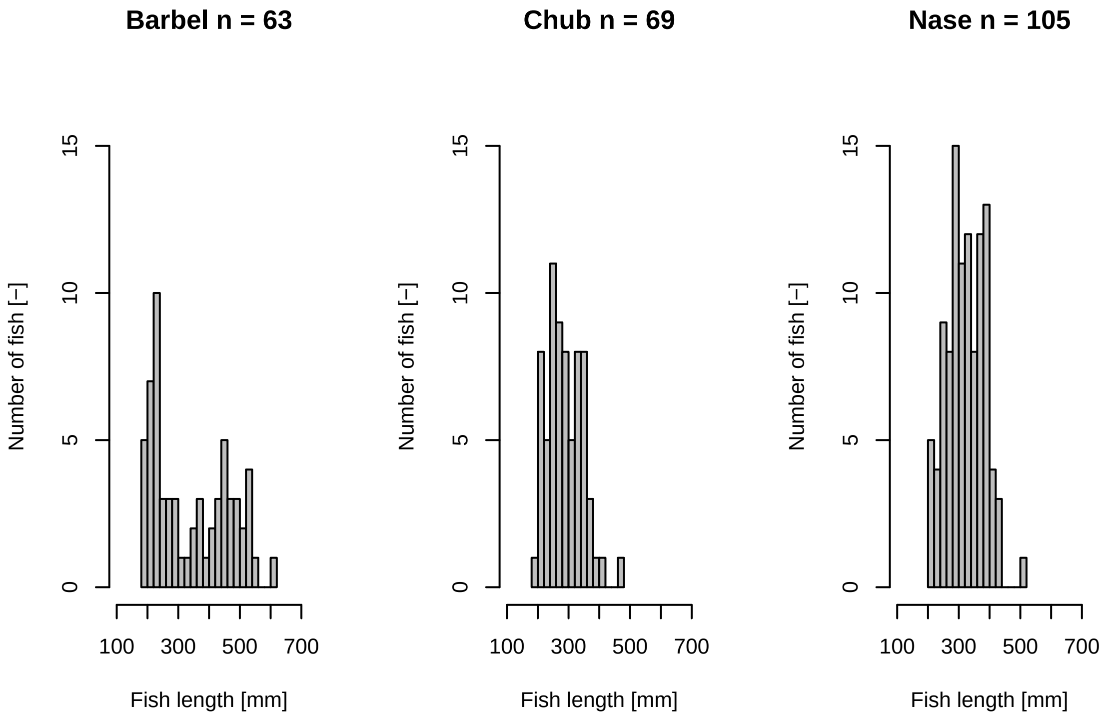


Figure 4.2 Fish size distribution, barbel (number of fish (n) = 63, mean fish length (L_{barbel}) 344 ± Standard deviation (SD) 123 mm), chub (n = 69, mean L_{chub} 290 ± SD 57 mm) and nase (n = 105, mean L_{nase} 325 ± SD 60 mm)

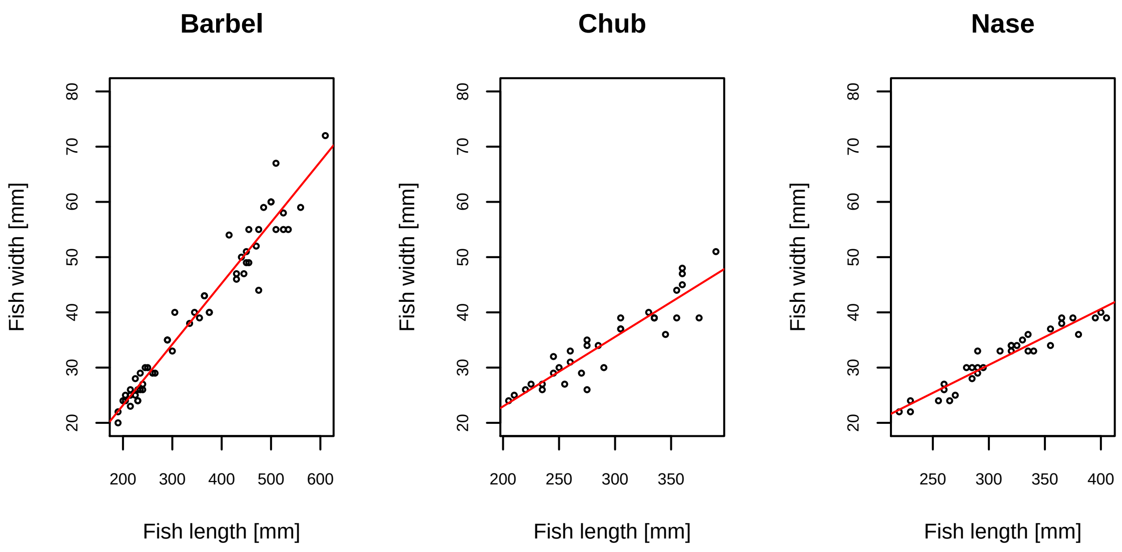


Figure 4.3 Linear regression for the fish length and width for each species

4.2.3 Fish monitoring

A Passive Integrated Transponder (PIT) tag was injected into the body cavity of each fish by EZB Consulting Office two weeks before the beginning of the experiments. PIT is a biotelemetry method which allows monitoring of fish passage (Castro-Santos et al. 1996). The chip (12 x 2 mm, Biomark) is passive and does not need any power supply. It provided for each fish a unique code which was recorded when the fish passed through a compatible antenna. Four antennas (61 x 61 cm) were provided by EZB. They were connected to a computer which recorded the passage of the fish during the whole test duration. Four squared PIT antennas were installed in the test section (figure 4.4): One at the top of the screen (A1) representing the bypass entrance, one at the end of the bypass (A2) and two superposed (A3 and A4) below the bypass which correspond to the turbine location. The antennas detected a PIT tagged fish when it approached to a distance of around 10 cm to the antenna. With regard to data storage and processing the antennas delay was set to four minutes, which means that one fish could be recorded one time within four minutes. The fish could be observed from the surface by taking care not to disturb their behavior. An observation window allowed the surveillance of the fish in front of the screen (figure 4.5). From there photos and video documentations were performed.

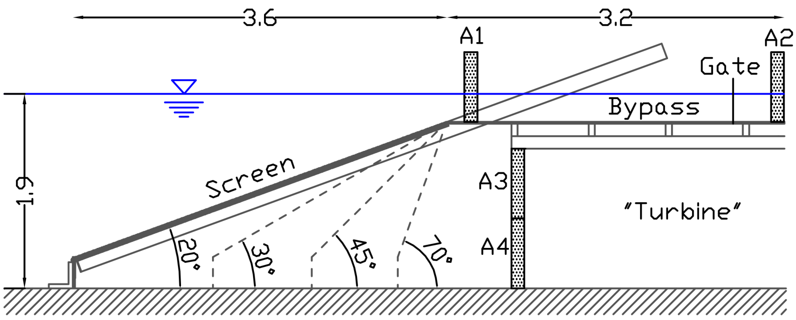


Figure 4.4 Longitudinal section of the experimental setup [m], A: PIT antenna

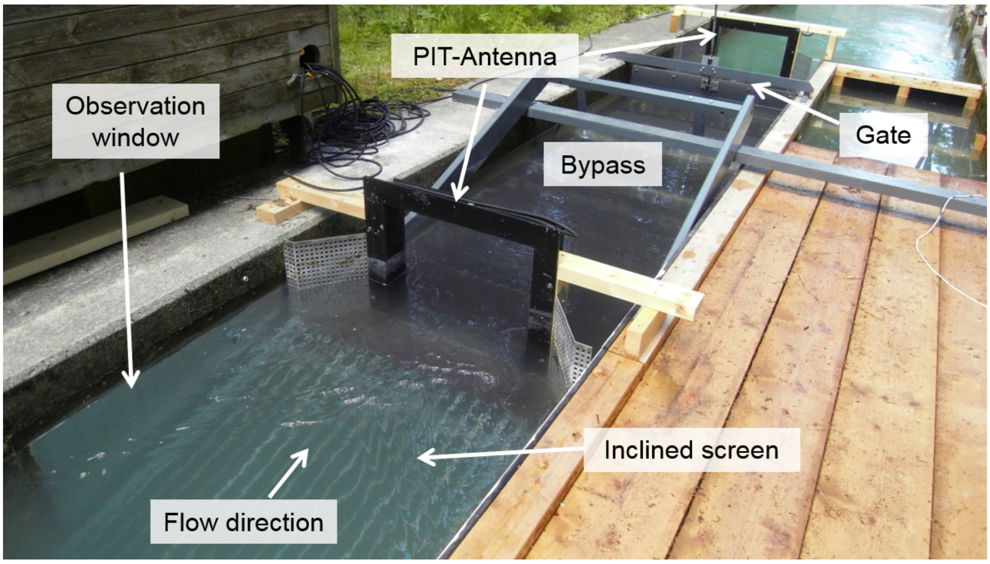


Figure 4.5 View from upstream of the experimental channel in operation

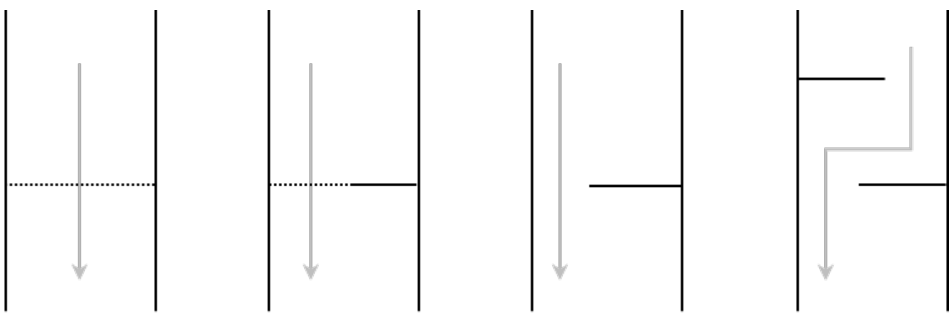


Figure 4.6 Schematic plan view of the bypass configurations, from left to right: Gate 5 cm overflowed (BP_1), gate 10 cm overflowed (BP_2), one slot (BP_3), two slots (BP_4), gray arrow: Main flow, dotted line: Gate overflowed

4.2.4 Experimental procedure

For all tests conducted the same procedure was performed: The test channel was supplied by 1.1 m^3/s from the Isar River and the water level was adjusted to 1.87 m at the screen. The target approach velocity at the screen of 0.5 m/s was controlled by an Ott-propeller at the beginning and at the end of each test. Two series of tests were conducted. The first one consisted in varying the screen inclination and the bar clearance and keeping the configuration in the bypass constant. The water depth in the bypass was 0.27 m and the gate was closed to get zero velocity in the bypass. The variation of the bypass configuration was realized in the second series of tests. Four different configurations were investigated (see figure 4.6). For all of them the inclination of the screen (α = 30°), the bar clearance (b_c = 20 mm), the water depth (W_{BP} = 27 cm) and the flow velocity in the bypass entrance (V_{BP} = 0.25 m/s) were kept constant. The first bypass configuration investigated, consisted of an inclined board with 5 cm overflow (BP_1). In the second configuration the overflow was reduced to half of the gate's width and the overflow depth was increased to 10 cm in order to keep 0.25 m/s in the bypass entrance (BP_2). The third configuration consisted of a vertical slot 25 cm wide on the right hand side (BP_3). The last one was done with two vertical slots, each 40 cm wide (BP_4) (see pictures in annexe A2). It has to be mentioned that the investigation of the bypass configuration was originally not included in the objective of the experiment. That is why these configurations were simplistic and no detail hydraulic measurements were conducted.

For both test series, the experiments were started between 7 and 9 o'clock a.m. by putting the fish in the headwater of the test setup about 18 m upstream of the inclined screen. However, some variation of the start time occurred because of technical problems or weather difficulties (see table 4.1). Each time 50 fish per species with representative size distributions of the available pools were employed. Water turbidity was measured at the beginning and at the end of the test by means of a Secchi disk. Water temperature was recorded during the whole test duration with a 5 minute interval. Each experiment ran 24 hours during which the four antennas recorded the fish passage. Along the test progress photos and videos were performed from the surface and from the observation window to document the fish swimming behavior and the flow conditions. A video motion detection software was installed to record fish as they reached the screen. The weather station in Einsiedl situated 2 km far from the model test was checked to gather information relating to the precipitation during the test. The day and night duration and the phase of the moon were as well documented. After 24 hours the discharge was considerably reduced and all fish in the test channel were captured. The health status of each fish was checked. As the fish were damaged, dead or missing (probably due to raptor birds), they were replaced by the «reserve» fish to get the same number of fish for the following test. The fish got at least 12 hours rest time in the pool between two tests.

Table 4.1 Chronology and configuration of the tests conducted, T_n: Test number, α: Screen inclination, b_c: Screen bar clearance, BP: Bypass configuration, V_{BP}: Bypass velocity

T_n [-]	Starting date [dd.mm.yyyy]	Starting time [hh:mm]	α [°]	b_c [mm]	BP [-]	V_{BP} [m/s]
1	15.07.2010	17:19	20	50	0	0
2	20.07.2010	07:30	20	20	0	0
3	27.07.2010	12:00	70	50	0	0
4	29.07.2010	07:45	70	20	0	0
5	03.08.2010	08:00	45	20	0	0
6	10.08.2010	08:30	30	20	0	0
7	12.08.2010	08:30	30	20	1	0.25
8	17.08.2010	08:00	30	20	2	0.25
9	19.08.2010	07:45	30	20	3	0.25
10	24.08.2010	07:45	30	30	0	0
11	26.08.2010	08:00	30	30	1	0.25
12	01.09.2010	08:45	30	20	4	0.25

4.2.5 Data analysis procedure

The PIT antennas provided a file in text format for each test. Each line corresponded to the signal of one fish which passed through an antenna. Considering all the tests, 81563 fish passages were recorded. The number of signals recorded during the 24 hours experiment duration varied between the tests. The output files from the PIT record consisted of four columns: The antenna number (1 to 4), the fish code which provided the fish species and fish length, the date and the time of passage. The files were imported to excel for data processing. Statistical analysis were performed using R free software environment (R Core Team 2013). Different regressions were carried out to estimate the relationships between the investigated variables.

4.3 Results and discussion

The PIT antennas recorded the fish passage along the whole experiment duration for each test and provided plenty of data. Variable aspects were investigated like the influence of climatic parameters, the screen and bypass configurations on the fish passage. The results are presented in the following parts.

4.3.1 Fish handling

Despite all the precautions taken, some fish did not survive the test series. Most of these fish died in the pools and not during the experiment. The death was probably due to fish conditioning and handling, resulting in stress, skin damage and fungal infections. As presented in figure 4.7, the nase was the most sensitive species with 50 % mortality compared with the chub 35 % and the barbel 10 %.

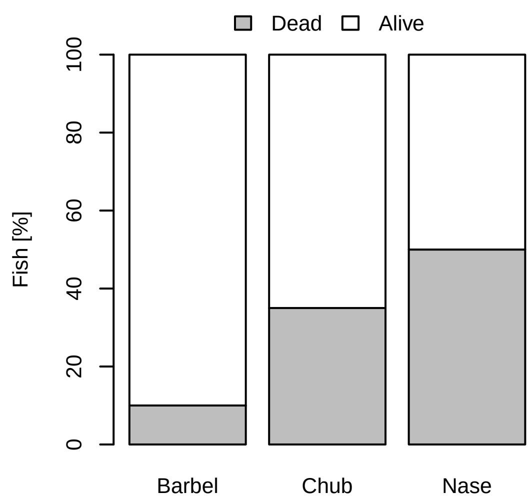


Figure 4.7 Fish mortality during the 2 months test period

4.3.2 Test reproducibility

Within 50 days, 12 different tests were conducted. No repetition could be realized because of time limitation. In order to prove the reproducibility of the test results, a statistical analysis was conducted between five tests with the same screen inclination (α = 30°) and the same bar clearance (b_c = 20 mm). The test conditions only differed with regard to the bypass configuration. However, the bypass configuration had no influence on the passage through the screen (see section 4.3.11.2). Therefore the tests number

6, 7, 8, 9 and 12 could be compared considering the number of fish passing through the screen. After extracting the first passage of each fish for the five tests a one-way analysis of variance (ANOVA) was used to test for significant differences between the means among the five tests. In annexe A1, the ANOVA method is described. It revealed that the passage of fish did not differ significantly across the five tests: F (4, 453) = 0.453, p = 0.77. These tests yielded consequently similar results and it can be considered that the tests were reproducible under the same hydraulic and climatic conditions.

4.3.3 Test duration

Fish migration might vary between day and night (Ebel 2013). The test duration was set to 24 hours in order to have the whole day cycle. Moreover, it provided time for the fish to adapt themselves to the conditions in the channel. To evaluate if the test duration was sufficient to get as much as possible fish record, the cumulative number of different fish detected by the four PIT antennas per hour was calculated for each test. The results are represented in figure 4.8 in function of the test duration. None of the tests recorded the entire number of fish introduced (n = 150). Except for the test number 4 (α = 70°, b_c = 20 mm), all of the tests showed the same trend: The number of fish detected strongly increased up to the thirteenth hours. From the thirteenth hours of test duration the number of fish detected by the antennas stayed constant or was only slightly increasing. The few number of fish detected during test number 4 revealed a repulsing effect of the steep screen on the fish which were therefore not trying to swim downstream (see section 4.3.11.2). Consequently, the 24 hours test duration was sufficient to get the most of active fish since they were detected during the first thirteen hours. Further parameters could be investigated by keeping a 24 hours test duration. For example water temperature or light condition might influence fish activity (Schwevers 2000).

4.3.4 Migration activity in function of the species

In the present study, an active fish was defined as a fish which passed at least one time through one PIT antenna during a test. On the other side a fish which was not detected by any antenna was considered as an inactive swimmer because it did not search to migrate downstream. The proportion of active fish per hour p_f was calculated for each species as follows:

$$p_f = \frac{n_a}{n_t} \tag{4.1}$$

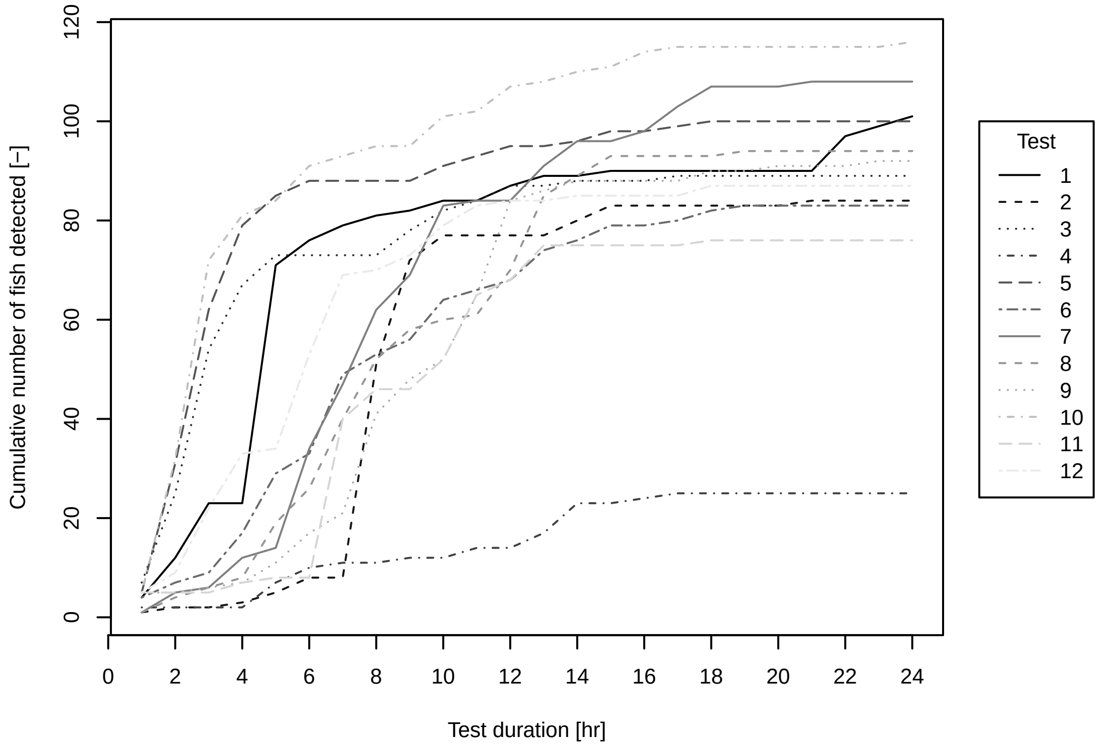


Figure 4.8 Fish activity along the test duration

where n_a was the number of different fish detected within one hour and n_t was the total number of fish introduced at the beginning of the test: 50 fish per species, 150 fish all species together. The process led to 288 data sets (24 hours per test and 12 tests). Figure 4.9 illustrates the difference in the fish migration activity between the three species studied. The box plot representation shows the data distribution: Minimum and maximum value, median, lower and upper quartile and outliers. The barbel was the most active species followed by the chub and the nase as last one. This revealed differences in the activity to swim downstream for the species studied under the employed experiment conditions. Along their whole life, potamodromous species migrate in both downstream and upstream directions in the river (Schwevers 2000). They swim upstream to spawn and swim downstream after the spawning season. Barbel are spawning between May and July, chub between April and June and nase between March and May. The presented study was conducted between the middle of July and the beginning of September. For all of the three investigated species the spawning season was over. The end of the spawning season of the barbel concords with the beginning of the test period. It could explain the high activity of the barbel for the downstream migration. Further parameters influence fish migration and swimming activity like the water temperature and the moon phase.

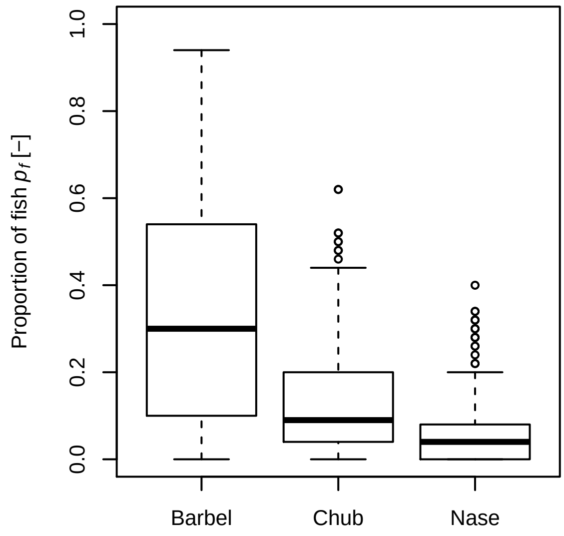


Figure 4.9 Fish activity in function of the species

4.3.5 Time of the day

The proportion of fish registered p_f as defined in equation 4.1 in function of the time of the day is represented in figure 4.10 for the three species. The species studied showed a similar response to the time of the day. Three main phases could be distinguished: The first one in the morning with an increase in the activity corresponding to an adaptation phase of the fish to the experimental conditions, the second phase from midday to late evening with a high activity and the last one from late evening to the early morning with a decrease in activity. The barbel had a high activity between 14:00 to 22:00, the chub and nase between 14:00 and 20:00. The lowest activity was observed at dawn, the higher activity at dusk. As described in Zitek et al. 2004b, downstream migration is higher during dusk and dawn, in particularly for juvenile fish. The activity of fish varied along the day as well as the water temperature and the illumination. The influence of these parameters on fish migration activity was also investigated and is described in the following parts.

4.3.6 Water temperature

The water temperature in the experimental channel was recorded every 5 minutes during the whole test duration. The water supply came from the Isar River. Figure 4.11 shows the temperature evolution during the day considering all the tests executed. The measures revealed a temperature between 6.99 and 14.27°C with a mean of 10.4°C. From 18:00 to 22:00, the temperature reached the maximum value. The lowest

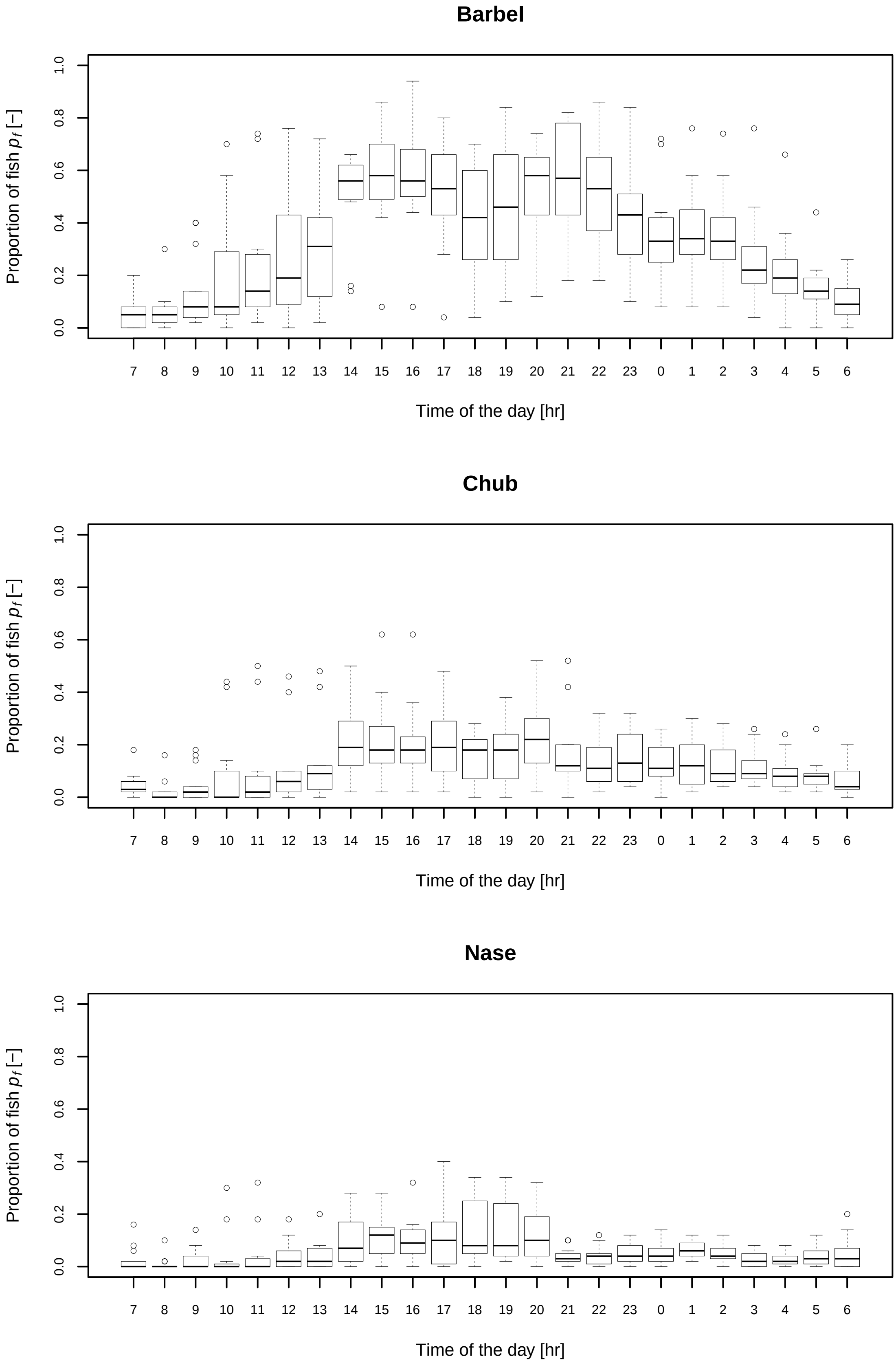


Figure 4.10 Fish activity along the day considering all tests

temperature was measured in the early morning. As fish are poikilothermic animals their body temperatures follow closely the temperature of the ambient (Hart et al. 2008). Water temperature can thus influence the growth, the metabolism, the food intake, the spawning and the swimming capabilities of fish. Depending on the fish species and fish size the thermal optimum range varies. Actually the water temperature in the barbel region where the experimental fish originated, fluctuates between 12 and 18°C. It is much warmer than the actual temperature in the laboratory: 6.99 to 14.27°C. In order to see if the water temperature influenced the fish, the proportion p_f of fish active in function of the water temperature measured is represented in figure 4.12.

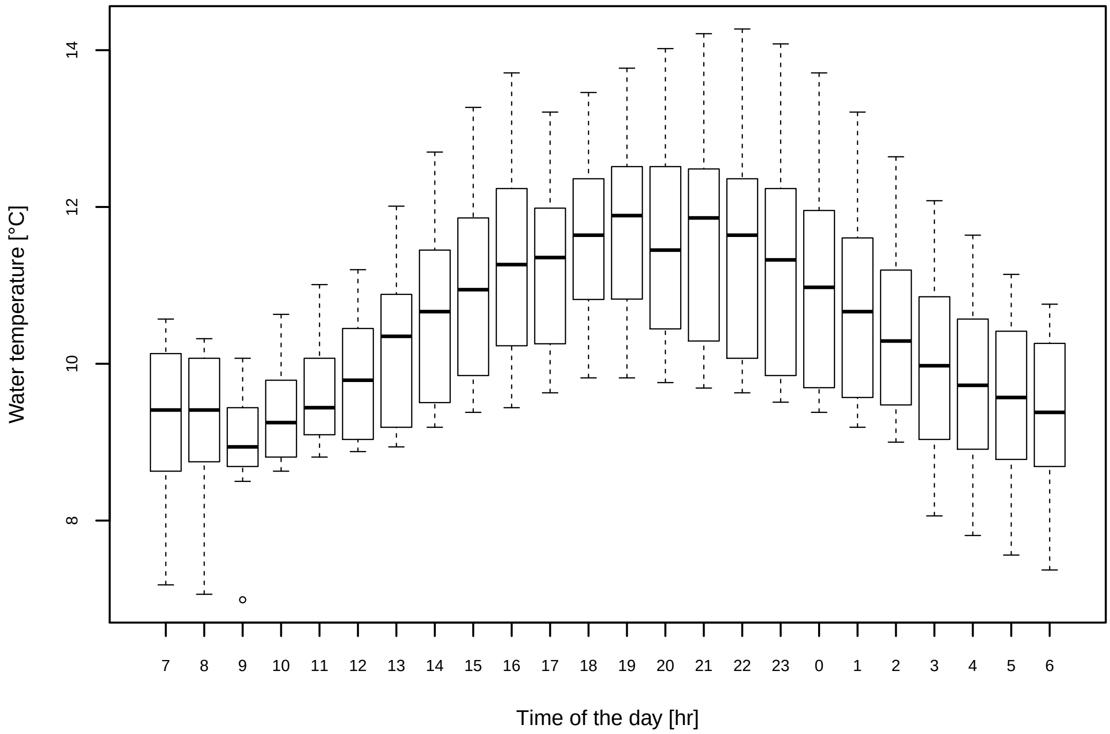


Figure 4.11 Water temperature evolution along the day considering all tests

To reveal an eventual relationship among the water temperature and the fish activity, a simple linear regression was performed in R for each species. p_f was the response variable and the water temperature was the explanatory variable (see annexe A1 for statistical method). The proportion of active fish could be predicted from the water temperature by the following formula:

$$p_f = \beta_0 + \beta_T \times T \tag{4.2}$$

where p_f was the fish activity as described in equation 4.1, β_0 was the intercept (value at which the fitted line crosses the vertical axis), β_T was the regression coefficient

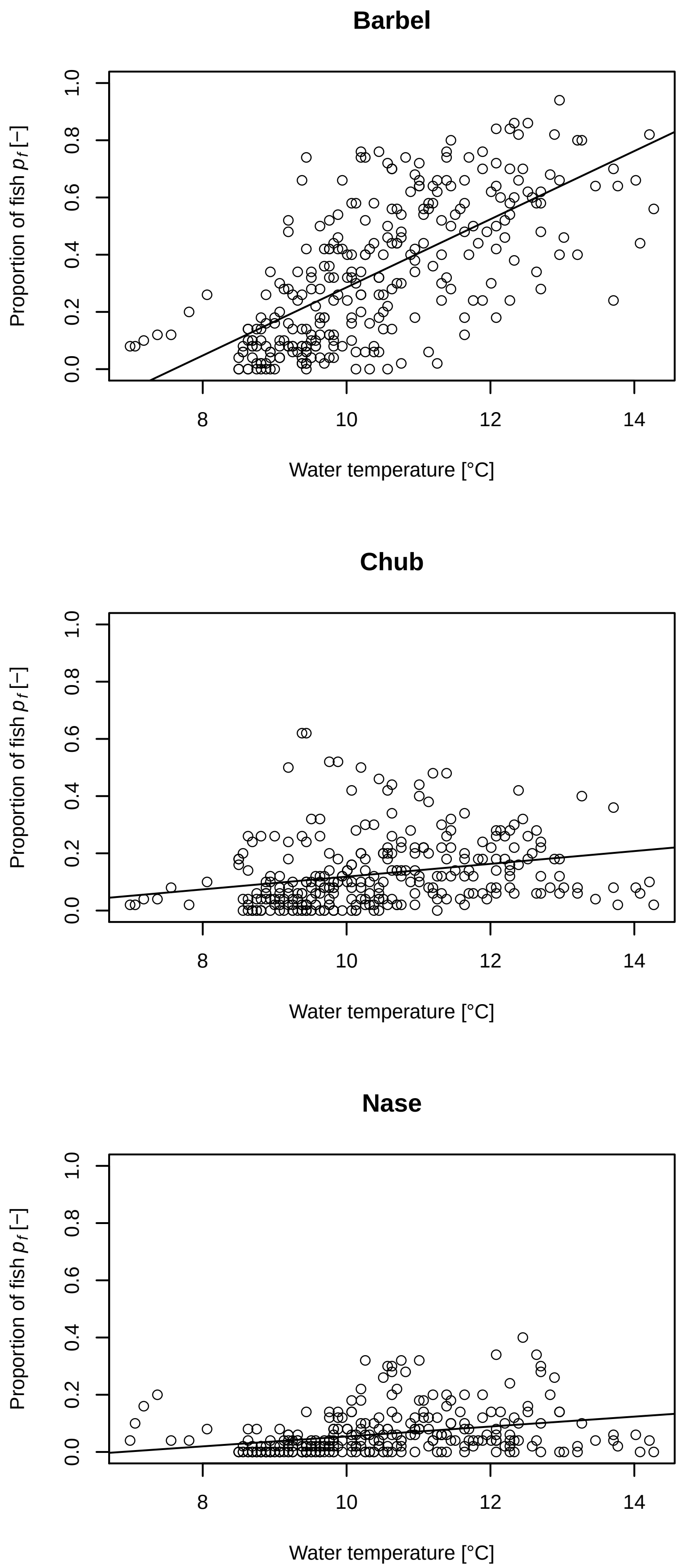


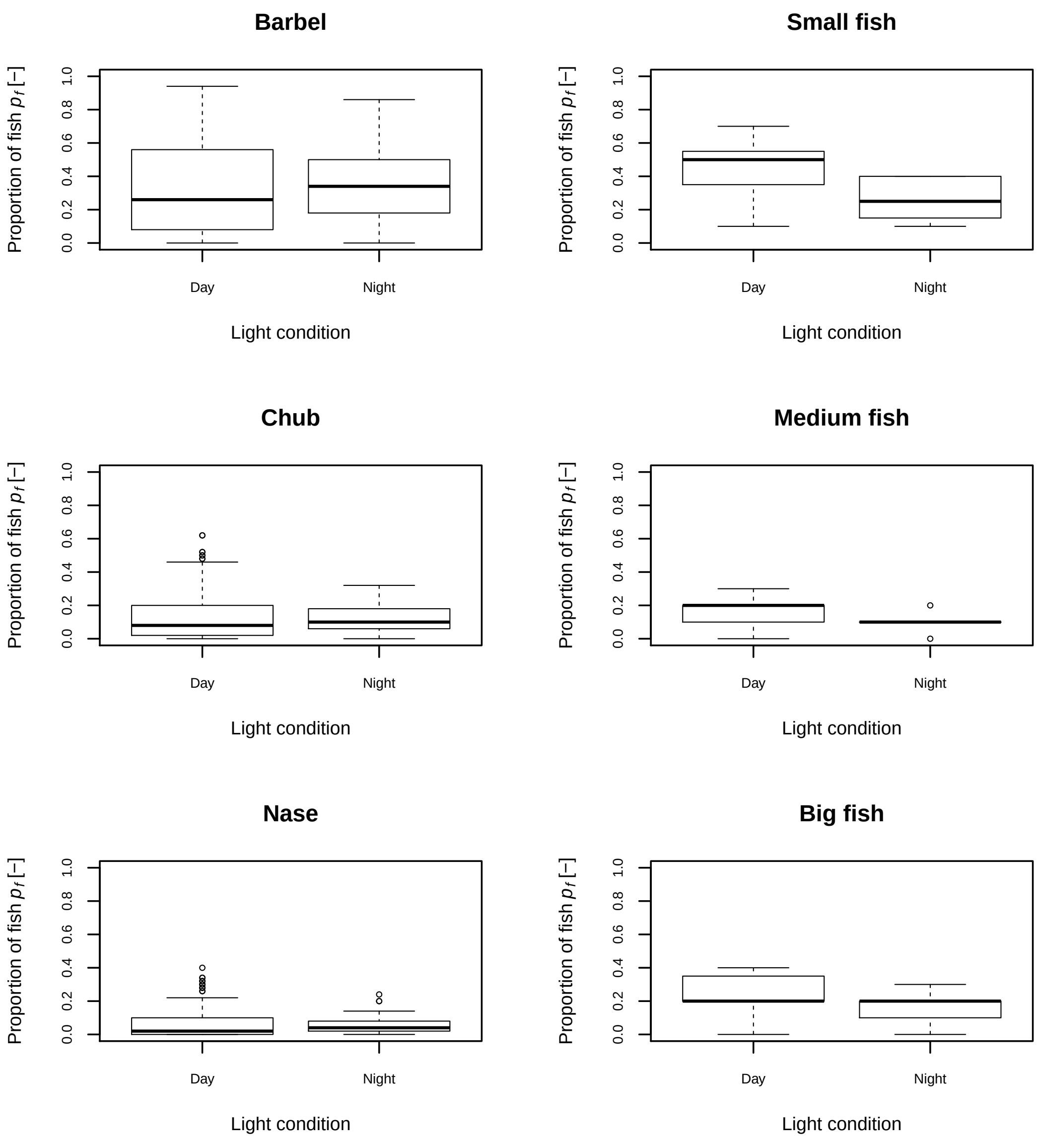
Figure 4.12 Fish activity and water temperature considering all tests

i.e. the slope of the regression line and T was the water temperature in degree celsius. The regression line is represented in figure 4.12. The regression carried out revealed that the water temperature significantly influenced the proportion of the active barbel ($\beta_T = 0.119$, $p < 0.05$), chub ($\beta_T = 0.022$, $p < 0.05$) and nase ($\beta_T = 0.017$, $p < 0.05$). Moreover, the regression coefficient had for all of them a positive value: The fish activity was increasing with the water temperature. This observation is valid only in the water temperature range studied (from 6.99 to 14.27°C). As illustrated in figure 4.12 and confirmed by the regression coefficients, the species reacted differently to the water temperature increase. The barbel was the most active fish followed by the chub and the nase as last one. The difference in activity between the species could be explained by their optimum temperature range. Considering the nase, the optimum temperature range is between 15 and 24°C (Souchon et al. 2012). It is above the water temperature range in Obernach (6.99-14.27°C) and could explain the low activity of the nase by inhibiting their swimming capacity. The same could explain the low activity of the chub which have an optimum temperature range between 14 and 24°C (Ebel 2013; Souchon et al. 2012). However, the temperature range in Obernach is closer to the barbel's preferences (10 and 24°C, Souchon et al. 2012) and could justified their high activity compared with the other species.

Moreover, the effect of the temperature increase was investigated. The difference in water temperature between two following hours was calculated in function of the proportion of active fish p_f. A regression was carried out to see if the water temperature difference (explanatory variable T_d) influenced the fish activity (response variable). The regression revealed no influence for the chub and the nase ($p > 0.05$). However, the regression executed for the barbel featured a significant effect ($\beta_{Td} = 0.055$, $p < 0.05$). Therefore, both the water temperature and the increase in temperature between two following hours, influenced the downstream migration of the barbel under the presented conditions.

4.3.7 Diurnal variation

Diel pattern of fish activity vary in function of the species, the life cycle and the season (Helfman 1986). As observed by Schmalz 2010; Zitek et al. 2004b and Prchalova et al. 2006, fish migrate downstream mostly during the night. However, this pattern may change in function of the season (Prchalova et al. 2006). Light has an influence on the water temperature, the visibility of the fish, the exposition to predators and the migration. To reduce the risk of visual predation, fish may avoid migration during light period and migrate during night and twilight. According to Pavlov et al. 1989



(a) (b)

Figure 4.13 Fish activity and light condition in function of the species (a) and the size category (b) considering all tests fish lose their visual capacity in the night and let themselves be drifted. The visual capacity of fish get better as the fish grow up; the smaller fish tend to drift by higher illumination as the big ones (Ebel 2013).

As the test ran 24 hours, a change in the fish activity among day and night might be apparent. The proportion of active fish p_f in function of the light phase and the dark phase of the day is represented in figure 4.13a for each species. The differentiation between day and night was set to the time of sunset and sundown for each day. Because the tests were executed along a period of 2 months, the length of the night increased with the number of the test. As the response variable; the proportion of active fish, was continuous and the explanatory variable, the light condition, was categorical with two levels (day/night) a one-way analysis of variance (ANOVA) was proceeded. The ANOVA revealed no significant influence of the light condition on the fish activity for the barbel and the chub ($p > 0.05$). On the other side, the nase was significantly influenced by the light condition and featured a higher activity during the day: $F(1, 290) = 4.21$, $p < 0.05$. Further analysis were carried out by distinguishing the fish size in three categories: The small one corresponding to fish smaller than 20 cm body length, the medium one from 20 cm to 40 cm and the big one up to 40 cm. An ANOVA was as well carried out and revealed a difference between the size categories (figure 4.13b). The small $F(1, 22) = 7.415$, $p < 0.05$ and medium fish $F(1, 22) = 5.5$, $p < 0.05$ showed a significantly higher activity during the day, while the big fish ($p > 0.05$) revealed no difference between day and night. The visual capacity could explain these results. The small and medium fish might have rested upstream from the antennas in a calm zone during the night because of their relatively low ability to see. In contrary, the bigger fish might have better visual abilities and stayed active also during the night.

4.3.8 Lunar cycle

The lunar cycle has an effect on the behavior and physiology of animals (Zimecki 2006). The fish migration activity is as well influenced by the moon (Ebel 2013; Holzner 2000). The exact effect on fish is not fully understood yet. There are different theories considering the moon's influence on fish activity. One of them is that the moon illumination is the factor causing the change in behavior. As observed by Horky et al. 2006, the moonlight may increase or inhibit fish activity. The visibility of nocturnal predators is higher by times of full moon which may increase their activity. On the other hand the prey fish might decrease their activities by full moon to avoid fish predator attack. In return the prey fish might be more active during the new moon since the illumination and the risk of predation are lower. On the other side, the full

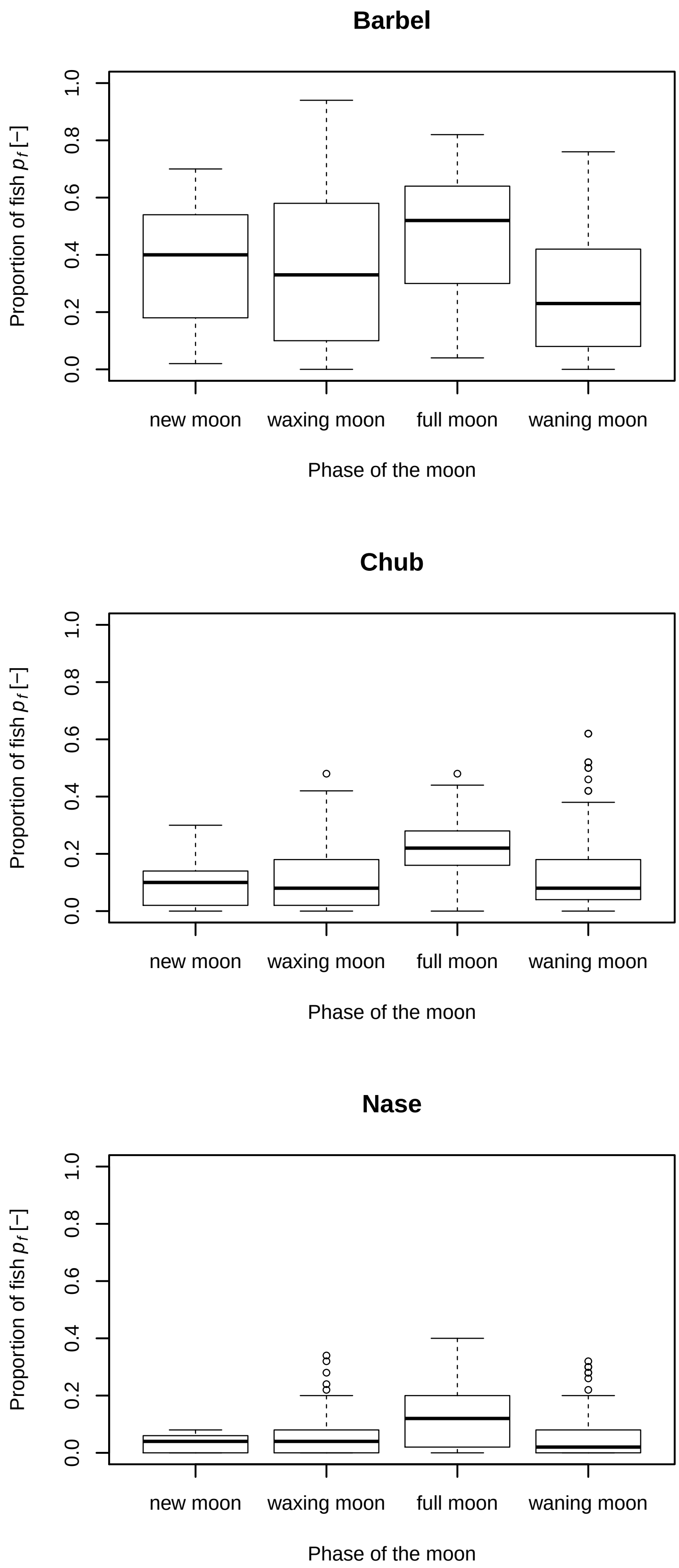


Figure 4.14 Fish activity and phase of the moon considering all tests

moon has for example an inhibitor effect on the eel migration (Adam et al. 1994), which prefer to move during the waning moon and just before the new moon phase. Experiments with silver eel isolated from the natural light conditions show that the eel were still influenced by the lunar cycle (Jens 1953). The gravitational force is meant to explain this reaction. The «solunar theory» developed by John Alden Knight in 1926 and used by fishermen to get the best period to fish says that the moon influences the eating habits of fish and that the highest activity is during the new or full moon when the gravitation force is the strongest.

A one-way ANOVA was carried out to assess the effect of the moon on the fish activity during the tests. The explanatory variable (moon phase) had four levels: The new moon, the waxing moon, the full moon and the waning moon. For the three species, the moon revealed a significant influence on the fish activity (barbel: $F(3, 288) = 6.819$, $p < 0.05$, chub: $F(3, 288) = 7.11$, $p < 0.05$, nase: $F(3, 288) = 9.28$, $p < 0.05$). A post-hoc Tukey's HSD test which allows multiple comparisons was proceeded between the four phases of the moon. Figure 4.14 illustrates the results. Chub and nase showed a higher activity during the full moon ($p < 0.05$) compared with the other moon phases. The barbel had a higher activity during the full moon only compared with the waning moon ($p < 0.05$) while the difference with the other phases was not significant ($p > 0.05$). The barbel showed also a higher activity during the waxing moon compared with the waning moon ($p < 0.05$). All other comparisons were not significant ($p > 0.05$). The moon phase effectively influenced the fish activity during the experiments with a higher activity during the full moon. It might be due to the illumination which could improve the fish visibility. Further analysis should be realized to distinguish whether fish activity is influenced by the moon illumination and/or the gravitation force.

4.3.9 Water turbidity

During the experiments, water turbidity was measured by means of a Secchi disk. The turbidity was scaled from 0 to 10. The value 0 featured murky water and the value 10 limpid water. A one-way ANOVA was conducted to assess the influence of the water turbidity on the fish activity. The explanatory variable had two levels: Murky (secchi scale from 1 to 5) and clear (secchi scale from 6 to 10). The barbel showed a significant higher activity for clear water as for murky water ($F(1, 290) = 11.16$, $p < 0.05$). On the other side the nase and the chub were not influenced by the water turbidity ($p > 0.05$) like illustrated in figure 4.15. The turbidity decreased the fish ability to see and might therefore reduce the activity of the barbel. Moreover, murky

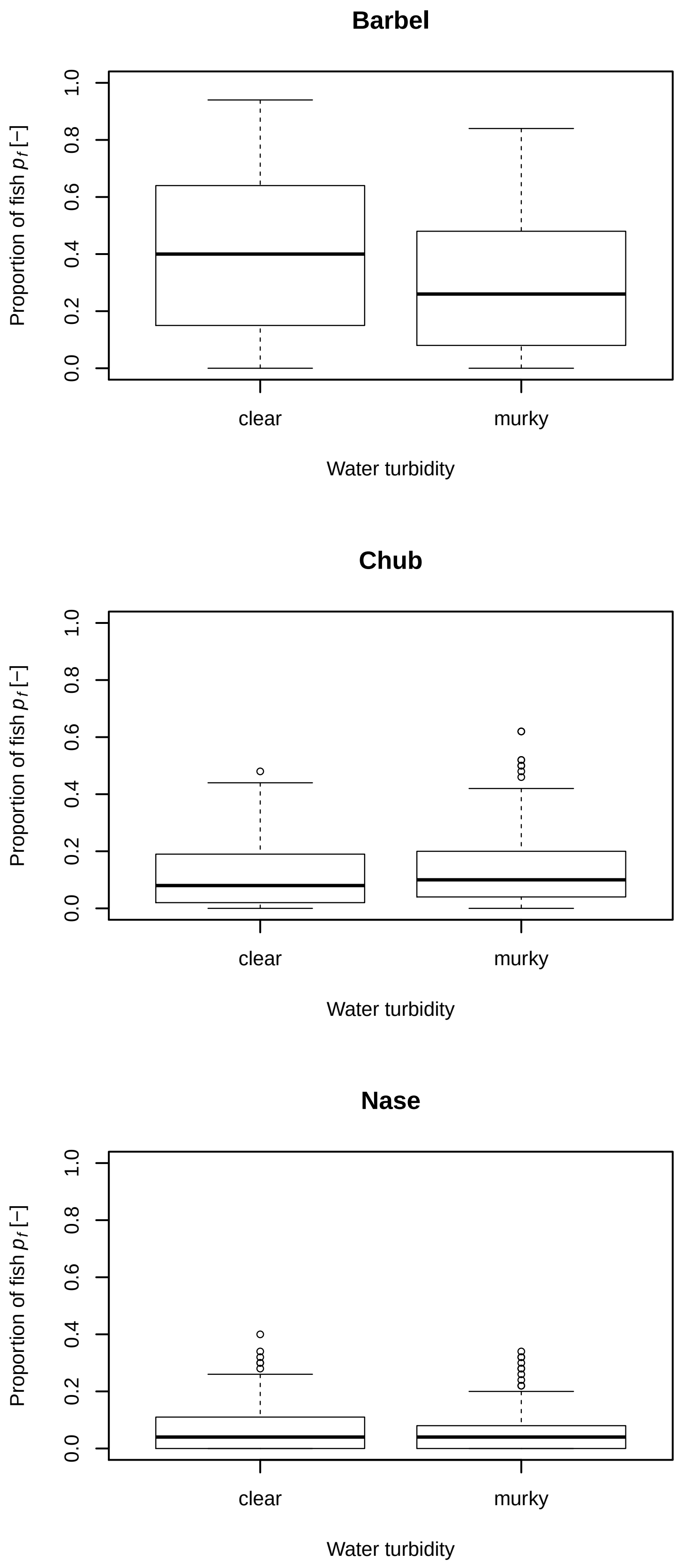


Figure 4.15 Fish activity and water turbidity considering all tests

water was usually induced by precipitation which entailed colder water temperatures. This might also cause or contribute to lower activity.

4.3.10 Social behavior

The social behavior of the fish was documented by video records from the observation window. The three species showed different behavior: The barbel seemed to swim more often in swarm compared with the nase and the chub. In order to quantify this observation, the data concerning the fish passage through each antenna were considered. For all the tests conducted and the whole test duration, the number of fish passing through an antenna within a delay of one minute was extracted to evaluate the swarm size. Up to 19 fish were recorded in one swarm. Four swarm categories were distinguished: The first one was one fish swimming alone, the second one a group from 2 to 5 fish, the third one from 6 to 9 fish, and the last one equal or bigger than 10 fish. The relative frequency of each swarm group was calculated for each species considering all the tests. It is represented in figure 4.16. In 72 % of the time the nase swam alone against 64 % for the chub and 47 % for the barbel. The barbel swam in 48 % of the time in groups between 2 and 5 fish. Up to 17 barbel were registered in one swarm. This consideration confirmed the observed differences in the social behavior of the three species. The barbel and chub swam often in swarm in contrary to the nase which moved downstream mostly alone. As regards the barbel and chub, these conclusions are according to literature references (Freyhof et al. 2008; Penaz et al. 2002). Thus the fish showed a rather natural behavior despite the laboratory condition. Therefore a good transferability of the results obtained from the fish experiments to the nature might be expected.

Moreover, the distinction between the four PIT antennas revealed that 60 % of the time the fish swam alone during the passage through the screen against 40 % during the passage to the bypass. The passage into the bypass seemed more intentional than the one through the screen, since the fish stayed in swarm as they reached the bypass entrance. The passage through the screen was probably forced by exhaustion.

The composition of species inside each swarm was analysed. The pie chart in figure 4.17a provides the species composition of the swarms registered. The intraspecific swarms, composed of one species, were representing 48 % for the barbel, 4 % for the chub and 1 % for the nase. The interspecific swarms, composed of different species, were in 45 % of the case including the barbel. The barbel showed a strong social behavior. They swam in intraspecific swarm as well as interspecific swarm. The chub and nase swam rather together with other species.

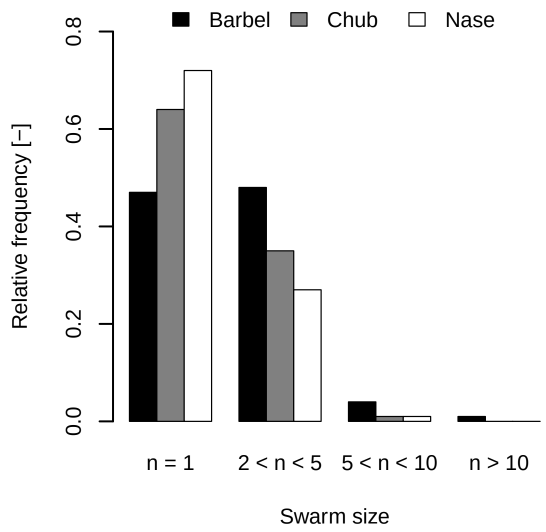
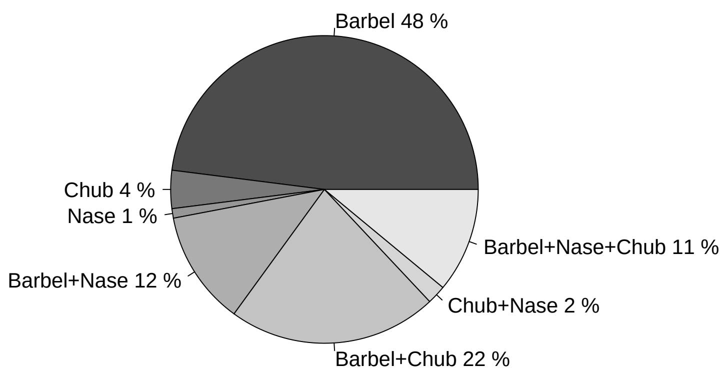
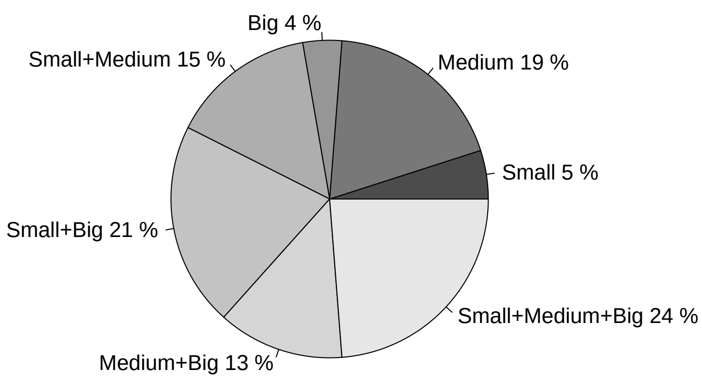


Figure 4.16 Relative frequency of the swarm size for each species



(a)



(b)

Figure 4.17 Intra and interspecific swarm composition (a) and composition of the swarms relating to the size category (b)

Furthermore, the fish size categories inside a swarm were distinguished (figure 4.17b). A big fish, longer than 40 cm, was present in 58 % of the all swarms registered. It was confirmed by the video records where the bigger fish were often observed as leader fish followed by smaller ones. Here again despite of the laboratory condition, the fish showed a social behavior like under natural condition.

4.3.11 Screen configuration and fish passage

A total of 12 different tests were conducted by varying the screen inclination (20, 30, 45, 70°), the bar clearance (20, 30, 50 mm), the bypass configuration and the velocity in the bypass entrance like described in table 4.2. With 50 fish per species and 24 h test duration, up to 14780 signals were recorded within one test. In order to evaluate the fish behavior in front of the screen and the findability of the bypass, only the first passage i.e. the first signal for each fish was considered for every test. Figure 4.18 gives an overview of the results for all tests conducted by representing the part of fish passing through the screen and the part swimming to the bypass entrance.

Up to 150 fish passages could be reported since only the first passage of every fish was considered. However, between all tests a difference in the number of fish recorded was observed. For the test number 4 corresponding to α = 70° and b_c = 20 mm, the number of fish recorded was near 20 which was very low compared with the other tests (mean = 79). The almost vertical screen seemed to be repellent for the fish: They were neither passing through the screen nor to the bypass (like observed in section 4.3.3). The fish stayed upstream from the screen and did not try to search for another passage. As expected, the number of fish passing through the screen differed with the test, i.e. the screen configuration. The tests with the largest bar clearance, test number 1 (α = 70°, b_c = 50 mm) and 3 (α = 20°, b_c = 50 mm) showed the biggest partitions of fish passing through the screen. Compared with the 20 mm bar clearance, the tests number 10 and 11 with b_c = 30 mm induced also more passage through the screen but not as much as with b_c = 50 mm. The bar clearance showed a strong influence on the fish passage through the screen. Like expected, the flattest screen with the smallest bar clearance (Test number 2, α = 20°, b_c = 20 mm) gave the best results with no fish passing through the screen and about 80 fish reaching the bypass entrance. A low inclination of the screen seemed to help the fish to find the bypass at the surface. These results included all the fish without distinction between the species and the fish size.

However, it could be expected that the fish behavior and the passage of the fish varied in function of the fish species and size. Further analysis were necessary to clarify these aspects. The best way to take advantage of the whole data was to process statistical

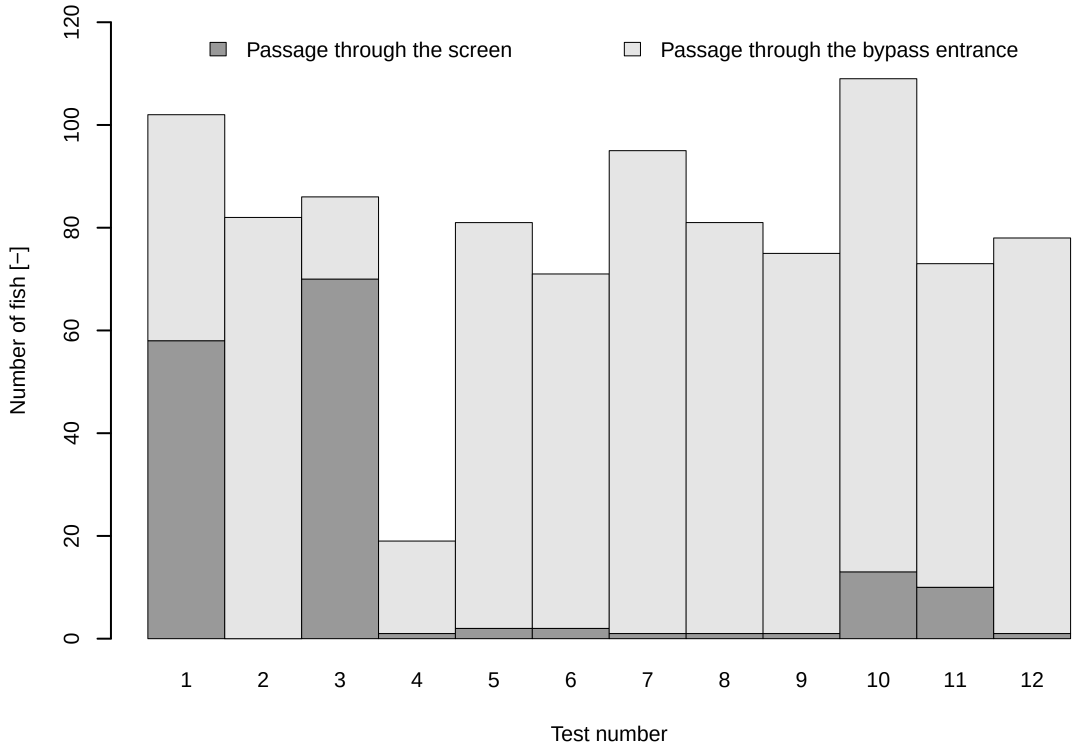


Figure 4.18 Fish passage distribution in function of the test

Table 4.2 Description of the tests conducted, T_n: Test number, α: Screen inclination, b_c: Screen bar clearance, BP: Bypass configuration, V_{BP}: Bypass velocity

T_n		1	2	3	4	5	6	7	8	9	10	11	12
α	[°]	20	20	70	70	45	30	30	30	30	30	30	30
b_c	[mm]	50	20	50	20	20	20	20	20	20	30	30	20
BP	[-]	0	0	0	0	0	0	1	2	3	0	1	4
V_{BP}	[m/s]	0	0	0	0	0	0	0.25	0.25	0.25	0	0.25	0.25

analysis. The objective was to estimate the influence of the screen inclination, the bar clearance, the fish length and the bypass velocity on the fish protection i.e. the passage through the screen and the guidance into the bypass entrance. After extracting the first passage of the fish from the raw data, the resulting data was processed in R. For each recorded fish passage, the species, the fish length, the screen inclination, the bar clearance, the bypass velocity, the bypass configuration and the antennas were known. Only the first passage chosen by the fish was taken into account. The findability of the bypass is investigated and presented in the following section. The functionality of the bypass to conduct the fish into the tailwater is reported in section 4.3.12.

4.3.11.1 Logistic regression

The objective of the statistical analysis was to investigate if the fish passed either through the screen or into the bypass related to the screen inclination (α), the screen bar clearance (b_c), the fish length (L_{fish}) and the bypass velocity (V_{BP}). During the experiment, the fish had three possibilities: They stayed either upstream of the screen and were not recorded by the antennas, they passed through the screen, or they passed into the bypass. The inactive fish, i.e. the fish not recorded by the antennas, were not taken into account in the following analysis. Therefore, two options remained for each fish: Passage through the screen or over the screen. By means of a regression analysis the passage of the fish could be predicted. The response variable i.e. the final output of the regression was the passage of the fish and was binary coded, taking value zero when the fish passed into the bypass and value one when the fish passed through the screen. The explanatory variables, which were used to calculate the response variable, were the bar clearance, the screen inclination, the bypass velocity and the fish length. As the outcome variable was categorical (fish passage) and binary (passage through the screen and passage into the bypass) a multiple logistic regression was carried out (see annexe A1). The variables used for the logistic regression are presented in table 4.3. Fish species, screen inclination, bar clearance, bypass velocity and the fish length were continuous variables. More information concerning the fish length is presented in figure 4.2.

By using a logistic regression model, the statistical significance of the influence of the predictor (i.e. the explanatory variable) on the response variable (the fish passage) could be tested. Moreover, the regression coefficient enabled to determine if the relationship between the explanatory variable and the probability of a fish passing through the screen was positive or not. Finally, it provided information to estimate the probability of one fish to pass through the screen in function of the significant explanatory variables.

Table 4.3 Characteristics of the variables used for the logistic regression

Variable	Definition	
Response variable	Passage of the fish	0: Bypass, 1: Turbine
Explanatory variable	Fish species	barbel, chub, nase
	Inclination	20, 30, 45, 70°
	Bar clearance	20, 30, 50 mm
	Fish length barbel	350 ± 120 mm
	Fish length chub	302 ± 52 mm
	Fish length nase	321 ± 49 mm
	Bypass velocity	0, 0.25 m/s

4.3.11.2 Results from the logistic regression

In order to distinguish the fish behavior among the three species studied, a multiple logistic regression for each species was carried out. The results of the logistic regression model are reported in table 4.4, 4.5 and 4.6. The first column contains the explanatory variables with intercept (I) as a mathematical constant. In the second column, the coefficient β refers to the mathematical weighting of the explanatory variable in log-odds units. SE is the standard error associated with the coefficient β to estimate its precision. Wald's X^2 is the value from the Wald test to test the null hypothesis that the coefficient is 0. If the *p*-value is smaller than the critical value of 0.05 the null hypothesis is rejected and the corresponding variable is significant. Since the log-odds of the coefficient is not easy to interpret, the odds ratio is calculated using exp(β). Finally *CI* refers to the 95 % confidence intervals for the estimated odds ratio. If the interval is above 1 there is a positive association between the response variable and the explanatory variable. If the interval is below 1 there is negative association. There is no relationship if the interval contains 1. For further information about the statistical aspects see annexe A1.

Table 4.4 reports the results from the logistic regression considering the barbel. They indicated that the fish passage through the screen or to the bypass was related to the fish length, the screen inclination and the bar clearance ($p < 0.05$ for each one). However, the velocity in the bypass entrance revealed no influence of the fish passage ($p > 0.05$). Moreover, the log-odds of the regression coefficient of a barbel passing through the screen was negatively related to the fish length and positively related to the screen inclination and the bar clearance. This means that the probability to pass through the screen decreased with increasing fish length and increased with increasing bar clearance and screen inclination. More specifically for every unit increase in fish length (i.e. mm) the odds of passing through the screen decreased by 0.963. For every unit increase in the inclination (i.e. degree) the odds of passing through the screen increased by 1.053. For every unit increase in the bar clearance (i.e. mm) the odds of passing through the screen increased by 1.343.

The overall model fit was tested thanks to a likelihood ratio test (LRT). It compared the full model considering all the explanatory variables with a restricted model where the explanatory variables were omitted. The *p*-value of the test was calculated using the X^2 distribution. The likelihood ratio test statistic was $X^2 = 321$ with a *p*-value of 2.2e-16. Hence, there was strong evidence in favor of the full model with fish length, inclination and bar clearance as explanatory variables.

Table 4.4 Results of the logistic regression considering the barbel, I: Intercept, L_{fish}: Fish length, α: Screen inclination, b_c: Screen bar clearance, V_{BP}: Bypass velocity, β: Regression coefficient, SE: Standard error, CI: Confidence interval

Variable	β	SE	Wald X^2	*p*-value	Odds Ratio	95 % CI
I	-1.935	1.031	-1.877	0.06	0.144	0.019-1.089
L_{fish}	-0.037	0.006	-6.226	4.79E-10	0.963	0.952-0.975
α	0.051	0.019	2.7	0.007	1.053	1.014-1.093
b_c	0.295	0.042	6.945	3.78E-12	1.343	1.236-1.459
V_{BP}	0.35	2.143	0.163	0.87	1.419	0.021-94.724

With regards to the chub (table 4.5), the fish length and velocity in the bypass entrance showed no significant impact on the fish passage through the screen ($p > 0.05$ each). Nevertheless, the inclination and the bar clearance of the screen were significantly influencing the fish passage ($p < 0.05$ each). Since the regression coefficient were both positive, the same conclusion as for the barbel were made. The risk to pass through the screen increased with the screen inclination and the bar clearance. The odds of passing through the screen increased by 1.046 for every unit increase in the inclination. For every unit increase in the bar clearance the odds of passing through the screen increased by 1.192.

A likelihood ratio test statistic was as well done and gave $X^2 = 191.41$ with a *p*-value of 2.2e-16. There was strong evidence in favor of the full model including the both significant variables: Inclination and bar clearance.

Table 4.6 reports the results of the logistic regression related to the nase. The fish length, the velocity in the bypass entrance and the screen inclination showed no significant influence on the probability of the fish to pass through the screen or to the bypass ($p > 0.05$ each). Only the bar clearance revealed a significant positive relationship on the passage of the nase ($p < 0.05$). The odds of passing through the screen increased by 1.111 for every bar clearance increase of one millimeter. The likelihood ratio test statistic gave $X^2 = 42.609$ with a p-value of 6.683e-11. Here again there was strong evidence in favor of the model including the bar clearance as explanatory variable.

The probability to pass through the screen or not in function of the significant explanatory variables could be calculated for the three statistical models obtained as described in annexe A1.

Table 4.5 Results of the logistic regression considering the chub, I: Intercept, L_{fish}: Fish length, α: Screen inclination, b_c: Screen bar clearance, V_{BP}: Bypass velocity, β: Regression coefficient, SE: Standard error, CI: Confidence interval

Variable	β	SE	Wald X^2	p-value	Odds Ratio	95 % CI
I	-7.864	1.95	-4.033	5.51E-05	3.84E-04	0.000-0.018
L_{fish}	-0.006	0.005	-1.124	0.261	0.994	0.983-1.005
α	0.045	0.012	3.667	2.45E-04	1.046	1.021-1.072
b_c	0.175	0.027	6.386	1.70E-10	1.192	1.129-1.258
V_{BP}	-64.33	6633	-0.01	0.992	1.15E-28	0.000-Inf

Table 4.6 Results of the logistic regression considering the nase, I: Intercept, L_{fish}: Fish length, α: Screen inclination, b_c: Screen bar clearance, V_{BP}: Bypass velocity, β: Regression coefficient, SE: Standard error, CI: Confidence interval

Variable	β	SE	Wald X^2	p-value	Odds Ratio	95 % CI
I	-2.774	3.541	-0.783	0.433	0.062	0.000-64.492
L_{fish}	-0.002	0.007	-0.336	0.737	0.998	0.985-1.011
α	-0.089	0.068	-1.311	0.19	0.915	0.801-1.045
b_c	0.105	0.038	2.726	0.006	1.111	1.030-1.198
V_{BP}	-67.04	6320	-0.011	0.992	0	0.000-Inf

A multiple linear regression revealed that the screen inclination and the bar clearance had a significant effect on the fish activity ($p < 0.05$). The proportion of active fish per hour p_f as described in equation 4.1 significantly decreased as the inclination of the screen increased and the bar clearance decreased.

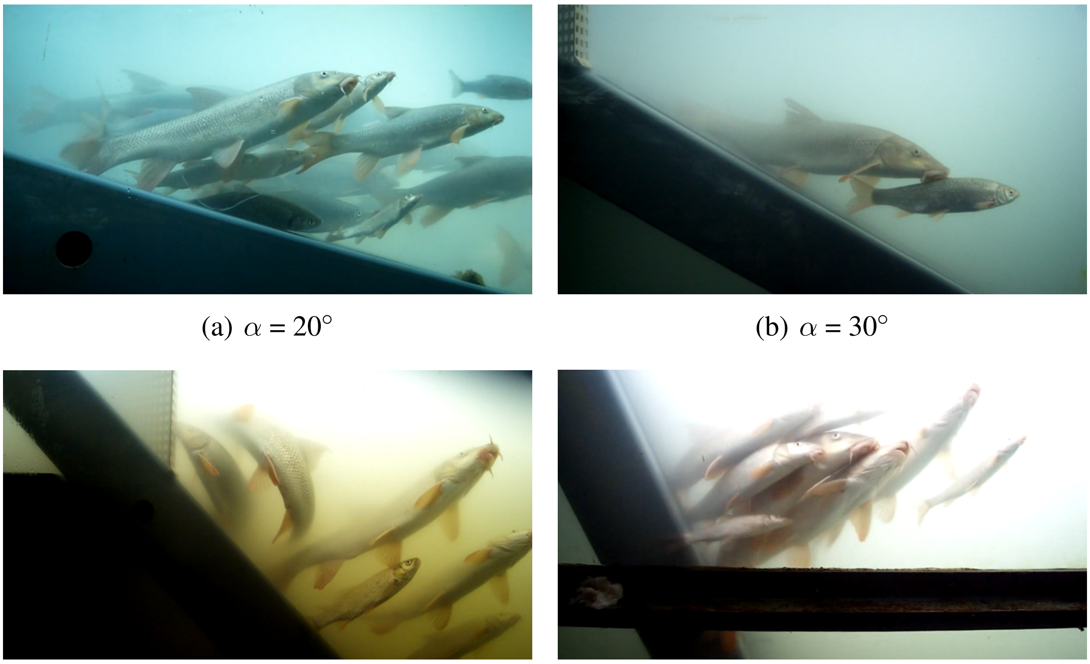
4.3.11.3 Discussion relating to the screen configuration

The results obtained from the logistic regression are discussed in the present part considering one explanatory variable after another. The results are represented graphically to facilitate the interpretation. Finally, the advantages and limits of the statistical model for practical use are discussed.

The influence of the velocity in the bypass entrance on the fish passage was originally not included in the investigation. However, by changing the bypass configuration the velocity in the bypass entrance varied as well. It was necessary to determine if this variation actually affected the fish passage through the screen or not. The logistic regressions showed that none of the three studied species was influenced by the velocity of 0.25 m/s in the bypass entrance compared to the zero velocity. This was comprehensible since the velocity was relative low and not perceptible near the screen. The fish could not perceive it before they reached the bypass entrance. The independence of the fish passage with regard to the bypass velocity was advantageous for the analysis as it enabled to compare all the tests conducted without considering the bypass configuration.

Considering the barbel, the logistic regression revealed that the probability to pass through the screen was depending on the fish length. As the fish length increased, the probability to pass through the screen decreased and the probability to reach the bypass entrance increased. This result was expected since the screen is a physical barrier. The passage through the screen was stopped as the bar clearance was close to the fish's width. Bigger fish had more chance to find the bypass. However, this was not the case for the nase and the chub which showed no significant relationship between the fish length and the fish passage. The results stated that the probability to pass through the screen or into the bypass was independent of the fish size for the chub and the nase. It was quite unexpected and should be interpreted carefully. The size distribution of the nase and chub employed, i.e. the standard deviation of the fish length, was more than twice smaller than the one for the barbel (mean L_{barbel} 350 $\pm$ SD 120 mm, mean L_{nase} 302 $\pm$ SD 52 mm and mean L_{chub} 321 $\pm$ SD 49 mm). The relative narrow fish size range could explain why the logistic regression could not reveal a difference between the fish sizes employed. In addition, the chub and nase activity was considerably lower than the one of the barbel, presumably because of the relatively cold water temperature inhibiting their swimming performance (see part 4.3.6). The size range of the available fish pool and the small number of active fish might be inappropriate to reveal a significant influence of the fish size on the fish passage considering the chub and the nase. Further experiments with a larger fish length distribution, more fish and a warmer water could clarify this point.

The inclination of the screen showed a significant influence on the passage of the barbel and the chub. The more the screen was inclined close to the vertical, the higher was the probability that the fish passed through it and the lower was the chance that they reached the bypass entrance on the surface. This result was expected and confirmed by the video observations of fish at the screen. The fish showed a positive rheotaxis by swimming head against the flow direction. By an almost vertical screen the fish had more contact with the screen, resulting in injury and exhaustion and finally in the passage through the screen. By a flatter screen, the fish could detect the screen more easily and had better possibilities to move away since the caudal fin movement was not obstructed between the screen bars (figure 4.19). Avoiding the contact while getting drifted toward the downstream, gradually guided the fish to the surface whereas an almost vertical screen reduced the attempts of the fish to search for a surface passage.



(a) $\alpha = 20°$ (b) $\alpha = 30°$

(c) $\alpha = 45°$ (d) $\alpha = 70°$

Figure 4.19 Fish swimming at a 20, 30, 45, and 70° inclined screen

On the other side, the logistic regression revealed that the passage of the nase through the screen or to the bypass was not influenced by the screen inclination. Again this was unexpected and should be interpreted carefully. A reason could be that the nase might have a better capacity to perceive the screen visually or through the lateral line. As the fish notice the barrier, whatever the inclination, they remained in the upstream where they were not registered by the antennas. Another explanation could be that the nase swam near the surface. In this case, the screen inclination did not play a role for the passage to the bypass and through the screen. The most probable explanation was the cold water affecting the nase activity. The few data obtained for the nase could not reveal any influence of the inclination of the screen. Further tests with appropriate water temperature should be conducted to reject or confirm the independence between the nase passage through the screen and the screen inclination.

The bar clearance revealed a significant influence on the passage for the three studied species. As expected an increasing bar clearance was related with an increasing probability to pass through the screen and with decreasing chances to find the bypass entrance. However, the three species did not respond with the same intensity to the bar clearance increase. Figure 4.20 illustrates this trend with an example.

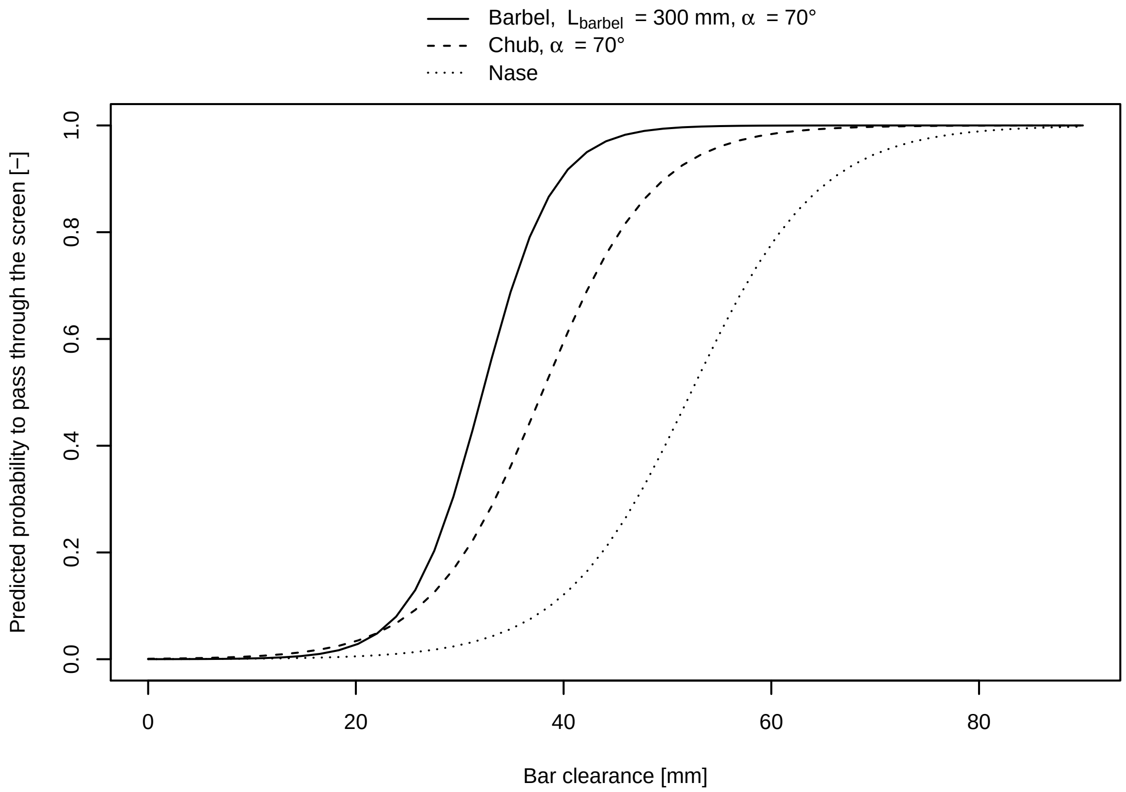


Figure 4.20 Predicted probabilities to pass through the screen in function of the bar clearance for the three species investigated

The horizontal axis represents the bar clearance from 0 to 90 mm. The vertical axis shows the probability to pass through the screen with 1 as maximal value which corresponds to 100 % risk to pass through the screen. The three curves represent the different species investigated. As the passage of the barbel was influenced by the fish length and the screen inclination, these parameters had to be specified to calculate the probability to pass through the screen. As an example, a 30 cm long barbel with a 70° inclination was chosen. The chub passage was also influenced by the inclination and the probability for the chub to pass the screen was as well calculated with a 70° screen inclination. On the other side, the fish length and the screen inclination for the nase had not to be specified since they showed no influence on their passage.

According to the model, up to 15 mm bar clearance a 30 cm long barbel had no risk to pass through the 70° inclined screen. Between 15 mm and 45 mm bar clearance the probability strongly increased. This bar clearance range was close to the fish width which was around 33 mm for a 30 cm long barbel (figure 4.3). Above 45 mm bar clearance the 30 cm long barbel had 100 % probability to pass through the screen. The chub showed a similar trend with a more slowly increase between 15 mm and 60 mm bar clearance. A bar clearance larger than 60 mm conducted in all cases to the passage through the 70° inclined screen. Considering the nase, the fish were 100 % protected from the passage through the screen up to a 25 mm bar clearance independent of the screen inclination and the fish size. Above 80 mm bar clearance no nase was protected by the screen.

As discussed above the results of the logistic regression concerning the chub and the nase were questionable. The conditions during the experiments like the cold water temperature might be unsuitable for these species and considerably reduced the fish activity compared with the barbel. It conducted to fewer recorded fish passages. The available data might be misleading because of the suboptimal condition which could have affected the natural fish behavior. That is why it was preferable to reject the statistical model for the chub and the nase. On the other side, the barbel showed a relative high swimming activity in downstream direction. The results of the logistic regression relating to the barbel were rational and credible. Therefore, the model predicting the probability of the barbel to pass through the screen or into the bypass in function of the fish length, the screen inclination and the bar clearance is further discussed by means of graphic representations.

The probability to pass through the screen is calculated as follows:

$$p = \frac{e^{(\beta_0+\beta_1 \times L_{Barbel}+\beta_2 \times \alpha+\beta_3 \times b_c)}}{1+e^{(\beta_0+\beta_1 \times L_{Barbel}+\beta_2 \times \alpha+\beta_3 \times b_c)}} \tag{4.3}$$

where β_0 is the intercept, β_1 is the coefficient for the fish length, β_2 for the screen inclination, β_3 for the bar clearance from table 4.4, L_{Barbel} is the body length of the barbel in millimeters, α is the inclination of the screen in degrees and b_c is the bar clearance of the screen in millimeters.

Figure 4.21 shows the influence of the screen inclination on the probability to pass the screen in combination with the bar clearance for a 30 cm long barbel. According to figure 4.3, the maximal body width of a 300 mm long barbel was close to 33 mm. Thus, a bar clearance equal or narrower than 30 mm constituted a physical barrier for the fish. However, a bar clearance larger than the fish width could have a repulsive effect on the fish and might acted as behavioral barrier. As represented in figure 4.21, up to 20 mm bar clearance, the probability for a 30 cm long barbel to pass through the screen was near zero and was independent of the screen inclination. For 30 and 40 mm bar clearance, the probability to pass through the screen was strongly dependent on the screen inclination. By inclining the screen close to the horizontal, the chances for the fish to avoid the screen passage and to find the bypass entrance was increased. Theoretically a 33 mm thick barbel could not pass through the 30 mm bar clearance. The results obtained could be explained by measurement errors concerning the fish body width, the screen bar construction and an inaccuracy of the statistic model. A flat inclination of the screen (α = 20°) yielded an effect as behavioral barrier for 40 mm bar clearance. The fish had a probability of 0.4 to pass through the screen although the body width was smaller than the bar clearance. For 50 mm bar clearance the risk to pass the screen was close to 100 % independent of the inclination. No more behavioral barrier effect was present for such a large bar clearance.

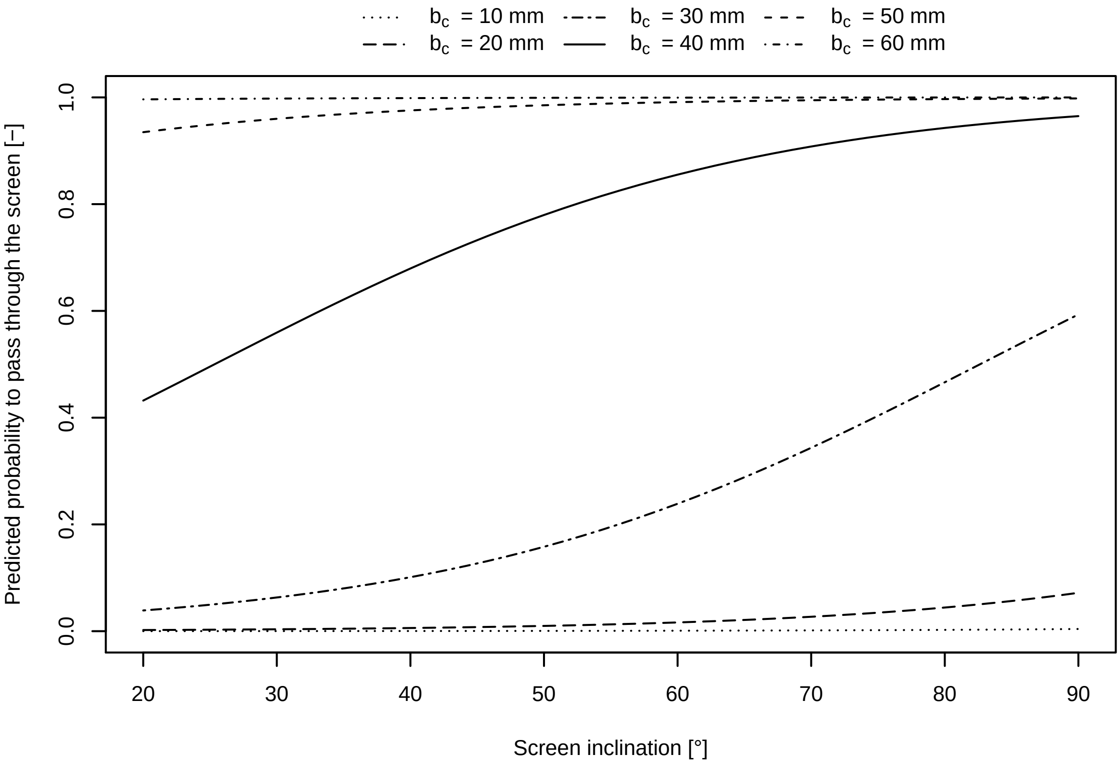


Figure 4.21 Predicted probabilities for a 30 cm long barbel to pass through the screen in function of the screen inclination for different bar clearances b_c

In figure 4.22 the probability to pass through the screen as calculated by the model is represented in function of the barbel's body length and for different bar clearances. The inclination of the screen was set to 70°. Considering a 200 mm long fish, the risk to pass through the steep screen was 0 % for 5 mm bar clearance, 5 % for 10 mm, 60 % for 20 mm and 100 % above 30 mm bar clearance. When the bar clearance was close to the fish's width, the probability to pass through the screen shifted very fast. It was the limit where the physical barrier effect was no more present, but a behavioral barrier effect might occur. The video observation showed that the 50 mm bar clearance resulted in frequent and serious injuries of big fish. When the bar clearance was close

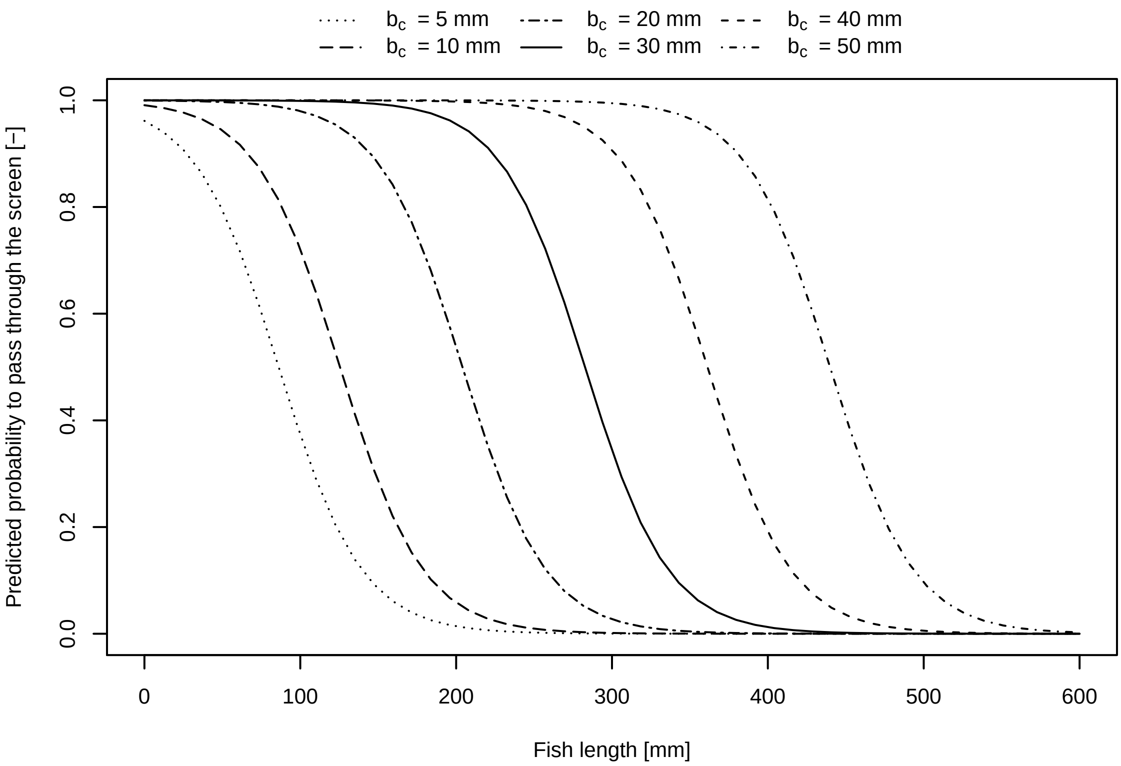


Figure 4.22 Predicted probabilities for a barbel to pass through the 70° inclined screen in function of the fish length for different bar clearances b_c

to the fish's width, the fish could easily get stuck between the bars. It conducted to considerable lesions as the fish tried to swim away from the screen. Nowadays, a 20 mm bar clearance is often recommended (ATV-DVWK 2005). According to the model, fish longer than 350 mm could be fully protected from the passage through the screen. On the other side, fish smaller than 100 mm would by no means be stopped by a 70° inclined screen. Considering the fish between 100 and 350 mm body length, the probability to pass through the 20 mm screen strongly increased as the fish length decreased. The risk of a fish to pass through the screen if the bar clearance equaled the fish's width increased with decreasing fish length. This could be explained by the influence of the swimming capacity which increases with the fish length. Test with different approach velocities could clarify this aspect. However, it demonstrated that the model reproduced detailed behavioral characteristics and provided qualitative orientation for the screen passage probabilities.

The presented graphics intended to demonstrate the influence of the different investigated parameters on the fish passage through the screen. Finally, the goal of the statistical analysis was to provide a tool which could help making decision to protect as many fish as possible with regard to the construction of new power plants or improvements at present ones. For example, the probabilities to pass through the screen in function of the fish length for four selected screen configurations is given in figure 4.23. Arrangements with a screen 70° inclined and a large bar clearance of 50 mm are comparable to numerous existing hydro power plants. According to the statistical model it would provide a fish protection only for fish longer than 550 mm. By reducing the distance between the bars to 20 mm, the fish from 300 mm length would not pass through the screen. Nevertheless, an almost vertical screen would be repellent for the fish but would not yield guidance to the surface. The inclination of the screen near the horizontal would improve the fish protection and the guidance to the surface bypass. A 30° inclined screen with a 20 mm bar clearance would provide the protection of fish longer than 250 mm. However, by keeping a large bar clearance from 50 mm, the inclination of the screen alone would not be enough to protect fish smaller than 500 mm. The passage through the screen would be avoided by a small bar clearance, while a low inclined screen would improve the guidance to the bypass entrance at the surface. A combination of both narrow bar clearance and low inclined screen would provide the best success to protect the fish and guide them to the downstream passage entrance on the surface.

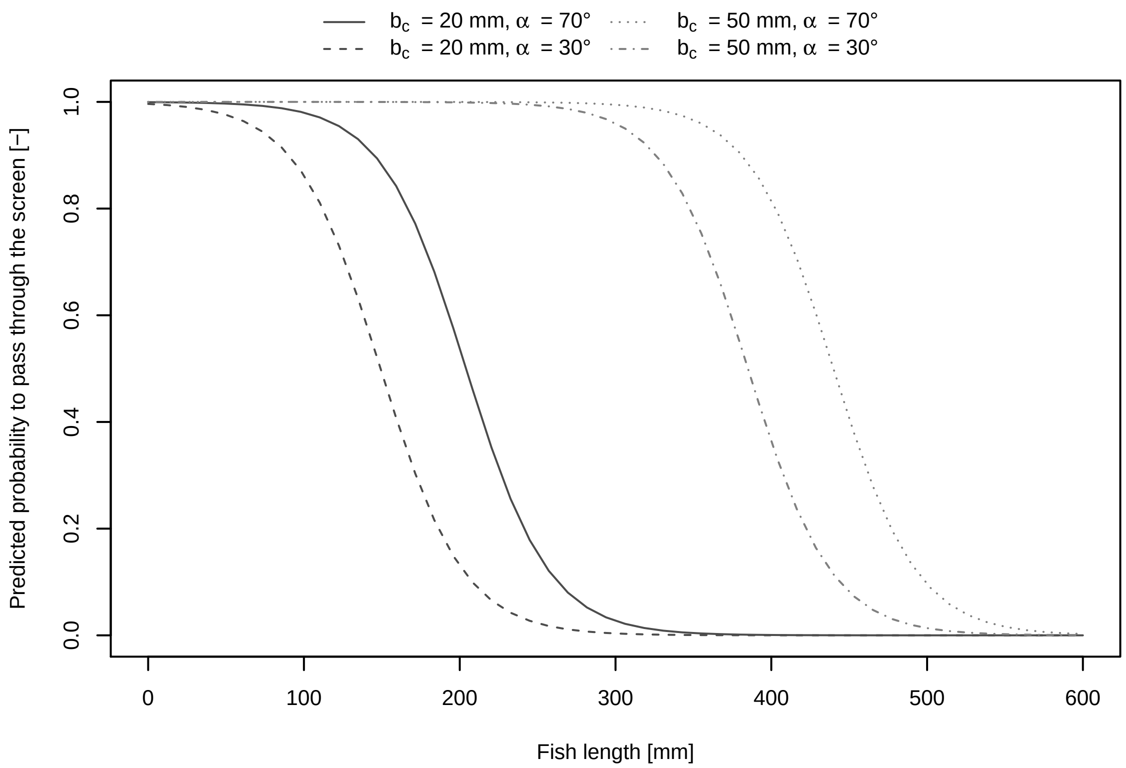


Figure 4.23 Predicted probabilities for a barbel to pass through the screen in function of the fish length for different screen configuration

Fish protection at a hydro power plant for all fish species and fish sizes is actually not practicable. Usually target species and/or target fish sizes are selected depending on the river system considered and the actual fish population endangered. Figure 4.24 gives another possible illustration of the statistical model output which could provide a tool to assist decision making in order to protect the key fish size selected. Four plots are presented corresponding to different fish length: 200, 300, 400 and 500 mm. The contour plot show the probabilities to pass through the screen (color key) as a function of the bar clearance (horizontal axe) and the screen inclination (vertical axe). The red zones represent probabilities higher than 0.8 to pass through the screen, while the blue areas indicate probabilities below 0.2.

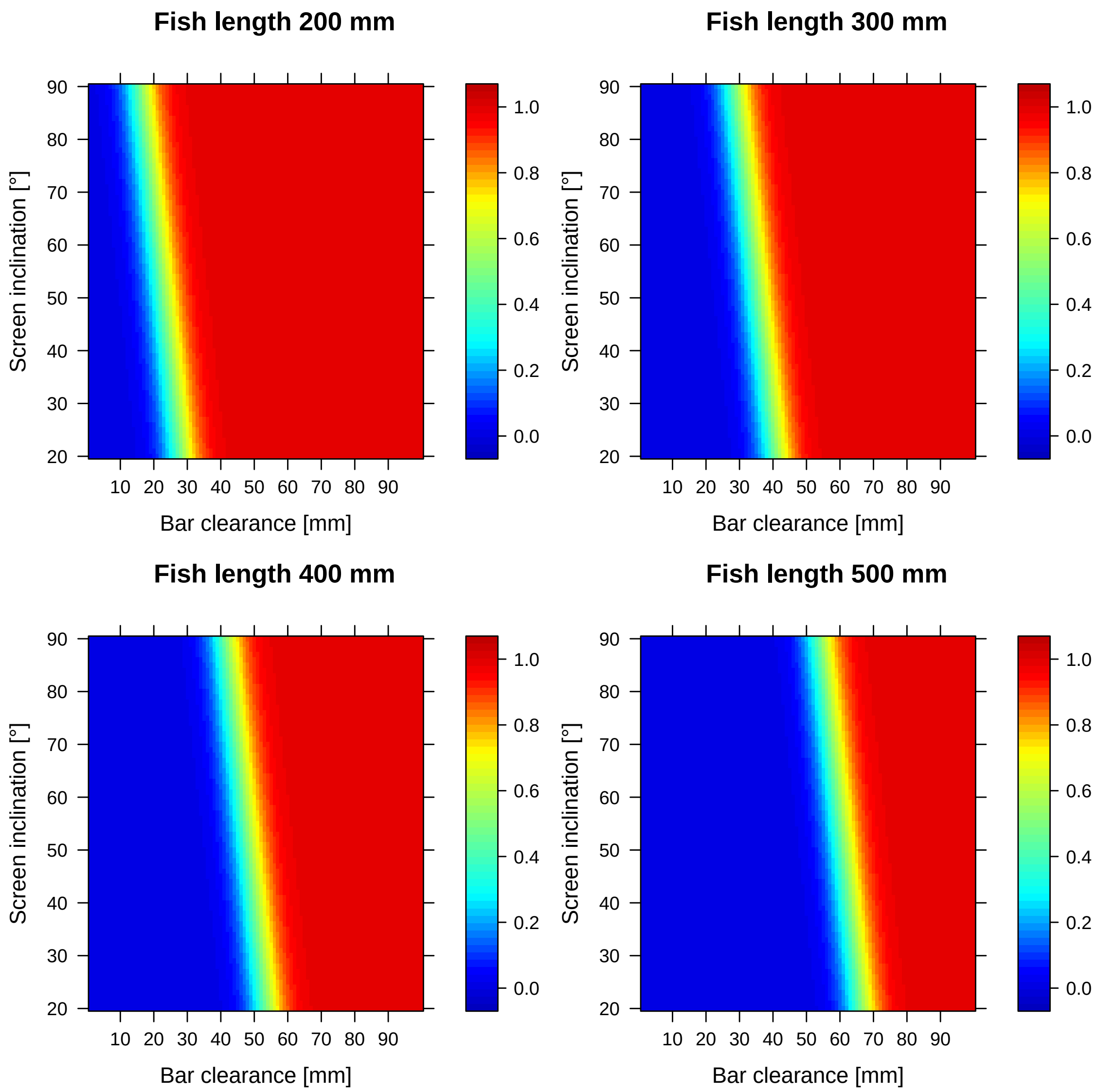


Figure 4.24 Predicted probabilities for a barbel to pass through the screen in function of the fish length for different screen configurations

The blue area where a 200 mm barbel would be protected from the passage through the screen is very limited compared with the one for a 500 mm long fish. For a 20° inclined screen the bar clearance should not be larger than 32 mm regarding a 200 mm long barbel and not larger than 20 mm for a vertical screen. Otherwise the probability to pass through the screen would be close to 1. Regarding a 500 mm long barbel a bar clearance larger than 55 mm would not protect the fish with a vertical screen. However, for a low inclined screen (α = 20°), the bar clearance should not be larger than 70 mm to protect some of the 500 mm barbel.

The statistical model showed that the bar clearance was a decisive parameter to protect fish from passing through the screen and has to be considered in relation to the fish size. However, an almost vertical screen with small bar clearance was not enough to guide the fish to the bypass near the surface. Actually, a steep screen was repellent for the fish and conducted to less movement towards the surface. An inclination of the screen close to the horizontal was necessary to improve the fish guidance to the surface bypass and thus to reduce the passage through the screen.

The model arose from mathematical concepts and could not exactly describe the natural processes of fish behavior. However, it provided the trend of the fish behavior in front of a screen. Since the available data were based on experimental investigation under laboratory condition, the model had limits. First of all, all the tests were conducted with an approach velocity at the screen of 0.5 m/s. Other velocities at the screen would give different results since the swimming performance of the fish depends on it. Moreover, only 4 inclinations (20, 30, 45, 70°), 3 bar clearances (20, 30, 50 mm) and fish length from 190 to 610 mm were investigated. Therefore, the probabilities calculated outside from these ranges were extrapolated and should be carefully interpreted. While it worked quite well for the bar clearance, the interpolation regarding the inclination was questionable. Thus the model would not be valid for a screen inclination below 20°. Moreover, the available fish had a length distribution from 190 mm to 610 mm. The derived model would not be appropriate for fish outside from this length range, in particularly for the small ones which have lower swimming performance. Finally, only the data for the barbel passage could be used to produce a consistent model. In theory this statistical model should not be used for other fish species since they have different behavior and swimming performance. But in practice it can be used for species having similar body form and swimming capacity. Improvement of the model is always possible, for example by investigating other fish species and larger size distribution or by adapting the water temperature to reach the temperature optimum of the fish employed. More tests with different combinations of the screen inclination, bar clearance and velocity could also improve the significance of the model.

Nevertheless, the model obtained provided meaningful information about the fish passage through the screen in function of the fish length, the screen inclination and the bar clearance. It could be an orientation tool for planning or rebuilding a hydro power plant since fish protection is nowadays a crucial topic. Furthermore, the passage through the screen does not inevitably entail the death of the fish. The fish mortality and injury rates due to the passage through a hydro power turbine depend amongst others on the fish size and the type of turbine (see section 2.2). Models for evaluating fish mortality are developed as well (Ebel 2013; Larinier 2008; Montén 1985) and could be combined with the present one to predict the whole fish passage and mortality rate.

4.3.12 Bypass design

Further experiments were conducted to optimize the bypass configuration. The objective was to get more information about the fish swimming behavior during the downstream migration facing different flow conditions. Like described in figure 4.6 and in annexe A2, four different bypass configurations were tested. For each of them the inclination of the screen (α = 30°), the bar clearance (b_c = 20 mm), the velocity (V_{BP} = 0.25 m/s) and the water depth (W_{BP} = 27 cm) at the bypass entrance were kept constant. The discharge in the bypass was around 80 l/s corresponding to 7 % of the whole discharge in the channel. Configuration number 1 consisted of an inclined board 3 m after the bypass entrance at the end of the upper floor. The board was 5 cm overflowed over a width of 125 cm to allow the passage of the fish to the downstream. It provided a slow laminar flow. In the second configuration the board was 10 cm overflowed over a width of 62 cm in order to keep the same flow velocity in the bypass entrance (0.25 m/s). Configuration number 3 was composed of one slot on the right hand side, allowing the passage of the fish on the whole water depth over a width of 25 cm. The last configuration studied had two vertical slots. Each of them was 40 cm wide and produced an alternation of turbulent flows and calm zones with velocity in the slots around 0.7 m/s.

PIT antennas, registering the fish passages, were installed at the beginning and at the end of the bypass (see figure 4.4). Thereby, it was possible to know if the fish found the bypass entrance (fish registered in antenna number A1) and if they successfully used the bypass (fish registered in A1 and A2). The success of passage for each configuration was calculated by the following formula:

$$E_{BP} = \frac{n_{a_1+a_2}}{n_{a_1}} \tag{4.4}$$

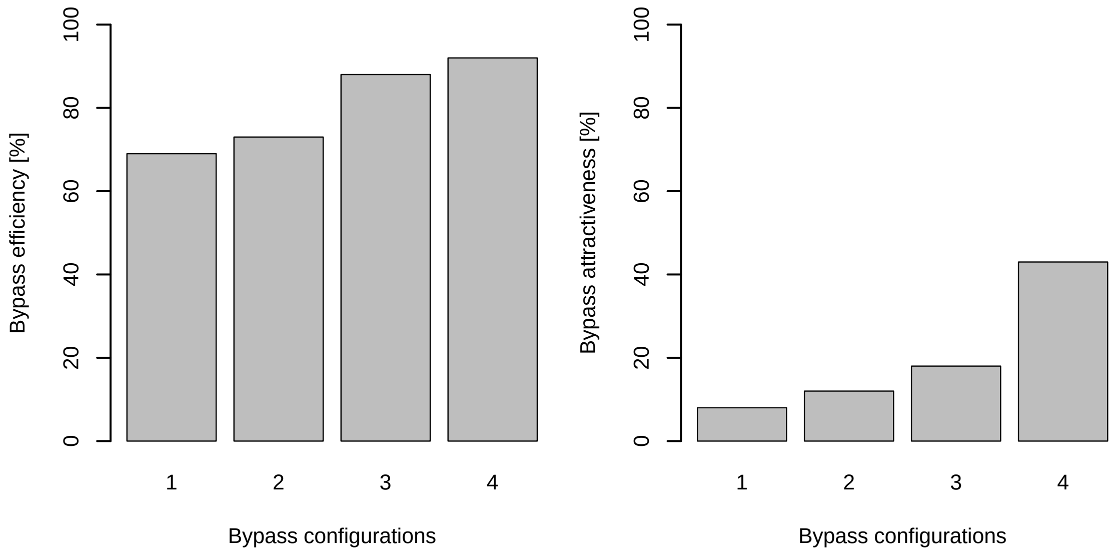
where $n_{a_1+a_2}$ is the number of fish which found and successfully passed the bypass (registered in both antennas A1 and A2) and n_{a_1} was the number of fish reaching the entrance of the bypass (A1). To characterize the efficiency of the bypass configuration with regard to the efforts it took to pass downstream, the attractiveness parameter a_{BP} was introduced:

$$a_{BP} = \frac{n_{a_1+a_2}}{N_{a_1}} \tag{4.5}$$

where N_{a_1} was the total number of passages at the bypass entrance (through A1) for all fish which got through the bypass (A2). If the passage was attractive the value of a_{BP} tended towards 1 whereas a smaller value of a_{BP} indicated that the fish passed many times at the bypass entrance (through A1) before reaching the bypass end (A2). Because of the 4 minutes sampling interval it was not possible to calculate the exact duration that the fish needed to pass between antenna 1 and 2. Nevertheless, the number of signals through A1 gave a representative measure.

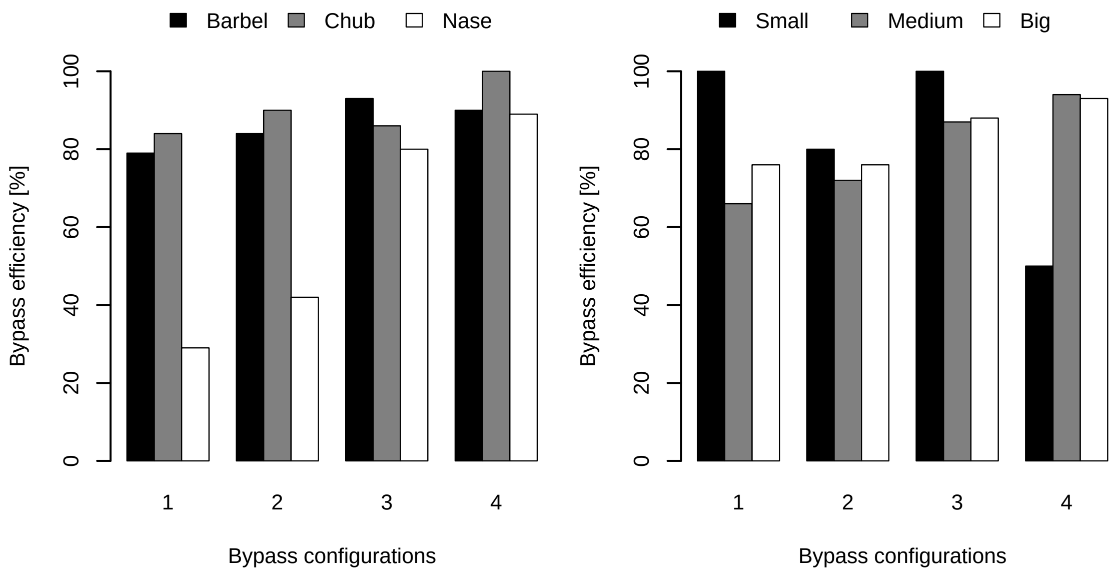
In figure 4.25 the passage success (E_{BP}) and the attractiveness (a_{BP}) for each bypass configuration are represented. Both gate constructions (BP_1 and BP_2) showed about 70 % downstream passage efficiency. Raising the overflow depth from 5 to 10 cm and reducing the overflow width yielded better results with regard to the attractiveness (12 % for 10 cm instead of 8 % for 5 cm). The fish passage over the gate was more comfortable as the water depth increased since it reduced the fish's contact with the gate and therefore reduced the potential injury. The investigated vertical slot configurations had total efficiencies of 88 % for one slot (BP_3) and 92 % for two slots (BP_4). The attractiveness was 18 % for the first setup and 43 % for the second one. The compact flow and the higher water depth in the vertical slot configuration strongly favored the passage efficiency compared with the configuration 1 and 2.

However, these results might change in function of the fish size and the species since the swimming performance is varying (Pavlov et al. 1989). Therefore, the success of passage considering the species and size category were calculated and are represented in figure 4.26. For all configurations tested, barbel and chub had a success of passage higher than 79 %. It means that if they reached the bypass entrance there was a high probability that they successfully swam to the downstream. They showed a slight preference for the slot configurations. This could be expected for the barbel since it is a bottom near oriented species. On the other side the nase showed only 29 % efficiency for the 5 cm gate overflow and 42 % for the 10 cm variant. The nase are used to fast current and showed a strong preference for the slot configurations and in particularly for the configuration with two slots.



(a) (b)

Figure 4.25 Bypass efficiency (a) and attractiveness (b)



(a) (b)

Figure 4.26 Passage efficiency for each configuration tested in function of the species (a) and the fish size category (b)

Figure 4.26b illustrates the success of passage in function of the fish size. Three size categories were defined (see part 4.3.7). The passage success between the medium and big fish showed similar results: They had similar swimming behavior i.e. swimming capacities. The configuration with two slots gave the best efficiency. On the other side, there was a large difference between the smaller fish and the medium and big ones (fish longer than 200 mm). Smaller fish had not the same swimming capacity than the bigger ones. A low velocity and a laminar flow like in configuration one, two and three were preferable for small fish. In contrary turbulent flow and high velocity like in the configuration with two slots were repellent for small fish probably because they did not have the appropriate swimming capabilities to control their movement.

In conclusion a vertical slot was appropriated for the medium and big fish considering the three studied species. The combination of fast flows, calm zones and high depth provided good efficiency and attractiveness. However, due to the high velocity in the slots, it was not adapted for small fish.

4.4 Conclusion

Thanks to PIT tagging, comprehensive data concerning fish movements were available providing detailed information about the fish migration activity in function of the species, the fish size, the water temperature, the time of the day, the water turbidity and the phase of the moon. The social fish behavior was as well investigated and revealed differences between the three species studied. Moreover, the passage of the fish at the modeled hydro power plant intake was examined for different configurations of the screen inclination and the bar clearance. It revealed that the bar clearance and the screen inclination were decisive for the fish passage. A combination of both narrow bar clearance and a low inclined screen conducted to the best results for fish protection and the guidance to a surface bypass. A statistical model was developed, allowing the prediction of the fish passage through the screen or to the bypass. Finally, the fish passage to the downstream for different configurations of the surface bypass was tested and revealed that the fish had difference response to the flow according to the species and the fish size.

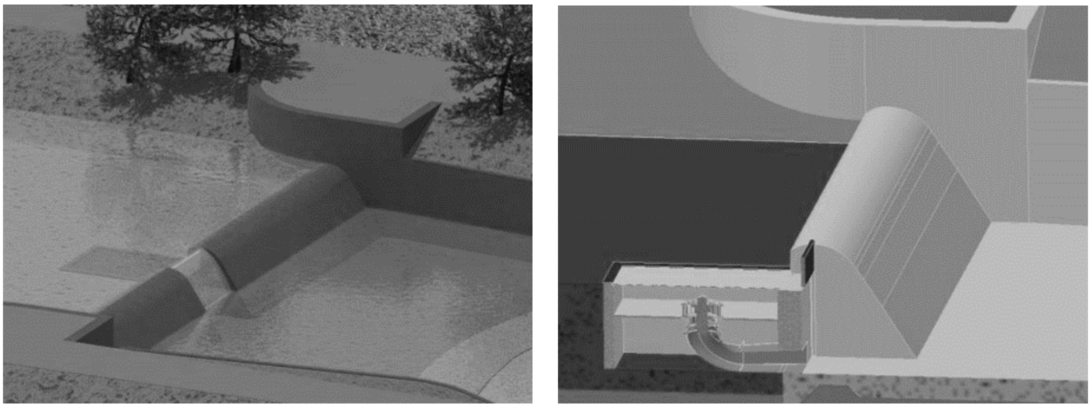
5 Fish experiments at a horizontal screen

5.1 Introduction

At the Department of Hydraulic and Water Resources Engineering of the Technische Universität München an innovative hydro power concept has been developed: The TUM Hydro Shaft Power Plant (Rutschmann et al. 2013). Beside economical and operational advantages, it is also meant to be ecologically more compatible than other common hydro power concepts. Fish protection is intended by a horizontal screen, which is installed flush with the river bed. Its surface is dimensioned according to hydraulic model tests which assure that the maximum velocity towards the screen remains underneath the given limit for the local fish population (e.g. 0.5 m/s). The bar clearance is relatively narrow (e.g. 20 mm) and can be adapted to meet the respective fish protection requirements. The downstream migration corridor is provided by openings in a vertical gate alongside the screen in the plane of the weir. They create an outflow directly to the downstream, where a water cushion prevents harm from the descending fish. Number, size and location of these openings can be adapted to the fish population. Figure 5.1 shows schematic sections of a Hydro Shaft Power Plant facility.

The hydraulic model tests can guarantee the compliance of the velocity criteria for fish protection and the close special proximity of the screen and the downstream migration corridor suggests a good findability. However, due to a lack of experimental references, it remained unclear if horizontal screens are feasible for fish protection at all and whether the velocity guidelines which were developed for vertical screens hold valid for horizontal ones. To clarify these issues and the actual effectiveness of the migration corridor, the situation had to be investigated by the observation of the behavior of fish under realistic conditions. This is the most direct and reliable method to investigate the functionality of fish protection and fish downstream migration efficiency. Therefore corresponding experiments have been conducted at the VAO laboratory.

The investigations presented initial research about fish protection and downstream migration at horizontal screen. Similar to the previous experiments with inclined screens the tests were done with a simplified setup. It reproduced the flow conditions upstream of the screen without employing an actual turbine. Since only fish larger than the bar clearance were considered, PIT tagging was not necessary to describe the passage of the fish.



(a) (b)

Figure 5.1 Schematic longitudinal section (a) and visualization of service (b) of a TUM Hydro Shaft Power Plant

5.2 Methodology

5.2.1 Experimental Setup

The experimental setup for the fish behavior observation was installed in an open air lab flume upstream from the channel reach where the inclined screens had been investigated. The tests were conducted with a simplified setup which reproduced the hydraulic conditions in the headwater of a Hydro Shaft Power Plant but did not include moveable parts. The turbine was replaced by a bottom outlet (dimensioned for 1.72 m^3/s discharge at 1 m head). The shaft was 2.5 m broad, 2.8 m long and 3.0 m deep. It was covered by a horizontal screen flush mounted with the river bed which was 2.6 m long and 2.4 m wide with a rectangular screen bar profile. The spacers between the bars were 15 mm wide, the notches which accommodated the bars were about 9 mm wide and the bar thickness was alternating between 8 mm and 5 mm. Thus the average bar clearance was 17.5 mm and varied locally between 15 mm and 20 mm. The screen was installed just in front of the weir which was 10.1 m broad and 1.1 m high. It did not include the area beside the shaft to achieve higher flexibility of the test facility. The separation between shaft inside and downstream area was realized with a steel and wood structure. Wooden stop-logs simulated a vertical gate alongside the screen. It was not moveable as this was not required for the fish behavior tests. Similarly, there was no trash rack cleaner installed. Figure 5.2 shows a plan of the test facility.

Images of the headwater and tailwater perspective of the test site are provided in figure 5.3. The gate was equipped alternately with one of two opening variants for the fish downstream migration (each 25 cm high x 30 cm broad), one at the surface (variant 1) and one close to the screen (variant 2) (see figure 5.3). The top edge of the gate and the opening were rounded to avoid fish injury during the passage. Headwater (7.5 m long, 10.1 m wide, 0.7 m water surface elevation) and tailwater (10 m long, 5.5 m wide, 2.7 m water surface elevation) of the test zone were separated from the surrounding canal system by grids to prevent the fish escape (mesh size ≤ 10 mm). A 55 m long and 9 m wide canal connected the test zone with an up-scaled Rehbock flume gauge which provided the system with water from the Isar River. It enabled a discharge measurement with an accuracy of about 2 % for up to 2 m^3/s. Debris was held from the test area with a cleanable trash rack upstream of the test facility. The tailwater surface elevation could be controlled by a gate downstream of the experimental channel.

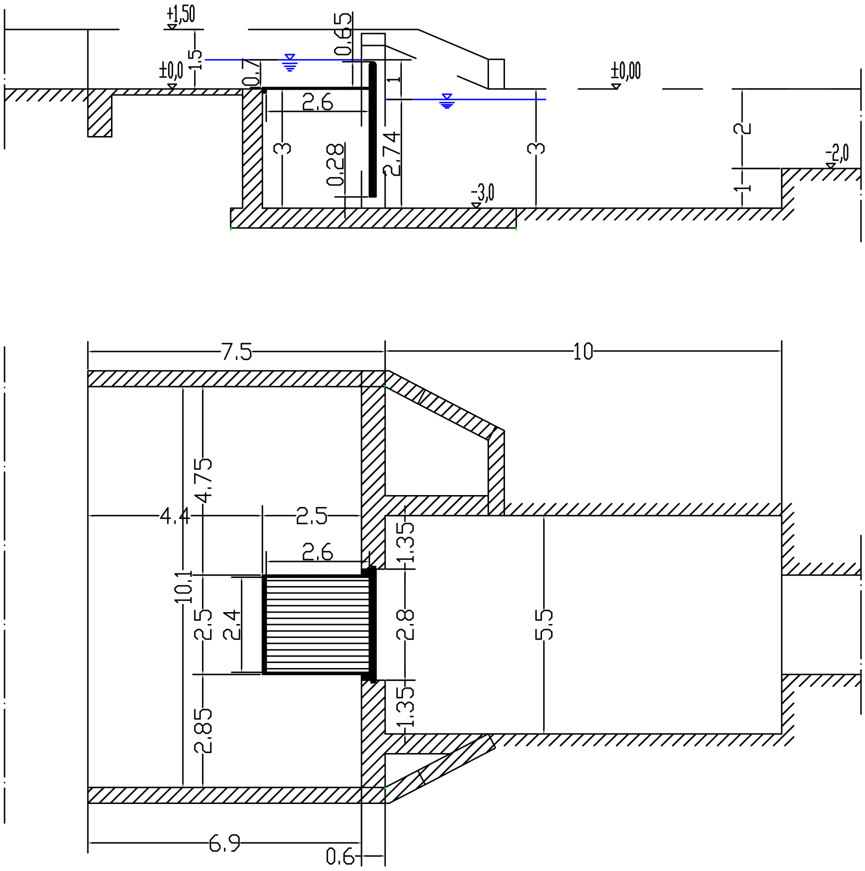
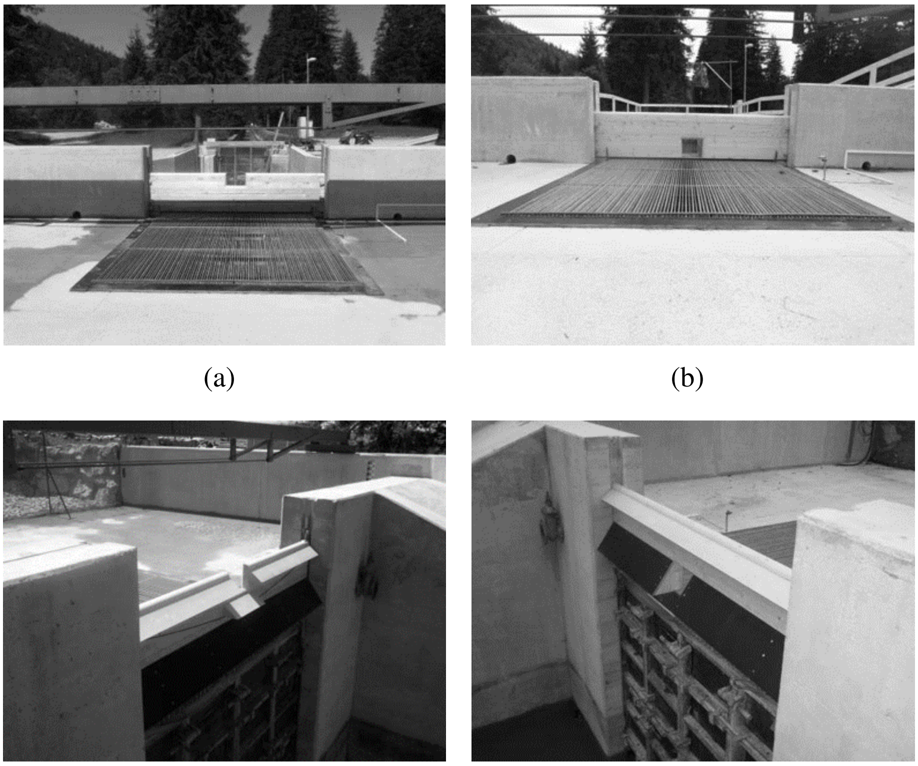


Figure 5.2 Longitudinal section (top) and top view (bottom) of the test facility; Flow direction from the left to the right [m]



(a) (b)

(c) (d)

Figure 5.3 Headwater perspective for variant 1: Surface opening (a) and variant 2: Bottom opening (b) and tailwater perspective for variant 1 (c) and variant 2 (d) of the gate

5.2.2 Fish collection and care

To account for different swimming preferences and behavior characteristics, a fish pool of several species and size distributions were employed for the investigations. According to the advice of fish biologists and river ecologists and with regard to workable conditions concerning fish acquisition, handling and statistical analysis, three species were chosen: Barbel (*Barbus barbus*), chub (*Squalius cephalus*) and brown trout (*Salmo trutta*). Their swimming behavior and ecology are described in chapter 2. They represent a main part of the ecological spectrum of fish in the rhithral and epi-potamal zones. With regard to the possibility of different behavior between wild and farm fish, it was aspired to use wild fish for the experiments. However, brown trout could not be acquired in natural watercourse in a sufficient number and had to be supplied by farm facilities. The fish for the experiments were provided by the Institute for Fishery of the Bavarian State Research Center for Agriculture (Institut für Fischerei des LfL), the Bavarian Environment Agency, Fish and Freshwater Ecology (Referat für Fisch- und Gewässerökologie des LfU) and the Fishery consultant from the district of Schwaben (Fischereifachberatung des Bezirks Schwaben). Barbel and chub were extracted from the Ammer River, the Siebenbrunner River and the Schwarzach River during July 2011, using electrofishing equipment. The brown trout were supplied by the fish farms of the LfL and the LfU, which featured good (nature like) genetic material. Figure 5.4 shows the number and size distribution of the fish pool. 16 barbel with a mean total length (L_{barbel}) of 520 mm ± standard deviation (SD) 160 mm, 176 chub; mean L_{chub} 260 ± SD 60 mm and 98 brown trout; mean L_{trout} 280 ± SD 80 mm were supplied. Only 80 fish of each species could be employed during the test series due to animal experiment restrictions. The size distribution of each fish group was chosen according to the provided fish stock.

The result of the fishing procedure and also the stock in the farm facilities yielded fish numbers and size distributions which were not uniform or standardized. This circumstance was not ideal from the scientific point of view, especially with regard to statistical analysis. However, the experiments had to accommodate with the given conditions.

The fish width can be estimated by equation 2.2. With $W_{trout,rel}$ = 0.1, $W_{barbel,rel}$ = 0.11, $W_{chub,rel}$ = 0.12 (Ebel 2013). Only fish larger than the bar clearance (b_c = 17.5 mm) were employed. Thus, all fish which were found in the downstream area could be considered as migrated through the migration corridor. The fish were distributed in three size categories: Small, medium and big. Table 5.1 provides the definition of the categories for each species.

The fish were first kept in the respective institutes for at least one week to adapt them to the new environment (water temperature, fish pool). A sample of each fish pool was examined at the animal health service in Grub. No diseases, bacterial or viral infections exceeding normal conditions were found and a good health condition of the fish was stated. Subsequently the fish were transported to the VAO laboratory, using aerated fish transport containers. The fish (n = 290) were held in two circular flow tanks (each 2 m x 2 m x 0.7 m) supplied with constant tap water (oxygen supply) and water from the Isar River (adaption to the test conditions). The fish tanks were covered with 20 mm mesh nets to avoid fish escape or attack from predator (fox, bird). A tent shielded them against weather conditions. Water temperature (min. 10.0°C, max. 14.4°C) and dissolved oxygen concentration (min. 7.7 mg/l, max. 10.6 mg/l) in the tanks were controlled every day. The fish were fed every two days. After a thermal and chemical acclimation period the first test was started.

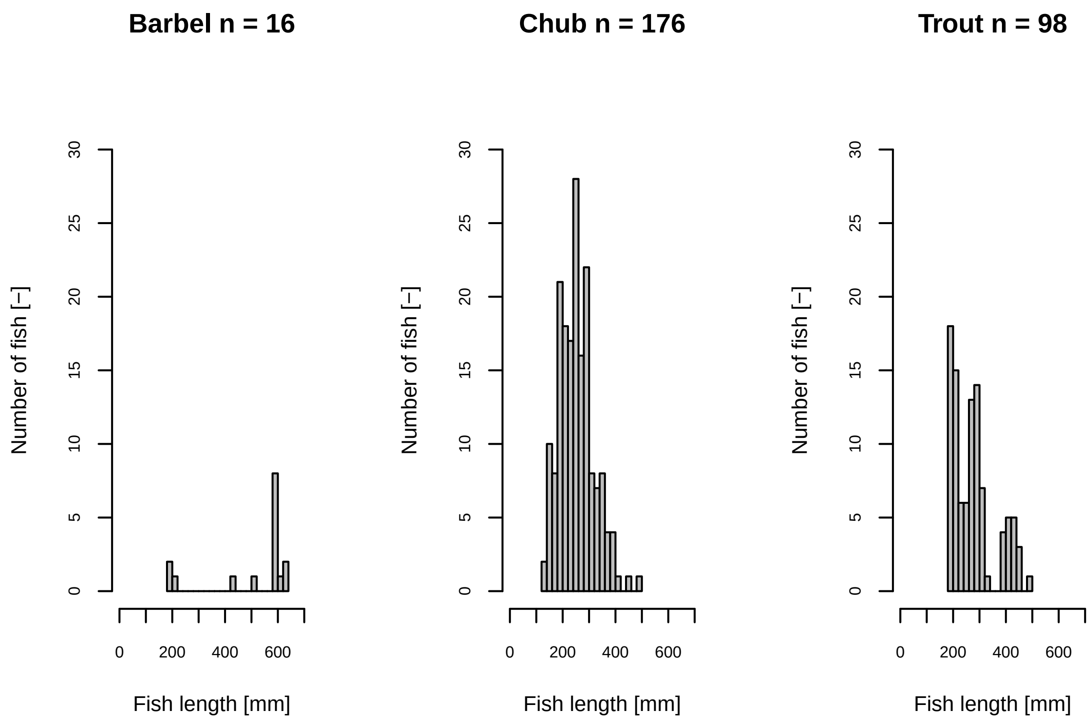


Figure 5.4 Fish size distribution of the supplied fish pool with n: Number of fish

Table 5.1 Definition of the fish length categories for each species, L = fish length [mm]

Size category	Barbel	Brown trout	Chub
Small	L < 250	L < 250	L < 200
Medium	250 < L < 400	250 < L < 350	200 < L < 300
Big	400 < L	350 < L	300 < L

5.2.3 Hydraulic conditions

Similar hydraulic conditions as the normal turbine service were created for the investigation of the fish behavior. The total discharge in the model consisted of three partitions: The turbine discharge ($Q_{turbine}$), dimensioned according to the results of a physical model test (Rutschmann et al. 2011) so that the maximum velocity at the screen could be expected to be 0.4 m/s, the discharge across the gate (Q_{weir}) for hydraulic vortex prevention at the turbine intake representing about 5 % of the turbine discharge distributed along the gate and the discharge in the migration corridor opening ($Q_{opening}$), dimensioned according to Poleni respective Toricceli approximation. The individual discharge distributions in the test facility for both variants are summarized in table 5.2. One may note that a discharge proportion of 8 % for the downstream migration corridor in variant 2 was uneconomically high. This was due to the minimum size of the opening and the relatively small turbine discharge. At real hydropower sites with larger turbine discharges the discharge proportion would be correspondingly lower.

The headwater surface elevation was meant to be 0.7 m with regard to appropriate intake hydraulics as known from the model test. This was achieved by the dimensioning of the bottom outlet which represented the turbine. The overflow height of the gate was about 50 mm. The downstream water surface elevation was maximized under the given boundary conditions because of the lack of energy transformation in the turbine. Thus, the head and therefore the energy density in the tailwater had to be minimized in order to protect the fish during the tests. The resulting elevation was about 2.7 m.

Table 5.2 Discharge distribution in the model for both gate variants with variant 1: Surface near opening and variant 2: Bottom near opening

	Variant 1		Variant 2	
	[m^3/s]	[%]	[m^3/s]	[%]
Q_{weir}	0.05	3	0.06	3
$Q_{opening}$	0.07	4	0.15	8
$Q_{turbine}$	1.72	93	1.72	89
Q_{total}	1.84	100	1.93	100

5.2.4 Experimental procedure

A total of 6 experiments were conducted for the horizontal arrangement. Both migration corridor variants were tested three times each. To reduce the influence of seasonal change in the comparison of the results, both variants were switched each time (see table 5.4). In order to avoid learning effects, the fish should be employed only once if possible. With regard to the available fish pool and permission, this was possible for a number of repetitions concerning the chub and the brown trout. However, because of a too small number of barbel (n = 16), they had to be employed for each test. A learning effect for this species cannot be excluded. A total of 58 fish, including the three species were employed for each test (see table 5.3).

At the beginning of each test, the discharges and water levels were adjusted to simulate the turbine service situation. Different discharges were used for both variant: 1.84 m^3/s for the surface opening, 1.93 m^3/s for the bottom opening. The test was started by introducing the fish in the headwater of the test setup about 3 m upstream of the screen on the right side. The fish behavior at the screen and near the opening was recorded by underwater video camera and video from outside. No artificial light sources were used to exclude a disturbance of the fish behavior. Thus, the observation was limited to times of daylight. After 24 h the migration corridor was blocked, the discharge was reduced, the water surface elevations were lowered and all fish in head and tailwater were caught. The number and type of fish (species and size category) in headwater and tailwater were recorded. A break of minimum 22 hours was realized between each two tests, which allowed a rest time for the barbel.

Additionally, water turbidity (Secchi disc) and dissolved oxygen concentration (Oximeter WTW Oxi 2000) were measured at the beginning and at the end of each test. Water temperature was recorded during the whole test duration every five minutes. Precipitation was provided from data of the meteorological station in Einsiedl, which is 2 km far from the VAO laboratory and representative for the catchment of the facility water supply.

Table 5.3 Species and size categories of fish employed for each test

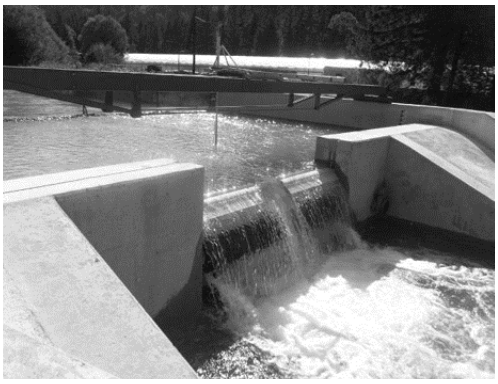
Size category	Barbel	Brown trout	Chub
Small	3	6	4
Medium	0	6	18
Big	13	3	5
Total	16	15	27

5.3 Results and discussion

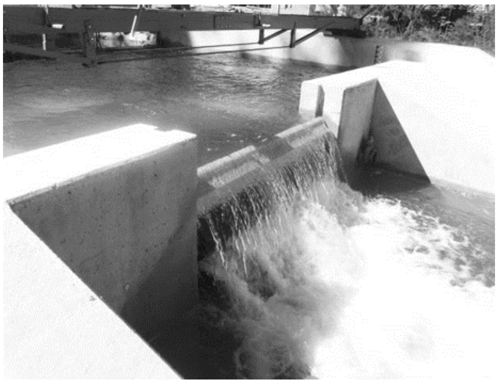
5.3.1 Hydraulic conditions

The resulting surface flow conditions corresponded well to those observed at the physical model with a turbine (Rutschmann et al. 2011; Sepp et al. 2011). Figure 5.5 provides a view of the flow conditions for both gate configurations. To verify that the flow field at the screen of the simplified setup was equal to the one at a real hydro power site with a turbine in service, three-dimensional ADV (Acoustic Doppler Velocimetry) measurements were conducted in the intake area. Velocities were measured in heights of 50 mm and 350 mm above the screen and a horizontal measurement grid with 600 mm lateral resolution. Figure 5.6 shows visualizations of the results, were the x-axis is parallel to the main flow direction and the z-axis goes vertically upward.

The velocity distributions corresponded to those measured at the physical model including a turbine and confirmed the transferability of the results. Concerning the maximum velocities towards the screen, which were relevant for fish protection, the design objective of 0.4 m/s could be affirmed. For both variants the influence of the opening was visible. In variant 1 there were positive values for V_z at x = 3 m, y =

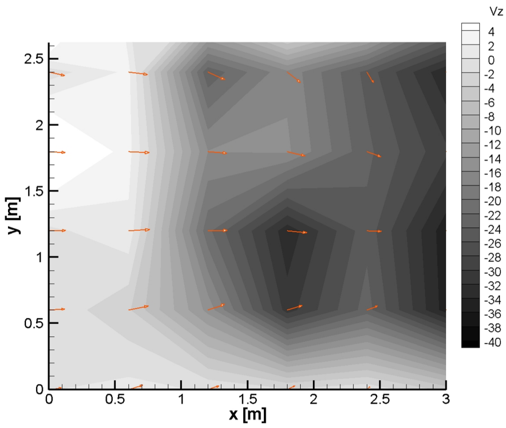


(a)

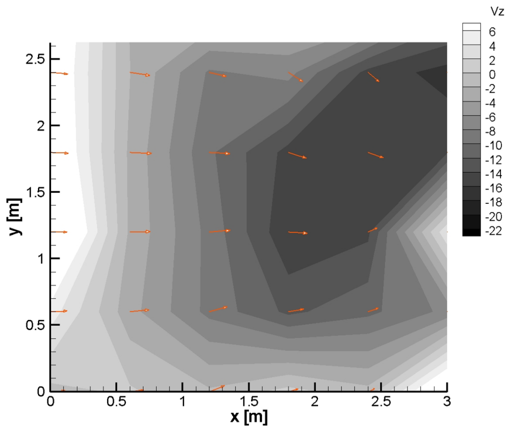


(b)

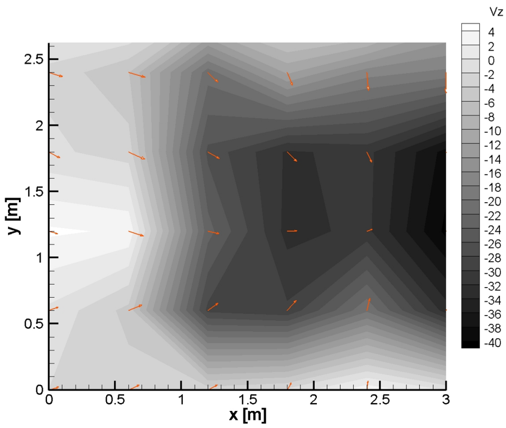
Figure 5.5 Variant 1: Surface opening (a) and 2: Bottom opening (b)



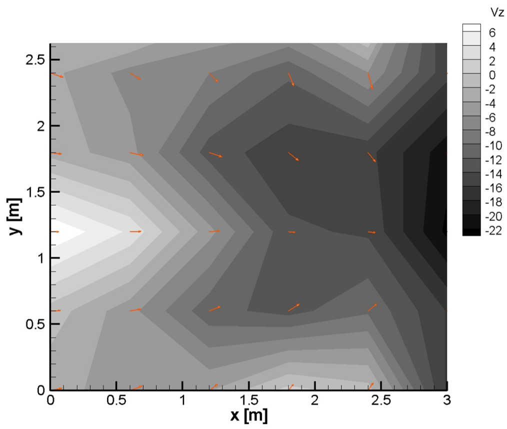
(a) Variant 1, z = 0.05 m



(b) Variant 1, z = 0.35 m



(c) Variant 2, z = 0.05 m



(d) Variant 2, z = 0.35 m

Figure 5.6 Velocity distributions at the screen for the variant 1 and 2. The red arrows represent the horizontal velocity vector V_x+V_y, the grey scale level represents the velocity distribution in the vertical direction V_z [cm/s], the screen starts at x = 0.4 m

1.2 m, z = 0.35 m which represented the flow towards the surface near the opening (lower edge at z = 0.45 m). The visualization for variant 2 showed a local minimum for the vertical velocity next to the gate which was also due to the outflow through the opening (upper edge at z = 0.25 m).

Additional ADV measurements were made 100 mm in front of the migration openings. Measurements in the opening were inhibited by air entrainment. The velocity in the x-direction was 0.96 m/s for the surface opening and 1.21 m/s for the bottom opening. The higher velocity in the bottom opening was due to the differing water columns. Furthermore ADV measurements confirmed total velocities close to zero in the calm zones near the conjunction of bay and weir, providing calm zones for the fish.

5.3.2 Abiotic boundary conditions

Abiotic factors like water turbidity and temperature could influence the fish behavior (see chapter 4). To assess the comparability of the test results, the relevant parameters were recorded (Table 5.4). Due to constant and favorable weather conditions with almost no precipitation, the water turbidity was very low (Secchi scale = 10) and enabled under water video observation throughout all tests. The water temperature was also relatively constant during the test period. Accordingly, the results concerning the fish behavior and downstream migration probabilities featured good comparability between all tests.

Table 5.4 Experimental condition for each test, T_n: Test number, Var.: Variant, Turb.: Water turbidity (Secchi scale), Prec.: Precipitation, T: Water temperature, Ox.: Dissolved oxygen, ND: No data

T_n	Var. [-]	Starting date [dd.mm.yy]	Starting time [hh:mm]	Turb. [-]	Prec. [mm]	T min-max [°C]	T mean [°C]	Ox. [mg/l]
1	2	30.08.11	11:00	10	0.0	8.8 - 12.2	10.6	11.3 - 11.1
2	1	01.09.11	09:30	10	0.0	8.9 - 9.8	9.3	11.6 - ND
3	2	05.09.11	13:45	10	1.9	8.9 - 10.8	10.0	9.1 - 9.4
4	1	07.09.11	08:45	10	0.9	8.7 - 10.9	10.2	9.6 - ND
5	2	12.09.11	13:30	10	0.0	9.0 - 12.6	11.3	10.8 - 10.3
6	1	15.09.11	09:30	10	0.0	9.1 - 12.0	10.7	10.0 - 11.1

5.3.3 Fish handling

During the research period sanitary impacts were observed at a few individuals (see figure 5.7). Most of the dead fish died in the tank (n = 25). Especially the brown trout was very sensitive to fungal infection. The comparison of the fish exposed to the test conditions with a control group in the pool stated that the complications were caused by stocking and handling. The extent was at common levels for comparable situations (natural fish in artificial environment and fish from aquaculture in river water). There was no indication for fish damage caused by the screen or during downstream migration. Five fish died during the experiment and showed skin injury probably due to contact with the fine grid closing the experiment zone in tailwater. Barbel, brown trout and chub were well suitable for the experiment conducted in the VAO laboratory.

Figure 5.7 Fish mortality due to handling

5.3.4 Fish activity

At the beginning of the tests, no fish could be observed at the screen. It required an adaptive phase before they started to be active and to explore the whole headwater area. After a few hours, during the afternoon, it was possible to observe the fish at the screen. As already found in the previous fish experiments (see chapter 4), the fish activity varied along the day and especially with the water temperature. The water temperature reached a peak at the end of the day, which corresponded to the maximal activity of the fish observed at dusk. It should be noted that no fish was forced to enter the intake area or the migration corridor. There were large zones with low velocities in the headwater area (theoretical average velocity < 26 cm/s) and two calm zones at the intersection of the weir and the bay (velocities towards zero). Hence, the fish were free to move in all directions and were not forced to migrate downstream.

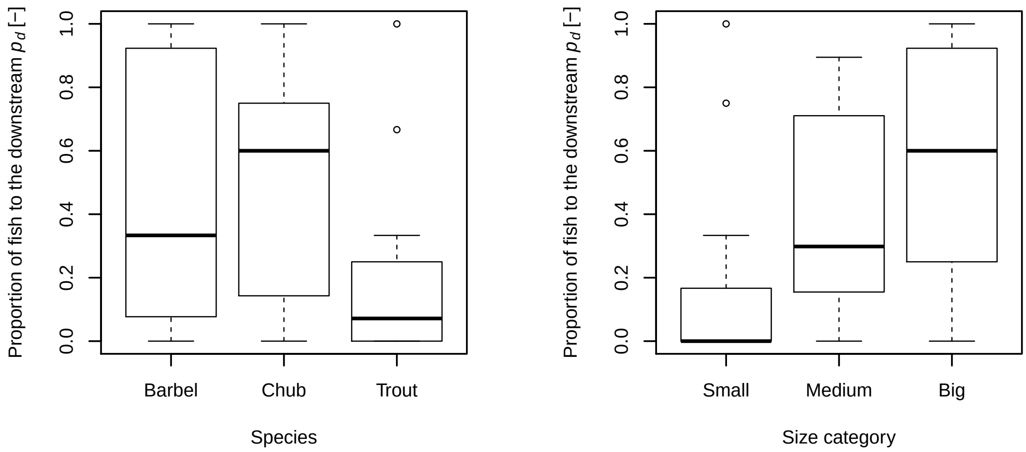
The chub and the barbel showed a gregarious behavior and swam mostly in swarms, whereas the brown trout rested alone and competitive in their territory. The chub and the barbel were observed more often at the screen compared to brown trout.

The fish had actually only two possibilities: They stayed either upstream or they passed through the opening to the downstream. None of the fish could passed through the screen because of the body width larger than the bar clearance. The fish activity p_d representing the proportion of fish which passed to the downstream was defined:

$$p_d = \frac{n_d}{n_t} \tag{5.1}$$

where n_d is the number of fish which swam to the downstream by using the opening and n_t is the total number of fish introduced. In figure 5.8 the fish activity p_d is illustrated in function of the species and the size category. A one-way ANOVA was conducted with R (R Core Team 2013) to compare the fish activity to swim to the downstream in function of the species. It differed significantly among the investigated species: $F(2, 44) = 4.3$, $p < 0.05$. A post-hoc Tukey's HSD test which allows multiple comparisons was proceeded between the three species. The chub showed a higher migration compared with the trout ($p < 0.05$). There was no difference between the barbel/trout and the chub/barbel ($p > 0.05$). The relative cold water temperature in the laboratory compared with the temperature in the barbel region at the relevant season of about 15°C might motivate the barbel and the chub to move downstream to areas of higher water temperature. On the other side the temperature was well fitting for the brown trout (optimal temperature) which might thus have had less motivation to migrate downstream at this time of the year. The different origin of the fish species could also be a reason for the behavior differences. The barbel and the chub from river sites were used to current flow whereas the breeding brown trout were conditioned to resting water. The employed brown trout might not have been familiar with or trained for challenging flow conditions with velocities as present in the intake area and especially in the migration corridor. Therefore, they might have avoided these areas and preferred calm rest zones in the headwater. These aspects should be clarified, for example by competitive tests with farm and wild fish of the same species and size under identical conditions.

Relating to the fish activity in function of the size category (see figure 5.8b), the ANOVA revealed a significant difference among the employed size categories: $F(2, 44) = 6.8$, $p < 0.05$. A post-hoc Tukey's HSD test for multiple comparisons was proceeded between the three sizes. The big fish showed a higher migration activity compared to the small ones ($p < 0.05$). There was no difference between the small/medium and the big/medium fish ($p > 0.05$). Because of their low swimming capability, the small fish probably stayed in calm zone and had smaller probability to reach the passage to the downstream compared with the big fish which stayed longer above the screen, like observed in the video documentation.



(a) (b)

Figure 5.8 Fish downstream migration in function of the species (a) and the size category (b) considering all tests

5.3.5 Fish behavior at the screen

During the test series all kind of employed species and size categories could be observed in the intake area above the screen in an active-passive migration (see figure 2.5). They mostly let themselves drift into the area. Some rather active fish headed towards it. While remaining above the screen, the fish showed a positive rheotaxis and oriented themselves with the local effective flow direction (see figure 5.9). They kept a certain distance, about 5-10 cm, above the screen surface and avoided any contact with it. No fish was impinged or stuck at the screen. The fish were safe to stay at the screen without having any injury or being exhausted. They could leave the intake area at any time and could swim against, with or cross to the flow direction. However, it was visible that the bigger the fish were, the easier they could swim freely at the screen. The velocities at the intake required more efforts for the small fish, which was consistent with their lower swimming capability.

For the given conditions, the functionality of the horizontal screen and the hydraulic setup for fish protection revealed promising results. For the maximum velocity of 0.4 m/s and 17.5 mm bar clearance, none of the investigated fish species or sizes showed difficulties or got harmed at the screen. It should be kept in mind that only fish bigger than the bar clearance and relatively strong swimming fish species were investigated. The effective orientation of the fish indicated favorable conditions for fish protection compared with conventional vertical screens with vertical bars. The fish entered the intake area through one of the three vertical inflow cross sections. Due to the gradual change of the flow direction from the horizontal to the vertical there was only a potential exposure of the caudal fin bottom tip in most of the intake area.

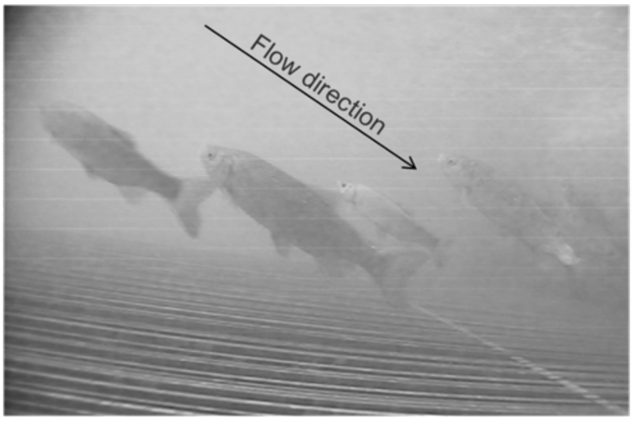


Figure 5.9 Medium chub above the screen, oriented with the local flow direction

5.3.6 Fish passage to the downstream

The general functionality of both migration corridors could be documented by video records from under and above water surface. The fish could be observed passing through the openings. Figure 5.10 gives an example of a brown trout traversing the surface near opening. However, the probability to observe a fish passing through the opening was low and the possibility to identify the species and the size was limited. For detailed analysis of the downstream migration all fish were captured after 24 hours by shutting down the discharge in the test section and reducing the water surface elevations. The species, the size category, the health status and the passage were recorded for each fish. The fish were either caught in the headwater, which meant no migration, or in the tailwater, which meant that they used the opening or the overflow over the gate to pass downstream. No differentiation could be made between the fish which passed through the opening and the ones which passed over the gate.

Unfortunately, not many fish per size category were available (see table 5.3). Three repetitions per opening position were conducted to improve the significance of the results. Figure 5.11 shows the results for both variants (bottom/surface) including all fish. The proportion of fish which stayed upstream or passed downstream was not significantly different between the three repetitions for one variant (ANOVA, $p >$

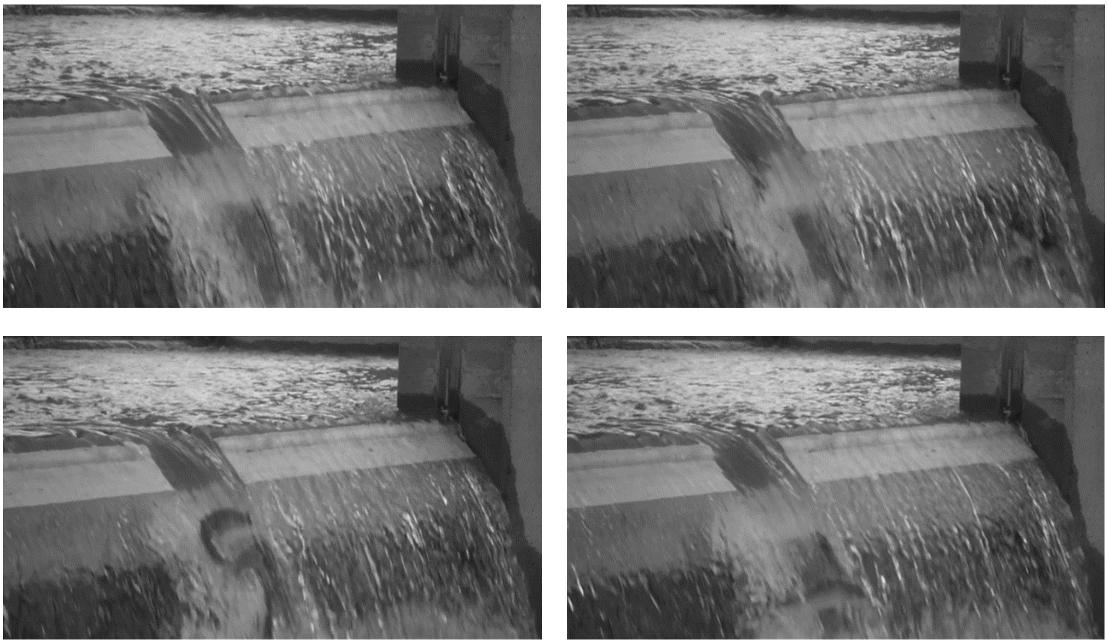


Figure 5.10 Image sequence of a brown trout passing through the surface near opening; time is advancing from left to right and from top to bottom

0.05). Thus, it could be conclude that the tests were reproducible. A learning effect could be excluded for the brown trout and the chub since new individuals were used for each test. In contrary, the barbel had to be employed each time because of a too small number of fish available (n = 16). A learning effect for this species might be possible.

The proportion of fish p_d which passed successfully downstream was calculated for each species (see equation 5.1). An analysis of variance (ANOVA) was conducted to reveal an eventual relationships between the fish passage to the downstream (p_d), the opening variant (bottom/surface) and the size category (small, medium, big). The mean proportion (over the three repetitions conducted) of the barbel which passed through the opening in function of the opening variant (surface/bottom) and the fish size category (small/big) is illustrated in figure 5.12. The opening variant had a significant influence on the barbel's passage: $F(1, 8) = 41.5$, $p < 0.05$. The passage was higher with the bottom opening than with the surface opening. This was plausible since the barbel is a bottom oriented species. The passage to the downstream was likewise depending on the size category $F(1, 8) = 6.7$, $p < 0.05$, with higher success for the big fish compared with the small ones. No medium barbel were available. The small fish had a lower swimming performance and stayed probably in calm zones. They had thus smaller probability to pass the intake area and to reach the opening. However, the bottom opening had high passage success for small barbel (mean p_d =

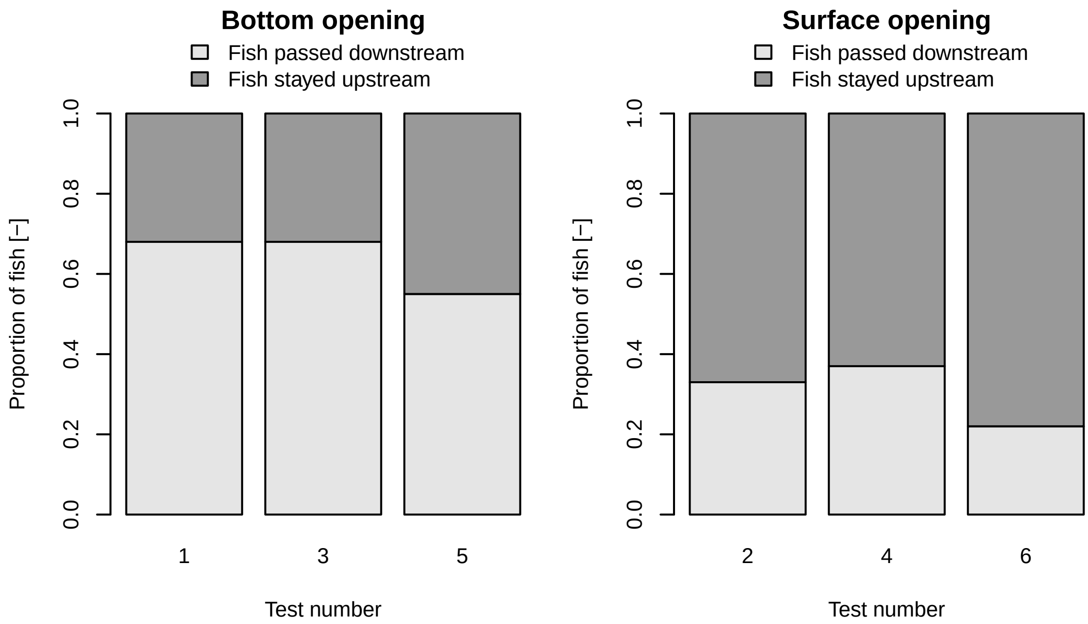


Figure 5.11 Passage to the downstream in function of the opening position considering all tests and fish

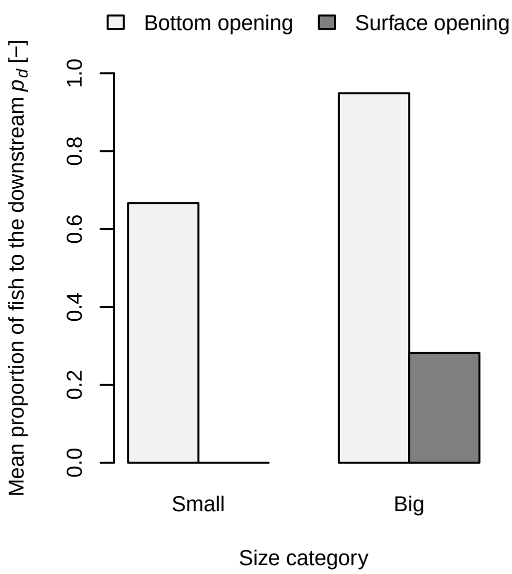


Figure 5.12 Barbel passage in function of the opening variant and the fish size category

0.66) and the big ones ($p_d = 0.95$). In contrary the small barbel did not use the surface opening at all ($p_d = 0$), the big ones did a bit more ($p_d = 0.28$).

The passage of the brown trout was likewise significantly influenced by the position of the opening: $F(1, 12) = 5.6$, $p < 0.05$. The bottom opening showed a higher passage success than the surface opening (see figure 5.13). The passage to the downstream was likewise depending on the size category $F(2, 12) = 6.3$, $p < 0.05$. The post-hoc Tukey's HSD test for multiple comparisons was proceeded between the three size categories. The big brown trout showed a higher success compared with the small ones ($p < 0.05$). There were no significant differences between the medium and the big brown trout and between the small and the medium ones ($p > 0.05$). Moreover, the relationship between the opening positions and the passage success depended on the fish size category ($p < 0.05$). The small brown trout preferred the surface opening in contrary to the big ones which rather used the bottom one. The mean passage success of the bottom opening was $p_d = 0$ for the small brown trout, $p_d = 0.16$ for the medium and $p_d = 0.66$, for the big ones. Regarding the surface near opening the mean passage success of the brown trout was very low: $p_d = 0.05$ for the small brown trout, $p_d = 0.11$ for the medium and $p_d = 0.08$ for the big ones.

Concerning the chub, the opening position had as well a significant influence on the fish passage: $F(1, 14) = 5.6$, $p < 0.05$. The passage success was higher for the bottom opening than the surface opening (see figure 5.14). The passage to the downstream was likewise depending on the size category $F(2, 14) = 8.2$, $p < 0.05$. The post-hoc Tukey's HSD test revealed that the medium and the big chub showed a higher success compared with the small ones ($p < 0.05$). There was not difference between the medium and the big chub ($p > 0.05$). The mean passage success of the bottom near opening was $p_d = 0.25$ for the small chub, $p_d = 0.81$ for the medium and $p_d = 0.86$ for the big ones. Concerning the surface opening, the passage success were $p_d = 0.08$ for the small chub, $p_d = 0.51$ for the medium and $p_d = 0.50$ for the big ones.

Finally for all the species investigated and on the described hydraulic conditions, the position of the opening had a significant influence on the passage to the downstream. The passage success was higher for the bottom opening for all available species and size categories, except for the small brown trout which slightly preferred the surface opening. The bottom opening was especially adapted for bottom oriented species like the barbel. Moreover, it provided probably a better guidance towards the screen by the flow to the opening. In general fish avoid the surface because of possible predators from land and air, which could also explain why the surface opening featured lower success for downstream migration. Furthermore, the discharge and the velocity in

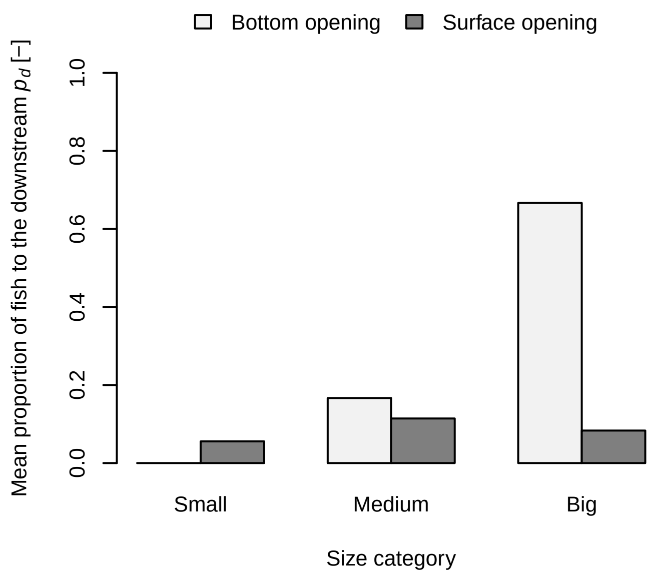


Figure 5.13 Brown trout passage in function of the opening variant and the fish size category

Figure 5.14 Chub passage in function of the opening variant and the fish size category

the bottom near opening were higher than in the surface opening inducing a better findability.

The passage success varied in function of the size categories. For the three investigated species, the big fish had more success to pass downstream than the smaller ones. This is likely to be explainable by the swimming capability. The longer is the fish, the higher is the swimming capability. Consequently, the big fish could stay a longer time in the intake area above the screen and had thus a higher probability to find and use the opening than smaller ones. There was no difference between the medium and the big fish for the chub and the brown trout which probably had similar swimming performance. The relative high velocity near the opening could be moreover repellent for the small fish because of their low swimming capacity.

5.4 Conclusion

Fish experiments have been conducted to investigate fish protection and fish downstream migration at the TUM Hydro Shaft Power Plant. The present investigations were accomplished with a simplified setup which reproduced the hydraulic conditions at the screen and in the migration corridor, although no actual turbine was involved. The present stage of the investigations concerned fish larger than the bar clearance to clarify fish protection and downstream migration of typical adult fish of comparatively strong swimming capacity.

The fish behavior investigation at the horizontal screen revealed a functional fish protection for the employed species (barbel, brown trout and chub), sizes (from 15 to 64 cm body length), screen setup (17.5 mm bar clearance) and hydraulic conditions (0.4 m/s maximum velocity towards the screen). This showed the principle suitability of horizontal screens for fish protection purpose, at least concerning fish of large size. Moreover, the investigations provided information about the fish behavior at horizontal intake plane. The clarification of the fish orientation at the screen indicated a lower risk of injury at the specific trash rack bar arrangement, compared with classical vertical intake planes with vertical bars.

Video observation of the opening and fish counting at the end of the test confirmed the functionality of the migration corridor. For all the three species tested, the opening position had a significant influence on the success of passage. The bottom opening provided higher efficiency. The passage success was also depending on the fish size category. The big fish had higher chances to use the passage to the downstream. The limited swimming performance of the small fish seemed to reduce their tendency to enter the intake area and reach the opening.

The results obtained under laboratory condition concerning the fish protection at the horizontal screen and the functionality of the downstream passage at the TUM Hydro Shaft Power Plant were very promising. In 2013, the prototype in the VAO laboratory was supplied with a turbine and a 20 mm bar clearance screen. Further tests were conducted with small fish which featured low swimming capacity to investigate the passage distribution through the screen and the opening and to evaluate mortality due to the turbine passage. The tests yielded encouraging results (Geiger et al. 2014). However, the transferability of the results to real river sites has not been clarified yet.

6 Discussion

The fish experiments conducted in the VAO laboratory revealed new knowledges concerning the fish behavior in front of the turbine intake at inclined and horizontal screens. The guidance of the fish by inclining the screen led to promising results. In the following parts, the findings concerning fish protection at screens, guidance of the fish to the bypass, bypass design, laboratory evaluations with fish and transferability of the results are summarized and discussed.

6.1 Fish protection and guidance at the screen

The main parameters influencing fish protection at turbine intake screens are the approach velocity, the bar clearance and the inclination of the screen. The velocity at the screen should not be higher than the critical swimming speed (U_c) of the target fish to avoid any fish impingement (see chapter 2). The approach velocity at the screen was constant within the three fish experiments conducted (chapter 3, 4 and 5). However, due to the inclination of the screen (chapter 3 and 4), the approach velocity V_A was decomposed into the tangential component V_T and the normal component V_N according to equation 2.4 and 2.5. The normal velocity component is responsible for the fish impingement while the tangential velocity component might provide a guidance along the screen. Courret et al. 2008 recommend a normal component smaller than the critical swimming speed to avoid fish impingement and a tangential component twice as high as the normal component to provide the guidance of fish along the screen to the surface. Therefore, the inclination of the screen should be at least α = 25° or lower. The results obtained during the preliminary experiments (chapter 3) revealed a slight influence of the screen inclination on the fish passage over the screen overflowed. The lowest inclination (α = 25°) showed a better guidance of the fish to the surface compared with the other inclinations tested (α = 35, 45 and 90°). The tests conducted at a one-to-one scale with PIT marked fish provided a lot of data which enabled a detailed analysis of the actual effects of the screen inclination and the bar clearance on the fish passage through the screen and the guidance along the screen to the surface bypass. The bar clearance, the screen inclination and the fish length had a significant influence on the fish passage. A mathematical formula (see equation 4.3, chapter 4) was developed from a logistic regression to calculate the probability to pass through the screen or to the bypass in function of the bar clearance, the fish length and the inclination of the screen for the barbel at an approach velocity of 0.5 m/s. In short the conclusions were:

- The lower the inclination of the screen was, the smaller was the probability to pass through the screen and the higher was the probability to reach the entrance of the surface bypass.
- The larger the bar clearance was, the higher was the probability to pass through the screen and the smaller was the probability to reach the entrance of the surface bypass.
- The smaller the fish length was, the higher was the probability to pass through the screen and the smaller was the probability to reach the entrance of the surface bypass.

A low inclination of the screen effectively increased the protection of the fish from passing through the screen and increased the guidance along the screen to the surface bypass. This supports the theory from Courret et al. 2008 concerning the decomposition of the velocity in two components at an inclined screen reducing impingement of fish at the screen and increasing the guidance of the fish along the screen. A direct comparison of the velocity ratio with the achieved results had no significance since the results obtained during the fish experiments also depend on the fish size and the bar clearance. However, the fish investigation demonstrated that the fish passage through the screen decreased and the guidance along the screen increased with a low inclined screen and therefore with a lower normal velocity component compared with a more vertical screen. While one can explain these results by the velocity components (V_T and V_N), the inclination of the screen might have as well an influence on the fish behavior independently from the velocity components. Actually a 70° inclined screen had a repulsing effect on the fish. They swam back upstream as they perceived the barrier. The fish swimming at the screen showed a positive rheotaxis. The caudal fin was thus the first part of the fish in contact with the screen. As the screen was almost vertical (α = 70°) the whole caudal fin touched the screen affecting the fish locomotion and causing an obstruction of the fish movement. Consequently the fish avoided the screen area to reduce possible injury. On the other side, for a low-slope screen only the bottom tip of the caudal fin was in contact with the screen which less disturbed the fish swimming ability and therefore allowed the fish to swim up forward along the screen. In this way the fish were guided along the screen to the surface bypass. Moreover, the fish might not visually notice an almost vertical screen, since it might not be in their field of view. By a low inclined screen, the fish swam above the screen and might sooner perceive the screen which was then in their field of view. Hence, the fish could better respond to the approach of a low inclined screen.

Finally the fish might be physically and visually guided along the inclined screen by avoiding contact with it. In addition, a low inclination of the screen could increase the tangential component velocity and the guidance to the surface bypass while the normal component was reduced and might decrease the risk of impingement of the fish at the screen.

As well as the inclination of the screen and the velocity at the screen, the bar clearance is definitely essential for the fish passage through the screen. Both the velocity and the bar clearance should be adapted to avoid the fish impingement and the passage through the screen towards the turbine. The conventional screens provide a physical barrier and therefore it is evident that the fish length i.e. the fish width and the bar clearance are determinant for the passage through the screen. The bars can furthermore induce a repulsive effect on the fish in certain conditions: Within a limited range, fish smaller than the bar clearance can be protected. On the other side, a bar clearance equal to the fish width can entail a high potential for fish injury since the fish could be stuck between two bars like observed by Hübner et al. 2011. As the fish try to release from the bars, high skin injury occurs. Therefore a bar clearance smaller than the fish width should be installed to avoid the blockage of the fish.

The size of the fish showed also an effect on the fish passage to the surface bypass. Due to their lower swim capacities, the small fish had lower probability to reach the bypass entrance than the bigger ones. In addition, they had higher probability to pass through the screen and therefore smaller probability to reach the bypass entrance. The aspects of fish size and bar clearance are strongly related and might be considered by the proportion of these parameters. However, the absolute fish size also influences the swimming capacity. This one has to be accounted for in relation to the approach velocity and depends on the fish species. The resulting complexity of statements for the fish guidance can be managed by statistical models like demonstrated for the barbel.

The investigation of fish protection and fish downstream migration at inclined screens promised the best protection and guidance for flat screens and small bar clearances. As an extreme this leads to a horizontal screen with small bar clearance like employed at TUM Hydro Shaft Power Plant. A series of experiments was conducted to investigate and improve fish protection and downstream migration at this hydro power concept considering fish larger than the bar clearance (b_c = 17.5 mm). The test conducted with large fish provided promising results concerning the fish protection and the findability of the downstream passage. The homogeneous velocity distribution and the low velocities at the screen provided a safe movement of the fish above the horizontal screen. By entering the shaft, the velocity was decomposed into the vertical velocity component (V_z). Since V_z was low (max. 0.4 m/s), no impingement of the fish at the horizontal screen occurred. The fish moved in all direction above the screen without difficulty and could leave the intake area and return to calm zones at any time. They showed a positive rheotaxis to the flow and had an angular orientation above the screen (see figure 5.9). In contrary to a classical vertical screen with vertically oriented bars, the probability of the fish to have interference with the horizontal screen was smaller. It is comparable to a low inclined screen where the fish had contact with the screen only with the bottom part of the caudal fin. The locomotion of the fish was not disturbed and the potential of injury significantly lower. Consequently, the fish could keep swimming above the screen and had then more chance to find the opening constituting the downstream passage facility. Similarly to the low inclined screen, the fish swam above the horizontal screen which was then in their field of view. The fish could then better apprehend the screen to avoid any contact. While the fish could stay a long time above the horizontal screen without major risk, it maximized the chance to find the opening in the vertical gate and to pass to the tailwater. The results of the horizontal screen cannot be compared directly to those of the inclined screen due to differences in the concepts and the experimental procedures.

6.2 Bypass design

The inclined screen was combined with a surface bypass located at its downstream end. The construction was at the scale one-to-one but represented only a part of the HPP intake width. The bypass surface was on the whole width of the screen (1.25 m). Two velocities in the bypass were tested: 0 and 0.25 m/s. The logistic regression revealed no influence of the velocity in the bypass on the passage of the fish through the screen or to the bypass entrance. The zone of influence of the bypass entrance, i.e. the zone where the velocity is noticeable, was probably too reduced to enable the detection by the fish. Therefore, the velocity tested did not improve the findability of the bypass. However, higher velocities than 0.25 m/s will probably enhance the findability since the zone of influence will increase as well (Larinier et al. 2002). The discharge in the bypass should be adapted to provide a sufficient zone of influence. To improve the findability, several bypass entrances are recommended along the screen width of HPP. One bypass entrance on the middle of the screen is disadvantageous since it produces vortices which strongly reduce the findability (Raynal 2013). Two bypasses entrance at both sides of the screen already yielded good results in Sweden (Calles et al. 2009). In general the number of bypasses should be adapted to the width of the intake screen.

Four different configurations of the bypass were tested. The velocity at the bypass entrance was 0.25 m/s for each setup (section 4.3.12). Considering the fish which reached the bypass entrance, the passage efficiency was from 70 to 92 %. The slot configurations revealed better results compared with the gate configurations. These configurations enabled the passage of the fish on the whole water depth (W_{BP} = 0.27 m) and provided fast flows and calm zones. The bypass attractiveness was evaluated by the number of passages at the bypass entrance before the fish reached the bypass end. The configuration with two slots showed the best attractiveness. The fish passed faster to the downstream as they reached the bypass entrance compared with the three others configurations. The combination of fast flow, calm zones and constant water depth was enhancing the efficiency and attractiveness of the bypass. While a fast flow improved the passage to the downstream for the big fish, it was repellent for the small ones which featured lower swimming capacities. The gate overflow provided good results but the overflow has to be deep enough (approx. 15 cm) to avoid any contact of the fish with the gate. A passage through a slot should be however more adapted for a larger range of species.

At the TUM Hydro Shaft Power Plant, an opening (0.25 m high and 0.30 m broad) in the vertical gate enabled the passage of the fish to the downstream. There was no actual bypass geometry since the fish fell directly into the tailwater. The size, the position and the number of openings can be adapted according to the fish species and sizes present in the river concerned by the HPP. Like described in chapter 5, a bottom opening gave better results than the surface opening for all species and sizes considered except for the small brown trout. The better efficiency was probably due to the greater velocity because of the higher water column than for the surface opening. Moreover, the bottom opening is more findable since the flow provided a guidance towards the screen. Finally, several openings distributed along the gate with a combination of both surface and bottom opening could be a good way to enable the passage to the tailwater for different fish species and sizes. The water cushion should be deep enough to avoid any injury and mortality during the plunge in the tailwater. The standard water depth recommended is 25 % of the water head and a minimal value of 0.9 m (Odeh et al. 1998).

6.3 Laboratory evaluations with fish

Numerous knowledges concerning fish experiments was gathered during the test series. Four different species were employed: Brown trout, barbel, chub and nase. The nase were the most sensitive of all to the experimental conditions in the VAO laboratory. The fish storage as well as the fish handling had unfavorable influences on the nase health condition. Actually about 50 % of the nase died in the fish pool. The reason was probably the high sensitivity of the nase with respect to the water quality (Jankovic 1973), although the water was continuously renewed and came from the Isar River mixed with tap water. Moreover, stress and skin disturbance due to the fish handling were probably a further source of health problem. It is of most importance to handle the fish carefully with adapted professional fishing tools (fish net, fish scoop) to avoid any skin injury. Like it was often the case for the brown trout, a small skin injury can induce fungal infection altering the fish health and swimming behavior.

During the transfer of the fish to the laboratory pool an adaption phase to the new conditions and particularly the water temperature should be conducted to avoid a temperature shock (Lehmann et al. 2012). To reduce the fish mortality due to the pool storage, the water should be renewed continuously and the water quality should be controlled every day. The main parameters to be measured in the pool are the water temperature, the dissolved oxygen concentration and the pH-value. By partially covering the fish pool, one can provide dark hiding places to reduce stress. The fish pool should also be covered with a net to avoid the escape of the fish or potential attack from outside. It is recommended to keep the fish in the pool not more than 2 weeks and to clean the pool regularly. The number of fish in one pool should be conformed to the pool size. Moreover, it should be accounted for the species and fish size mixture within one pool to exclude predation among the fish.

The nase were very demanding with regard to the water quality in the pool and unfortunately not less during the experiment in the channel. Actually the nase were the only fish showing a very low movement activity. Most of the time the nase stayed in the calm zones at the upstream end of the experimental channel. The most probable cause was the water temperature which was much colder than the optimal temperature of the nase inducing the fish quasi to winter dormancy. That is why few passage information concerning the nase were recorded. The few passages recorded might be irrelevant since their swimming capacities were altered. Finally, the nase are definitely not adapted to fish experiments in the VAO laboratory and probably in general to any fish experiments since they are very sensitive to the water quality and handling.

The barbel, brown trout and chub in contrary to the nase were more active and swam frequently to the downstream. Considering the barbel and the chub, the actual water temperature in the laboratory was as well much colder than their optimal temperature. In contrary to the nase, the cold water temperature did not reduce the fish activity but rather initiated the downstream migration. Barbel and chub were very active, especially the barbel. While the cold water temperature might explain the low activity of the nase, it could be the reason for the high activity of the chub and barbel which might tend to migrate downstream to reach warmer water. A different sensitivity of the temperature between the species could be the reason. Beside the objectives of the experiment, the fish species have to be chosen with regard to the temperature of the water supply in the laboratory. It is of most importance since the water temperature strongly influences the swimming capacities and behavior. Consequently, the water temperature should be as close as possible from the optimal temperature of the fish considered.

During the experiments farm and wild fish were used. Wild fish might have higher swimming capacities since they have practice compared with farm fish which are used to low flow conditions in a pool (Pearson et al. 1990). Consequently, it is recommended to use wild fish having a more representative behavior and swimming capacity from fish at real river sites. In detail, the suitability of farm fish might differ with regard to the specific farming conditions of their origin, for example whether they were kept in large basins or small circular pools.

Fish have the capacity to learn (Laland et al. 2003; Odling-Smee et al. 2003), therefore a learning effect could occur during the experiments conducted. Consequently, one fish should only be used once to exclude any learning behavior. This means that a large number of fish should be requested for the experiments. Since the fish supply was effectively limited depending on the fish species, the fish size and the origin of the fish, the available fish were mostly used more than once during the test series. For the first tests conducted, the same fish was used once within two weeks. The assumption was that the fish have a short-term memory. During the second test series, the fish were PIT marked. Since the number of fish was limited, the same fish were used almost for each test. Consequently, a learning effect during this experiments might have occurred. For the experiments at the horizontal screen, with the exception of the barbel, the fish were used only once. Consequently the number of fish per size category was reduced to enable the repetition of the test. Therefore, the number of fish necessary to conduct test series should be preliminary estimated by taking into account the number of fish per test, species and sizes, the number of repetitions and the eventual loss of fish due to handling and storage.

The experimental procedure of different tests within one test series should be similar to allow comparisons between the tests conducted. The tests should start at the same time of the day. At the beginning of the tests, the fish are under stress and disoriented, therefore the test duration should include an adaption phase. Since the tests were executed in open air, the climatic condition and especially the day variation could influence the fish. For the preliminary test the test duration was 48 hours, for the second and third test series it was 24 hours to include the diurnal variation. A precise documentation of the hydraulic condition, the abiotic parameters like the water temperature, the illumination and the turbidity is of great importance. They are useful to understand and explain the fish behavior.

With regard to the fish monitoring, two methods were used. The first one consisted of marking the fish with PIT. It required biologists to inject the chip and special antennas to record the fish passage. Since the PIT antennas are working with electromagnetic fields, they are sensitive to the close environment. The records might be altered by unfavorable conditions. For example a rolled electric cable strongly interfered the magnetic field and disturbed the fish passage records. The antenna delay was set to four minutes to reduce the data storage and processing. Thus, one fish could be registered once in a four minute interval. While it had no influence on the results concerning the fish passage because only the first passage was considered, it reduced the information concerning the bypass configuration. Actually it was not possible to estimate the exact duration the fish needed to pass from the entrance to the end of the bypass. Anyhow, the introduction of the factor a_{BP} allowed the estimation of the bypass attractiveness. The PIT records gave plenty of data allowing the subsequent analysis of the fish passage. Linking this data with the documented abiotic parameters provided further knowledge about the fish behavior and migration. For the third test series, the fish were not PIT marked. The passage of the fish was determined by means of physical barriers separating the fish between the tailwater and the headwater. The fish had two possibilities, either they stayed upstream or they swam to the downstream. The passage of the fish was then clearly to distinguish.

Fish nets and grids at the upstream and at the downstream end of the test zone were installed to avoid any fish escape. These nets were fine enough according to the fish size employed and with adaptive material to avoid fish injury. Consequently to the fine grid, accumulation of floating debris altered the flow and had to be regularly cleaned.

At the end of the tests, the discharge was turned off and the fish were captured. Since potential fish injury was actually not the topic of the investigation, the health status was documented but not analysed in detail.

6.4 Transferability of the results

Laboratory investigations enable targeted test conditions, comparable test series, parameter studies and a complete record of all fish movements and damages. The transferability of the results obtained in laboratory to real sites is often a critical question and has to be considered carefully. The behavior of the fish is governed by various internal aspects and external factors. It depends on the fish species, sizes and origin, which have to be accounted for by employing all relevant fish categories and by using wild fish caught in the respective river system if possible. The migration is also influenced by complex relations (reproduction cycle, alimentation and environmental conditions). Internal aspects, i.e. those related to the fish itself are difficult to handle. A veterinary investigation can assure a good and representative health and nutritional status of the fish. Other factors like the hormonal cycle can hardly be comprehended or manipulated. Whereas the experimental conditions like fish pool storage, handling and artificial environment do certainly influence the fish and affect its comportment. Therefore, the migration movement is likely to be disturbed and a transferability for example of migration percentages is in general not recommended.

However, the spontaneous reaction of the fish to a specific situation especially a flow condition is kind of intrinsic and can be transferred (Adam et al. 2011). The differentiation between complex/non-transferable and inherent/transferable behavior is vague and one objective of the actual research in ecohydraulics. A minimization of disturbing influences like stress, handling and artificial environment is principally required to achieve natural behavior and therefore transferable results. External boundary conditions like temperature and light conditions will favor this. Consequently, reactions such as the avoidance of the screen passage or the guidance to the surface should remain unchanged. Such movement distributions are supposed to be transferable. An exact reproduction of the flow condition which serves as the primary stimuli is of course essential.

The meaningful of the results obtained in laboratory depends thus on the quality of the laboratory conditions under which the tests were conducted. The experiments conducted at the VAO laboratory were conducted under near-natural conditions improving the transferability:

- The test were conducted at the scale one-to-one
- The flow condition were comparable to the real one
- The water in the test channel was derived from a natural river

- The test were conducted in an open air channel with natural light (sun, moon)
- The test were conducted for 24 hours including diurnal and temperature variation

Moreover, the results from the experiments provided evidences for the good quality of the test condition:

- The tests were reproducible indicating that the fish passage was not the results of hazard but it was the response of the fish to specific conditions
- The fish showed a social behavior and swam in swarm like observed in nature
- The migration varied with the temperature and the diurnal variation

The significance of the results obtained in laboratory strongly depends on the conditions at which the experiments were conducted. However, the results obtained in the laboratory have to be consistent. For example the results relating to the nase and the chub in chapter 4 were preferably excluded from the analysis, since they were not coherent. Furthermore, the tests conducted can hardly reproduce exactly the same conditions as in the nature. In the presented experiments, no turbine was installed. While the hydraulic conditions were comparable to a real one, the absence of turbine might affect the fish behavior. Noise and vibrations caused by the turbine might have a repulsing effect on fish and potentially reduce the probability for the passage through the screen.

For the interpretation of the data, the circumstances of the experiments have to be considered. A direct comparison with other similar tests is not possible since the conditions were different. But like observed by Adam et al. 1999; Hübner et al. 2011 in a laboratory flume and Calles et al. 2012 in the nature, the inclination and the bar clearance strongly influence the fish passage, supporting the statements and significance of the results obtained in the VAO laboratory.

6.5 Conclusions and Perspectives

The experiments described in the present thesis provided new findings concerning the behavior of potamodromous species. The fish behavior was investigated at an inclined screen and at a horizontal screen revealing significant knowledges to improve the protection of fish at HPPs during the fish downstream migration.

According to the results obtained, a low inclined screen with a narrow bar clearance combined with a surface bypass can provide fish protection and a safe migration to the downstream. However, a general statement is not possible. Each HPP has to be considered separately to find the best solution adapted to the respective site. Especially the location and the design of the bypass entrance is essential to provide a good attractiveness.

Further researches are advised. Changing the approach velocity at the inclined screen could yield additional combinations to enable the fish to find the bypass and avoid the passage through the turbine. Additional fish species and a large range of fish sizes should be studied. Moreover, the hydraulic conditions at the bypass entrance i.e. the zone of influence should be precisely investigated to optimize the flow in order to avoid any repulsing effect and to improve the bypass attractiveness. Combinations with behavioral means like light or sound might also improve the barrier effect of the screen and/or the bypass attractiveness.

The TUM Hydro Shaft Power Plant gave promising results for fish larger than the bar clearance due to the low velocities at the horizontal screen and the well findable opening allowing the passage to the downstream. Further investigations are needed to clarify the protection of small fish and weak swimmers at such a HPP. By now, more experiments were conducted at a prototype in the VAO laboratory to study the fish passage distribution of small fish between the turbine and the opening as well as the fish turbine mortality. The experiences gave encouraging results (Geiger et al. 2014).

The transferability of the results obtained in laboratory with those observed in nature should be investigated to evaluate the quality of such fish experiments in laboratory. Nevertheless, they provide knowledge about the fish behavior facing specific hydraulic conditions. This is of high interest to enhance fish protection at HPPs and to enable fish to freely move in the rivers.

Annexes

A1 Statistical methods

This part provides an overview of the statistical methods used in the thesis. The following texts are derived from selected statistical papers. Some adaptations were made to fit the contents of the thesis. The sources of the papers cited are written in brackets. For more information concerning the statistical methods please refer to the respective sources.

A1.1 Linear regression (from Bewick et al. 2003)

Linear regression is used to analyze continuous relationships. In this thesis, the effect of abiotic parameters (the predictor or explanatory variable: *x*) on the fish activity (the response variable: *y*) was studied. The objective was to estimate the underlying relationship with a linear approximation. Regression can be used to find the equation of this line. This line is usually referred to as the regression line. The equation of a straight line is given by:

$$y = \beta_0 + \beta_x \times x \tag{A.1}$$

where the coefficients β_0 is the intecrept of the line on the y axis and β_x the regression coefficient i.e. the slope of the regression line.

A1.2 The *p*-value (from www.statsdirect.com)

The *p*-value or calculated probability is the estimated probability of rejecting the null hypothesis (H_0) of a study question when the corresponding hypothesis is true. The null hypothesis is usually an hypothesis of no difference e.g. no difference between fish activity of barbel and chub. The alternative hypothesis (H_1) is the opposite of the null hypothesis. If the *p*-value is less than the chosen significance level then the null hypothesis is rejected. The choice of the significance level at which the null hypothesis is rejected is arbitrary. Conventionally the 5 % (less than 1 in 20 chance of being wrong), 1 % and 0.1 % ($p < 0.05$, 0.01 and 0.001) levels are used. Most authors refer to statistically significant as $p < 0.05$ and statistically highly significant as $p < 0.001$ (less than one in a thousand chance of being wrong).

A1.3 ANOVA (from www.edanzediting.com)

Analysis of variance (ANOVA) is used to compare differences of means among more than two groups. This is done by looking at variations in the data and where that variation is found Mathematically, ANOVA can be written as:

$$x_{ij} = \mu_i + \varepsilon_{ij} \tag{A.2}$$

where *x* are the individual data points, *i* and *j* denote the group and the individual observation, ε is the unexplained variation and the parameters of the model (μ) are the population means of each group. Thus, each data point (x_{ij}) is its group mean plus error. Like other classical statistical tests, ANOVA is used to calculate a test statistic (the F-ratio) with which the probability (the *p*-value) of obtaining the data assuming the null hypothesis can be obtained. A significant *p*-value (usually taken as $p < 0.05$) suggests that at least one group mean is significantly different from the others.

– Null hypothesis: All population means are equal.

– Alternative hypothesis: At least one population mean is different from the rest.

ANOVA separates the variation in the dataset into 2 parts: Between-group and within-group. These variations are called the sums of squares, which can be seen in the equations below.

Variation between groups
The between-group variation (or between-group sums of squares, BSS) is calculated by comparing the mean of each group with the overall mean of the data. Specifically, this is:

$$BSS = n_1(\overline{x}_1 - \overline{x})^2 + n_2(\overline{x}_2 - \overline{x})^2 + n_3(\overline{x}_3 - \overline{x})^2 \tag{A.3}$$

i.e., by adding up the squares of the differences between each group mean and the overall population mean, multiplied by the sample size, assuming three groups are compared (i = 1, 2 or 3). The BSS is divided by the number of degrees of freedom to get the estimate of the mean variation between groups.

Variation within groups
The within-group variation (or the within-group sums of squares) is the variation of each observation from its group mean.

$$SS_R = s^2_{group1}(n_{group1} - 1) + s^2_{group2}(n_{group2} - 1) + s^2_{group3}(n_{group3} - 1) \tag{A.4}$$

i.e., by adding up the variance of each group times by the degrees of freedom of each group.

The F ratio
The F ratio is then calculated as:

$$F = \frac{MeanBetween - groupBSS}{MeanWithin - goupBSS} \tag{A.5}$$

If the average difference between groups is similar to that within groups, the F ratio is about 1. As the average difference between groups becomes greater than that within groups, the F ratio becomes larger than 1. To obtain a *p*-value, it can be tested against the F-distribution of a random variable with the degrees of freedom associated with the numerator and denominator of the ratio. The *p*-value is the probably of getting that F ratio or a greater one. Larger F-ratios gives smaller *p*-values.

Tukey HSD Test
Tukey's HSD test is a post-hoc test, meaning that it is performed after an ANOVA test. The purpose is to determine which groups in the sample differ.

A1.4 Logistic regression (from Bewick et al. 2005)

Logistic regression is a method for modelling the dependence of a binary response variable on one or more explanatory variables. Continuous and categorical explanatory variables are considered. The outcome is often coded as 0 or 1, where 1 indicates that the outcome of interest is present, and 0 indicates that the outcome of interest is absent. The logistic or logit function is used to transform an 'S'-shaped curve into an approximately straight line and to change the range of the proportion from 0-1 to $-\infty$ to $+\infty$. The logit function is defined as the natural logarithm ($\ln$) of the odds of passage through the screen. Odds are a numerical expression to reflect the likelihood that a particular event will take place. That is,

$$\text{logit}(p) = \ln\left(\frac{p}{1-p}\right) \tag{A.6}$$

Where p is the probability of passage through the screen for example. The relationship between probability of passage though the screen and the explanatory variable could therefore be modelled as follows:

$$\text{logit}(p) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + ... + \beta_i X_i \tag{A.7}$$

where p is e.g. the probability of passage through the screen and X_1, X_2 ... X_i are the explanatory variables (e.g. fish length, screen inclination, bar clearance). The method of including variables in the model can be carried out in a stepwise manner going forward or backward, testing for the significance of inclusion or elimination of the variable at each stage. The tests are based on the change in likelihood resulting from including or excluding the variable. Several models may produce equally good statistical fits for a set of data and it is therefore important when choosing a model to take account of biological considerations and not depend solely on statistical results. The model A.7 is equivalent to the following:

$$\frac{p}{1-p} = e^{(\beta_0+\beta_1 X_1+\beta_2 X_2+...+\beta_i X_i)} \tag{A.8}$$

or

$$p = \frac{e^{(\beta_0+\beta_1 X_1+\beta_2 X_2+...+\beta_i X_i)}}{1+e^{(\beta_0+\beta_1 X_1+\beta_2 X_2+...+\beta_i X_i)}} \tag{A.9}$$

Estimates of the parameters β_0, β_1 and β_i are obtained using R. The model can be used to calculate the predicted probability of passage through the screen (p) for a given value of the explanatory variables. After estimating the coefficients, there are several steps involved in assessing the appropriateness, adequacy and usefulness of the model. The importance of each of the explanatory variables is assessed by carrying out statistical tests of the significance of the coefficients. The overall goodness of fit of the model is then tested. Additionally, the ability of the model to discriminate between the two groups defined by the response variable is evaluated. Finally, if possible, the model is validated by checking the goodness of fit and discrimination on a different set of data from that which was used to develop the model.

The Wald statistic

Wald X^2 statistics are used to test the significance of individual coefficients in the model and are calculated as follows:

$$\left(\frac{coefficient}{SE\ coefficient}\right)^2 \tag{A.10}$$

where SE is the standard error. Each Wald statistic is compared with a X^2 distribution with 1 degree of freedom. Wald statistics are easy to calculate but their reliability is questionable, particularly for small samples. For data that produce large estimates of the coefficient, the standard error is often inflated, resulting in a lower Wald statistic, and therefore the explanatory variable may be incorrectly assumed to be unimportant in the model. Likelihood ratio tests are generally considered to be superior.

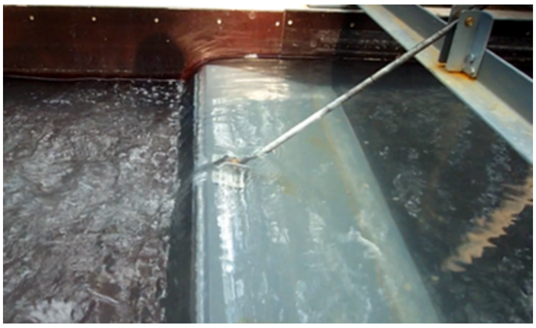
Likelihood ratio test

The likelihood ratio test (LRT) for a particular parameter compares the likelihood of obtaining the data when the parameter is zero (L_0) with the likelihood (L_1) of obtaining the data evaluated at the MLE (maximum likelihood estimate) of the parameter and is calculated as follows:

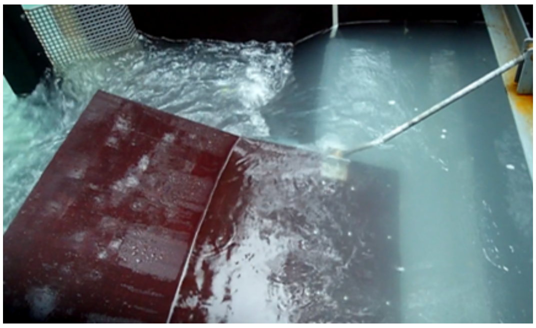
$$-2 \times \ln(likelihood\ ratio) = -2 \times \ln\left(\frac{L_0}{L_1}\right) = -2 \times (\ln L_0 - \ln L_1) \tag{A.11}$$

It is compared with a X^2 distribution with 1 degree of freedom.
The logistic transformation of the binomial probabilities is not the only transformation available, but it is the easiest to interpret, and other transformations generally give similar results. In logistic regression no assumptions are made about the distributions of the explanatory variables. However, the explanatory variables should not be highly correlated with one another because this could cause problems with estimation. Large sample sizes are required for logistic regression to provide sufficient numbers in both categories of the response variable. The more explanatory variables, the larger the sample size required.

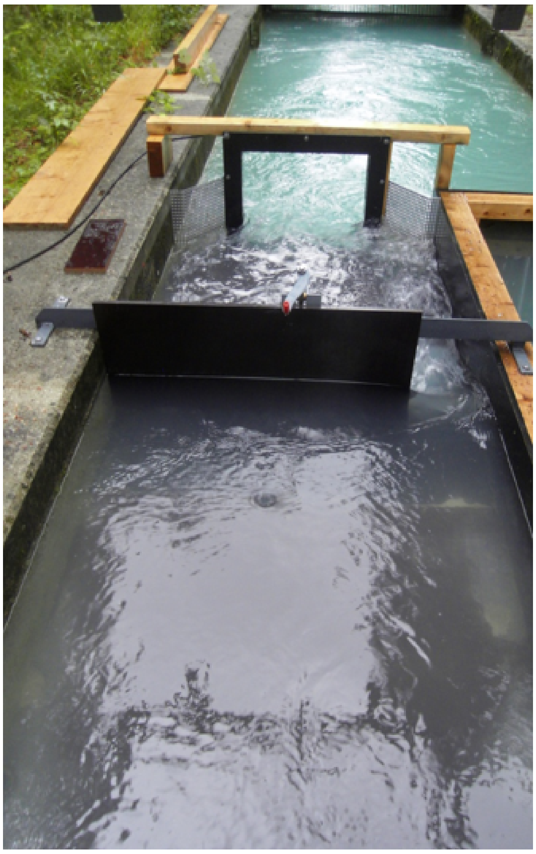
A2 Bypass setup



(a) BP_1: Gate 5 cm overflowed



(b) BP_2: Gate 10 cm overflowed



(c) BP_3: One slot

(d) BP_4: Two slots

Figure A.1 View of the bypass configurations tested

List of Symbols

a_{BP}	[-]	Bypass attractiveness
A1	[-]	Antenna 1
A2	[-]	Antenna 2
A3	[-]	Antenna 3
A4	[-]	Antenna 4
α	[°]	Screen inclination to the horizontal
b_c	[mm]	Bar clearance
β	[°]	Screen inclination angled to the flow
β_0	[-]	Intercept
β_x	[-]	Regression coefficient
BP_1	[-]	Bypass configuration 1
BP_2	[-]	Bypass configuration 2
BP_3	[-]	Bypass configuration 3
BP_4	[-]	Bypass configuration 4
b_w	[mm]	Bar width
E_{BP}	[-]	Bypass efficiency
F	[-]	Value from the F-test
L_{fish}	[mm]	Fish length
n	[-]	Number of fish
n_a	[-]	Number of different fish detected within one hour
N_{a1}	[-]	Total number of passages at the bypass entrance
n_{a1}	[-]	Number of fish reaching the entrance of the bypass
n_{a1+a2}	[-]	Number of fish which found and successfully passed the bypass
n_d	[-]	Number of fish which swam to the downstream by using the opening
n_t	[-]	Total number of fish introduced at the begining of the test
p	[-]	p value
P	[-]	Passability index
p_d	[-]	Proportion of fish which passed to the downstream
p_f	[-]	Proportion of active fish per hour
$Q_{opening}$	[m^3/s]	Discharge in the opening
Q_{total}	[m^3/s]	Total discharge in the experimental flume
$Q_{turbine}$	[m^3/s]	Turbine discharge
Q_{weir}	[m^3/s]	Discharge above the weir
T	[°C]	Water temperature
T_n	[-]	Test number
T_d	[°C]	Difference in water temperature between two following hours
U_c	[m/s]	Critical swimming speed
V_A	[m/s]	Approach velocity
V_{BP}	[m/s]	Velocity in the bypass

V_N	[m/s]	Normal velocity component
V_T	[m/s]	Tangential or sweeping velocity component
V_x	[cm/s]	Horizontal velocity component
V_y	[cm/s]	Cross-flume velocity component
V_z	[cm/s]	Vertical velocity component
W_{BP}	[m]	Water depth in the bypass
W_{fish}	[mm]	Fish width
$W_{fish,rel}$	[-]	Relative fish body width
X^2	[-]	Value from the Wald test

List of Abbreviations

ADV	Acoustic doppler velocimetry
ANOVA	Analysis of variance
CI	Confidence interval
EU	European Union
EZB	Eberstaller Zauner Büros
HEPP	Hydroelectric power plant
HPP	Hydro power plant
HSD	Honestly significant differences
Hylow	Development of hydro power converter for very low head differences
LfL	Fishery of the Bavarian State Research Center for Agriculture (Institut für Fischerei der Bayerischen Landesanstalt für Landwirtschaft)
LFU	Bavarian Environment Agency, Fish and Freshwater Ecology (Referat für Fisch- und Gewässerökologie, Landesamt für Umwelt)
LMS	Lawler, Matusky & Skelly Engineers
LRT	Likelihood ratio test
ND	No data
PIT	Passive integrated transponder
PIV	Particle image velocimetry
R	Free software environment for statistical computing and graphics
SD	Standard deviation
SE	Standard error
TUM	Technische Universiät München
VAO	Laboratory of Hydraulic and Water Resources Engineering (Versuchsanstalt Obernach)
VLH	Very Low Head

List of Figures

List of Tables

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