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International Commission for the Protection of the Danube River

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Measures for ensuring fish migration at transversal structures

Technical paper

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List of abbreviations

Δh	height difference
BL	body length
D. salmon	Danube salmon
DFP	downstream fish pass
D_{min}	min. hydraulic depth
d_{min}	min. hydraulic depth in bottlenecks and sluices
DRB	Danube river basin
DRBMP	Danube river basin management plan
FP(s)	fish pass(es)
g	force of gravity (9.81 m/s²)
h	height
H_{fish}	max. fish height of size-decisive species
HP	hydropower
HPP	hydropower plant
HQ_x	x-years flood
h_{tot}	total water level difference
L_{fish}	length of size-decisive species
L_p	min. length of the pool
l_{tot}	total length of the FP
MALF	mean annual low flow
MF	mean flow
n	number of pools/basins
P_D	power density
pw	water density (1000 kg/m³)
Q	discharge
Q_a	discharge of attraction flow
Q_0	operational discharge of the FP
Q_{tot}	total discharge ($Q_0 + Q_a$)
Q_x	discharge that is undercut x days per year
rpm	rotations per minute
S_d	safety coefficient for FP dimensions
S_p	safety coefficient for the power density
S_v	safety coefficient for the flow velocity
SWMI	Significant Water Management Issue
v	flow velocity
V	volume of the pool
V_m	mean flow velocity
v_{max}	maximum velocity
w_b	width of the borders between the pools
WFD	Water Framework Directive
W_{fish}	max. width of size-decisive species
w_p	min. width of the pool
w_s	slot width

Glossary

1+	Fish with an age of 1 or older.
Attraction flow	Flow that is required to guide fish towards the entry of a FP.
Attraction flow discharge	Required discharge to provide sufficient attraction flow.
Autochthonous fish species	All river-specific fish species that would occur under natural (anthropogenically undisturbed) conditions. With regard to the WFD, not only species composition but also species abundance and age structure of populations is considered.
Bottom roughness	Roughness of the riverbed.
Competitive current/flow	Flows that compete with the attraction flow of the FP (e.g. flow coming from the turbines).
Continuity interruption	(See migration barrier).
Critical velocity	The velocity at which fish start to drift downstream after 20 s.
Epirhithral	Upper trout region.
Fish coenosis	Typical fish community of a river section.
Guiding values	Values considering safety coefficients. These have to be considered for planning to ensure compliance with threshold values (see threshold values).
Hyporhithral	Grayling region.
Impulse	Product of discharge and flow velocity.
Key species	Typical species of a fish region.
Metarhithral	Lower trout region.
Migration barrier	Barrier/weir that is not passable for fish and interrupts the continuity.
Operational discharge	Required discharge in a FP to ensure the required morphometric thresholds.
Passability	Possible and safe passage of fish with regard to morphometric and hydraulic conditions in the FP.
Perceptibility	Conditions of the attraction flow and at the entry of a FP which ensure that fish find the FP.
Potamal	Lowland river (barbel, bream, stoneloach and gudgeon region).
Residual current/flow	Flow that is present in the main channel after water abstraction (e.g. at a diversion hydropower plant).
Rheoactive velocity	Required minimum flow velocity of fish for orientation in a river (species- and age-specific).
Rheophilic species	Species preferring higher flow velocities.
Screen/rake	A combination of several bars to avoid floating debris (or fish) coming towards the turbines.
Threshold values	Values that have to be met when the FP is in operation to ensure its functionality.

Disclaimer

This document provides a summary of existing knowledge on technical solutions for restoring river continuity for fish migration but does not claim for completeness. The information provided has been dealt with, and is presented, to the best of our knowledge. Nevertheless inconsistencies cannot be ruled out.

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This document aims to inform the Danubian countries regarding knowledge on existing technical solutions for restoring river continuity for fish migration. Several guiding documents for the construction of fish passes (FPs) already exist (more details can be found in the list of references):

- **AG-FAH (2011):** Basics for an Austrian guideline for the construction of fish passes (see BMLFUW 2012)
- **BMLFUW (2012):** Guideline for the construction of fish passes (Austria)
- **Seifert (2012):** Handbook "Fish passes in Bavaria" (Germany)
- **BAFU (2012):** Restoration of up- and downstream fish migration at hydropower plants (Swiss Agency for the Environment, Forests and Landscape)
- **DWA (2010, draft):** Fish passes and fish-passable barriers – planning, dimensioning and quality management (Germany)
- **Dumont et al. (2005):** Barrier manual (Germany: North Rhine-Westphalia)
- Other documents and scientific literature

All guidelines currently available in the upper Danube catchment were considered. Their comparison showed that their overall structure and content is basically consistent and that deviations are only marginal in most cases. Possible differences are discussed within this document.

Since most guiding documents are only available in German language, this document aims to provide the most important facts in English language. Therefore, the content is based mainly on the guidelines listed above and is complemented by further literature research.

This report is only a brief summary and does not claim to be complete. It can therefore only provide a rough orientation for the construction of FPs, covering the most important aspects. The construction of a functional FP depends highly on the specific situation and therefore requires expert knowledge and detailed planning.

The restoration of connectivity within the Danube catchment aims to provide migration pathways for all fish species including sturgeons. However, knowledge with regard to FPs supporting the migration of this species is sparse. Only some of the guidelines listed above provide thresholds considering the special requirements of sturgeon. Therefore, the following chapters provide only limited information with regard to the restoration of sturgeon migrations.

1. Introduction

1.1 Background

River and habitat continuity interruptions constitute a major pressure and are defined as part of hydro-morphological alterations as a Significant Water Management Issue (SWMI) in the Danube River Basin (DRB). The assessments undertaken in the course of the elaboration of the 1st Danube River Basin Management Plan[1] (DRBMP) in 2009 showed for the Danube and its major tributaries (rivers with catchment areas larger 4,000 km^2) the presence of more than 900 continuity interruptions, stemming from different infrastructure projects such as flood protection, hydropower generation and navigation. In addition to the transversal structures in the main rivers, a large number of barriers are also located in the smaller rivers of the basin.

These structures represent barriers for fish migration and are therefore influencing natural migration patterns of migratory fish species by preventing access to habitats and suitable spawning grounds. Addressing these pressures by implementing suitable measures (such as FPs, transformation of weirs into ramps and removal of dams no longer in use) constitutes a major challenge for the improvement of environmental conditions and for the achievement of the objectives of the EU Water Framework Directive (WFD).

Apart from giving priority to supporting decisions on river restoration measures in the most ecologically efficient way, it is also of key relevance to ensure that the implemented measures are effective and allow for the migration of all autochthonous fish species (river-specific fish fauna). This is not only the case for migration barriers already in existence, but also for new infrastructure projects. Different guidance documents were recently developed or are currently under elaboration[2], providing support in the planning, construction and operation of FPs. These guidance documents are not only a useful tool for government administrations or consulting engineers, but also for the operators of infrastructure facilities by providing planning security for the required investments.

While significant knowledge and practical experience is already available on the planning and design of measures to ensure upstream migration of different fish species, effective measures on downstream migration are still to a certain extent an open issue in need of further research and practical experience. River networks are highly connected ecosystems and spatial-temporal connectivity manifests itself in four dimensions (Jungwirth et al. 2003): longitudinally along the main stem and its tributaries; laterally to the shoreline and floodplains; vertically to the interstitial (ground water); and over time (temporally). Aquatic organisms, especially fish, are highly adapted to the habitat diversity provided by the four-dimensional river network.

1.2 Biological basics of fish migration

All species perform targeted "habitat shifts" at least in certain life stages (e.g. larvae or juveniles) as a consequence of changing habitat requirements (Schmutz et al. 1997, Jungwirth 1998, Northcote 1998, Mader et al. 1998) and to optimise resource use and productivity (e.g. distribution, growth, reproduction, shelter and protection from predators) (Northcote 1978, Larinier 2000). Reproduction migrations mostly occur in upstream direction. Some species perform their spawning migration at low flows (brown trout from summer to autumn, burbot during winter), other species reproduce at higher discharges (e.g. grayling, nase, barbel and Danube salmon) (Zitek et al. 2007). Downstream migrations occur for the purpose of spreading, drift (of juveniles or during floods) toward autumn/winter habitats or back to their main habitat after reproduction (Seifert 2012, BMLFUW 2012).

The integrity of fish populations relies to a high degree on the availability of required but spatially separated habitat patches within the river network (Seifert 2012). As a result, continuity interruptions/barriers have negative impacts and threaten fish populations (BMLFUW 2012).

Fish migrations are usually induced by several complex interacting factors, which can be grouped into internal and external factors (Pavlov 1989, Colgan 1993, Lucas & Baras 2001). External factors are abiotic conditions such as water temperature, season, light, discharge, water quality, oxygen saturation. Important internal factors are hormonal readiness for reproduction, nutrition requirements, stress or other endogenic (genetic or ontogenetic) determinants, e.g. imprinting and homing to a birth place (i.e.

1) http://www.icpdr.org/main/publications/danube-river-basin-management-plan
2) e.g. in Bavaria, Austria, Switzerland, Food and Agriculture Organisation of the United Nations (FAO)

"homing effect") (Lucas & Baras 2001). In general, internal factors are highly influenced by external factors (Pavlov 1989; Albanese et al. 2004). Migrations occur at seasonal, monthly or daily intervals (Northcote 1984, Jonsson 1991, Hvidsten et al. 1995, Lucas & Baras 2001).

Fish species are classified according to migrations between and within freshwater and marine environments and grouped into the following migration guilds (Jungwirth et al. 2003):

Diadromous species inhabit both sea- and freshwater and can be further divided into anadromous, catadromous and amphydromous species. While anadromous species live in the sea and migrate to freshwater habitats for spawning, catadromous species live in freshwater and reproduce in the seas. Amphidromous species frequently switch between sea- and freshwater but also for other purposes than reproduction.

Potamodromous species migrate only within freshwater and can be further divided into long-, medium- and short-distance migratory species (i.e. > 300 km, 30–300 km or < 30 km in one direction per year).

1.3 Swimming capabilities

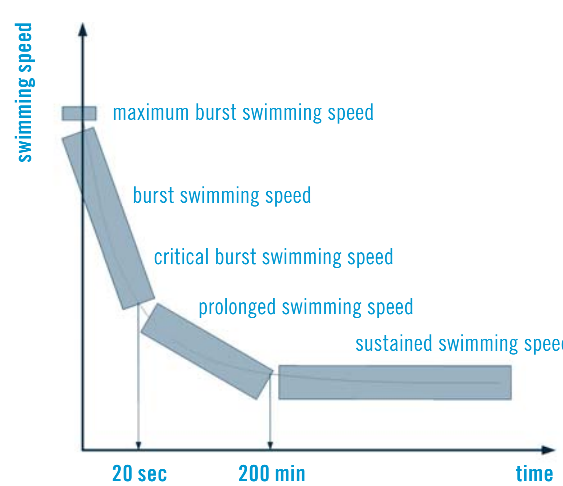
An important factor for the planning of FPs is the specific swimming capability of certain fish species. The swimming speed is not a constant but rather depends on a set of influencing factors such as body shape, size, muscular system and the water temperature (Jens et al. 1997, DWA 2010, draft). Furthermore, the swimming speed of a fish in relation to its environment also depends on the flow velocity (DWA 2010, draft).

Swimming speed is expressed in body length per second (BL/s) (DVWK 1996, Jens et al. 1997, ATV-DVWK 2004) and can be categorised into four groups depending on its duration (Beamish 1978):

- Sustained swimming speed is used for normal locomotion and can be sustained for a long time (> 200 min) without fatigue of the muscles. This speed is usually used for migration. Based on DWA (2005), it is approximately 2 BL/s.
- Prolonged swimming speed can only be sustained for shorter periods (20 sec to 200 min) and leads to fatigue of the muscles.
- Burst swimming speed can be sustained by the use of anaerobic metabolism of the musculature for very short periods (< 20 sec) and has to be followed by a relaxation phase.

  The critical burst swimming speed is, according to Clough & Turnpenny (2001), the speed at which a drift occurs after 20 seconds. According to new approaches, this speed is used for ecohydraulic planning (Clough et al. 2001, Clough & Turnpenny 2001, Turnpenny et al. 2001, Clough et al. 2004, Watkins 2007). SWIMIT 3.3 (Jacobsaquatic 2006) is a special software that allows this swimming capability to be calculated with regard to fish species, fish size and water temperature. Approximations for salmonids are 10 BL/s and for cyprinids 4–5 BL/s (e.g. roach with 15–30 cm or bream with 20–50 cm BL, Jens et al. 1997).
- The maximum burst swimming speed is the theoretical maximum achievable speed of a certain fish. Maximum burst swimming speeds are 2–3 m/s for brown trout or 0.7–1.5 m/s for cyprinids (Jens 1982, Jens et al. 1997). This speed can be of high importance for the passability of bottlenecks in a FP.

Relation between swimming speed and its duration (adapted from BMLFUW 2012, based on Pavlov 1989 and Clough & Turnpenny 2001) *FIGURE 1*



The (critical) burst swimming speed of the "weakest swimmer" among the river-specific fish-fauna should be used to define the thresholds of flow velocities within the migration corridor of the FP. The "weakest" are usually juveniles and small fish species (e.g. bullhead and stone loach) (BMLFUW 2012).

With regard to the fish region, upper thresholds for the maximum flow velocity based on Seifert (2012) are defined as 1.5–2.2 m/s for rhithral rivers and 0.8–1.4 m/s for potamal rivers. BMLFUW (2012) suggests maximum velocities of 1.5–2.0 m/s for rhithral and 1 m/s for potamal rivers and refers to the following authors: Jungwirth and Pelikan (1989), Gebler (1991), Steiner (1992), Dumont et al. (2005). However, these values only represent rules-of-thumb and should be seen as an upper limit (Seifert 2012). Laboratory tests have shown that the critical burst swimming speed for small and juvenile fish is approximately 0.35–0.6 m/s (Jens et al. 1997). These moderate velocities can be ensured close to the bottom or in peripheral areas by means of roughness (BMLFUW 2012). Although theoretically derived values provide a good indication, Turnpenny et al. (1998) recommend the application of lower velocities for the construction of FPs to avoid migratory bottlenecks.

More detailed information can be found in Clough et al. (2001), Clough & Turnpenny (2001), Turnpenny et al. (2001), Clough et al. (2004) and Watkins (2007).

1.4 Orientation and migration behaviour

During migrations, fish use all their senses for orientation. The optical and tactile senses and the lateral line organ are used for orientation in the immediate environment and alignment of the swimming direction (e.g. upstream). The relevance of hearing is under discussion. However, it is known that flow conditions and underwater structures show typical acoustic signatures, which also might act as an orientation guide. The terrestrial magnetic field guides diadromous fish species in the sea (e.g. Atlantic salmon (Rommel & McCleave 1973, Varanelli & McCleave 1974) and European eel (Tesch & Lelek 1974, Tesch et al. 1992)) and the sense of temperature and smell (Hasler & Scholz 1983) are relevant for identifying specific rivers.

Basic knowledge concerning the perception of flow, orientation and swimming behaviour of fish can be summed up as follows: All fish are able to detect flow velocity, use it for orientation and swim towards it (positive rheotaxis) (Lucas & Baras 2001). If the flow velocity falls below a species- and age-specific threshold (see Table 1), fish lose their positive rheoactive orientation (DWA 2010, draft). Therefore, the flow velocity in the migration corridor has to be larger than the rheoactive velocity. The following table shows rheoactive velocities for selected species and age classes:

Rheoactive velocities for selected species and age classes/sizes

TABLE 1

Species	Age class / size	Rheoactive velocity [m/s]	Source
bullhead, stone loach, Eurasian minnow, stickleback	juveniles	0.15	Adam & Schwevers 1997
brown trout, grayling, Eurasian dace	≤ 12 cm	0.15	Adam & Schwevers 1997
most cyprinids, somonids and other families, adults of small fish species (Eurasian minnow, stone loach)	juveniles	0.15	Seifert 2012
most cyprinids (barbel, nase, European chub), salmonids (brown trout, grayling) and other families	adults	0.20	Seifert 2012
most species	adult	0.20	Pavlov 1989
barbel European chub, Eurasian dace	adult	0.20	Adam et al. 1999
anadromous salmonids	adult	> 0.30	Pavlov 1989
Danube salmon	adult	> 0.30	Seifert 2012

Fish primarily use the flow acting directly on their body for orientation, while laterally occurring weaker flows remain unnoticed. For upstream migration, most fish species migrate within or parallel to the main current, whereby each species and age class prefers a certain flow velocity. If several flow paths with different velocities intersect, fish mostly choose the current with the highest velocity for orientation. Highly turbulent flow conditions, reverse flows or still waters disturb or interrupt the upstream orientation of fish (Pavlov et al. 2000). As a result, the attraction flow coming from a FP has to be actively recognised and tracked, which is the case if its velocity is high enough or compared to competitive currents in the immediate surroundings. The flow velocity of the attraction flow should be between the rheoactive velocity and the critical velocity, whereby good results were obtained by the application of 0.7–0.8 times the critical velocity (Pavlov 1989, BMLFUW 2012). According to Pavlov (1989), flow velocities between 0.7–1.0 m/s are suitable for most potamal species. BAFU (2012) recommends velocities at the entrance of 0.8–1.5 m/s (BAFU 2012). Salmonids and anadromous species prefer flow velocities of 2.0–2.4 m/s (Larinier 2002). An attraction flow of 1.0 m/s might still attract species with high performance without excluding weaker fish (DWA 2010, draft). However, to ensure suitable conditions for all species, two entries with different flow velocities might be advantageous for the functionality of the FP in particular situations (DWA 2010, draft). Furthermore, the velocity of the attraction flow should be about the rheoactive velocity, which is higher (0.15–0.20 m/s, Pavlov 1989) than the velocity fish prefer for upstream migration.

Beside the important factors for orientation described above, the selected migration corridor depends also on the species-specific preferences, morphology and structural characteristics of the river. Fish show different behaviour during their upstream migration and can also be classified with regard to their preferred migration corridor as (1) riverbed, (2) shore line, (3) close to the bottom or (4) open water orientated (Seifert 2012). Bullheads prefer to migrate in contact with the substrate and use large stones as protection from the current. Even small vertical drop-downs (18–20 cm) represent migration barriers for this species (Utzinger et al. 1998).

Graylings and other species of the barbel region overcome barriers by swimming, whereby the water column has to obtain a sufficient depth. For barbel and nase, drop structures with a maximum height of 30 cm are only passable if sufficient flow is available. Only brown trout are able to overcome barriers by leaping, however they depend on the size of the respective pool downstream of the barrier (BMLFUW 2012, Seifert 2012).

In general, fish migrate upstream in or parallel to the main current as long as their swimming capabilities allow it. If they cannot find an appropriate way upstream, they start a lateral search for opportunities, however with a search radius reduced to the border zones of the main current. Following the strongest current acting on their body, they will always return to the main current if they do not receive a stronger alternative impulse (Seifert 2012). This has to be considered for the dimensioning of the attraction flow and the location of the FP entrance (see chapter 2.2).

1.5 Relevant fish species, fish lengths and age classes

As described in previous chapters, fish species migrate for various purposes during different periods of their life cycle. This involves – among other things – spawning migration of adults, habitat shifts of juveniles and drift of larval fish. Ideally, FPs enable migration for all types of species, life stages and fish sizes.

There is a strong link between the size of a specific fish species and the size of the FP designed for this species. The size-decisive fish species depends on the fish region and river size and can be defined as the largest species or the species with the highest space demands. Table 2 includes the body length of the size-decisive fish species according to the Austrian fish pass guideline (BMLFUW 2012) using representative fish sizes of the reproductive age class taking the mean flow (MF) into account. Table 3 shows the body dimensions (height and width depending on the fish length) of the respective species.

Body lengths of the size-decisive species (BMLFUW 2012)

TABLE 2

Fish region	Size-decisive species
Upper trout region	
< 2 m³/s MF	30 cm brown trout
> 2 m³/s MF	40 cm brown trout
Lower trout region	
< 2 m³/s MF	40 cm brown trout
> 2 m³/s MF	50 cm brown trout, grayling
Grayling region	
small (< 2 m³/s MF)	50 cm brown trout, grayling, 50 cm burbot
medium (> 2 m³/s MF)	60 cm burbot, barbel/nase
medium (> 2 m³/s MF–20 m³/s MF) with Danube salmon	80 cm Danube salmon
large (> 20 m³/s) with Danube salmon	100 cm Danube salmon
Barbel region	
medium without Northern pike, without Danube salmon	60 cm barbel/nase
medium with Northern pike, without Danube salmon	90 cm Northern pike, 50 cm common bream
medium with Danube salmon	90 cm Danube salmon, 50 cm common bream
large with Danube salmon	100 cm Danube salmon
large without Danube salmon but with catfish	120 cm catfish
large without Danube salmon and without catfish	90 cm Northern pike, 50 cm common bream
Stone loach and gudgeon brook	
stone loach brook (Eastern Lowlands and Uplands)	40 cm European chub
Large rivers	
Danube and large tributaries	100 cm Danube salmon, 120–150 cm catfish, 100 cm Northern pike
Lake out- and inflows	
lake out- and inflows	90 cm brown trout, 90 cm Northern pike, 70 cm Perlfisch*, 60 cm barbel, 50 cm common bream

* Rutilus meidingerii

Rivers that are passed during the reproduction migration of large fish (e.g. Danube salmon) might require deviating thresholds. However, in such cases, biological monitoring is recommended.

Body measurements of size decisive fish species (comparison of Jäger et al. 2010 (used in BMLFUW 2012) and DWA 2010, draft)

TABLE 3

Size-decisive species				Body size
		Jäger et al. 2010		DWA 2010 (draft)
	Length [cm]	Width [cm]	Height [cm]	
Asp	80			18
Barbel	60	7	11	
Barbel	80			13
Bream	50	5	15	
Bream	70			21
Brown trout	30	3	6	
Brown trout	40	4	8	
Brown trout	50	5	10	9
Burbot	50	7	7	
Burbot	60	8	8	
Burbot	70			13
Catfish	90	13	14	
Catfish	120	22	23	
Catfish	150	30	31	
Catfish	160			35
Common/Atlantic sturgeon	300			51
Crucian carp	45			14
Danube salmon	80	10	13	
Danube salmon	90	12	14	
Danube salmon	100	12	16	17
Danube salmon	120	14	19	
European carp	80			24
European chub	40	5	8	
European chub	50	6	11	
European chub	60			12
European perch	40			11
Grayling	40	5	9	
Grayling	50	6	11	9
Ide	70			18
Lake trout	90	11	20	
Lake trout	100			17
Nase	60			15
Northern pike	60	6	8	
Northern pike	90	8	12	
Northern pike	100			17
Perlfisch	70	7	13	14
Pike perch (zander)	100			16
Sterlet	90			15
Tench	60			12
Vimba bream	50			13

Measurements took place outside of reproduction periods. Therefore, depending on the species, the fish width might be several cm higher during reproduction periods.
The scientific names of the species listed above are presented in Table 16 in the annex.

2. Facilities for upstream migration

Fish passes are structures supporting fish (and benthic invertebrates) to overcome/pass an artificial barrier (Jungwirth and Pelikan 1989), thereby restoring both up- and downstream connectivity. While the first FP solutions usually focused only on upstream migration, the importance of downstream connectivity is also recognised today. However, since up- and downstream migration require different settings that cannot easily be combined in one single facility, two separate fish passes are required, with one serving the restoration of up- and the other the restoration of downstream migration. Facilities for downstream migration and fish protection are therefore discussed in a separate chapter (chapter 5).

The knowledge of hydrological conditions and hydro-morphological requirements of the local fish fauna is indispensable for planning and constructing a functional FP. The following chapters discuss important parameters for the design, construction and operation of FPs for upstream migration.

2.1 Seasonal functionality of fish passes

A FP should be functional throughout the year (BMLFUW 2012). However, it might not be possible to construct a fish pass that provides suitable conditions at all possible discharge situations and it is biologically unnecessary for fish to migrate 365 days a year. Therefore, functionality on 300 days per year (between Q_{30} and Q_{330}*) seems to be sufficient (BMLFUW 2012, DWA 2010, draft). These thresholds represent only suggestions and might not be suitable for all rivers. However, the FP should be functional for as many days as possible, and especially when reproduction migrations occur. For instance, in rivers with brown trout/lake trout and burbot, functionality should also be provided in low flow situations, since these fish species perform their reproduction migrations in autumn/winter with naturally low flows. On the other hand, in potamal rivers with a migration peak in spring/summer, functionality has to be guaranteed for higher flows. FPs in rivers with a balanced flow regime have to be passable for more than 300 days. Even in periods when the FP itself is not functional, sufficient flow to ensure the survival of the fish in the FP has to be provided (BMLFUW 2012).

* Flow which is undercut at 30/330 days per year.

2.2 Perceptibility of the FP

The better the perceptibility of the FP, the more fish will find its entrance. Unfavourably located FP entries can cause inefficiency of fish passes or time delays since fish need more time to find their way upstream. Several consecutive barriers with unsuitable perceptibility intensify the time lag. As a result, fish may not reach the reproduction habitat in time, which can cause reproduction losses or even the extinction of individual species (DWA 2010, draft).

2.2.1 Position of the FP and its entry

In this chapter, general findings with regard to the position of the FP and its entry are presented. However, it should be considered that only general recommendations are discussed. Therefore, for the realisation of a functional FP, more detailed project documentation is necessary containing detailed knowledge about the flow regime, hydraulic conditions at the barrier/hydropower plant, competitive flows and the requirements of the local fish community.

Furthermore, in large rivers (width > 100 m), at least two FPs on either side of the dam should be realised to ensure the perceptibility for all fish species (Larinier et al. 2002). Some fish migrate along the banks or are forced to migrate toward the banks, e.g. by strong turbulent currents induced by hydropower operation.

2.2.1.1 Position of the FP

With regard to the most suitable position of the FP, it is also important to consider the purpose of the respective barrier. The following situations have to be considered (DWA 2010, draft; Seifert 2012):

– Barriers without water use: In this situation, competitive currents are absent. Controllable weirs can be used to attract the fish to one river side. In general, a FP should be situated close to the shoreline and the main current (i.e. undercut bank).

– At diagonal barriers, the FP should be situated on the riverside with the pointed angle where fish usually gather (see Figure 2 and Figure 6a).

– Barriers with hydropower plant: In most cases, the main current of the hydropower plant leads fish towards the power house (i.e. turbines). Therefore, the FP should be located close to the power house and the shoreline (see Figure 3).

– Barriers with water diversion: These barriers represent a special challenge since fish usually follow the main current, which leads them into the tail race channel. The main channel often obtains residual flow, which provides only limited attraction flow in comparison to the water coming from the hydropower plant. Since most fish will follow the tail race channel, FPs located in the main channel (at the diversion weir) might have a reduced functionality. Furthermore, since the main channel usually obtains a higher width and less discharge than the tailrace channel, the flow velocity during low flows might not provide the required rheoactive velocity or sufficient depth for fish to migrate upstream. The best solution would be the construction of two FPs, one at the diversion weir and one at the power house.

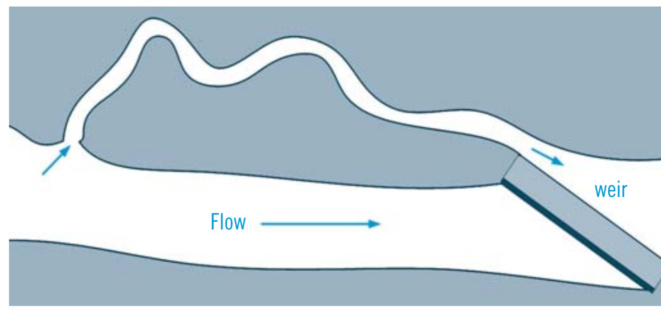
  However, if this is not possible, the perceptibility of the diversion stretch should be improved (e.g. sufficient flow and depth and flow velocity) or a bypass connecting the tailrace channel and the main channel should be constructed (DWA 2010, draft; Seifert 2012).

– For large weirs, the construction of two FPs might be required (see Figure 5).

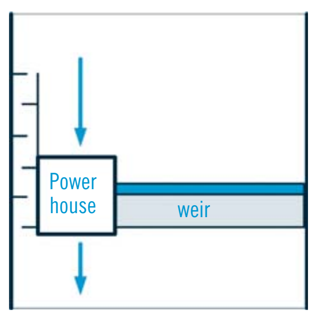
2.2.1.2 Position of the entry

It is particularly important that the entry of the FP is easily and quickly recognised by upstream migrating fish. Not only the position, but also the eco-hydraulic conditions (attraction flow and competitive currents) should be planned in such a way that as many fish as possible are guided into the FP and as few as possible enter the dead-end towards the barrier.

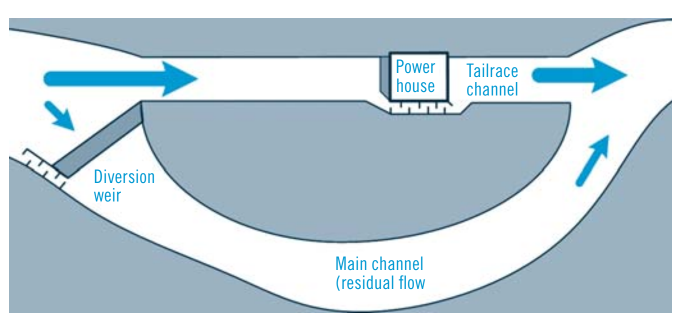
FP entry in the pointed angle of an oblique weir (Dumont et al. 2005) FIGURE 2



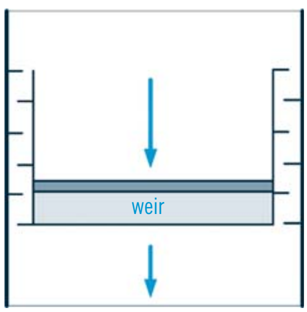
Location of the FP close to the power house (based on DWA 2010, draft) FIGURE 3



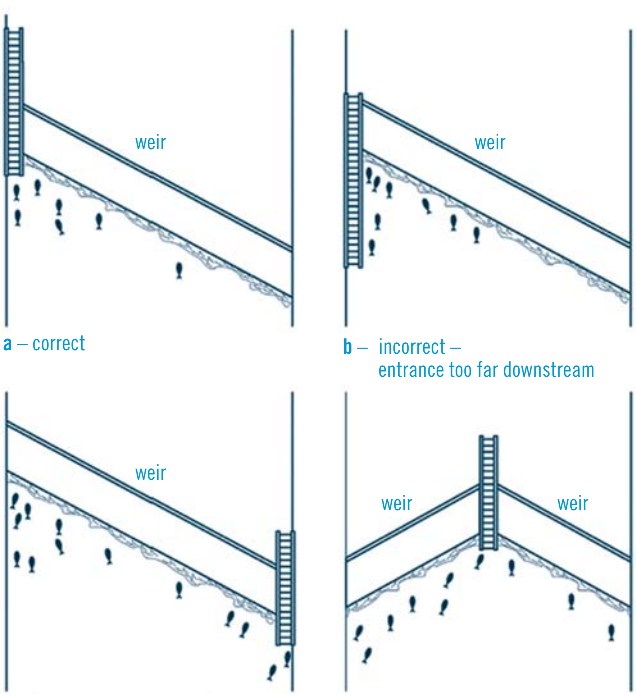
Location of FPs for diversion hydropower plants (based on DWA 2010, draft) FIGURE 4



Location of FPs if both sides are equal or for large weirs (adapted from DWA 2010, draft) *FIGURE 5*



Schematic plans illustrating the installation of a fish pass on an oblique weir (Larinier 2002). *FIGURE 6*



a – correct

b – incorrect – entrance too far downstream

c – incorrect – entrance on the wrong side

d – correct, but problems of access and maintenance

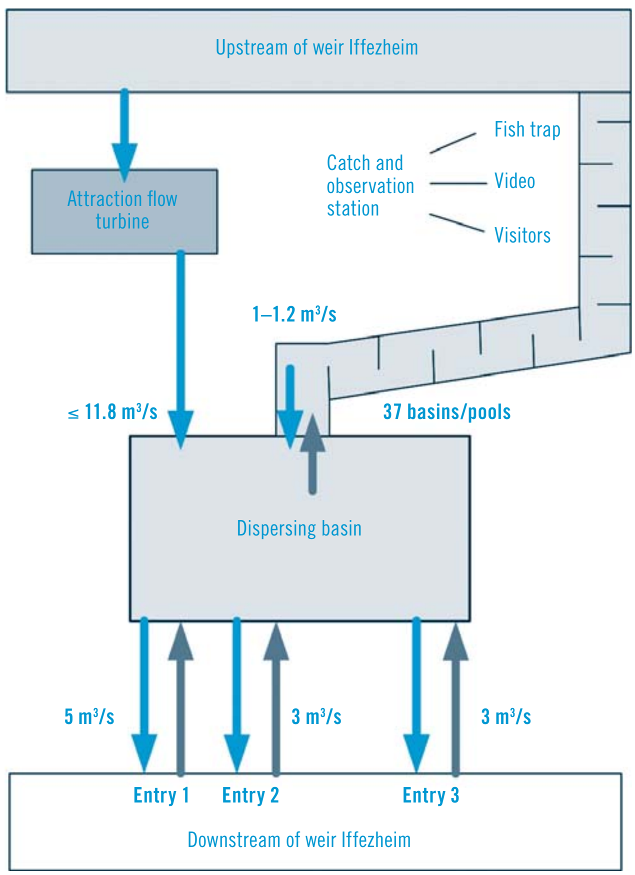
There is at least one optimal position (key position) of the entry that lies in the interface between the downstream limits of the barrier (or the turbulent zone) and the longitudinal corridor of migration (Dumont et al. 2005). Furthermore, directly at the FP entry, the attraction flow should be as parallel as possible to the main current (< 30°) (DWA 2010, draft).

The location of the entry is discussed by several authors and guidelines (e.g. BMLFUW 2012, DVWK 1996, Adam & Schwevers 2001, Gebler 2009, Dumont et al. 2005 and Larinier et al. 2002). The approximate location can be determined by the following parameters:

a) Within or in close proximity to the migration corridor
b) Close to the barrier but downstream of the area with high turbulence (white water zone)
c) Close to the shoreline
d) On the side of the main current (outer bank)
e) On the side where the hydropower plant is located
f) On the side of the turbine outlet close to the end of the suction hose and parallel or in pointed angle (max. 30°) to the current coming from the head race.
g) With regard to bottom-dwelling fish, the consideration of a continuous connection to the river bottom is very important (bottom ramp with slope < 1:2) (see chapter 2.3.4)
h) For diagonal weirs, the pointed angle of the weir (upstream view) (see Figure 6, location a/d – correct and c – incorrect) might be more suitable.
i) For centred turbine outlets or if the optimal location is not clearly visible, it might be necessary to include two entries (one at the side and one in the middle) (Larinier et al. 2002). Several entries are also suitable to cover the requirements of species with different demands.

   Example: A new FP was constructed and finished in 2000 at the Iffezheim hydropower plant on the river Rhine (see EnBW Kraftwerke AG 2009). The vertical slot FP has three entries, which meet in a dispersing basin (Figure 7). Upstream of this basin, the discharge is approximately 1.2 m^3/s. An attraction flow turbine introduces additional water (up to 11.8 m^3/s) into the dispersing basin. The total attraction flow therefore accounts for 11–13 m^3/s. Two of the entries are designed for species preferring higher flow velocities, while the third entry is located close to the shoreline and suitable for weaker fish.

Functional principle of FP Iffezheim at river Rhine (adapted from Degel 2010) *FIGURE 7*



Although these general recommendations provide a rough guideline for how to define the optimal location, it is highly recommended to consider all flow- and hydraulic conditions at the location and to investigate the optimal solution with regard to the biological requirements for fish. During high flows, the main flow should rather be released at the middle weir fields since fish might prefer migrating outside of the area with high flow velocity and turbulence. On the other hand, during low flows, the main flow should be released at the weir fields close to the FP, guiding the fish towards the FP entry (DWA 2010, draft).

Local flow measurements for 3D numerical modelling (performed by adequate specialists) might be needed to find the best location of the FP and its entrance. In very complex situations even physical models might be necessary.

Since some of the above described parameters can vary with regard to the actual flow condition, it is suggested to use the flow occurring during the main migration season of the key species as a reference. Another possibility is the construction of several entries for different flow conditions (DWA 2010, draft; Seifert 2012).

Since especially rheophilic fish species (e.g. nase, barbel and Danube salmon) follow the main current, the attraction flow has to be connected to the main current of the river (Zitek et al. 2008). Other species (e.g. brown trout, grayling, European chub and burbot), juveniles, stagnophilic and indifferent species usually migrate closer to the shoreline and might therefore prefer a different position of the entry (Ecker 2000, Zitek et al. 2008). Especially for large rivers with several species covering a wide spectrum of swimming capabilities, several entries or collection galleries might be required (Larinier et al. 2002, Dumont et al. 2005).

Optimum flow velocities at the entry to the FP are 0.7–0.8 times the critical burst swimming speed of fish (Pavlov 1989). If the entrance is not in an ideal position, more discharge may be required for attraction flow (Larinier 2002).

2.2.2 Attraction flow

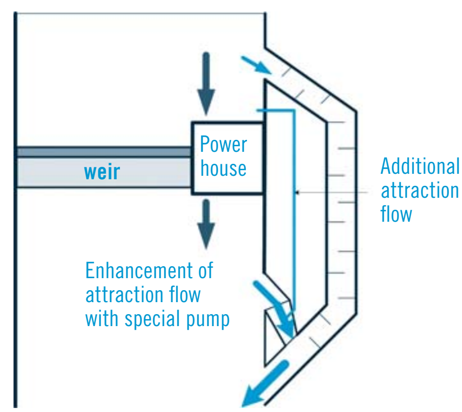
The attraction flow serves the purpose of connecting the migration corridor of the downstream river section with the migration corridor of the FP. The functionality of the attraction flow is related to the flow velocity, flow volume and the position of the entry. Guidelines for its functionality include (DWA 2010, draft; Seifert 2012):

- A low angle between migration corridor and the competitive main current (< 30°). At higher angles, the attraction flow might be dissolved by the turbulences of the main current.
- Low turbulences
- No interruption of the current towards the entry (connected migration corridor)

– High impulse of the flow (as a product of volume and flow velocity, based on Larinier 2002) with a higher velocity than the competitive currents but without exceeding the maximum swimming capabilities of critical species
– Consideration of turbulence caused by the turbines

Since the operational discharge of the FP serves mainly the passability of the FP, it might not be sufficient to act as attraction flow. If this is the case, additional flow can be introduced into the lowest pool of the FP to enhance the attraction flow. However, the introduced water should be slowed down before released into the FP. Therefore, a pool equipped with various devices (concrete battles, staggered vertical beams or steel bars) for sufficient dissipation of energy should be included. Furthermore, the water has to be adequately de-gassed (Larinier 2002) and measures preventing fish from migrating into the inlet of the attraction flow have to be taken (DWA 2010, draft; Seifert 2012).

Attraction flow pump (adapted from Hassinger s.a.) *FIGURE 8*



An alternative for larger rivers is to install a small hydropower plant for attraction flow, which produces additional energy and enforces the attraction flow (see example of FP in Iffezheim at river Rhine in chapter 2.2.1.2). Furthermore, it is possible to include special pumps which use the water coming from the main hydropower plant to reinforce the attraction flow (see Figure 8). An example of such an attraction flow pump was developed and patented by the University of Kassel (Germany, Hassinger s.a.).

The impulse of the flow depends on the flow velocity and the water volume (Larinier 2002). While the flow velocity is restricted to the swimming capabilities of fish with low performance, the water volume can be increased to optimise the attraction flow in comparison to the competitive flow (DWA 2010, draft). The attraction flow should have a dimension of at least 1 -5 % of the competitive flow (Bell 1980, Larinier et al. 2002, Dumont et al. 2005, Larinier 2008). For optimally positioned FPs in large rivers (MQ > 50 m^3/s), approximately 1 % of the flow is required, while in medium rivers (MQ 25–50 m^3/s) around 1–2 % is recommended. Small rivers (< 25 m^3/s) require a higher percentage; the operational discharge (i.e. discharge to ensure the morphometric thresholds) is sufficient in most cases. Additional attraction flow is usually only required for rivers with a MF > 25–50 m^3/s. For large rivers such as the Danube, where 1 % of the MF would result in a very high flow, individual considerations are recommended (BMLFUW 2012).

The required attraction flow depends highly on the local morphological and hydraulic situation, also taking seasonal changes into account. To find an optimal solution, detailed hydraulic modelling is required (BMLFUW 2012). In France, attraction flow represents 3–15 % (at low flow) or 0.8–2.4 % (at mean flow) of the actual discharge (Larinier 2009). A dynamic increase should be possible with regard to natural flow variations (Larinier et al. 2002) (see chapter 2.2.3). As previously mentioned, it is also possible to add attraction flow via a small hydropower plant (see example in chapter 2.2.1.2).

2.2.3 Perceptibility/fish pass entry at different water levels

Proper allocation of the FP entry under changing water levels requires expert knowledge and experience. An increase of the tailwater level can cause an inundation of lower pools of the FP, which can lead to the loss of the attraction flow at this location, while the actual entry at the end of the FP is untraceable for fish. Unfortunately, there is no overall solution for this problem. Therefore, the FP should be designed in such a way that its functionality is at least ensured during the main migration periods and the respective flows (see chapter 2.1). However, during the planning of the FP, it has to be considered that for all flows and water levels between Q_{30} and Q_{300} the discussed requirements with regard to maximum flow velocities, attraction flow and minimum depth have to be met (DWA 2010, draft).

Therefore, technical solutions to optimise the perceptibility for a certain range of variation are required (DWA 2010, draft; Seifert 2012):

1. FP with adaptable discharge (over the entire FP or by means of an additional attraction flow at the lower part): Adjustable sluices or additional water intakes are only possible for rectangular pools with sufficient high walls. Furthermore, the walls of the last pool (entry) have to be high enough to counteract an inundation by the tailwater.
2. FP with several entries: The respective entries are locked or opened by regulatory devices (high controlling effort).
3. For sectional ramps, the attraction flow can be maintained despite increased tailwater if,
    a. it does not reach too far into the headwater over the lateral axis of the barrier,
    b. inundated areas of the ramp have a sufficient slope for maintaining attraction flow. Furthermore, lateral entry into the ramp should be possible for fish.

Such solutions require detailed hydraulic calculations covering the entire range of possible flow conditions.

2.3 Passability

A FP is only functional if it represents a suitable migration corridor for all species and age classes. This is the case if:

- the hydraulic conditions are designed in such a way that even the weakest species and age classes (at least 1+ fish) can overcome bottlenecks of the FP,
- the FP has a connected flow path with the rheoactive minimum flow velocity of 0.3 m/s for rivers with salmonids and 0.2 m/s for all other species,
- the spatial dimension/geometry (depth, width, length) is sufficient for adult fish of the size-decisive species (spawning fish) to pass bottlenecks of the FP.

Important factors are therefore maximum height differences, flow velocities, turbulences and water depths (Seifert 2012).

There are two approaches for defining morphometric and hydrologic thresholds:

1. With regard to BMLFUW (2012), the morphometric and hydraulic thresholds for the dimensioning of a FP depend on the key species and accompanying species of the respective fish region. The dimensions of the size-decisive fish species were already discussed in chapter 1.5.

Slope dependent on the river region (based on Huet 1949, DWA 2010, draft)

TABLE 4

Fish region	Slope				
	< 1m	1 – 5 m	5 – 25 m	25 – 100 m	> 100 m
upper trout	10.00 – 1.65	5.00 – 1.50	2.00 – 1.45		
lower trout	1.65 – 1.25	1.50 – 0.75	1.45 – 0.60	1.250 – 0.450	
grayling		0.75 – 0.30	0.60 – 0.20	0.450 – 0.125	– 0.075
barbel		0.30 – 0.10	0.20 – 0.05	0.125 – 0.033	0.075 – 0.025
bream		0.10 – 0.00	0.05 – 0.00	0.033 – 0.000	0.025 – 0.000
stone loach, gudgeon	by tides-influenced estuary				

2. With regard to the natural gradients of flow, slope (see Table 4) and turbulence in the course of a river stretch and the consecutive fish coenoses depending on these factors, DWA (2010, draft) suggests another approach. Also in this case, the morphometric thresholds are selected on the basis of the dimensions of the key species (largest expected individual with regard to the autochthonous species composition). However, the definition of hydraulic thresholds takes place on the basis of fish regions/zones.

Furthermore, DWA (2010, draft) defines two different kinds of values: threshold values and guiding values. Thresholds are not allowed to be exceeded/undercut, otherwise the functionality of the FP is endangered. To ensure compliance with these threshold values, guiding values should be used for planning as they also include other aspects (e.g. susceptibility, practical problems during construction, uncertainties of the hydraulic dimensioning), which are considered using safety coefficients. If these guiding values are not considered for the planning of the FP, there is a danger that the threshold values may be exceeded/undercut when the FP starts operation. The guiding values (safety coefficients) depend on the respective construction type (DWA 2010, draft).

DWA (2010, draft) suggests the following approach to defining the morphometric and hydraulic thresholds:

1. Definition of the fish region and the limit values for the specific energy dissipation.

2. Definition of the FP type (based on topography, costs, complexity, etc.).

3. Definition of the required FP length, the total height difference and the maximum flow velocity.

4. Definition of the potential (historic) local fish fauna (minimum flow velocity with regard to required rheoactive velocity).

5. Definition of the morphometric thresholds (based on size-decisive fish species).

2.3.1 Morphometric thresholds for dimensioning of the FP

The morphometric thresholds and reference values are based on the body measurements of the size-determining fish species of the respective river section. A prerequisite for successful passage is a sufficient hydraulic water depth (D_{min}, measured from the stone pits to the water surface), pool width (W_p) and pool length (L_p) for size-decisive fish to pass contact-free. Moreover, the dimensions of bottlenecks and sluices (i.e. ds_{min} as the minimum depth and ws_{min} as the minimum width of sluices and bottlenecks) also have to be considered. Suggested thresholds for these parameters are presented in Table 5. To avoid log jams, the width and depth should be 0.2 m at least (DWA 2010 (draft), Larinier et al. 2002, Dumont et al. 2005).

Despite the minimum thresholds stated above, the actual geometric dimensions should be based on

- the river-specific size differences of the size-determining fish species,
- space and depth requirements/preferences of the limiting species and
- region-specific power densities (energy dissipation).

Larnier et al. (2002) suggest a minimum depth of 0.6 m for small rhithral rivers as trout prefer deeper areas. For larger rhithral rivers, mean depths of 0.8–1.5 m and for potamal rivers 1.0–2.0 m are required (Jungwirth and Pelikan 1989). For nature-like bypasses, the hydraulic maximum depth should be at least 0.7–1.20 m (1.70 m for large rivers such as the Danube) (AG-FAH 2011).

For some FP types, more detailed information is presented in the respective chapters (see chapter 3 and subchapters). Furthermore, Table 17 and Table 18 (see annex) provide suggestions for the dimensions discussed above based on the size-decisive fish species.

2.3.2 Hydraulic thresholds

The hydraulic thresholds should be selected with regard to the natural river type and fish region (DWA 2010, draft) or the local fish community (BMLFUW 2012) to reflect the swimming capabilities of the fish assemblage. In general, the flow velocity and energy dissipation (in W/m^3) and the roughness decrease in a downstream direction along the natural river course.

The maximum flow velocity (v_{max} in m/s) in the area of bottlenecks, sluices or spillways depends on the height difference (Δh in m) and can be calculated as

$$v = \sqrt{2g\Delta h}$$

where g represents the force of gravity with 9.81 m/s².

The velocity as calculated above occurs where the water jet submerges in the water of the lower pool, whereas the flow velocity in the sluice itself is approximately 70 % of the calculated velocity (Gebler 2009, Larinier 2006). Especially for vertical-slot bypasses with a rough bottom, these high velocities occur only in areas close to the surface, while the velocity decreases towards the bottom where weaker fish are able to pass.

The application of the equation for height differences of 20, 15, 13 and 10 cm results in maximum flow velocities of 2.0, 1.7, 1.6 and 1.4 m/s. Therefore, the maximum flow velocities can be used to define the maximum height differences in FPs.

For FPs imitating natural rivers with continuous reduction of the fall height (i.e. without consecutive pools): the maximum flow velocity is related to the slope I:

$$v = \sqrt{I}$$

The maximum flow velocity also depends on the total length of the FP. To counteract the exhaustion of fish, long FPs should have a lower flow velocity than short FPs. Furthermore, the introduction of resting pools would be possible. However, the characteristics

Morphometric criteria and threshold values (based on DWA 2010 (draft), BMLFUW 2012, AG-FAH 2012) TABLE 5

Parameter	Application	Thresholds for size-decisive fish species
pools		
min. hydraulic depth (D_{min})	general	$2.5 \cdot H_{fish}$ [1]
	for technical pool FPs	> 50 – 60 cm [3]
	for nature-like bypasses	> 70 to 120 cm (170 for Danube) [3]
min. pool length (L_P)	for technical/pool FP incl. rough bypasses	$3 \cdot L_{fish}$ [1] [2]
	for technical pool FPs/rough bypasses	50 to 67 % of L_p [1]
min. pool width (W_p)	for technical pool FPs/rough bypasses	$2 \cdot L_{fish}$ [1] [2]
bottlenecks and transition zones		
min. hydraulic depth of sluices (d_s)	general	$2 \cdot H_{fish}$ [1] [4] (2.5 · H_{fish} for grayling) [4]
	nature-like bypasses	$2.5 \cdot H_{fish}$ and > 0.2 m [2]
	nature-like pool passes/ramps	2/3 of D_{min} (= 2/3 of 2.5 H_{fish}) [2]
	rivers in Epirhithral and small Metarhithral	$2 \cdot 2.5\ H_{fish}$ [2]
min. width of sluices (w_s)	general	$3 \cdot W_{fish}$ [1] [2] and > 0.15 m [2]
	for nature-like constructions (pool pass/bypass)	larger: 1.25 to 1.5 · (3 · W_{fish}) [3]

With H_{fish} as max. height, W_{fish} as max. width and L_{fish} as length of the size-decisive fish species.
Note: Higher values might be required to meet the hydraulic thresholds

[1] DWA (2010, draft), [2] BMLFUW (2012), [3] AG-FAH (2011), [4] Gebler (2009)

of such resting pools (e.g. low flow velocity and turbulence) favour the deposition and accumulation of fine sediments and might therefore impair the functionality of the FP (DWA 2010, draft).

Furthermore, minimum flow velocities have to be ensured to allow a rheotactic orientation of the species as stagnant areas could represent barriers themselves, especially for rheophilic species (see chapter 1.4).

The following table shows the limit values for the maximum flow velocities with regard to the total height difference and the fish region based on DWA (2010, draft). The corresponding maximum fall height has to be selected with regard to these values (DWA 2010, draft).

Turbulence reduces the swimming capabilities of fish (Pavlov et al. 2008) and causes exhaustion or even injuries such as scale losses (Degel 2006). It is measured in W/m³ and describes the reduction of introduced power with regard to the pool volume (energy dissipation) (DVWK 1996). It changes in relation to the water level (head- and tailwater). The specific power density for pool-like FPs (P_D in W/m³) is calculated as

$$P_D = pw \cdot g \cdot Q \cdot \frac{\Delta h}{V}$$

where *pw* represents the water density (1000 kg/m³), *Q* is the discharge (in m³/s), *Δh* the fall height between two pools and *V* the volume of the pool (= length · width · mean depth).

Threshold values for the maximum flow velocity [m/s] (DWA 2010, draft)

TABLE 6

Total height difference	Upper trout	Lower trout	Grayling	Barbel	Bream	Stone loach, gudgeon
Pool-like FPs						
< 3	2.2	2.1	2.0	1.8	1.7	1.6
3 to 6 m	2.1	2.0	1.9	1.7	1.6	1.5
6 to 9 m	2.0	1.9	1.8	1.6	1.5	1.4
> 9 m	1.9		1.8	1.7	individual decision	
Bypass FPs						
< 5	2.0	1.9	1.8	1.6	1.5	1.4
5 to 10 m	1.7	1.6	1.5	1.4	1.3	1.2
> 10 m	1.1	1.1	1.0	0.9	0.9	0.8
Rockfill ramps						
< 5	2.0	1.9	1.8	1.6	1.5	1.4
5 to 10 m	1.9	1.8	1.8	1.6	1.5	1.4
> 10 m	1.7	1.6	1.5	1.4	1.3	1.2

The specific power density for bypass channels is calculated as

$$P_D = pw \cdot g \cdot v_m \cdot I$$

where v_m is the mean flow velocity and I the slope (DWA 2010, draft).

Maximum thresholds are set to 300 W/m³ (Larinier 2007) and 200 W/m³ (Dumont et al. 2005) in rhithral rivers, 80 W/m³ in the bream region (Dumont et al. 2005) or even 55 W/m³ for smaller species or age classes with low swimming capabilities (Larinier 2007). Evidence of compliance with these thresholds has to be provided for extreme situations in which the total energy dissipation has to be ensured (DWA 2010, draft).

According to Larinier (1998), brown trout show no impairment of migration up to 200 W/m³, while species of lowland rivers (e.g. pikeperch and Northern pike) avoid power densities above 100 W/m³.

To counteract the fatigue of the fish, it is suggested to include a resting pool (< 50 W/m³, BAFU 2012) every 2 (BAFU 2012) to 3 m (Seifert 2012) of height difference or to reduce the height differences between the single pools and to increase the FP length in upstream direction (see Table 7).

In comparison to Table 7, the Austrian guideline (BMLFUW 2012) suggests lower values for the specific power density (see Table 8). However, in the Austrian guideline, special attention is given to juveniles (≥1+).

2.3.3 Slope

The maximum slope of ramps is approximately between 1:15 (upper trout region) and 1:50 (barbel region) and is usually selected with regard to the natural river type (Dumont et al. 2005). For vertical slot and pool passes, the slope is a result of the pool dimension, the flow and the maximum energy dissipation, but should not exceed 1:10. Nature-like bypass channels represent a special type. The respective slopes for this type are given in chapter 4.3.

Threshold values for energy dissipation in pool-like FPs and rockfill ramps (DWA 2010, draft) *TABLE 7*

Fish region	Threshold values for the energy dissipation PD [W/m³]	
	Pool pass	Rockfill ramps
upper trout	250	300
lower trout	225	275
grayling	200	250
barbel	150	200
bream	125	175
stoneloach, gudgeon	100	150

2.3.4 Continuous rough substrate, connection to head- and tailrace water

The bottom of the FP should consist of coarse substrate with a thickness of at least 0.2 m, thereby reducing the flow velocity towards the bottom (Gebler 1991). As an excessively rough bottom substrate can increase turbulences and therefore deteriorate the conditions for weaker fish, Adam et al. (2009) suggest the construction of a support corset of larger stones (35–45 cm and 4-5 stones/m²) surrounded by a mixture of rubble stones (5–15 cm) and gravel (8–32 mm) so that the larger stones still protrude at least 0.1 m. The substrate of the FP should be continuously connected to the natural river, which can be ensured by a ramp with a maximum slope of 1:2 (DWA 2010, draft). This also ensures the upstream migration of benthic invertebrates.

2.3.5 Light conditions

Although it is assumed that fish do not migrate through longer canalised river sections, it is known that fish migrate occasionally through darkened constructions such as pipes (Ökoplan 2002). Nevertheless, the FP should provide natural light conditions without abrupt light changes (DWA 2010, draft).

Guiding values for energy dissipation in pools of vertical slots, nature-like pool passes and ramps (at mean annual low flow (MALF)) with regard to the fish region to ensure a non-exhausting and safe passage of small and juvenile fish ≥ 1+ (BMLFUW 2012) *TABLE 8*

Fish region	Height difference between pools Δh [m]	Specific power density PD [W/m³]
upper trout	0.20	160
lower trout (without grayling)	0.18	140
lower trout (with grayling)	0.18	130
grayling	0.15	120
barbel	0.13 – 0.10	100
bream	0.08	80

2.3.6 Exit in the tail water (inflow)

The exit should have a sufficient distance to the turbine inlets (Jäger 2002), whereby 5 m seem appropriate for a turbine inflow velocity of 0.5 m/s. For higher velocities, a minimum distance of 10 m should be guaranteed (DWA 2010, draft). For large rivers, distances of 50–100 m might be required (BMLFUW 2012). The inflowing water (into the FP) should have a higher flow velocity than the flow passing the FP (DWA 2010, draft).

If the water level in the upstream area (forebay) is constant, the inflow construction is usually unproblematic. For varying levels, the top pool may be used to adjust to different headwater levels, while the second pool can be used for fine-tuning the flow (Jäger et al. 2010). In general, a discharge control should be possible for the inflow. However, for level fluctuations of 0.5–1.0 m, a vertical intake slot seems adequate. If the level differences are higher, several inflows with closure function should be included (DWA 2010, draft).

The inflow should be constructed in a way that allows the introduction of monitoring equipment (e.g. fish traps or counting basins, see chapter 6). Furthermore, the entrance has to be protected from driftwood jams by means of submerged baffles of floating beams. Furthermore, performance checks and maintenance work should be planned on a regular basis (DWA 2010, draft; Seifert 2012, BMLFUW 2012).

2.4 Operational discharge of the FP

The adequate discharge for the FP is a result of the criteria defined in the previous chapters. However, this discussion is limited to barriers with hydropower production as the required discharge for the FP competes with hydropower production.

There are three discharge values:

– the required operational discharge (Q_O),
– the required discharge for the attraction flow (Q_a) and
– the overall discharge ($Q_{tot} = Q_O + Q_a$)

While Q_a depends on so many factors that it is not possible to capture all components in a formula (see chapter 2.2.2), Q_O can be calculated hydraulically with regard to the morphometric thresholds of the FP and the slope (Seifert 2012).

The annex presents calculated thresholds for the Q_O with regard to the fish species and the dimensions of the respective FP. However, the table includes only approximate values and Q_O has to be defined and calculated for each case separately.

3. Evaluation of basics and selection of the FP type

Only if the migration corridors and the specific requirements of the key species are known is it possible to plan the hydraulic and spatial conditions in a way that the entrance is perceivable and that the FP is passable.

Therefore, the local conditions such as the barrier itself, its environment (possible building areas or constraints), the total height difference between entry and outlet and water level variations over time, basic data of the fish fauna and the migration corridors have to be investigated.

Hydrological data are necessary to define the operating time of the FP (usually Q_{30}–Q_{300}) and the corresponding water levels up- and downstream and their natural or artificial variation. The total water level difference (h_{tot}) and the maximum height differences (in- and outflow) between the pools (Δh, defined by the key species) allows the total number of pools to overcome the total height difference to be defined.

$$n = \frac{h_{\mathrm{tot}}}{\Delta h} - 1$$

The total length (l_{tot}) of the FP can be defined using the number of pools (n), their required length (L_p) with regard to the size-decisive fish species and the width of the borders between the pools (w_b).

$$l_{tot} = n\,(L_p + w_b)$$

The hydraulic, hydrological, morphological (riverbed formation) and ecological investigations are summed up in an eco-hydraulic overall assessment to define the migration corridors and most suitable location of the entrance of the FP.

The selection of the most suitable FP requires a high level of technical and ecological knowledge and is based on the following main criteria:

a) Type of barrier (removal possible, hydropower production)

b) Availability of areas and slope
   - For large height differences and less space, technical solutions (vertical slot, rough channel ramp) are more suitable
   - For small height differences and sufficient space, nature-like types (pool pass, nature-like bypass channel) are usually preferred
   - For large height differences and sufficient space, nature-like and technical types or combination thereof are possible

Finally, the functionality of each FP has to be investigated (e.g. fish traps, counting basins, see chapter 6). Monitoring and maintenance work is also required periodically (Seifert 2012).

4. FP types

FPs are structures that help fish to overcome/pass an artificial barrier (Jungwirth and Pelikan 1989). Measures to restore the continuum are classified as:

- Removal of the barrier
- Rough ramps or river bottom sills, which are totally or partially made of natural material and cover the entire riverbed (entire discharge) or only parts of it (partial ramps).
- Nature-like bypass channels or nature-like pool-type fish passes are nature-like constructed FPs circumventing the barrier for a short distance (pool-type FP) or long distance (bypass channel).
- Technical FPs with mainly geometrical channel form constructed predominantly with artificial or processed material (concrete, wood or plastics) that guide the fish through the barrier (e.g. pool pass, vertical slot pass).
- Special constructions (e.g. fish locks, fish elevators).

In the following chapters, the commonly used types will be explained in detail. However, also the possibility of a barrier removal or a bristle pass (combined use for fish and canoes) will be included. Other types, such as the Denil pass, have not proven to be suitable for multi species purposes and are therefore excluded.

4.1 Removal of the barrier

The removal or partial removal of barriers is a sustainable solution and should be discussed first. Many existing barriers no longer fulfil their purpose or have lost their functionality. Although this opportunity should certainly be considered, it will not be further discussed here. However, the consequences of a removal have to be investigated in detail to avoid damage to other facilities such as flood protection measures (DWA 2010, draft).

4.2 Rock ramps and bottom sills

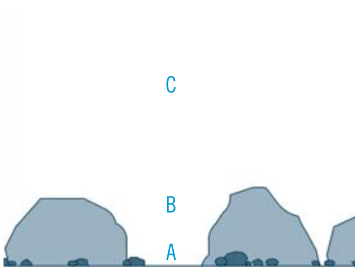
Rock ramps have more functions than restoring the connectivity for fish since they also retain water, stabilise the riverbed and concentrate the energy dissipation. Furthermore, they differ from usual FPs as they are (in most cases) charged by the total river discharge and therefore experience high discharge, velocity and turbulence variations. For fish, rock ramps have the following advantages: good perceptibility, provision of several migration corridors, low sensitivity to debris and therefore low maintenance costs, restoration of up- and downstream migration and habitat enrichment for rheophilic species (Gebler 2007). The disadvantages are very high construction costs and possible problems with regard to passability during low flows (BMLFUW 2012).

Ramps can be divided into those covering the entire river width (full ramps using the entire discharge) and partial ramps, which do not cover the entire river width and therefore receive only a proportion of the total discharge. If the entire discharge flows across the ramp, they have to be dimensioned with regard to the mean daily low flow to be passable also at low flows. The functionality for low flows can be ensured by including a low flow corridor. Furthermore, during floods, full ramps have to carry the entire discharge and therefore have to be sufficiently stable (BMLFUW 2012).

Based on DWA (2009), the following migration corridors can be defined and have to be considered in the ramp (see also Figure 9):

- A Transitional zone between substrate and interstitial for bottom-dwelling small species and juveniles (flow velocity threshold < 0.2 m/s)
- B Within the roughness height (> 15 cm) and the above lying flow-reduced layer for fish with a body length below 30 cm (flow velocity with regard to the river region 0.2–0.5 m/s)
- C1 Above the roughness height, open water, flowing wave (without chutes, spillovers or bottlenecks) for fish with a body length over 30 cm (flow velocity thresholds of 0.6–1.5 m/s)
- C2 For even slides without roughness elements (free flow) divided into lengths of a) up to 5 m (see threshold of C1) and b) up to 10 m (thresholds from 0.5–1.2 m/s)
- D1 Passages/sluices at pools (free flow) with thresholds for the maximum velocity of 1.4–2.2 m/s (depending on the fish region)
- D2 Jets in low-flow channels for construction with roughness stones with flow velocity thresholds of 1.0–2.0 m/s

Schematic display of the different migration corridors (adapted from Seifert 2012, based on DWA 2009) FIGURE 9



With regard to corridor A, the slots have to be deep enough for bottom-linked species to pass them; hydraulic steps at the bottom should be avoided (AG-FAH 2011).

Ramps can be divided with regard to their structural construction type:

- Embedded boulder constructions (flat roughened channel, uniform) have a surface of poured coarse boulders with a uniform and homogenous (but low) roughness and are therefore not the best possible solution. In any case, it is necessary to include asymmetric cross sections or stepped profiles with berm (horizontal slope sections) and migration channel to ensure passability also for low flows. It is applicable up to slopes of 1:10 (10 %) (BAFU 2012). The length should not exceed 10 m (DWA 2010, draft).
- Rockfill constructions (boulder type roughened channel) contain regularly dispersed single boulders building a certain pattern to increase the roughness and the water depth in the migration corridor. However, also in this case asymmetric or v-shaped profiles should be used to ensure passability during low flows. They can be used up to a slope of 1:15 (6.5 %). Furthermore, this type should be applied for short lengths or in combination with other types (DWA 2010, draft).
- Cascaded constructions (pool type roughened channel) include linearly arranged large stones (0.6–1.2m in diameter) in the form of a lattice structure resulting in a sequence of spillovers and pools. The design includes a high roughness. It is applicable for slopes up to 1:30 (3.5 %) and long lengths.

The migration corridor within the ramps may vary depending on the actual flow condition or the species and age classes. However, the migration corridor has to be traceable and passable with regard to the morphometric and hydraulic thresholds (DWA 2010, draft).

For the definition of guiding values based on the threshold values, the following safety coefficients (S) are considered (DWA 2010, draft):

- $S_v = 0.9$ (for the flow velocity of cascaded constructions)
- $S_v = 0.8$ (for the flow velocity of embedded boulder constructions and rockfill constructions)
- $S_d = 0.9$ (for the dimensions of ramps with cascaded construction)
- $S_d = 0.8$ (for the dimensions of embedded boulder constructions, rockfill constructions and cascaded constructions)
- $S_p = 0.9$ (for the energy dissipation of rockfill constructions and cascaded constructions, not relevant for embedded boulder constructions)

The hydraulic and morphometric rated values for the three construction types (i.e. embedded boulder construction, rockfill construction and cascaded construction) are presented in the annex (Table 19 to Table 24).

Although salmonids might be able to pass slopes up to 6 (or 10) %, guaranteeing the required flow velocities for cyprinids at slopes higher than 3.5 % is problematic (BAFU 2012).

4.2.1 Cascaded constructions

The design includes construction stones (of natural, frost-resistant material), larger stones and boulders as roughness elements. Several drops are followed by pools and connected by rectangular or trapezoidal (not v-shaped!) slots (BMLFUW 2012). The slots should be included in an alternating way (crosswise) with a width of 0.2–0.4 m. A main quality attribute of these slides is the availability of areas with different hydraulic and morphological conditions, building a mosaic of migration corridors according to the requirements of different fish species. Furthermore, the natural substrate transport has to be considered for the pool depths as pools that are too shallow are sensitive to substrate depositions.

The following depths are recommended (AG-FAH 2011):

- Trout region (MF > 2 m^3/s): basic depth > 80 cm
- Grayling region (MF > 20 m^3/s): basic depth > 100 cm
- Barbel region (MF < 100 m^3/s): basic depth > 140 cm
- Bream region (MF > 100 m^3/s): basic depth > 140 cm

During low flows, fish migrate through rough passages between larger stones ("slots"). To ensure a connected substrate without "jumps", the bottom of the pools should be raised towards the slots. The stones, forming the border between the pools, should be higher towards the shoreline (≥HQ1), forming a v-shaped cross section, so that fish find protective zones for resting even at high flows. If boat traffic is expected, the construction of a boat channel might be necessary (Seifert 2012).

The slope, fall height and energy dissipation have to be defined with regard to the respective fish region.

The following table includes approximate values for these parameters. However, since the dimensions depend to a great extent on the construction type, river size and river type, detailed planning is necessary.

Approximate values for the slope and water level differences (among pools/steps) of ramps with regard to the fish region (AG-FAH 2011) *TABLE 9*

Fish region	Slope	Water level difference Δh [cm]
upper trout	1:15	20
lower trout	1:20	18
grayling	1:20 – 1:30	15
barbel	1:30 – 1:50	≤15*

In general, the slope depends on the river region and river size and should be selected with regard to these parameters.

* ≤ 10 based on Seifert 2012

Nature-like FP at the HP Kemmelbach on the river Ybbs in Austria *FIGURE 10*

4.3 Nature-like bypass channel

Nature-like bypass channels mimic a natural river and circumvent the barriers on a large scale, which means that they sometimes even bypass the impoundment caused by the barrier. Besides restoring the continuity, this type creates a free-flowing section including suitable habitats for reproduction and juveniles.
Such bypass channels can support the achievement of the good ecological status/potential in case of chains of impoundments.
A negative aspect of this type are the large spatial requirements. In particular, difficulties arise with regard to the design of an optimal entry under restricted spatial conditions (BMLFUW 2012).

It is essential to consider the natural river characteristics with regard to the slope, geometry and morphology, structures, substrate and materials. In any case, heterogenic depths with pool-riffle sequences should be ensured.

The slope values (see Table 10) are selected with regard to the fish regions (based on Huet 1959) and adapted based on monitoring results (BMLWUF 2012).

The hydro-morphological conditions, e.g. cross section, discharge, slope, fall height, flow velocity, have to match the fish-ecological requirements. Partly dynamic discharges (from MALF to 2MF) ensure some kind of dynamic channel development while the substrates should be suitable for reproduction at least in some areas.

Suggestions for construction based on Seifert (2012) include

- Mean flow velocity in the corridor of maximum velocity ~ 0.5 > 1 m/s
- Maximum flow velocity at chutes 1.4–2.0 m/s (rhithral) and 1–1.2 m/s (potamal rivers)
- Asymmetric cross section to favour a deeper channel
- Pool-riffle sequences to reflect natural flow conditions
- Maximum fall height of 0.15–0.20 m (rhithral) or 0.10–0.15 m (potamal rivers). The water depth at chutes should be high enough for fish to pass (> 0.20 m)
- Substrate layer should be at least 0.2 m high and the gravel size should be selected in a way suitable for reproduction taking present hydraulic conditions into account.
- Regular "flushing" and gravel introductions are required to maintain suitable conditions for reproduction (e.g. to avoid clogging).

4.4 Nature-like pool pass (weir pass)

Similar to a rock ramp with cascades, a nature-like pool pass consists of several drop structures with pools in between leading to a pool-riffle sequence in longitudinal direction. The drops have to be designed in an asymmetric way and the openings should have a rectangular or trapezoidal shape (reaching down to the bottom). The openings/slots between consecutive drops should alternate to ensure a pendulous flow. Asymmetric cross sections with the highest depth below the outlets are suggested. The geometric dimensions can be derived from the thresholds

Table 10: Orientation values for the slope and minimum flow of nature-like bypass channels dependent on the mean flow of the river and the fish region (BMLFUW 2012) TABLE 10

MF [m³/s]	in the river	5	10	20	50	100	200	> 200
	in the FP	0.25	0.5	0.8	1	1.5	2	> 2
Slope [%]	upper trout reg.	2.0 – 3.0	1.5 – 2.5	1.2 – 2.0	1.0 – 1.5	0.9 – 1.4		
	lower trout reg.	1.5 – 2.0	1.0 – 1.5	0.9 – 1.2	0.8 – 1.0	0.7 – 0.9		
	grayling reg.	1.0 – 1.5	0.8 – 1.0	0.7 – 0.9	0.6 – 0.8	0.5 – 0.7	0.4 – 0.6	
	barbel reg.	0.7 – 1.0	0.6 – 0.8	0.5 – 0.8	0.5 – 0.7	0.4 – 0.7	0.3 – 0.6	0.3 – 0.4

for technical solutions, however adaptations are necessary: an increase of 25–50 % for length and width and an increase of 20–30 % for depth in comparison to vertical-slot passes seems to be adequate (Seifert 2012).

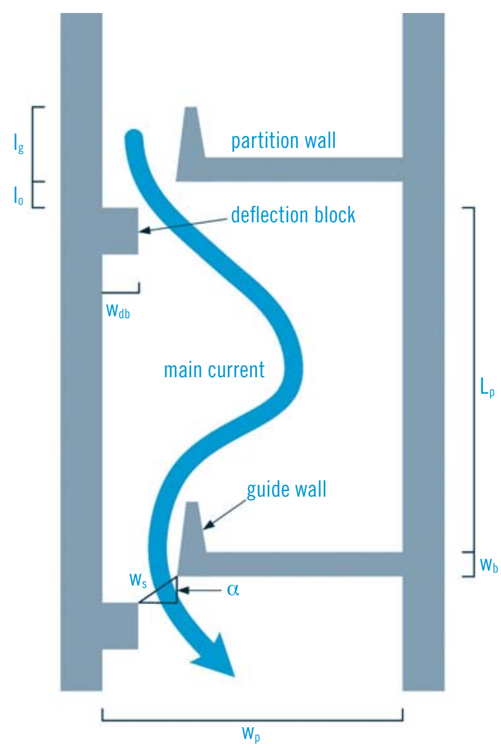
4.5 Vertical slot pass

Vertical slot passes represent technical FPs, whereby the slope-processing occurs over defined, constant height differences between two pools, thus reducing the kinetic and potential energy within each pool. The single pools are connected by vertical slots (ranging from the top to the bottom), which are usually situated on the same side (see Figure 11). Usually, the entire FP consists of concrete, but also could be made of wood. This type allows a mean slope of 1:8 and therefore represents a suitable solution for limited space. Advantages of this FP type are the low spatial demands and the possibility to construct an optimally located entry under spatial restrictions. However, the construction is more expensive (in comparison to nature-like by-/pool passes) and requires more maintenance. Furthermore, the FP itself does not represent a suitable habitat for fish (BMLFUW 2012).

An important parameter is the slot width (w_s) determining the minimum cross section and therefore the discharge and the flow velocity. The minimum slot width (w_s) depends on the body width (W_{fish}) of the size-decisive fish and is calculated as 3x W_{fish}. The pool length (L_p) represents the distance between two partitioning walls and should be higher than 3x L_{fish} (fish body length). L_p is used to determine the pool width (W_p = ¾ of L_p) (see Figure 12). The minimum depth (D_{min}) should be > 0.6 m (0.5 m for rivers of the small trout region) (BMLFUW 2012).

Vertical slot FP at the HP Greinsfurth on the river Ybbs *FIGURE 11*

Schematic design of a vertical slot (adapted from DWA 2010, draft) *FIGURE 12*



The maximum acceptable energy dissipation of the respective river type has to be considered. The slots usually include a hydraulic steering device to ensure an oscillating main current using the entire pool volume for a low-turbulence energy transformation (Heimerl and Hagmeyer 2005, Heimerl et al. 2008) as shown in Figure 12:

- The deflection block prevents a linear accelerating flow through the adjacent slots (hydraulic short-circuit), leading the flow into the corner between the side wall and the partition wall. The angle of deflection (α) should be between 20° (for small FPs, Gelber 1991) to 45° (Larinier 1992, Rajaratnam et al. 1986).

- An upstream hook-shaped extension (guide wall) ensures a consistent inflow without transverse flows, leading the main current back to the sluice, supporting the energy dissipation.

The dimension of these two extensions should be in accordance with the slot width (Larinier et al. 2002, Katapodis 1992).

Dimensions of a vertical slot in relation to the slot width (s) (based on Larinier et al. 2002, Katopodis 1992 in DWA 2010 (draft)), see Figure 12. *TABLE 11*

	factor x
slot width ws = x * ws	1.00
pool length Lp = x * ws [1)]	8.10 – 8.33
guide wall length (incl. width of partition wall) lg= x * ws	1.78 – 2.00
offset length lo = x * ws	0.41 – 0.83
width of the deflection block wdb = x * ws	1.15 – 1.49

	angle
lateral offset angle α	
for small FPs	> 20°
in general (Larinier 1992, Rajaratnam 1986)	30 – 40°

[1] insofar as the size-decisive fish or the energy dissipation do not require larger dimensions

The bottom should be continuously covered with rough substrate to reduce the flow velocity towards the bottom (see chapter 2.3.4).

Table 12 shows values that were proven to be suitable in the laboratory and in the field based on Katopodis (1990), Gebler (1991) and Larinier (1992).

Although vertical slot passes can cope with small water level fluctuations (up- and downstream), the discharge and also the hydraulic conditions change with any variation of the level, which has to be considered in defining geometric dimensions (Mayr 2007).

An advantage of the vertical slot is that the hydraulic parameters can be easily calculated. Furthermore, the migration corridors within the slots serve both benthic and water column fish species (Seifert 2012).

4.6 Rough channel pool pass

Rough channel pool passes represent a combination of a pool-like ramp and a nature-like FP with rectangular basic profile. The partition walls are replaced by upright positioned, stone rows more or less in resolution including slots (minimum width of 0.25 m) for passage. The fall heights between the pools (0.1–0.2 m), the flow velocity in the transition areas (1.4–2.1 m/s) and the specific power density for energy transformation within the pools (100–200 W/m^3) should reflect the natural river conditions and represent the requirements of the "weakest" fish species. It is important that the slots alternate at each stone row (preventing hydraulic short-circuit). The hydraulic thresholds have to include higher safety margins than technical partition walls and have to be optimised on site. Also in this case, slopes up to 1:8 can be made passable with this space-saving solution. The pool width should not be less than 1.5 m and the lengths between two stone rows at least 1.5 m (brown trout) up to > 3.0 m (Danube salmon). Furthermore, a minimum depth of 0.6 m (0.8 m for Danube salmon) and a continuous substrate with at least 0.2 m thickness should be ensured (Seifert 2012).

Geometric guiding values for the pool and slot width of vertical slot FPs (DWA 2010, draft)

TABLE 12

Selected fish species	Pool dimension [m]		Slot dimension [m]	
	Length L_p	Width W_p	Sloth width w_s	Water depth d_s
Brown trout	1.80 [1)]	1.35	0.15	0.50 [3)]
Grayling, European chub, roach	2.20 [1)]	1.65	0.20	0.50 [3)]
Barbel, zander, Northern pike, Danube salmon	3.00 [2)]	2.25	0.30	0.50 [3)]
Bream, carp	3.10 [3)]	2.33	0.38	0.48 + hΔ [4)]
sturgeon	9.00 [2)]	6.75	1.08	1.02 + hΔ [4)]
Decisive factors	[1)] Energy dissipation (P_D) [2)] fish length (L_{fish}) [3)] hydraulic conditions [4)] fish height (H_{fish})			

4.7 Bristles pass

Bristles passes are rectangular channels where the soil is covered with certain patterns of bristle bars (50 cm long plastic bristle bunches). These facilities allow the discharge to pass through the bristles or included slots and can be used by fish and canoes (Hassinger 2009). A negative aspect is obstruction by floating debris or algae, which changes the hydraulic conditions in the FP. Although this device can serve both the passage of fish and canoes, this can cause a conflict of interest. This type of FP is still in an experimental stage. Further investigations are necessary for final conclusions.

4.8 Shipping lock

Shipping locks can support the reconnection of continuity. However, they usually are not located according the requirements of perceptible FPs. For security reasons, shipping locks are mostly located in areas with low flow velocity and therefore outside of the migration corridor of most species. The guiding current is only temporarily present and the lock is usually only opened if traffic occurs. As a result, they can support fish migration but are insufficient as a FP on their own (DWA 2010, draft).

4.9 Fish lock

Fish locks are similar to shipping locks. Modern fish locks were designed by an engineer named Borland and are therefore also called Borland locks or Borland lifts (Aitken et al. 1966). In general, a fish lock includes a chamber with an up- and downstream lock.

Four phases can be distinguished (DWA 2010, draft):

- Entering phase: the lower lock is open and the water level equals the downstream water level. The upper lock is opened partially to introduce attraction flow, which guides the fish into the chamber, where they accumulate.
- Fill-up phase: After some time, the lower lock is closed and more water enters from upstream until the water level in the chamber equals the upstream water level.
- Exit phase: The upper lock is opened and the lower lock partially opened to generate an attraction flow, which leads the fish further upstream.
- Emptying phase: After a certain time, the upper lock is closed and the chamber emptied again until the level equals the downstream water level. Then the cycle starts again.

One cycle can last from 30 minutes to four hours (Pavlov 1989, Larinier et al. 1994, Redeker & Stephen 2006, Travade & Larinier 2002). The length of a cycle depends on the actual requirements. A small frequency allows the passage of more fish. In seasons with low migration activity, the interval can be reduced. The first and the third phase should be long enough for fish to be able to orientate and find their way in and out of the chamber (DWA 2010, draft).

Fish locks act selectively as they are more suitable for indifferent species (bleak, roach, common bream and white bream), while rheophilic species prefer common FPs. Furthermore, their functionality is limited over time as the lock can either collect or release fish, but not both at the same time.

Overall, fish locks are considered inefficient and might only serve as alternative passage for particular species such as sturgeons. In general, fish migration through shipping locks occurs mostly randomly as shipping locks are usually zones with calm conditions and attraction flow is lacking (Travade & Larinier 2002). Therefore, shipping locks can only supplement an existing FP (Zitek et al. 2007).

4.10 Fish lifts

In comparison to fish locks, fish lifts transport fish not in a water-filled channel but in a separate container. They can be applied for almost all height differences. Also in this case, fish are guided into a chamber by means of attraction flow. The size of the chamber depends on the size and number of migrating fish. Larinier et al. (1994) suggest approximately 15 litres per kilogramme of fish. The following dimensions are suggested (Larinier et al. 1994, Pavlov 1989, in DWA 2010, draft):

The attraction flow is introduced by a pipe. The flow velocity should not be too high, so that fish are able to gather. Larinier et al. (1994) suggest 0.3–0.6 m/s. To prevent fish from leaving again, fish traps should be included. A movable grid can be used to prevent fish from leaving and to densify them towards the transport container. This transport container includes a grid net and a bottom tub to supply sufficient water for the transport (6 litres per kilogramme of fish). The dimensions should be at least 1.5–1 m, with a minimum depth of 0.2–0.3 m (higher for larger fish species or fish species migrating in groups (DWA 2010, draft; Larinier et al. 1994). A power winch is used for the upstream transport. Upstream, fish are released by tilting the container or by opening a bottom gate. The duration of one cycle is usually between 10 minutes to 4 hours and depends on the number of migrating fish. In comparison to fish locks, transport up- and downstream and the exit phase is much shorter (DWA 2010, draft).

Chamber dimensions for fish lifts (DWA 2010, draft) TABLE 13

Key species	Length	Width	Height	Volume
Trout	> 1.5 m	> 1 m	> 0.8 m	> 1.2 m^3
Sturgeon	up to > 50 m	> 5 m	several m	~ 1000 m^3

5. Facilities for downstream migration and fish protection

The restoration of downstream connectivity is much less advanced than it is for upstream FPs. This is due to the fact that the re-establishment of connectivity started with upstream migration and that downstream migration problems have only been recognised and addressed more recently (Larinier & Travade 2002).

However, it is more and more recognised that facilities are needed to support both up- and downstream migration to restore overall connectivity. Downstream migration represents a significant process within the fish life cycle. Therefore, significant fish losses may result if continuity is not restored in both directions (Nok 2009).

As discussed in chapter 1.2, downstream migrations occur especially after reproduction or during the drift of fry and juveniles. However, detailed information concerning the extent of downstream migration and the behaviour of fish during downstream migration is still lacking. Downstream migration occurs either close to the surface (e.g. juvenile salmonids) or close to the bottom (e.g. eel, barbel, nase and bullhead) or within the water column. Therefore, downstream fish passes (DFPs) should include options for surface, water column and bottom migration. Similar to upstream migration aids, facilities for downstream migration have to be connected to the downstream migration corridor (Jäger et al. 2010). For instance, it is known that fish gather in the forebay of weirs. Since most upstream FPs cannot be used for downstream migration, additional DFPs are required (AG-FAH 2011).

DFPs, fish-friendly turbines, adaptations of the operational mode of spill flow (Cada & Coutant 1997, Holzner 2000) and modifications of the hydropower plant management are methods to enable downstream migration (AG-FAH 2011).

Downstream migrating fish also pass through turbines and get harmed or even killed. The main challenge of downstream migration is to prevent fish from entering the turbine and to guide them to an appropriate alternative for downstream passage. Measures for fish protection should therefore be included in all existing hydropower plants.

5.1 Fish protection

There are several approaches for fish protection. However, they have to be combined with solutions for downstream migration. The following chapters provide a selection of possible solutions for fish protection.

5.1.1 Special turbines

For high-pressure plants, mortality can be up to 100 % when fish pass turbines, while for low-pressure plants the mortality or damage rate depends on the diameter of the rotor and the distance between the rotor blades, rotation speed and pressure differences during turbine passage. To avoid clamping of fish, the distance between the blades and the turbine coat should be less than 3 mm (AG-FAH 2011).

Death or serious injuries can be caused by pressure or velocity changes, shearing effects, collision with turbine or dam structures, grinding, turbulence and abrasion (Wittinger et al. 1995, Larinier & Travade 2002, Larinier 2002). Examples for special turbines are presented in chapter 5.2.6.

5.1.2 Behaviour barriers

Behaviour barriers are facilities producing a stimulus for fish (repulsive or attractive), which are usually used to prevent the fish from entering the turbines. Examples include (BAFU 2012):

- Electrical screens (according to Gosset & Travade (1999), their efficiency is limited to 15 %)
- Bubble screens
- Sound screens (lacking experience)
- Fixed/mobile chain screens
- Light screens (attractive or repellent)
- Surface guide walls (deflect only fish migrating close to the surface)
- Louvre screens (louvred slats introducing current vortices and guiding fish to a FP)

However, experiences are not convincing in Europe (Gosset & Travade 1999) and their application is limited to flow velocities less than 0.3 m/s. Therefore, they are not further discussed here.

5.1.3 Physical barriers

Screens act as a physical barrier and mechanical filter. To provide effective protection, the facilities have to be sufficiently tight, whereby the bar distance of screens has to be selected with regard to the fish community and should not exceed 20 mm (Dumont 2005, Larinier & Travade 2002, DWA 2005). The inflow velocity (the flow velocity in the vertical profile in front of the screen) should not exceed the critical swimming speed of fish and should not exceed 0.25–0.5 m/s. Physical barriers lead to hydraulic losses causing lower energy production, whereby the losses depend on the geometry of the screen (e.g. distance between bars and profile of the bars) and on the flow velocity.

5.1.3.1 Fine screens

Screens with a distance between bars of 20 mm are required to avoid downstream migration of fish such as barbel (> 185 mm), common bream (> 205 mm), roach (> 175 mm), asp (> 210 mm), tench (> 160 mm), burbot and catfish (> 160 mm), Northern pike (> 200 mm) and nase (> 170 mm) (Holzner 2000). Physical barriers with a bar distance of 10–15 mm already provide good protection. However, since smaller individuals might still pass, a special rake with less than 10 mm bar distance is required to prevent juveniles and small fish from entering the turbine (Dumont 2008). However, with regard to clogging, such screens are not applicable for large HPPs.

5.1.3.2 Wedge wire screen

This screen consists of a row of tight lying bars (3–10 mm) shaped like a triangle. The screens are sloped towards the flow. Advantages include the smooth surface, which prevents injuries of fish and favours their escape. Therefore, wedge wire screens are suitable solutions for fish protection. However, the hydraulic losses are very high (BAFU 2012). Investigations showed, however, that they can only be used for discharges up to 10–20 m^3/s. For larger rivers, suitable solutions are still lacking (Dumont et al. 2005).

5.1.3.3 Special screens

Fine screens can be replaced by circulating shields in the form of perforated plates or weir grids, whereby the size of the holes depends on the present fish species.

There are different types (BAFU 2012):

- Stationary screens are constructed from a perforated metal plate in vertical or inclined direction.
- Travelling screens are rotating screens for which the rotation speed depends on the amount of floating debris. The diameter of the openings ranges from 1–6 mm. This type can be complemented by facilities that collect the fish and transport them downstream.
- Drum screens are comparable to travelling screens, however they have the form of a rotating drum (diameter 0.8–1.5 m for small, up to 6 m for large plants). The distance between the bars is usually 3–6 mm.

These special screens have been developed in the US and experiences are unavailable for Europe.

5.2 Downstream migration pathways

The following chapters present some selected pathways for downstream migration of fish. According to Larinier (2007), more water is required for downstream than for upstream migration (i.e. 2–12 % of the actual discharge).

5.2.1 Downstream migration via upstream migration facilities

FPs for upstream migration usually do not work for downstream migration since the behaviour of downstream migrating fish is different.

According to Larinier (2007), salmonids accept downstream migration aids positioned close to the screen, if the downstream flow is at least 40 cm deep, has a mean flow velocity of 0.4–0.6 m/s and the flowing section is at least 2–3 m long (AG-FAH 2011). Therefore, it would be possible to design a bypass leading the downstream migrating fish from the screen into an existing upstream FP or directly into the water downstream (Jens et al. 1997, Travade & Larinier 2007).

5.2.2 Trap and truck systems

This approach traps migrating fish and trucks them downstream, where they are released again. The system can also be used for upstream migrating fish and might be useful for large rivers where no satisfactory technical solution for downstream fish migration exists so far and for fish migration that occurs regularly and within a short time span (e.g. eel, salmon and sturgeon). This method is used in Germany on the rivers Main and Mosel for eel. Trap and truck is supported by systems that detect fish migration periods. They have the advantage that their functionality can be verified (monitoring data) and they overcome several barriers with one solution. However, they are generally not considered ecologically sustainable and are therefore not further discussed here (Dumont et al. 2005).

5.2.3 Opened weirs – spill flow

Fish migrate through partially or fully opened weirs. Arnekleiv et al. (2007) showed that the majority of smolts and kelts used short periods of surface water release to migrate downstream through the spillways. During their investigations, surface spill flows with water columns of 12–36 cm were used for downstream migration, while the submerged turbine shafts or deep water releases were neglected (Arnekleiv et al. 2007). These findings highlight the relevance of surface spill flows for downstream migration.

Spill flow can serve as a migratory pathway, as long as the water depth equals ¼ of the fall height and is at least 0.9 m (DWA 2005). Bell and Delacy (1972) showed that fish can be injured if the flow velocity exceeds 15–16 m/s. This critical velocity is reached after a free fall of 30–40 m (for 15–16 cm long fish) or 13 m (for > 60 cm long fish). However, BAFU (2012) states that the free fall should not exceed 2.5 m. A release below the surface is not recommended since fish might be harmed by the high deceleration (BAFU 2012), but due to lack of specific studies no standards can be formulated.

5.2.3.1 Spillway screens

Spillway screens replace a part of the weir. While the water falls through the grid, fish and debris (larger than the grid size) are flushed downstream across the surface of the grid (Turnpenny 1998). The Coanda screen represents a special type of spillway screens. It is constructed as a wedge wire screen (see 5.1.3.2), whereby the bars run from side to side across the width of the weir. The water follows the surface of the triangle-shaped bars into a collecting basin below the screen. The distance between the bars should be small enough to exclude all fish including fry. Depending on the type, the screen causes a head loss of 705–1270 mm. The acceleration plate resembles a circular arc (parabolic shape) to match the path of a natural water jet. They require very low maintenance since they are self-cleaned during high flows. However, the screen should be brushed approximately quarterly. Tests at the Colorado State University Larval Fish Laboratory showed that nearly 100 % of fish greater than 12.5 mm were successfully excluded (Bestgen et al. 2001).

5.2.4 Bypasses and trash racks

Bypasses should be located close to the area where fish concentrate (close to the weir or at a physical barrier towards the turbines). For juvenile salmonids, this bypass should have a rectangular entrance with a minimum dimension of 0.4–0.5 m (width and depth). The bypass has to be followed by transfer facilities downstream (Larinier & Travade 2002).

Trash racks can be combined with a downstream bypass, whereby the bypass entrances should be placed close to the trash rack face and on the side where fish gather (Larinier & Travade 2002).

5.2.5 Innovative concepts for hydropower plants

This type of power plant generates permanent water currents above the turbine unit. These currents "guide" fish downstream.

– "Moveable power plant" (www.hydroenergie.de/bewegliche-wka): turbine and generator are located together in a special device that can be moved up and down depending on the river discharge. Permanent water current enables downstream migration for fish that move close to the surface above the power plant, whereas fish that move close to the ground can migrate beneath the power plant when it is uplifted during higher flow conditions.

Moveable power plants have been installed in Germany. In the context of a LIFE+ project, ecological monitoring was performed at two power plants.

- Schachtkraftwerk (www.wb.bv.tum.de/Schachtkraftwerk/Flyer2011.pdf): This hydropower plant was developed by the Technical University Munich and is still in a testing phase. However, first tests showed promising results for fish protection and downstream migration (TUM 2012).

5.2.6 Downstream migration through fish-compatible turbines

Based on several investigations (Monten 1985, Larinier & Dartiguelongue 1989, Hadderingh & Bakker 1998, EPRI 1992), it is assumed that all turbines impair fish to a certain degree. However, adaptations of the turbine geometry, the operational mode and management of the hydropower plant with regard to key species are possible solutions. As a result, some turbines promise to be fish-friendly by causing no or reduced damage to fish passing the turbine.

The following list provides some examples of special turbines designed to allow a safe passage of fish:

- VLH (very low head) turbine: application for height differences of 1.4–3.2 m and flows of 10–26 m³/s (www.vlh-turbine.com). The turbine is used in France, Italy and Poland. Monitoring was performed for eel and salmon smolts, which were introduced directly in the turbine. A survival rate of 92.3 % was measured. However, this turbine has to be tested over longer periods with different fish species to allow an overall evaluation.

- Screw turbine (www.nptec.de/wasserkraft/schraubentrubine.html): application for height differences of 1–10 m and flows of 0.5–5.5 m³/s. Although the producer claims that this turbine is fish-friendly, no proof based on scientific analyses is available so far.

- Alden turbine (Cook et al. 2000) (http://energy.gov/articles/fish-friendly-turbine-making-splash-water-power): applicable for height differences from 20–30 m and flows above 30 m³/s. The turbine resembles a corkscrew and has three blades, no gaps, is big and rotates slowly, while energy production does not suffer. The turbine was successfully tested by the Alden Laboratory in 2001 and 2002 to show its biological functionality (results available at www.power-eng.com/articles/print/volume-114/issue-3/Features/fish-friendly-hydro-turbine.html). According to EPRI (2011), the predicted fish survival rate is 98.4 % for 20 cm long fish. The results of the model testing are available in English language (see EPRI 2011).

- Floating turbine system: the whole unit can be lifted above the water surface (easy flushing of the reservoir). The construction offers several entrances into an upstream migration device, and aquatic organisms do not have to look for one special entrance. Furthermore, the entire discharge is used as attraction flow as fish can pass the turbine harmlessly (no biologically critical pressure fluctuations) (Gumpinger 2009).

- The Archimedean Screw is thought to be fish-friendly due to its low rotation speed (28–30 rpm) and no significant shear forces or pressure changes. According to several studies, the rate of fish harmed by this type is quite low (depending on the fish species). Schmalz (2010) shows in a case study that three species remained unharmed (roach, tench and bream) and 92 % of all remaining species were unharmed. However, he argues that large gaps between the turbine and its case may cause injuries to fish and sharp edges of blades should be avoided.

6. Assessment of the functionality of the fish pass

Even if all recommendations for the construction of functional FPs are considered and comprehensive and detailed planning was performed for the construction of the FP, its functionality has to be tested in practice. The evaluation of a FP solely based on abiotic data (slope, discharge, fall height, etc.) without consideration of actual fish migrations is not considered adequate.

In Austria, a guideline defines the minimum requirements for the monitoring and evaluation of FPs and their functionality (i.e. Woschitz et al. 2003). Although several assessment methods seem adequate and can be applied, the basic concept of the Austrian guideline is explained here.

Full functionality is only ensured if all (potentially) occurring species (autochthonous fish fauna) and age classes are always (> 300 days per year) able to migrate without qualitative and quantitative restrictions.

In general, the evaluation of the functionality of a FP can be based on one of the following two approaches (Gumpinger 2001, Woschitz et al. 2003):

- Evaluation based on indirect parameters (abiotic)
  This evaluation method was frequently applied in the past by comparing easily measured parameters (e.g. perceptibility, guiding current, slope, hydraulic parameters (e.g. flow velocities) and morphometric dimensions) with reference values obtained from functional FPs or guidelines. Although this solution is quick, some parameters cannot easily be measured and comparable values might be missing. Although abiotic parameters can serve as valuable supplements for the evaluation of a FP, a reliable evaluation of its functionality is only possible on the basis of ecological evaluations.

- Evaluation based on fish-ecological investigations
  Several approaches such as expert opinion, fish trap investigation or counting basins are possible. However, it is important to select a method that allows a qualitative and quantitative evaluation.
  It is therefore not sufficient to evaluate only the number of fish that are currently in the FP (e.g. by electro fishing) as this provides no evidence as to whether the FP is passable or not.

Optical evaluations (via video monitoring in counting basins) work automatically. However, they are only suitable if visibility allows the detection of both species and age class of migrating species. The evaluations can take place for long periods und provide significant results. This solution might be too expensive, especially for small hydropower plants.

Telemetric surveys (via transponder) provide good data for the migration behaviour of fish. Downstream fish can be caught and equipped with a transponder to evaluate which fish are able to migrate further upstream. However, this evaluation approach is very expensive as a large number of fish are required to provide significant data.

Fish traps allow the qualitative and quantitative evaluation of up- and downstream migrations. If additional data on the actual fish stock is available (or if it is investigated in a first step), migrating fish can be related to the overall migration potential (Jungwirth et al. 1994, Eberstaller et al. 1998, Eberstaller et al. 2001). Compared to other approaches, this method seems effective and suitable. Therefore, the Austrian method suggests the application of fish traps in combination with quantitative fish stock evaluations (at least downstream of the barrier) (Woschitz et al. 2003):

It is preferable to perform the investigation over a year or more. However, since this might not be possible, the investigation should take place at least before and during the reproduction period(s) of the key species. It is also desirable to detect a wide spectrum of fish with regard to rheophilic behaviour, size and age under different discharge situations.

Although the investigation should be performed quickly after completion of the FP, it is recommended to wait one year to provide enough time for the ecosystem to compensate negative effects caused by the construction activity.

Time and minimal duration of fish trap investigations (Woschitz et al. 2003)

TABLE 14

Fish region	Key species	Main date	Additional date	Duration
Epi-/Metarhithral	brown trout	Sept/Oct/Nov	-	1 month
Hyporhithral	grayling, brown trout	Mar/Apr/May	Sept/Oct	1.5 months / 14 days
Potamal	key species and dominant species	Mar/Apr/May/Jun	Aug/Sept/Oct	2 months / 1 month

There should be at least one fish trap at the exit of the FP (upstream end of the FP). However, if an additional fish trap is included at the entry of the FP (downstream end of the FP), this can provide detailed information regarding the passability of the FP.

Although downstream migrations are as important as upstream migration for the restoration of connectivity, it has to be considered that downstream migrations (active or passive) can take place temporarily via the turbines, opened weirs or spillways, etc. Investigations dealing with downstream migration are expensive and only few examples exist in Europe. If downstream migration is investigated in the upstream FP, the fish trap should be located at the upstream end of the FP as it is very likely that the fish are able to migrate downstream.

It should be investigated whether the FP serves as a suitable habitat for the local fish community. Several investigations are required to evaluate the extent to which the FP is also suitable for reproduction.

Abiotic data (i.e. discharge and temperature) are important additional data for the interpretation of results acquired and have to be collected together with the biological data. Temperature should be measured at least on a daily basis.

Besides the discharge in the river (data can be obtained from the next gauging station), the discharge in the FP should be checked at least once. If the discharge in the FP is variable, the range should be investigated.

The evaluation of the efficiency is based on the following criteria (adapted from Eberstaller et al. 1998, Eberstaller et al. 2001):

- Qualitative fish migration (upstream)
- Quantitative fish migration (upstream)
  - Long-distance migratory species
  - Medium-distance migratory species
  - Short-distance migratory species
- Downstream migration
- Habitat suitability within the FP

The scores of the first two criteria are combined (arithmetic mean) to attain the result for the upstream fish migration. The overall score can be only one level higher than the worst of the two scores (Woschitz et al. 2003).

Functionality levels and score ranges (Woschitz et al. 2003)

TABLE 15

Class	Functionality	Borders
I	Fully functional	≤1.50
II	Functional	1.51 – 2.50
III	Limited functional	2.51 – 3.50
IV	Sparsely functional	3.51 – 4.50
V	Not functional	> 4.05

The other two criteria (downstream migration and habitat suitability) are only additional factors and are therefore rated separately (Woschitz et al. 2003).

Non-functional or limited functional FPs should be upgraded. Careful planning under consideration of the key parameters and proper construct are cheaper than readjustments.

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7. Annex

Fish species discussed and their scientific name

TABLE 16

Fish species	Scientific name
Asp	Aspius aspius
Atlantic sturgeon	Acipenser oxyrinchus
Barbel	Barbus barbus
Bleak	Alburnus alburnus
Bream	Abramis brama
Brown trout	Salmo trutta fario
Bullhead	Cottus gobio
Burbot	Lota lota
Common carp	Cyprinus carpio
Common sturgeon	Acipenser sturio
Crucian carp	Carassius carassius
Danube salmon	Hucho hucho
Eel	Anguilla Anguilla
European chub	Squalius cephalus
European perch	Perca fluviatis
Grayling	Thymallus thymallus
Ide	Leuciscus idus
Lake trout	Salmo trutta lacustris
Nase	Chondrostoma nasus
Northern pike	Eso lucius
Perlfisch	Rutilus meidingeri
Pike perch	Sander lucioperca
Roach	Rutilus rutilus
Sterlet	Acipenser ruthenus
Sturgeon	Acipenseridae
Tench	Tinca tinca
Vimba bream	Vimba vimba
Wels catfish	Silurus glanis
White bream	Abramis bjoerkna

Summarised (rounded) body measurements of size-decisive fish species with regard to the fish region (Jäger et al. 2010) and the resulting dimensions for the FP (L = large, M = medium, S = small) (AG-FAH 2011)

TABLE 17

Information given in cm if not declared otherwise

					Vertical slot		Nature-like pool pass and bypass channel				Operational flow (l/s)		
Fish region	MF (m^3/s) or size	Size-decisive species	Fish length	Max. level diff. between pools	Slot width	Hydr. min. depth below sep. wall	Mean width in transition zone	Hydr. min depth at transitions and fords based on fish height	Hydr. min depth at transitions due to bottom connection	Min. max depth pool	Nature-like pool pass	Vertical slot	Bypass channel
Upper trout					15/20*	50 60*	19 25*	20	40	70	75	150	100
	> 2	brown trout	40	20	15/20*	70	23 30*	20	40	80	120	200	175
Lower trout	< 2	brown trout	40	18	15/20*	60	19 25*	20	40	70	75	150	125
	> 2	grayling, brown trout	50	18	20	70	30	25	53	80	200	250	225
Grayling	< 2	brown trout, Eur. chub, grayling, burbot	50 (60)	15	20	60	30	25	50	80	175	175	175
	> 2	burbot, barbel	60	15	25	75	38	30	56	85	250	300	350
	> 2/ < 20	D. salmon	80	15	30	85	45	35	66	100	400	400	450
	> 20	D. salmon	100	15	35	100	53	40	73	110	500	550	550
Barbel	S	Eur. chub, grayling, barbel	60	13	20	60	30	25	46	70	150	175	175
	M	barbel	60	13	25	75	38	30	56	85	250	250	350
	M	North. pike	90	13	30	75	45	35	56	85	300	300	400
	M	D. salmon	90	13	32	90	48	37	66	100	400	400	450
	L	D. salmon	100	13	35	105	53	40	73	110	500	550	550
	L	catfish	120	13	50	120	75	45	79	120	800	900	950
Lake in-/outflow	-	BT	90	13	35	105	53	45	73	110	500	550	800
Stone loach, gudgeon	-	Eur. chub	40	10	15	60	23	20	40	70	100	125	100
Danube	-	catfish	150	10	60	160	90	60	112	170	1200	1400	1900

during reproduction periods, the fish width might be one to several cm higher

* values deviating from AG-FAH (2011) suggested by Seifert (2012)

Main fish region, body dimensions and morphometric limit values (DWA 2010, draft)

TABLE 18

	Main fish region					Morphometric limit values						
						L_{fish}	H_{fish}	W_{fish}	D_{min}	d_{min}	w_s	L_p
Species	Brown trout	Grayling	Barbel	Bream	Stone loach, gudgeon	Fish length [cm]	Fish height [cm]	Fish width [cm]	Depth [cm]	Sluices depth [cm]	Sluice width [cm]	Pool length [cm]
Brown trout	■	■				50	9	5	21	17	15	150
Grayling		■	■			50	9	5	21	17	15	150
Danube salmon		■	■			100	17	10	43	34	30	300
Lake trout		■	■			100	17	10	43	34	30	300
Perlfisch		■	■			70	14	8	35	28	25	210
European chub		■	■			60	12	7	30	24	20	180
Burbot		■	■	■	■	70	13	10	32	25	29	210
Roach		■	■	■	■	40	10	4	25	20	13	120
Barbel			■			80	13	9	32	26	26	240
Nase			■			60	15	7	38	30	20	180
Vimba bream			■	■		50	13	6	31	25	17	150
Sterlet			■	■		90	15	11	38	31	32	270
Ide			■	■	■	70	18	8	44	35	23	210
Bream			■	■	■	70	21	7	53	42	21	210
Asp			■	■	■	80	18	7	46	37	22	240
European perch			■	■	■	40	11	5	28	22	14	120
Northern pike			■	■	■	100	17	7	43	34	21	300
Pike perch			■	■	■	100	16	10	40	32	30	300
Wels/catfish			■	■	■	160	35	22	88	70	67	480
Common carp				■	■	80	24	13	60	48	38	240
Crucian carp				■	■	45	14	7	34	27	22	135
Tench				■	■	60	12	8	30	24	23	180
Sturgeon				■	■	300	51	36	128	102	108	900

Hydraulic rated values for the migration corridor of embedded boulder constructions (Sv = 0.8, Sb = 1) (DWA 2010, draft)

TABLE 19

River region	Mean velocity (v_m) [m/s]		
	Length of the ramp		
	up to 5 m	up to 10 m	> 10 m
Alpine	with regard to natural conditions		
Upper trout	1.6	1.4	0.9
Lower trout	1.5	1.3	0.9
Grayling	1.4	1.2	0.8
Barbel	1.3	1.1	0.7
Bream	1.2	1.0	0.7
Stone loach, gudgeon	1.1	1.0	0.7

for embedded boulder constructions > 10 m it is suggested to use resolved constructions

Morphometric guided values for the migration corridor of embedded boulder construction (Sg = 0.8) (DWA 2010, draft)

TABLE 20

Relevant fish species	Minimum water dept [m]	Minimum bottom width[m]
Brown trout	0.3 *	1.0
Grayling, Europ. Chub, roach	0.4 *	1.5
Barbel, like perch, North. Perch, Danube salmon	0.5 *	2.0
Bream, common carp	0.6 *	2.0
Sturgeon	1.5	3.0

* can be reduced by 20 % for Q30 to Q60 if mean low flow: mean flow < 9 %

Hydraulic rated values for rockfill constructions (Sv = 0.8 and Sp = 0.9) (DWA 2010, draft)

TABLE 21

River region	Mean flow velocity (v_m) in bottlenecks [m/s]			Max. energy dissipation [W/m³]
	5 m	10 m	> 10 m	
Alpine	with regard to natural conditions			
Upper trout	1.7	1.6	1.4	270
Lower trout	1.6	1.5	1.3	250
Grayling	1.5	1.4	1.2	225
Barbel	1.4	1.3	1.1	180
Bream	1.3	1.2	1.0	160
Stone loach, gudgeon	1.2	1.1	1.0	140

Morphometric rated values for rockfill constructions (Sg = 0.8) (DWA 2010, draft)

TABLE 22

Relevant fish species	Min. Depth below sluice [m]	Minimum clear distance between stones in flow direction [m]	Minimum clear distance between stones transverse to flow direction [m]
Brown trout	0.3	1.5	0.25
Grayling, Europ. Chub, roach	0.4	1.8	0.3
Barbel, like perch, North. Perch, Danube salmon	0.5	3	0.4
Bream, common capr	0.6	3	0.5
Sturgeon	1.5	9	1.4

Hydraulic rated values for cascaded constructions up to a total fall height of 6 m (Sv = 0.9, Sp = 0.9, higher fall heights require a reduction of the safety coefficients) (DWA 2010, draft)

TABLE 23

River region	Planned fall height between pools		Mean velocity in pool [m/s]	Maximum energy dissipation [W/m³]
	DWA 2010	Seifert 2012		
Alpine	with regard to natural conditions			
Upper trout	0.20	0.20	0.5	225
Lower trout	0.18	0.18	0.5	200
Grayling	0.15	0.15	0.5	180
Barbel	0.13	0.13 – 0.10	0.5	135
Bream	0.10	0.10 – 0.08	0.5	115
Stone loach, gudgeon	0.09		0.5	90

Morphometric limit values for cascaded constructions (Sg = 0.8) (DWA 2010, draft)

TABLE 24

Relevant fish species	Min. depth below sluice [m]	Minimum sluice height [m]	Minimum clear pool length [m]	Minimum clear pool width [m]	Min. sluice with for at least one sluice [m]
Brown trout	0.3	0.2	1.8	1.0	0.2* – 0.4
Grayling, Europ. Chub, roach	0.4	0.3	2.0	1.4	0.4* – 0.6
Barbel, like perch, North. Perch, Danube salmon	0.5	0.4	3.0	1.8	0.6
Bream, common capr	0.6	0.5	3.0	1.8	0.6
Sturgeon	1.5	1.0	9	5	1.1

* for small rivers

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