DWA-Topics

Fish Protection Technologies and Downstream Fishways

Dimensioning, Design, Effectiveness Inspection

July 2005

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Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V.
German Association for Water, Wastewater and Waste

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The DWA – German Association for Water, Wastewater and Waste – is in Germany spokesman for all comprehensive water queries and is intensively committed to the development and distribution of a secure and sustainable water supply. It works as a politically an economically independent organisation professionally in the fields of water management, sewage, waste and soil protection.

DWA is in Europe the association with the largest number of members within this field and therefore takes up a special position. This is because it provides professional competence regarding standardisation, professional training and information towards the public. Approximately 14.000 members represent the experts and executives from communes, universities, engineering offices, authorities and enterprises.

The main emphasis of its activities is on the acquirement and update of a uniform technical set of rules and standards as well as the cooperation on the list of technical norms on a national and international level. In this connection not only are the technical scientific topics involved, but also the economic and legal interests of the environment and water pollution forms a part.

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Foreword

Since the state-of-the-art of fish passes has been considerably improved, which not least is owed to the DVWK-publication 232 (1996), the demand for free passage for downstream migrating fish gains increasing importance. Next to an ecologically oriented operation management of dams and inlet works, fish protection facilities and downstream fishways are the only possibility to reduce the obstructing effect of in-stream obstacles (dams and weirs etc.) for migratory fish and to restore river continuity.

Fish protection facilities and downstream fishways in Germany have so far been built in a small number only. When dealing with this topic, it was discovered that the knowledge available was seriously insufficient with respect to the migratory behaviour and the functioning and application of fish protection facilities and downstream fishways. Application oriented research concerning the migratory behaviour of indigenous fish has started only recently, and individual fish protection facilities and downstream fishways were subjected to operational checks. Against this background, the knowledge and experience available in foreign countries had substantially to be taken as reference for this publication. It is therefore the main intention of this publication to contribute to intensified efforts for the eco-technical optimization of installations to ensure fish protection and downstream fish migration.

The present volume of the ATV-DVWK-*Topics* first of all deals with biological principles and explains the mechanisms of fish migration, which need to be considered as a vital precondition for functioning fish protection technologies and downstream fishways. General comments on obstacles follow, which cover all types of dams according to DIN 19700, including operational installations like weirs, hydropower plants and inlet works as well as sluices which will obstruct or delay the migration of fish and / or present hazards for migrating fish. The following technical recommendations for the design, hydraulic dimensioning and effectiveness of various migratory installations on the one hand differentiate between protection technologies, that prevent fish from entrainment into dangerous areas, and downstream fishways on the other hand, that provide fish with a safe passage into the tailwater of obstacles. These chapters are complemented by presentations of fish collection and transportation systems, descriptions of fish-friendly turbines, as well as alternative procedures, and finally offer suggestions for an installation management that is adjusted to migratory fish. Also frame conditions for planning and permission as well as legal matters are taken into consideration.

Fish Protection Technologies and Downstream Fishways

The Technical Committee “Hydraulic Engineering and Hydraulic Power” of the ATV-DVWK (now DWA) has installed the interdisciplinary Working Group WW-8.1 “Fish Protection Technologies and Downstream Fishways” to assess the knowledge available on the construction and operation of such installations. The following representatives of consulting companies, engineering consultants, energy supply companies, water associations and specialized authorities have cooperated in the preparation of this publication.

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The work has been subjected to a public appeal procedure prior to its publication, of which all objections received have been carefully reviewed and where suitable incorporated in the present publication. Thanks shall hereby be extended to all senders of constructive objections and remarks. Our special appreciation and thanks are also addressed to the Vereinigung Deutscher Elektrizitaetswerke (VDEW e.V. - Association of German Power Plants), representatives of the fishing trade, manufacturers of turbines, trash rack and screen cleaning machines as well as fish protection facilities, development institutes for hydropower technologies, dam operators as well as specialists from authorities and associations, who have supported our work with technical contributions and advice. Furthermore, we are grateful to the many foreign specialists, whose expertise has become a vital contribution to the success of this work.

Antrifttal, May, 2004 Beate Adam

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1 Introduction

The restoration of river continuity for fish and aquatic invertebrates contributes significantly to the ecological enhancement of water courses next to the complex problems of reducing chemical/physical loads, the restoration of morphological degradation and means for utilizations which are more compatible with nature. As a result from the intensive investigations into the phenomenon of upstream fish migration and fish passage restoration, today there are defined details on the dimensioning and design of functioning upstream fish passes available (e.g. DVWK, 1996). Additionally, numerous examinations give proof of the ecological value of upstream fish passes for the regeneration of aquatic communities and the revitalization of river systems (ADAM & SCHWEVERS, 1997b, 1998a; LANDESFISCHEREIVERBAND BAYERN, 2000; MUNLV, 2001).

It is undisputed that upstream fish passes contribute substantially to a sustainable protection of the ecosystem. However, investigations into fishways have so far excluded downstream migrations, although the passage of obstacles and water intakes holds a high risk of damage for fish (HOLZNER, 1999). Such damage to aquatic organisms caused by migration obstacles and water outlets are long since being discussed under economical views of the fishing industry. But ecological aspects as well as environmental laws and animal protection acts which affect this problem draw increasing attention to this matter. The European Water Framework Directive (EU-WFD 2000) too considers river continuity as a particular hydro-morphological quality criterion.

Functioning constructions, that prevent fish entrainment into hazardous installations and guide fish safely into the tailwater of impounding structures, are presently Europe-wide rarely in operation, despite the fact that appropriate facilities are demanded by the Prussian Fishery Law since 1916. In 1998 enquiries were carried out supported by the Vereinigung Deutscher Elektrizitaetswerke e.V. which stood in connection with the investigations for the present publication. The result disclosed that within the whole of the German Republic special fish protection facilities and downstream fishways are in operation only at less than 20 thermal power plants and hydropower plants, and that for the majority of them the efficacy is unknown. Also the few responses received to an enquiry on fish protection technologies addressed to all renowned German speaking manufacturers of turbines and screen cleaning machines carried out by the ATV-DVWK in 2001, has proven that until today there are no realizable solutions available in Germany. It shall be pointed out that no decisive reference is given on patent rights in this present publication, as their observation falls into the obligation of the user of any of the described procedures.

In the Netherlands, England and France, however, installations for the protection of migrating fish are in operation on a greater scale. The inclusion of functioning fish protection facilities and downstream fishways is also required in some States of the USA by the licensing authorities who approve applications for water intakes and hydropower plants. The effectiveness of the installations must be proven by the operator. In consequence of this requirement, there are already various fish protection and downstream passage systems in operation. Improvements to existing constructions as well as the development of new technologies are being elaborated with great force. There are for example fish guidance systems, special screens and fish-friendly turbines tested on ~~all~~ hydropower plants in the Columbia River with a mean runoff of 5,200 m^3/s. Amongst these is the 18 m high Bonneville Dam, where a bypass system exists to ensure the migration of the only 3 to 4 cm long smolts of different Pacific species of salmon (CHENOWETH, 1999). Furthermore, there are facilities in operation on the west coast of America, which are installed in front of all inlet works used for irrigation, and ensure an almost 100 % protection of the entire aquatic fauna.

The following recommendations therefore describe fish protection facilities and downstream fishways operated in Europe next to the technologies also known from the USA. However, it must be borne in mind that until present there is almost no practical knowledge available about the application of these systems under the conditions prevailing in Central Europe, where for example a greater amount of debris will involve large scale cleaning and maintenance problems.

Fish protection facilities generally serve as a means to reduce the risk of damage for migrating fish caused by constructions. For this purpose mechanical or alternatively behavioural barriers are used, which avail fish of their natural actions of shying and keeping away from disturbing sources, so to avoid animals getting into hazardous parts of the installation. Nevertheless, these measures alone are not sufficient to ensure a free migration. More important is to additionally offer a traceable migratory corridor for fish passage that will lead them safely into the tailwater.

Besides conventional possibilities of ensuring fish protection and downstream migration, there are complementary systems and strategies that can be employed like fish-friendly turbines, early warning systems in combination with an installation management aligned to migration periods, or even fish collecting and transport systems. Although hardly any knowledge exists in Germany about the efficacy of such procedures, they will also be introduced in this present volume of the ATV-DVWK-Themen in order to comprehensively document the actual knowledge level about procedures for the protection of fish and safeguarding their migration.

2 Biological principles

All aquatic animals migrate, and some have to overcome great distances. Especially fish benefit from their migratory behaviour by ideally exploiting the resources available in their habitat with respect to space and time. Thus, the change between habitats most suitable at the time of year helps to achieve the best possible population density (figure 2.1). Restricted room to move through obstacles will lead to a change of the composition and population density of species.

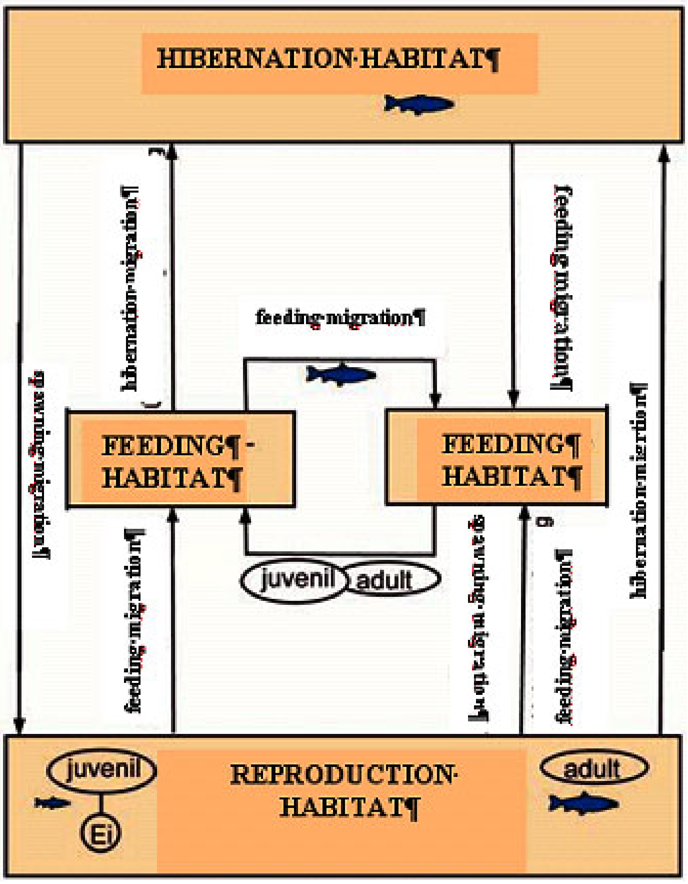


Figure 2.1 Migration of fish between different habitats

The life cycle of diadromous species like the Atlantic salmon and eel includes the change between marine and freshwater habitats. River continuity is therefore stringently required in order to preserve these species. The consequence however, is that migratory species are exposed to great jeopardy, because one single impassable obstacle can hinder their migration, and this can lead to their extinction in the entire water body system.

Nevertheless, the population of fish species which do not obligatorily migrate between sea and freshwater can show a lasting negative effect, if the free passage is obstructed, as can be exemplified by the burbot: The lower Elb, which is affected by the tides, was originally renowned for its rich population of burbots. Their anadromy took place during the winter months, and they returned between February and April. This vast population of burbots has become almost extinct, except for some minor stocks after the construction of the weir and lock in Geesthacht (KOOPS, 1960).

2.1 Migration behaviour

In order to establish a nomenclature that clearly defines the different migration forms, they are in the following outlined according to McKEOWN (1984):

diadromous:A general term for all migration movements between sea and freshwater.

anadromous: Refers to diadromous migrations, where independent of the distance to overcome the reproduction takes place in freshwater and the maturing phase in the sea

catadromous: These are diadromous migrations, where reproduction takes place in the sea and the maturing phase in freshwater.

potamodromous: This refers to migrations which are restricted to freshwater. There are neither differences applied to the length of the migration, nor are there any speculations made on their necessity.

The migrations of aquatic organisms fulfil different functions in dependence on species, development phase and season:

- **Moving between partial habitats**: During the course of a year fish undertake periodical migrations between their feeding and resting habitats, or populate during their specific development phases water sections which offer different living conditions. Young fish of many species repeatedly change their habitats over the first months of their life driven by their need for different kinds of food and also because they are gradually becoming strong enough to master the drift of the water.

  Within the course of a day the barbel move periodically between a day and a night station, where distances of up to 500 m may have to be overcome (PELZ & KAESTLE, 1989). It is known of adult fish of various potamodromous species, however, that they undertake greater migrations, which over the year may comprise several 100 km (STEINMANN, 1937). Diadromous migrations between inland rivers and the marine environment represent the extreme case of change between different partial habitats.

- **Spawning migration**: The spawning migration is to be seen as a special form of movement between partial habitats, and is undertaken by cyprinids, pikes, graylings and huchen in particular, but also by other species during their specific reproduction period. Depending on the species, the fish moves for this purpose from downstream winter quarters to upstream locations, fast overflowed gravelled sites, or the spawns is deposited on flooded sections of the bank. If the spawning migration is obstructed by impassable constructions, the fish may spawn in sections of the water body where the conditions are less suitable. The consequence of this so-called emergency spawning is a reduced volume of spawn or the entire loss of one year's reproduction.

- **Hibernation migration**: Various species of fish move to so-called winter quarters at the end of the summer. These are preferably located at the lower reaches of rivers, where the water is deeper and the current stilled, or in connected old branches. This is where the fish hibernate on the bottom of the water body and reduce their activity.

- **Feeding migration**: Spawning habitats are not necessarily suitable feeding habitats. This is why adult fish after their reproduction move into river sections where they can find better sources of nourishment. Especially species of no stable territorial bond roam through river systems in search for food, which has also been described for juvenile eels by SCHEURING (1930): *"The eel proves to be an unsettled fellow when searching for food at night […], as it does not only roam through its home regions of a river, but moves about restlessly, especially as a young fish, and likes to change its home, particularly when having risen from its winter quarter."*

  Also young fish move from their spawning area into river stretches which offer optimal feeding conditions. Therefore, gravel spawning fish spawn on heavily overflowed riffles while only gentle currents exist in the feeding biotopes of frys.

  A special form of the feeding migration is characteristic for the nase: This species of shoal fish crops growing plants from coarse substrates. Since this source of nourishment regenerates only slowly, the shoals of the nase must move over greater distances in order to encounter new feeding habitats.

  Even seawards directed migrations of the juvenile fish of anadromous species as well as the upstream migration of glass eels and elvers can be interpreted as feeding migrations.

- **Drift**: The drift of aquatic invertebrates (BRITTAIN & EIKELAND, 1988), but also of fish, is a general phenomenon in flowing water bodies. A drift is caused for various reasons and can be produced actively as well as passively. In the latter case for example as a so-called catastrophic drift resulting from a rising discharge (ANDERSON & LEHMKUHL, 1968).

  The frys of species that spawn on gravel for example, are not capable of mastering the strong current on spawning grounds and must find their feeding and maturing habitats in downstream river sections, which they reach by drift. The flow velocity on spawning grounds of graylings is approximately 0.5 m/s, the maximum swim capacity of the frys, however, is only 0.15 m/s (BAARS et al., 2001). Frys of bullheads drift almost 100 % downstream after they have left their protective breeding caves (BLESS, 1990).

- **Compensatory upstream migrations**: The territorial loss caused by drifts must be compensated actively through upstream migrations, so that a specific species is enabled to populate a river section permanently. For aquatic insects this can partly be achieved through the compensation flight of the adult animals which are able to fly (PECHLANER, 1986). Independent thereof, however, a general upstream migration tendency is evident (ELLIOTT, 1971; RUETTIMANN, 1980; ADAM, 1996). for insect larvae and likewise for freshwater shrimp *Gammarus pulex*, *Aselius aquaticus* and other organisms which are not able to fly in their adult phase.

  As soon as bullheads have obtained a body length of approximately 5 cm and are thus able to swim against the current, they compensate the territorial loss they made as frys through upstream migrations, whereby they travel up to 100 m in 2 weeks (BLESS, 1990).

- **Propagation**: The mobility of aquatic organisms plays an important role in the recolonization of river sections which have become depopulated either chronical or because of catastrophic events. An example can be presented by the fact that only a short while after the Sandoz-accident, an extensive recolonization could be noticed in the river Rhine (MUELLER & MENG, 1990), so that only two years later there was no further evidence of damage to the fish population (LELEK & KOEHLER, 1990) given. This rapid regeneration is especially attributed to the immigration from tributaries into the main river. The fast downstream directed propagation of fish even in rivers which are impounded many times, also gives evidence of the spreading grey knight goby in the Rhine system: This species has immigrated from the river Danube via the Main-Danube-Canal, where it was detected for the first in spring 1999, in the region where the Canal joins the river (SCHWEVERS, 1999). Already a few months later it had reached the lower stretches of the Hessian Main (SCHWEVERS & ADAM, 1999a), and meanwhile is represented also in the Dutch estuary region of the Rhine.

2.1.1. Anadromous migrations

The Atlantic salmon shall be taken as example for the life cycle of anadromous species (figure 2.2): Sexually mature salmon migrate from the sea to their spawning grounds in the upper reaches of rivers. While the distance the fish have to overcome in freshwater covers a few kilometres only in coastal rivers, the populations of the large river systems like the Rhine, Weser, Elb, Oder etc. must cover up to 1,000 km. The eggs are deposited and inseminated at suitable redds into the gravel of the river bottom. While most of the parent animals die after spawning, a few so-called Kelts return to the sea in order to reproduce during their

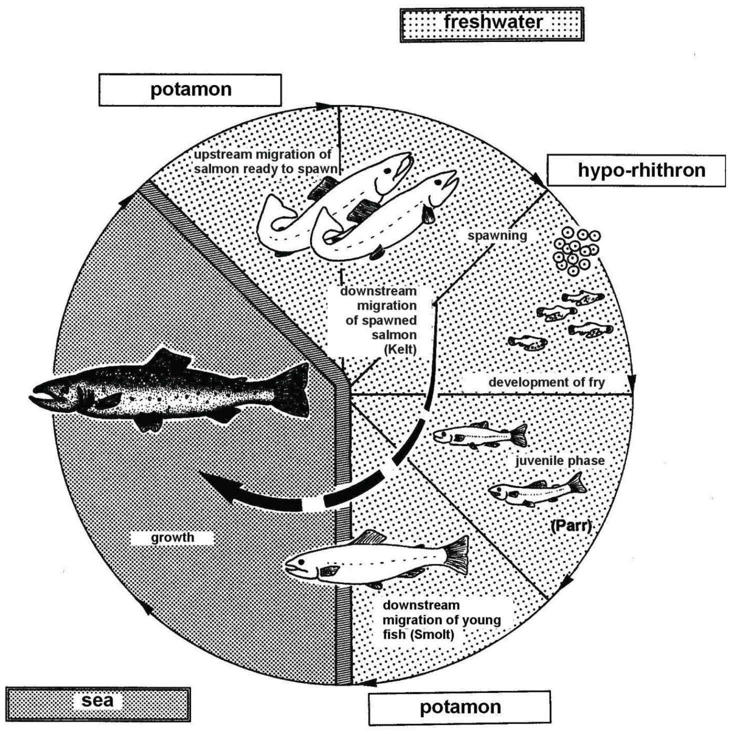


Figure 2.2: Life cycle of anadromous species exemplified by the salmon

life at least one more time. Optimally supplied with oxygen through the drift, develop egg and spawn in the sheltering interstices of the river bottom. The young fish, which are described as Parrs grow up in the river for one to two years until they turn into smolts, i.e. change into a silver colour, and migrate into the sea. The salmon stays in the sea for one or several years and as a sexually mature fish migrates upstream into freshwater systems. Guided by their excellent sense of smell they return to those spawning grounds where they were born.

Other species of German tributaries of the North Sea and Baltic Sea show a comparable development cycle, like the sturgeon, allis shad (*Alosa alosa*), twaite shad, sea trout, houting (*Coregonus albula*) and smelt. According to historical indications, only the beluga, Russian sturgeon and star sturgeon, as members of the indigenous sturgeon family in the Danube river system, have formerly populated the Austrian river stretches (ZAUNER, 1997). The river lamprey and the sea lamprey, that belong to the species of Cyclostomes and in the narrower sense do not belong to the species fish, have also developed an anadromous migration behaviour. Furthermore, there are intermediate forms of anadromous and potamodromous migrations.

- Within the species *Salmo trutta*, the potamodromous brown trout and the anadromous sea trout are differentiated as eco-types. A transition form represent such specimen, which although they leave their reproduction biotopes in brooks, they do not migrate into the sea but into large rivers or still water bodies near the coast, like the Ijsselmeer (The Netherlands), where they live until they migrate upstream again into suitable spawning biotopes. Additionally, there is the lake trout as a third eco-type which lives in the large Alpine lakes and reproduces in rivers but populates still water bodies for their feeding biotope.
- Even the Atlantic salmon does not obligatorily change between freshwater and the marine habitat. A considerable portion of the juvenile masculine specimen becomes sexually mature already as a Parr, and with a body length of 15 cm takes part in the spawning activity as a so-called precocious milter with the females that have migrated upstream from the sea. These specimens also turn into smolts during the following year. Furthermore, there are freshwater salmon in North American and North European lakes which like the lake trout migrate between rivers and large lakes.
- The smelt as a so-called anadromous migration smelt populates the estuaries and lower reaches of rivers, and together with the inland smelt creates a small freshwater form, which populates for example the larger lakes of the North German lowlands. Also the three-spined stickleback produces both the anadromous and the potamodromous populations.
- The lower the salt content of the seawater, the more species change from a potamodromous to an anadromous lifestyle. Thus, there are anadromous populations of the grayling, pike, perch, ide, roach and burbot (MÜLLER, 1987a, 1987b; MÜLLER & BERG, 1982) in the catchment area of the northern part of the Baltic Sea, where the salt content varies between 0.2 % and 0.6 %.

2.1.2 Catadromous migrations

The eel is the sole indigenous specimen of the obligatory catadromous migratory fish species. It grows up in rivers, and as an adult and sexually mature fish migrates downstream into the sea to overcome several thousand kilometres until it reaches the Sargasso Sea in front of the American East Coast. There it spawns in great depth. As so-called willow-leaf-larvae drifts the eel-fry in large quantities passively with the sea currents, mainly by the Gulf Stream, into the costal regions of Europe. Here the metamorphosis takes place, and the unpigmented, only a few centimetres long glass eel migrates upstream into freshwater regions. The young eel or so-called elvers swim upstream and actively overcome large distances in streams and rivers to disseminate in inland river systems. Once the eels have grown up over 8 to 15 years, during which period they have changed colour and become the so-called yellow eel, they migrate back into the sea (figure 2.3) sexually mature and silvery coloured, as the so-called silver eel.

A typical optional catadromous migratory fish is the flounder. It is known that these species migrate up to 100 km into freshwater systems, but their preservation is not stringently dependent on this migration mode. Optional catadromous species exist even amongst invertebrates. The from China originating species

Chinese mitten crab (*Eriocheir sinensis*) for example, migrates in large numbers upstream in tributaries of the German part of the North Sea for up to 500 km, but returns to the sea for the purpose of reproduction.

2.1.3 Potamodromous migrations

Potamodromous migrations are not restricted to changes of the location within rivers or still water bodies, but migrate between rivers and still water bodies. These changes, which originally were limited to flow-through lakes and riverine meadows also appear in reservoirs and impounded rivers.

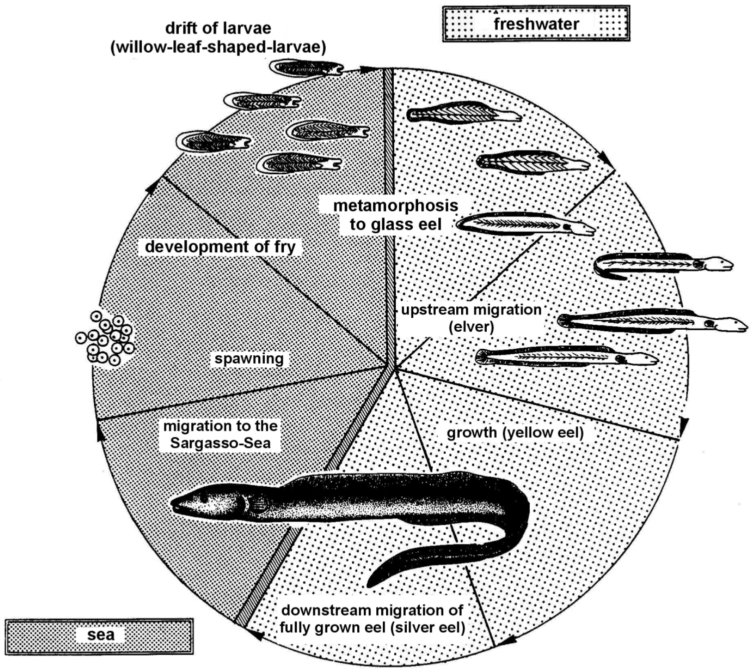


Figure 2.3: Life cycle of catadromous migratory fish exemplified by the Eel

Systematic investigations carried out by PAVLOV (1994) lead to the assumption that almost all fish species perform more or less extended migrations. The distance is dependent on the condition of the water body. The brown trout for example, migrates for only minor distances in manifold structured water bodies that offer sufficient spawning habitats. However, the more water bodies are degraded by anthropogenic activities, the less of the required habitat types are available, and can thus only be reached through expansive migrations. Although the distances overcome by potamodromous species are as a rule comparatively short, evidence could be provided that some species had covered substantial distances of several hundred km (table 2.1). Migration distances are inevitably much reduced if river continuity is restricted through impoundments.

Table 2.1:Migration distances of potamodromous species marked by fish

species	distance (km)		river	author
	upstream	downstream		
Barbel	300	300	Danube	STEINMANN et al., 1937
Nase	140	100- 446	Danube	
Chub	105	170	Danube	
Ide	105	170	Danube	
		> 150	Elb	FREDRICH et al., 1999
Asp		> 150	Elb	
Burbot		20	Elb	
	20 - 100		Elb	FREDRICH & ARZBACH, 2002
	> 200		Elb	SCHIEMENZ, 1962
Carp	several 100		Danube	SCHEURING, 1929
Vimbra abream or Zanthe	> 800		Vistula	BACKIEL, 1966
Yellow Eel	40 - 100		Elb	MANN, 1965

2.2 Relevant spectrum of species

Flowing water systems consist of a natural succession of regions, which are populated by different, yet in many cases overlapping communities of species. With respect to the re-establishment of the good ecological status according to the EU-WFD, the objective of restoration measures is to regain the type-specific inventory of species in a particular region. This requires a condition that allows free upstream and downstream movement within and between regions.

Considering the spectrum of species of the European freshwater fish fauna, it is to be stated that at present there is in many river systems no suitable habitat available for specific fish species. This too explains why 51 of the total of 70 fish species that exist in Germany are mentioned in the Red List as being extinct or endangered to varying extents (BLESS et al., 1998). By improving the water quality and endeavouring to upgrade the ecology of aquatic habitats, however, it was observed that many fish species have spread anew. For some years now there is an increased number of reappearing migratory fish reported for various river systems that were missing for decades. Next to sea trout, flounder and river lamprey which evidently steadily increase in their individual density, there are reports about sea lampreys that are spawning in the Sieg, Ahr and Murg rivers, and catches of the sturgeon in the Dutch estuary of the Rhine (VOLZ & de GROOT, 1992). These findings give reasons for hope that this positive development of stocks will continue. Therefore, the repopulation of formerly deserted river courses seems realistic even with demanding migratory fish species. Numerous repopulation projects (VDSF, 2003) support this development particularly in respect of the salmon.

It is therefore important for water management measures that next to the spectrum of species presently existing in water bodies, those species will be considered, which were originally indigenous to the specific water body and have actually found or will in the near future be provided with a suitable habitat. This entire spectrum of fish species typical for a specific water body meets the "potential natural fish fauna" (DVWK, 1996).

Since the definition of the potential natural fish fauna is a vital precondition for the correct assessment of the ecology of river systems and water body systems, and constitutes the basis for a correct dimensioning of fish protection facilities and downstream fishways, it should generally be implemented by ichthyo-specialists and ichthyo-scientists.

Following the traditional principles of ichthyo-biology the water course is divided into regions which are characterized by indicator fish species like the brown trout, grayling, barbel, bream as well as ruffe and flounder, and are populated with a typical spectrum of associated fish species. The order of these fish species is principally applicable to the ichthyocoenosis of all Central European water bodies, including those that are outside the propagation areas of the above mentioned species. Even populations of aquatic invertebrates can be similarly divided. In order to make this fact clear, ILLIES (1961) has replaced the designation of indicator fish regions by a generally applicable international nomenclature. It is hereby differentiated between brooks (rhithron) and rivers (potamon) of which each is further subdivided into three zones. For Central European rivers this kind of subdivision is synonymous with the division of rivers into indicator fish zones (table 2.2). Presently, however, it is uncertain in how far the zoning system of rivers is applicable also to lowland rivers.

Table 2.2: Biological zoning of rivers systems (according to: ILLIES, 1961)

river reach		German description	scientific description
brook	upper reaches	upper trout zone	epi-Rhithron
	middle reaches	lower trout zone	meta-Rhithron
	lower reaches	grayling zone	hypo Rhithron
river	upper reaches	barbel zone	epi-Potamon
	middle reaches	bream zone	meta-Potamon
	lower reaches	ruffe-flounder zone	hypo Potamon

HUET (1949) has proven that the formation of river zones is primarily dependent on the slope as well as in approximation to the discharge on the width of the river. The relationship between both parameters and the river zoning is presented in table 2.3.

Table 2.3: Slope classification of river zones (taken from: DVWK, 1996, according to HUET, 1949)

zone	Slope [%] for widths of rivers of				
	< 1 m	1 - 5 m	5 - 25 m	25 - 100 m	> 100 m
epi-rhithron	10.00 - 1.65	5.00 - 1.50	2.00 - 1.45		
meta-rhithron	1.65 - 1.25	1.50 - 0.75	1.45 - 0.60	1.250 - 0.450	
hypo-rhithron		0.75 - 0.30	0.60 - 0.20	0.450 - 0.125	- 0.075
epi-potamon		0.30 - 0.10	0.20 - 0.05	0.125 - 0.033	0.075 - 0.025
meta-potamon		0.10 - 0.00	0.05 - 0.00	0.033 - 0.000	0.025 - 0.000
hypo-potamon	Estuary areas influenced by the tides				

A simplified definition of the zone is possible with figure 2.4. By relating the indicator and associated fish species to the assessed zone the potential natural fish fauna can be ascertained as a first approximation on the basis of table 2.4.

However, further criteria for a comprehensive and exact determination of the relevant spectrum of species are to be considered as well.

Biogeography: The fish communities of German river systems differ to some extent greatly. All anadromous species are missing in the Danube river, while some potamodromous species like the huchen are exclusively indigenous to the Danube system.

Topography: Special topographic conditions are to some extent reflected by fish communities. No indicator fish species can be defined in rivers which flow through lakes or take their origin from lakes. Instead, micro biocoenosises occur which are characterized in still water areas by fish species of stagnant waters and in the area of lake outlets increasingly by riverine species.

Historical sources: Indicators of the potential natural fish fauna are usually obtained from historical sources (SIEBOLD, 1863; WITTMACK, 1876; BORNE, 1882, and others) or from analyses of historical catch reports, like for example the reconstruction of the former distribution area of the sturgeon in the Rhine river system by KINZELBACH (1987) or by KLAUSEWITZ (1975), who investi-gated the historical fish fauna of the Main river on the basis of old fish collections.

There is an increase in the distribution of fish species to be noticed in German rivers that were originally not typical for a specific water body, and is caused through stocking measures of the fishing industry, distribution through artificial canals and other anthropogenic impacts. This for example refers to the rising presence of species indigenous to the Danube river like zander and Danube bream in the Rhine river system, but also to the high population density of the eel in the Danube system. Furthermore, there are species that were originally not indigenous to Central Europe and now display a distinct distribution tendency like the stone moroko (*Pseudorasbora parva*) grey knight goby and sun-perch. This enlarged spectrum of species cannot be desirable under ecological aspects, and contradicts the objective of the EU-WFD to re-establish type-specific communities of species. Even though the protection of these species that are foreign to the fauna is to be aimed at for animal protection and fishery ecological reasons, they are not priority classed target species for fish protection and downstream migration (chapter 5.1.2).

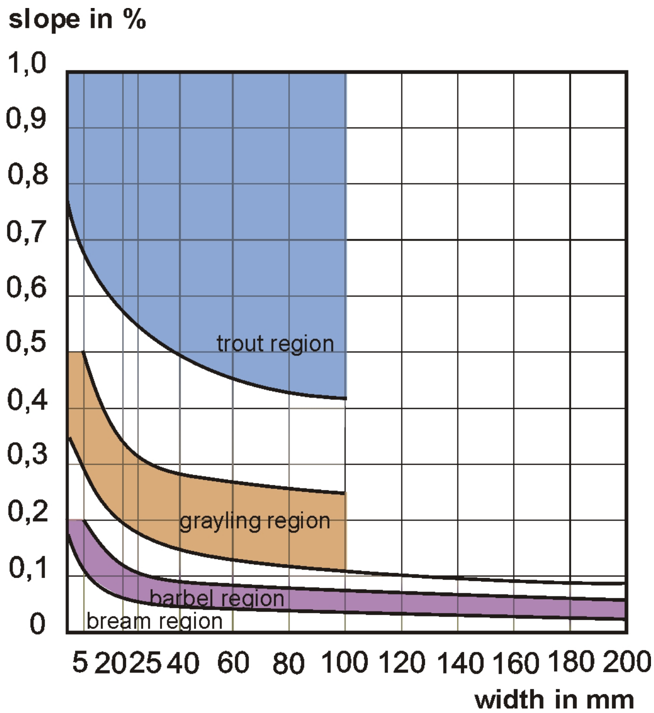


Figure 2.4: Graphical representation of the relation between slope, river width and river zoning for the determination of indicator fish zones (modified accor-ding to DVWK, 1996).

Table 2.4: Main distribution areas of selected fish species in indicator fish zones of Central European river systems (modified according to DVWK, 1996)

	epi-rhithron	meta-rhithron	hypo-rhithron	epi-potamon	meta-potamon	hypo-potamon
anadromous species						
sea trout			■	■	■	■
salmon			■	■	■	■
river lamprey			■	■	■	■
sea lamprey				■	■	■
allis shad				■	■	■
houting				■	■	■
twaite shad					■	■
sturgeon					■	■
smelt					■	■
catadromous species						
eel				■	■	■
flounder					■	■
potamodromous species						
brown trout	■	■	■			
bullhead	■	■	■			
brook lamprey	■	■	■			
loach		■	■	■		
minnow		■	■			
three-spined stickleback		■	■	■	■	■
grayling		■	■			
schneider		■	■			
dace		■	■			
chub		■	■			
gudgeon		■	■	■	■	■
roach		■	■	■	■	■
burbot		■	■	■	■	■
barbel				■		
nase				■		
vimba bream				■		
ide				■	■	■
bleak				■	■	■
bream				■	■	■
white bream				■	■	■
asp				■	■	■
perch				■	■	■
ruffe				■	■	■
pike				■	■	■
zander				■	■	■
catfish				■	■	■
rud					■	■
carp					■	■
tench					■	■

2.3 Migrating development stages

A migration or downstream directed propagation can be observed for all development stages of fish. Especially the drift of fish spawn, larvae and young fish is a wide spread and quantitatively significant strategy of the downstream directed propagation of potamodromous species (PAVLOV et al.; 2002). However, also juveniles of anadromous species clearly indicate a migratory tendency, as for example the larvae and precocious Parrs of salmon (BEALL & MARTY; 1983, SCHNEIDER; 1998). The portion of migratory stages usually declines with progressing age. The drift of eggs prevails for fish species that spawn at random in the lower river reaches. Hence, for example, the eggs of the allis shad, twaite shad and smelt sink down to the bottom and develop while drifting downstream over the bottom in direction of the estuary, where the conditions to mature are more favourable for these species. In some cases, however, it is assumed that lack of food or contaminated water may be the reason why larvae drift away, as only a drift into regions with richer nutrition sources and cleaner water offer survival chances.

The juvenile migrating stages of anadromous species present the majority of the migratory potential. The stage of turning into smolts that precedes the migration of salmon and sea trout is primarily induced by the body length of the fish and is influenced by the individual development conditions. Whilst up to 7 year old smolts migrate from the cold north European salmon rivers, the salmon from the Rhine system migrated downstream when they were 1 or 2 years old. Various details on the body length of juvenile migratory stages of anadromous species are compiled in table 2.5.

Table 2.5:Total length of juvenile migrating stages of anadromous species

species	age (year)	total length (cm)	author
salmon	1 2	11.0 - 17.4 20.0 - 23.5	SCHEURING, 1929
	1	12.0 - 15.0	LEONARDT, 1929
	1 2	11.0 - 15.8 12.7 - 18.2	SCHNEIDER, 1998
	1 2	12.0 - 14.5 14.0 - 17.0	SCHWEVERS, 1999b
sea trout	1	13.0 - 18.5	SCHWEVERS, 1998
houting	1	up to 17.0	BAUCH, 1953
river lamprey	4 - 6	12.0 - 15.0	HOLCIK, 1986
		12.0 - 18.0	WEIBEL et al., 1999
sea lamprey	4 - 6	12.0 - 15.0	HOLCIK, 1986
		12.0 - 18.0	WEIBEL et al., 1999
sturgeon	2	up to 60.0	MOHR, 1952
allis shad / twaite shad	1	8.0 - 11.0	EHRENBAUM, 1894

Whereas adult migratory stages of fish like the sea lamprey and river lamprey die after the spawning act, the spawn specimen of most anadromous species can return to the sea after reproduction, in order to spawn a second or several more times. The survival rate of these Kelts of salmon is to a great extent dependent on the period spent in freshwater and the distance and difficulties overcome during migration: Whilst a survival rate of up to 90 % is in some cases indicated for short Scandinavian and British coastal rivers, only a minor portion of salmon spawn has survived in large German river systems during migrations involving more than 100 km.

Also juveniles of catadromous species, especially the yellow eel, undertake expansive upstream or downstream migrations in dependence on season, discharge etc. The adult specimen (figure 2.5) forms the main group of downstream migrating eel that have spent 8 to 15 years in freshwater. The metamorphosis into the downstream migrating silver eel is connected with profound morphological and physiological changes (SCHEURING; 1930): *"The fish indicates that it is ready to migrate by a change of its colour. The commonly yellow or green eel turns into a silver eel, which means that the blunt colours of olive* *to green tones become darker, black-brown to a glossy black, and the bronze coloured, yellowish flanks and belly turn white to silvery and always show a metallic gloss. Next to the change of colour of the skin there are further morphological alterations: the skin turns firmer and thicker, the side line becomes more protruding and branched, the olfactory organ swells and especially the head becomes remarkably transformed. As the fleshy upper lips shrink, this makes the shape of the head of the eel which is a tipped-type even slimmer. Particularly noticeable are the enlarged eyes, which expand by 1.2 mm. The eel needs ¾ to 1 year to convert into its migration apparel."* First alterations take place in early spring, long before colour changes become visible, which mostly happen in August or September. As only a varying portion of the total of silver eels will actually migrate between August and December, the change of colour must not necessarily be an indicator for a migration to take place in the same year (JENS, 1953; FONTAINE, 1994). The migration of eels may also be interrupted by too low autumnal water temperatures of below 5 °C, and thus delay migration until autumn of the following year (VOLLESTAD et al., 1986).

The mean size of a migrating silver eel is approx. 65 cm according to investigations carried out at the Maas river (The Netherlands), whereby some masculine specimen obtain the silver eel stage already when they are 30 cm long, whilst feminine fish can obtain a maximum length of more than 90 cm (BRUIJS et al., 2003, figure 2.5).

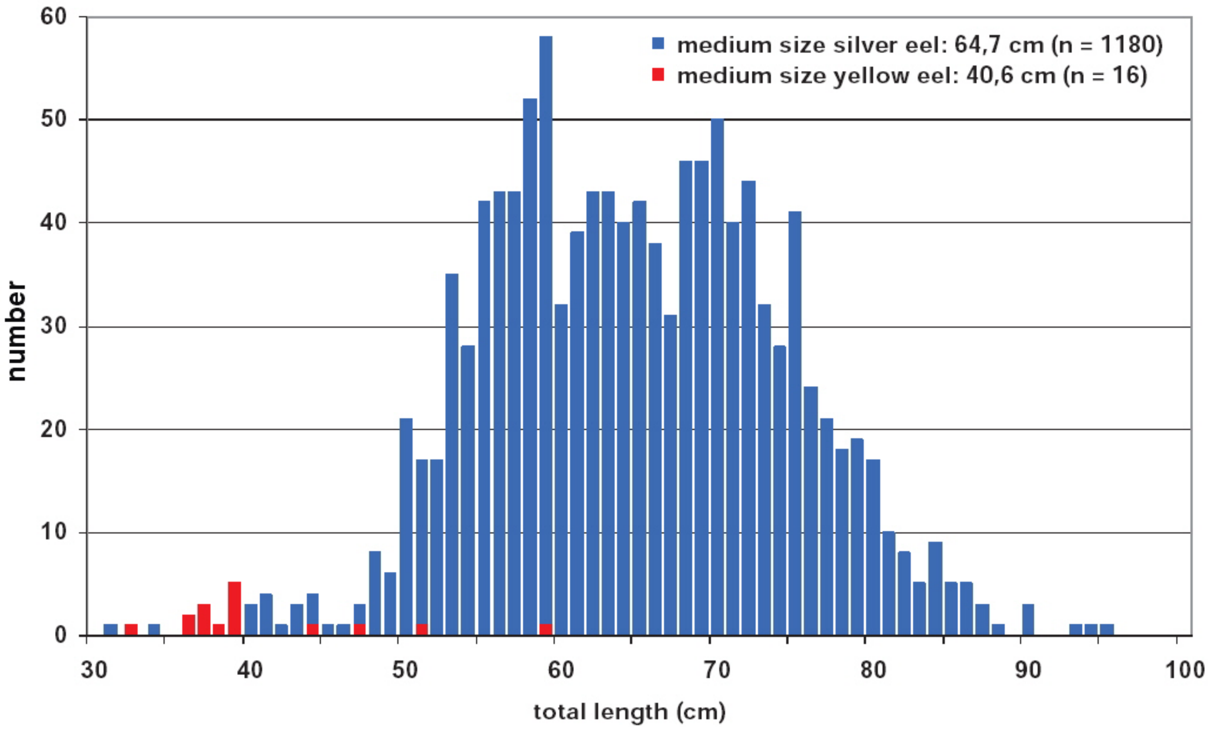


Figure 2.5: Stage and frequency of lengths of eels caught with fyke nets (according to data from BRUIJS et al., 2003) and registered during the period 2 September to 22 October, 2002, after turbine passage of the power plant Linne on the Maas river (The Netherlands)

Systematic examinations of marked Cyprinids in the Danube, Rhine, Main, Neckar rivers etc. prove that the voluminous upstream directed migrations of potamodromous species are confronted with a comparable quantity of return migrations. Nevertheless, the migration is only little synchronized in time, thus does not take place intermittently or in shoals (STEINMANN, 1937). KOCH (1932) could provide evidence that apart from upstream directed spawning migrations of Cyprinids in spring time, there is a general tendency to migrate during winter months. Overall, however, the migration of potamodromous species is clearly dominated by fry and young fish, as PAVLOV et al. (2002) have proven with the example of the Russian Ivan'kovskoe-reservoir (figure 2.6). The portion of migrating adult fish in impounded rivers is usually higher, but is also dominated by young fish of < 10 cm total length (HOLZNER, 2000; SCHMALZ, 2002a; figure 2.7).

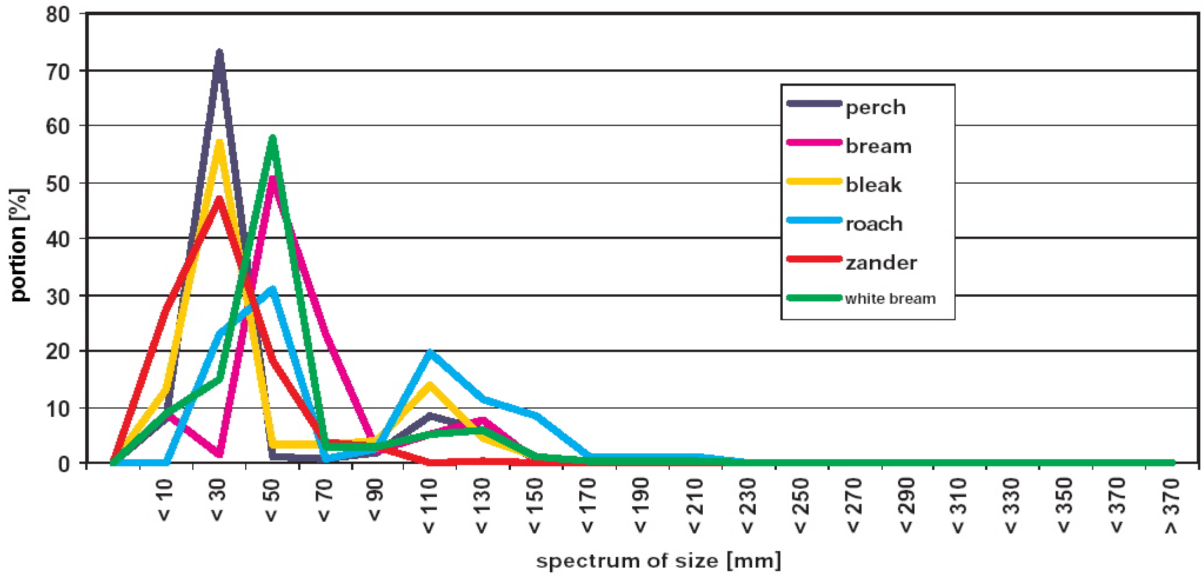


Figure 2.6: Spectrum of sizes of potamodromous fish species (according to details from PAVLOV et al., 2002) migrating from the Ivan'kovskoe-reservoir (Russia)

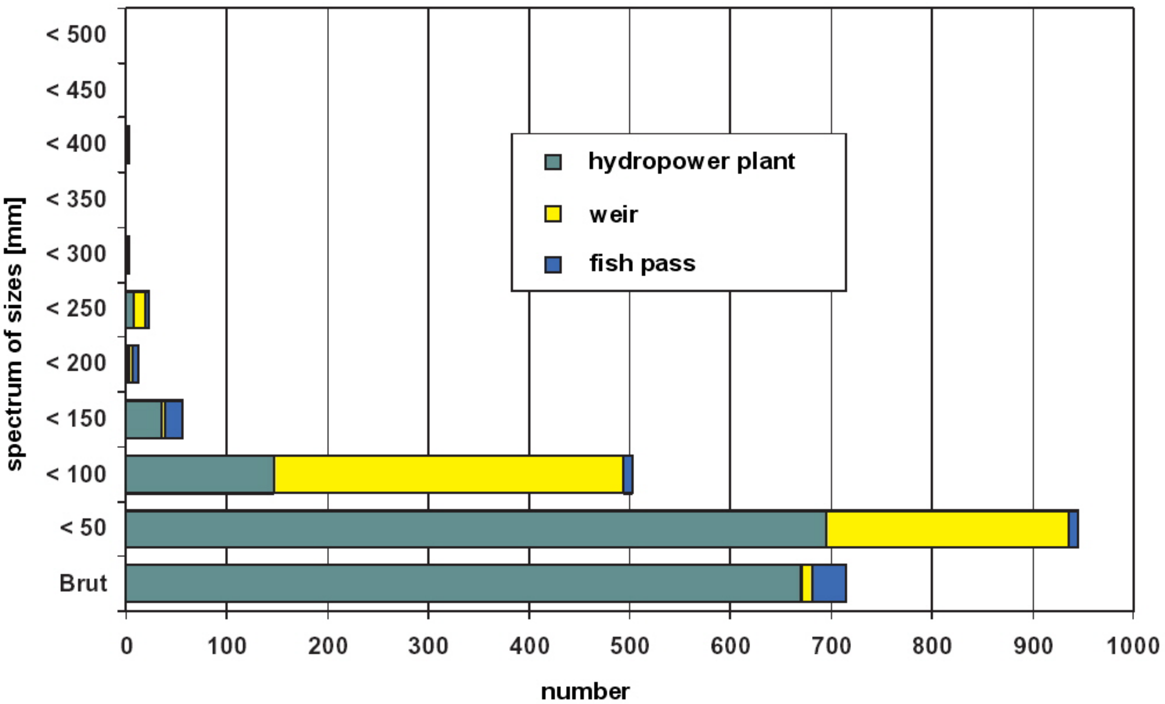


Figure 2.7: Spectrum of sizes of fish registered in the Saale river at the weir Jaegersdorf (Thuringia) whilst migrating through hydropower plant, weir and upstream fish passes over the period 26 June to 20 September, 2001 (according to details from SCHMALZ, 2002 a)

2.4 Timing and cause for migration

The moment that causes migration normally refers to environmental parameters which during the course of the year are subjected to long-term, natural variations. They influence the hormonal balance of the fish and so induce the willingness to migrate in a specific season. The length of the day, for example, is the most important factor for the Atlantic salmon to begin its metamorphosis from Parr to smolt (JONSSON & RUUDHANSEN, 1985).

Only when the willingness to migrate is established through the physiological reaction on the specific timer, can certain environmental parameters become the cause that determines the precise moment of migration. It is therefore also possible that migration starts only several months after metamorphosis. This specifically for many diadromous species effects the synchronization of all migration stages of one species in the water body. In dependence on the environmental parameters that act as a trigger, will fish of the same species not only migrate at different times in different water bodies, but the moment of migration can significantly be delayed in the same water body. The analysis of such correlations becomes very difficult (JONSSON, 1991) since migration is caused by many individual and interacting factors.

- The stimuli of the environment that effects migration can differ between various species. Even amongst one kind of fish that has adjusted to the specific environment conditions of a water body can the moment differ when migration is induced.
- The migration of different age groups or development stages from the same water body can be timed differently and induced for various reasons. This may for example apply to yellow eels and silver eels or salmon fry, respectively smolts.
- Migration is often not only controlled by one sole but a combination of several interacting triggers. Thus, the lunar migration rhythm of the silver eel can be entirely governed by the stronger impact of the discharge (JENS, 1953).
- There obviously is a hierarchy of triggers. If for example the spring flood as primary trigger is missing and migration becomes further delayed, other environmental factors may induce migration, which normally do not function as a trigger, like for example rising water temperatures.

The mechanisms which cause fish migration are long since discussed because of these complicated correlations. GERHARDT (1893) assumed that the start of migration of silver eels is dependent on the moon phases, the water temperature, the distance to the sea and *"the degree of putrefaction of the vegetation that exists in the river"*. In the course of the last decades the meaning of the different timing and cause of fish migration could be specified to a significant extent, but the causes and effects as well as the combination of the different factors that determine the moment of migration are still not clarified. Independent of the fish species observed, there are two factors which play a prominent role as a trigger: discharge and temperature, and obviously also the moon phase has a certain impact.

Table 2.6: Discharge changes as cause for fish migrations

species / development stage		discharge changes		author
		rising	falling	
Eel	yellow eel and early silver eel stages	upstream migration	downstream migration	SCHIEMENZ, 1960 KOOPS, 1962 MANN, 1965
	silver eel	downstream migration	-	LOWE, 1952 JENS, 1953 TESCH, 1983
Salmon	fry	-	downstream migration	BEALL & MARTY, 1983
	smolt	downstream migration	-	JONSSON, 1991 SCHWEVERS, 1998, 1999b

Discharge: Previous findings have shown that the discharge is a primary cause for the migration of diadromous species (table 2.6). Increased discharges offer the advantage to fish to be transported downstream effortless, and at the same time being better protected against predators in the larger and often turbid rivers. The rising discharge synchronizes the migration happening, determines the migration speed and direction. However, not the absolute discharge, but its rise is of obvious relevance. In the year 1996, salmon smolts migrated in the Lahn river system between April and end of May on days with an increasing discharge, although the river had not reached its average discharge (SCHWEVERS, 1998; figure 2.8). Also the migration of the silver eel indicates a distinct correlation with the discharge, whereby here as well it is not the absolute height, but the rise of the discharge which causes migration (figure 2.9).

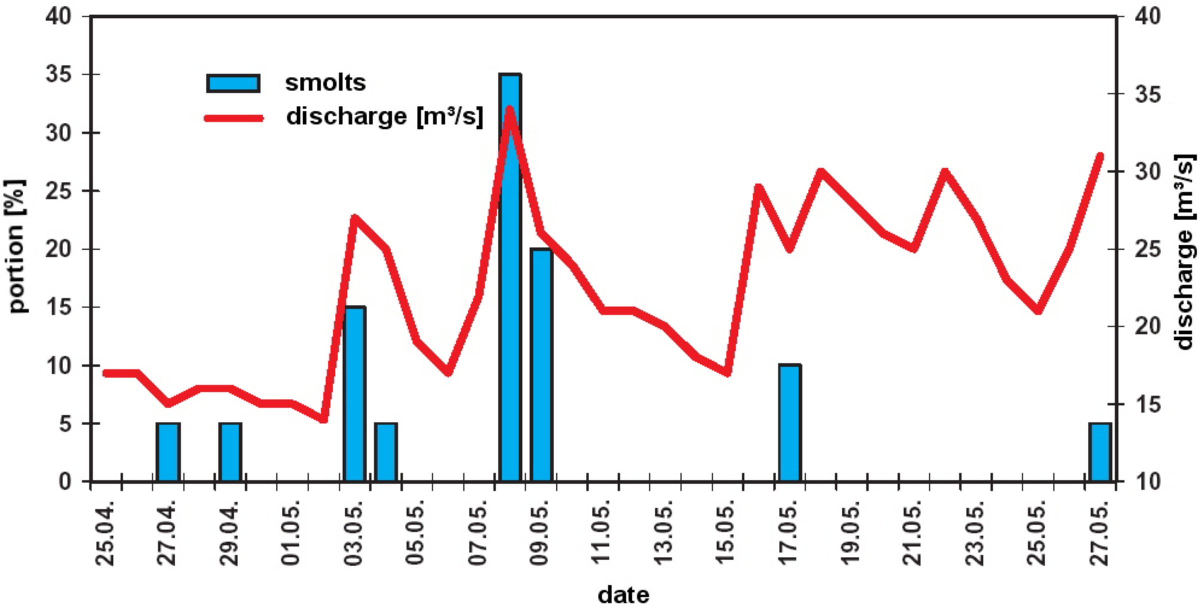


Figure 2.8: Correlation between the moment of migration of salmot smolts and the discharge of the Lahn river (Rhineland Palatina, Germany) during the period 25 April to 27 May, 1996 (changed according to SCHWEVERS, 1998)

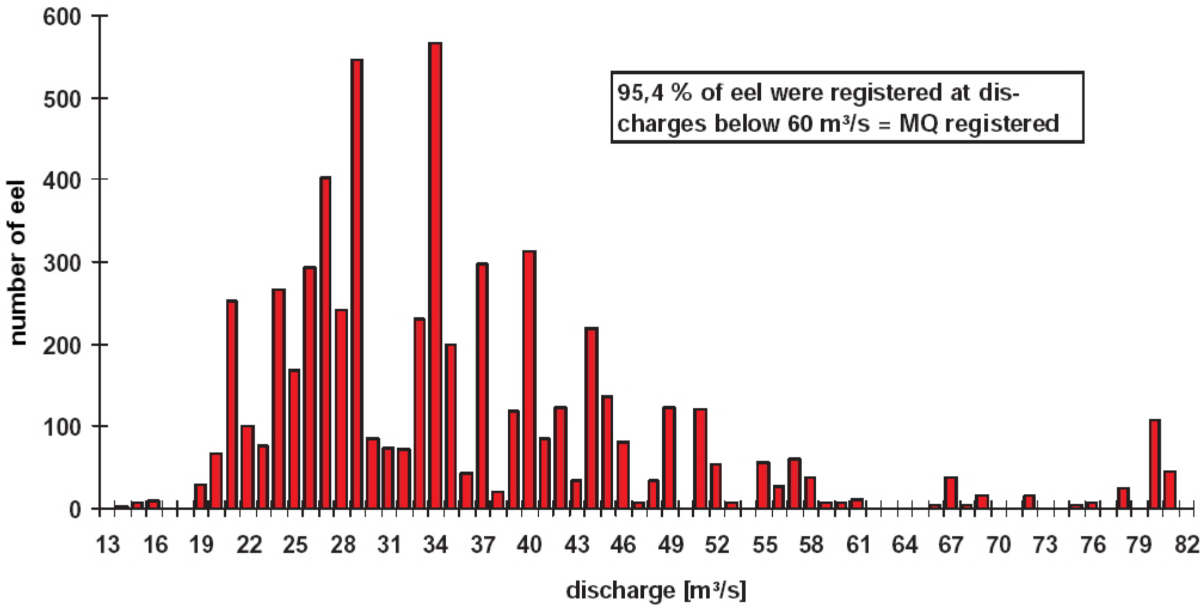


Figure 2.9: Total number of eels registered during eel fishing in the Fulda river (Lower Saxony, Germany) at Hannoversch Muenden during the period 1975 to 1991 in dependence on the discharge (changed by: ARBEITSGEMEINSCHAFT GEWAESSERSANIERUNG, 1998)

Discharge changes can have a contrary effect on potamodromous and diadromous species outside the migration phase of the true migration stages: Rising discharges do not cause yellow eels and silver eels of early stages to move downstream, but to migrate upstream. The time trigger for a drift of salmon larvae is not a rising but falling discharge (table 2.6).

Water temperature: The water temperature is very often the primary trigger for fish migration. In rivers where its flooding does not coincide with the migration of fish, the water temperature is the decisive time factor for migration. This for example applies to the migration of salmon smolts from north Scandinavian water bodies, where snow begins to melt only during the course of the summer (JONSSON, 1991).

Nevertheless, the water temperature is often not the direct cause for downstream migrations, but the discharge as most important timing factor can only become effective if specific temperature conditions prevail. Figure 2.10 demonstrates that according to tendency, the migration of silver eels in the Fulda river takes place at low temperatures, but is quickly brought to a standstill if below 6 °C. In such a case, therefore, low temperatures have the effect of a negative time trigger.

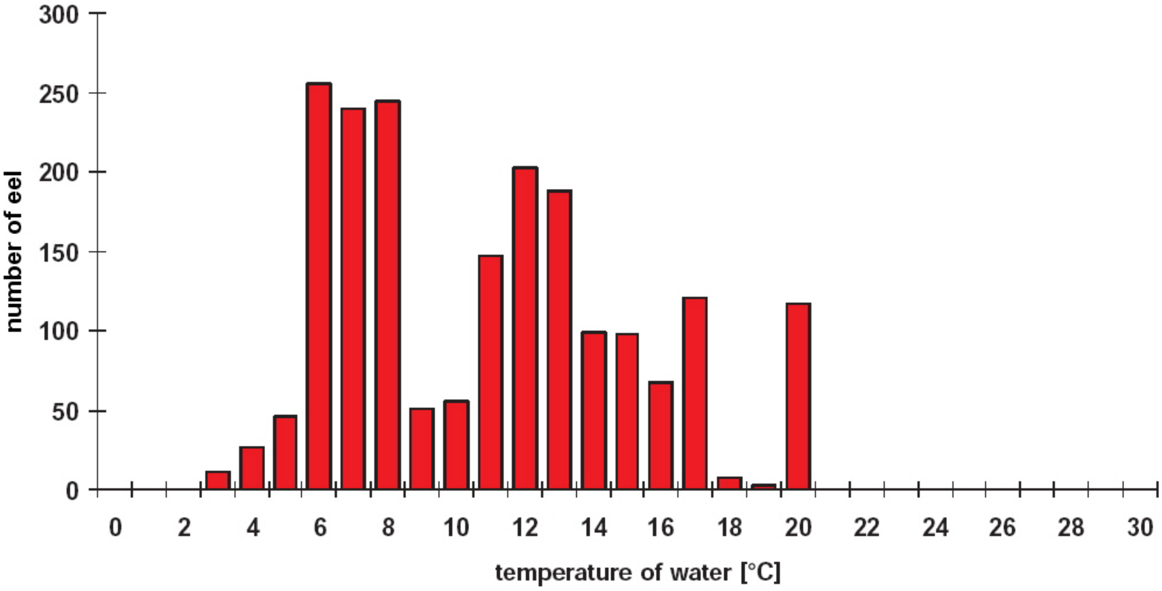


Figure 2.10: Total number of eels registered during eel fishing in the Fulda river (Lower Saxony, Germany) at Hannoversch Muenden during the period 1975 to 1991 in dependence on the water temperature (changed by: ARBEITSGEMEINSCHAFT GEWASSER-SANIERUNG, 1998)

Moon phase: For decades trials have repeatedly been undertaken in order to correlate the migrations of silver eels with the moon phase. For example, JENS (1953) has assessed that a regular rise of the catch was noticed at the time of the waning half moon, i.e. on the 22nd day of the moon period, and a minimum at the time of the waxing half moon on the 7th and 8th day of the moon period. A similar cycle for the migration of for example the silver eel in the Fulda river (figure 2.11) could also be discovered. Latest investigations on the Maas river (The Netherlands), however, could not disclose any correlations between the migration happening and the moon phase (BRUIJS et al., 2003). Therefore, the moon phase can by no means be classed as the primary cause, as it is to a great extent governed by other factors.

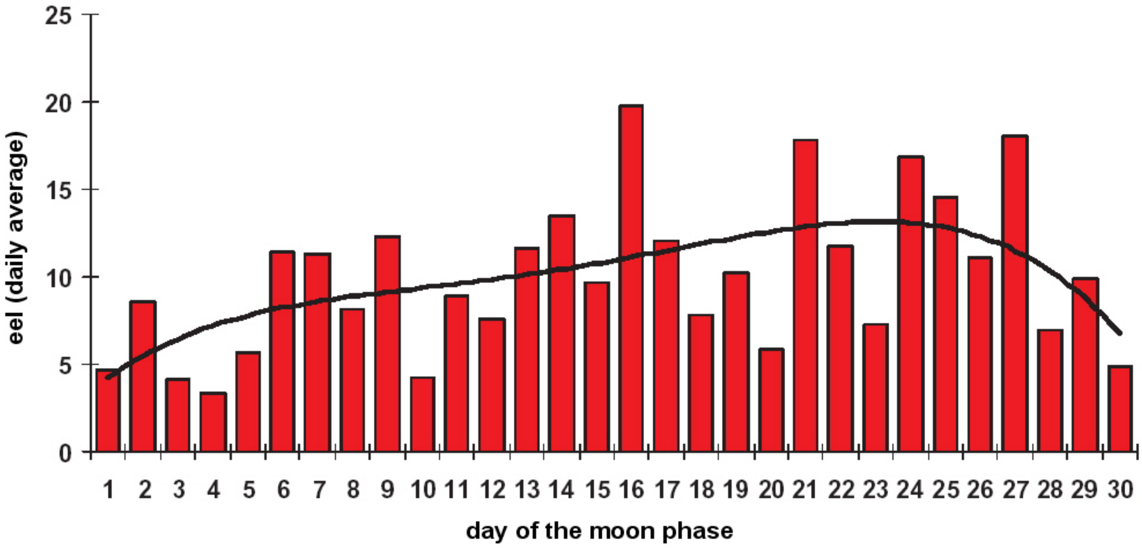


Figure 2.11: Daily average of eels registered during eel fishing in the Fulda river (Lower Saxony, Germany) at Hannoversch Muenden during the period 1975 to 1991 in dependence on the moon phase (new moon: 1st and 30th day, full moon: 15th day) (ARBEITSGEMEINSCHAFT GEWAESSERSANIERUNG, 1998)

2.5 Rhythm of migration

Biological rhythms which are correlated with significant environmental events play an important role in nature. They basically consist of two different components:

- The “inner clock” of an organism determines the approximate duration of the rhythm.
- External time triggers synchronize rhythm and its environment.

The most important biological rhythms are the 24 hours comprising circadian rhythm and the circaannual (= diurnal) rhythm, covering approximately one calendar year.

2.5.1 Annual rhythm

The migration of smolts of the migratory salmonide fish is usually precisely scheduled and synchronized, so that the majority of the individuals migrates within a short time window, and distinct migration peaks are ascertainable (table 2.7, figure 2.8).

The migration of the salmonide fish smolts generally falls into spring independent of the water body, whereby the peak of the migration is usually reached in April and ends early to mid May. According to HOEK (1901), the estuaries of German salmon rivers were reached by downstream migrating smolts around the second week of May. This indication was specified for the Rhine river by SCHEURING (1929): *“The first migrating fish are detected in the estuary of the Rhine with the draining spring flood wave in early May, and the major shoal normally appears between 4th and 18th May. It consists of the group of the one-summer salmons. The last latecomers, fish of the age group 2+ will still arrive by end July and the beginning of August”*.

The time of migration of Kelt spawns varies to a great extent. The weather plays a decisive role for the Rhine salmon (LEONHARDT, 1905): In mild winters migrated Kelts immediately after spawning, whilst the fish hibernated in deep river reaches in times of strong frosts and did not return to the sea before spring time.

The staging of migration of other anadromous species, however, is as such not precisely synchronized. Information on the appearance of distinct migration peaks do not exist. Also the time frame of the migration can only vaguely be defined on the basis of available literature (table 2.7). WEIBEL et al. (1999) registered downstream migrating river lampreys and sea lampreys in the cooling water intakes of thermal and nuclear power plants on the river Rhine over the entire winter half year between October and March. The main migration period fell into the months December to February.

Silver eels migrate from August to December, although the main migration periods cannot be defined. However, the synchronization via time triggers is so precise that each migration peak takes place during the night hours of a few days only. Nevertheless, silver eels are positively able to stay in freshwater for a longer period, so that the migration quantity will be strongly reduced if not completely missed out in years with no favourable timing constellation. Through comparison of the catch of eel in Lake Constance and Middle Rhine as well as in the middle and lower reaches of the Oder river, TESCH (1983) was able to testify that the migration of the silver eel starts earlier in the upper river reaches than in those stretches closer to the sea. Also gender-specific differences seem to exist. So dominate in coastal areas the smaller masculine eels at the beginning of the migration period, whilst up to 90 % of the silver eels are feminine fish towards the end of the migration period (DEELDER, 1984; TESCH, 1983). This could be related to the fact that the feminine fish that migrates much further upstream into the inland rivers than the masculine members of the same species, must overcome greater distances in downstream migration. Finally, the depth of the water body also plays an influential role on the moment migration starts: In shallow waters downstream migration takes place at the beginning of the migration season, but will be delayed by one to two months if the eels reach deeper water stretches (TESCH, 1983).

The downstream directed migration of potamodromous species can hardly be contained in time and differ species-specific to a great extent. The migration of juvenile bullheads for example is restricted to a very tight time corridor between the end of May and the beginning of June (BLESS, 1990). Adult cyprinids on the other hand show a general migration tendency during the last quarter of a year (STEINMANN et al., 1937).

Table 2.7: Annual rhythm of juvenile migratory stages of anadromous species

species	river	migration period	author
salmon	Imsa (Norway)	> 90 % in May	JONSSON & RUUDHANSEN, 1985
	Gave d'Aspe (France)	April: 77 % in 14 days > 50 % in 7 days	INGENDAHL, 1993
	Lahn (Rhineland Palatina, Germany)	end of April to end of May: 100 % in 32 days 60 % in 7 days	SCHWEVERS, 1999
	Sieg (North Rhine Westphalia, Germany)	mid March to end of May 100 % in 75 days 60 % in 14 days	STAAS & STEINMANN, 2002
sea trout	Lahn (Rhineland Palatina, Germany)	end of April to end of May 100 % in 28 days	SCHWEVERS, 1998
allis shad	Seine (France)	September to October	SCHEURING, 1929
	Rhine and Elb (Germany)	summer	
houting	Ob, Irtisch (Siberia)	spring and summer	SCHEURING, 1929
	Weser and Elb (Germany)	March to July	SCHEFFEL et al., 1995
river lamprey and sea lamprey	Rhine (Germany)	October to March with a main migration period between December and February	WEIBEL et al., 1999

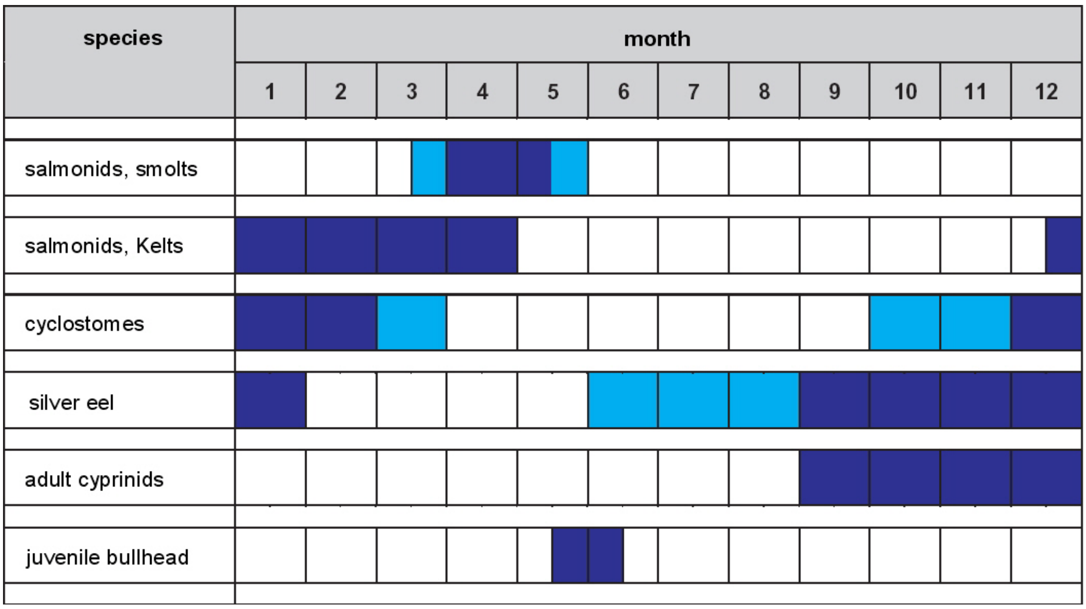


Figure 2.12: Downstream migration periods of selected fish species respectively groups of species according to bibliographic references in chapter 2.5.1 and table 2.7 (dark marking: main downstream migration)

2.5.2 Diurnal rhythm

Fish migrate mainly at night, but in very turbid water this can also happen during day time. Salmon smolts in the river Sieg, for example, start their migration shortly before sunset with its peak after midnight (MUNLY, 2001). Towards the end of the migration period, salmon smolts extend their activity stage increasingly also into the day time (FÄNGSTAM, 1993). River lampreys migrate mainly at night with an activity maximum at dusk and another weaker activity maximum at dawn. During day time, the migrating river lampreys dig themselves into the sediment and rest on the gravel banks (JONSSON, 1991). Also the migration activity of silver eels is strictly limited to darkness, and thus bound to night hours. The activity of fish is dependent on the intensity of light. This is why artificial light and the moon have an influence on the migration of eel. However, the dependence on the light intensity becomes only fully distinct if other overriding time triggers are not available.

2.6 Behaviour during migration

2.6.1 Migration corridors

Migrating fish drift with the main flow. The preferred migration corridor is therefore to be looked for where the flow velocity is the highest, which TESCH (1994) for example could confirm for silver eels through telemetric examinations in the rivers Weser and Elb. According to this behaviour, migrating fish gather at barrage power stations especially in the intake area of the power plant, if the total discharge is utilized and the weir not overflowed.

The depth at which fish migrate is obviously species-specific, but is furthermore also influenced by environmental parameters. Salmon prefer to migrate near the surface. Bypasses at hydropower plants which offer migration possibilities at the water surface have thus proven suitable specifically for salmon smolts. Fish larvae drift as rule also near the surface. Telemetric examinations in the rivers Weser and Elb have shown that silver eels migrate mainly in deep water at a maximum of 1.0 m above bottom (TESCH, 1994). According to latest findings, however, migrating fish can be expected in almost any water depth (HARO 2000).

2.6.2 Swimming behaviour

Fish generally orientate themselves by the current in running water and swim against it. This behaviour is called rheo-reaction, and any behaviour of fish in the current can be derived from this principle. The rheo-reaction is dependent on that the fish perceives the current, orientates itself in it and reacts with swimming movements, so that it would not be drifted away (PAVLOV, 1989). The perception of the current is primarily based on visual and tactile stimuli: In the free water body, the fish for example uses the structures of the embankment to orientate itself and to adjust its swimming speed to the current. If the visual perception of the environment remains constant, the swimming speed of the fish against the current (relative speed to the water, V_{rel}) is equivalent to the flow velocity (in the water body (V_A). Bottom-oriented species keep direct contact to the bottom of the water body. They are thus able to orientate themselves in the current also because of their tactile sense. In irregular currents and in current gradients which appear in running water bodies, fish use for their orientation also their sense of current located in their sideline-organ as well as their stato-acoustic organ. However, the orientation mechanisms by means of tactile and current stimuli develop only during the juvenile stage, so that the visual orientation prevails for fry and young fish. The consequence is that young fish under approximately 3 cm body length are incapable of orientating themselves at a low light intensity and will therefore drift with the current. This explains next to the low swimming capacity why the migration happening at night is dominated by fish fry and young fish (chapter 2.3).

The absolute speed of the fish ($\vec{V}_{abovebottom}$) results from the addition of the vectors flow velocity of the water body and swimming speed (relative speed) of the fish:

$$\vec{V}_{abovebottom} = \vec{V}_{rel} + \vec{V}_A$$

whereby V_A is always a downstream, and V_{rel} usually an upstream migration. Three cases may hereby occur:

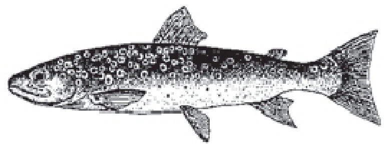
$\vec{V}_{abovebottom}$ against flow direction:upstream migration

$\vec{V}_{abovebottom}$ = 0:keeping the position

$\vec{V}_{abovebottom}$ in flow direction:downstream migration

Active and passive components can be defined for the downstream migration of fish, whereby the passive component refers to the utilization of the current (V_A) as a transporting force. PAVLOV (1994) principally differentiates between three different mechanisms, which cause a downstream directed movement:

Active components: The fish must decide to give up its normal mechanisms against the current directed, positive rheotactical orientation and resign itself to the current. FÄNGSTAM (1993) has provided proof with laboratory experiments that salmon smolts at times swim downstream actively, whereby their body axis is aligned head-at front in downstream direction. The absolute downstream directed speed is thus higher than the flow velocity.



$\vec{V}_A$	←
$\vec{V}_{rel}$	←
$\vec{V}_{abovebottom}$	←

active downstream migration

$$\left|\vec{V}_{abovebottom}\right| = \left|\vec{V}_{rel} + \vec{V}_A\right| > \left|\vec{V}_A\right|$$

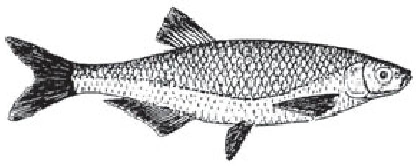
$\vec{V}_{rel}$ and $\vec{V}_A$ are synchronous

A similar active downstream migration behaviour of eels could be established during behavioural observations in a hydraulic model channel at a flow velocity of below 0.5 m/s (ADAM & SCHWEVERS, 1997a, 1999; ADAM et al., 1999, figure 2.13). Proof of such a migration mechanism in the open field was supplied by TESCH (1994) through telemetric examinations. In impoundments of the Weser river was the downstream migration speed of silver eels much higher than the flow velocity of the river.

Active-passive components: In the case of this mechanism, the downstream directed migration is composed of active and passive elements. Such behaviour was described for juvenile sea trout by SCHEURING (1929): The fish orientate themselves positive rheotactical with their head against the current, but the swim speed is lower than the flow velocity:

$$\left|\vec{V}_{rel}\right| < \left|\vec{V}_A\right|$$

This results in an entire downstream directed movement at a speed however that is lower than the flow velocity of the water body:



$\vec{V}_A$	←
$\vec{V}_{rel}$	→
$\vec{V}_{abovebottom}$	←

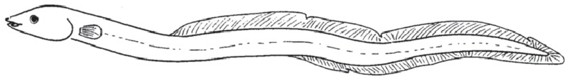
active/passive downstream migration

$$\left|\vec{V}_{abovebottom}\right| = \left|\vec{V}_A + \vec{V}_{rel}\right| < \left|\vec{V}_A\right|$$

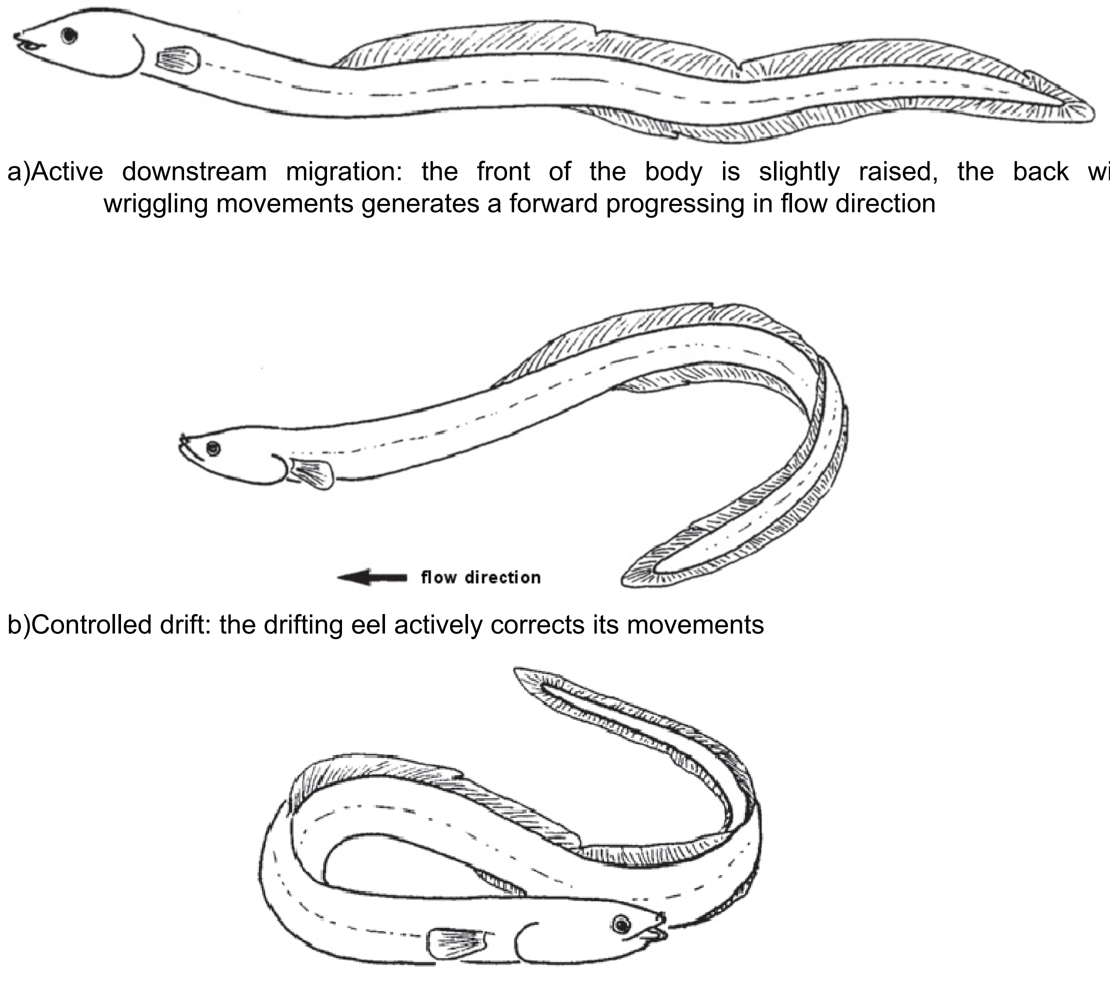
$\vec{V}_{rel}$ and $\vec{V}_A$ are asynchronous

In reaches of the Weser river, TESCH (1994) has contrary to impoundments observed that silver eels moved downstream slower than the flow velocity, which can only be explained with a combination of passive and active behavioural components. A “controlled drift” of silver eels was described under laboratory conditions, where the eels controlled their body length, swimming height and speed, and the drift speed of the fish was only insignificantly lower than the flow velocity (ADAM et al., 1999).

Passive components: A pure passive behaviour during downstream migrations is rare or interrupted by passive/active or active phases. JENS (1992) describes a “wintery eel activity” for example for silver eels at a water temperature below 6 °C, at which the eels drift passively with the current near the bottom: $V_{rel} = 0$. The absolute speed above bottom is equal to the flow velocity.

		**passive downstream migration** $\left|\vec{V}_{abovebottom}\right| = \left|\vec{V}_A + \vec{V}_{rel}\right| = \left|\vec{V}_A\right|$
$\vec{V}_A$	←	
$\vec{V}_{rel}$	0	
$\vec{V}_{abovebottom}$	←	

Such behaviour could also be observed on eels in laboratory experiments (ADAM & SCHWEVERS, 1997a; ADAM et al., 1999; figure 2.13).



a)Active downstream migration: the front of the body is slightly raised, the back with wriggling movements generates a forward progressing in flow direction

b)Controlled drift: the drifting eel actively corrects its movements

c)Drift: caught laterally by the current, the eel drifts in flow direction

Figure 2.13:Different migration forms of the eel (ADAM et al., 1999)

The migration of fish is not a uniform movement at a constant speed and uniform behaviour. Shoals of salmon smolts, for example, move downstream in batches according to ALLEN (1944). Laboratory examinations also have shown that phases of active downstream movements alternate with phases, during which the fish drift passively or rest in calm areas.

Salmon smolts migrate in shoals, that means in associations, where the individuals, although they do not know each other personally, nevertheless influence each other. Migration starts in upper reaches, and the smolts successively join their downstream passing fellow species. Salmon which separate from their shoal will later join other downstream migrating shoals (FÄNGSTAM et al., 1993).

2.6.3 Swimming speed

Fish have two different types of muscular systems which cannot only easily be differentiated by their colour, but also because of a different physiology and function (BONE & MARSHALL, 1985).

- The **red musculature** serves the non-tiring continuous swimming. It consists of a thin surface layer, which covers the white main part of the musculature. The physiological function of the red musculature is aerobic following the principle of glycolysis or fat-splitting (lipolytic), which allows optimal energy utilization. It is well supplied with blood in order to make the required oxygen available. This becomes distinct through its red colouring. The portion of the mitochondrions that support the energy metabolism amounts to 50 % of the cell mass, so that sufficient energy can be made available permanently.
- The **white musculature** forms the largest part of the body of a fish. Its function is anaerobic following the principle of fermentation of lactic acid. It is hence less well supplied with blood and has almost no mitochondrions. The volume portion of the muscel fibres therefore is almost 100 %, and allows a maximum performance. Nevertheless, the white musculature fatigues quickly and requires long regeneration periods until it regains its best performance capability.

The performance capability of fish differs species-specific, and is mainly dependent on the size of the fish. A common procedure in biology is to indicate the swimming speed of fish with the body length per second (L_{fish}/s) (figure 2.14).

The swimming speed is differentiated as follows (figure 2.15):

- The **darting swimming speed (V_{sprint})** is the maximum speed a fish can achieve. It amounts to approx. 10 to 12 L_{fish}/s (JENS et al., 1997) for adult Salmonids (*Salmonidae*), Cyprinids (*Cyprinidae*) and Percids (*Percidae*). The white musculature is used for this purpose but becomes quickly fatigued, so that this performance can only be maintained for a few seconds. If the white musculature is completely exhausted, it then requires up to 24 hours to regenerate before the fish is able to regain its maximum darting swimming speed. The darting swimming speed is therefore only employed when absolutely necessary. This applies for example when prey has to be captured, hazards to be escaped or rapids, waterfalls, but also upstream fish passes are to be mastered.
- **Sustained speed ($V_{sustained}$)**: The performance capability of the fish weakens with prolonging durations, whereby BAINBRIDGE (1960) stated that this primarily applies to the first 10 seconds. The swimming speed is afterwards only slightly reduced, and that speed which was gained after 20 seconds can then be kept by the fish almost steadily for up to 200 minutes. This performance is called the d swimming speed, and both, the white and red musculature are activated. Also the sustained speed has a fatiguing effect on the fish if performed for a long time, whereby tiredness occurs faster, the higher the speed. The sustained swimming speed should therefore either be indicated as the maximum value, i.e. a span or in dependence of the duration. The comprehensive scrutiny of literature by JENS et al. (1997) has confirmed the value of 5 body lengths per seconds for the sustained swimming speed of adult Cyprinids (*Cyprinidae*), Percids (*Percidae*) and Salmonids (*Salmonidae*) as this was already assessed by BAINBRIDGE (1960). Subsequently, the sustained swimming speed amounts to about 40 to 50 % of the darting swimming speed.
- The **cruising speed ($V_{cruising}$)** is the normal swimming speed of the fish, where the red musculature only is activated, so that the speed can be maintained without exhaustion over a longer period (> 200 min). An indicator for the cruising speed is quoted by TURNPENNY et al. (1998) do be approximately 2 L_{fish}/s for salmon smolts and potamodromous species.

- The **perseverance ($T_{perseverance}$)** refers to the period over which the fish can maintain a specific speed. This is greater the lower the swimming speed.

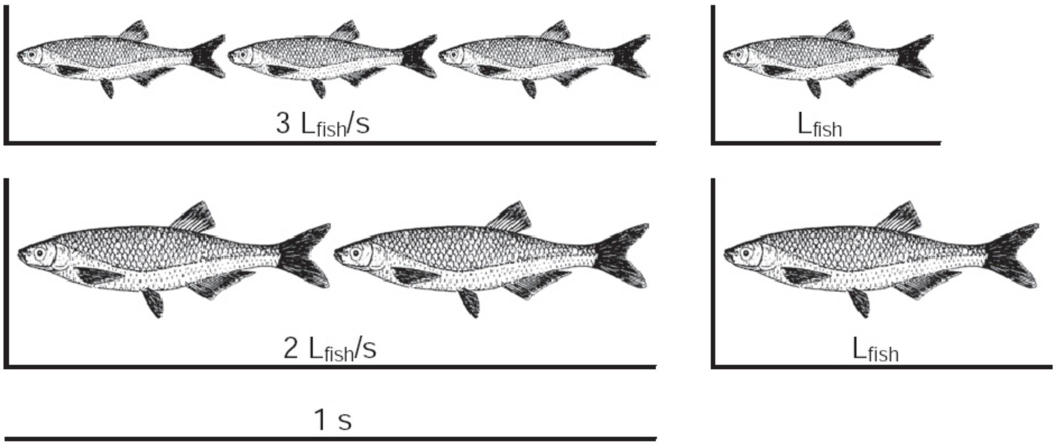


Figure 2.14: Relative swimming speed of fish (changed according to: JENS et al., 1997)

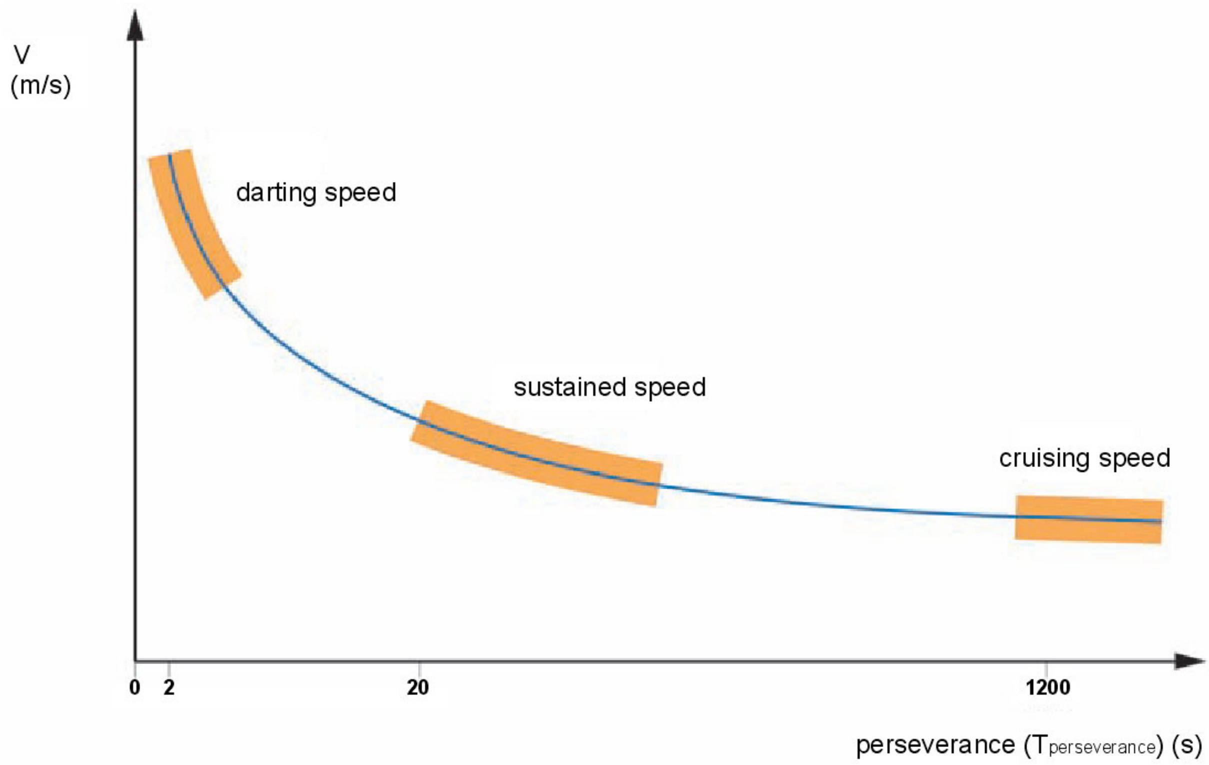


Figure 2.15:Swimming performance of fish (changed according to: PAVLOV, 1989)

In view of the dimensioning of fish protection facilities and downstream fishways, that flow velocity is of the greatest interest, which must be maintained at hydraulic plants to allow a safe downstream migration of the target species and stages. This flow velocity is called the critical speed ($V_{critical}$). In international literature (BAINBRIDGE, 1960; PAVLOV, 1989; LARINIER & TRAVADE, 2002; and others) the determination of the critical speed is based on the optimal combination of fish protection facilities and downstream fishways, so that the fish will be in a hazardous area for only a short while. Accordingly, the critical flow velocity is derived from the sustained swimming speed of the fish:

$$V_{critical} = V_{sustained} \times L_{fish}$$

Nevertheless, it must hereby be considered that the sustained swimming speed does not present a constant, but is influenced by various factors:

- Significant species-specific differences exist. Whilst Cyprinids, Percids and Salmonids achieve comparable sustained swimming speeds of approximately 5 L_{fish}/s maximum, this value quite obviously does not apply to eel-like species. BLAXTER & DICKSON (1959) state a darting swimming speed of 1.9 L_{fish}/s for silver eels, which equals a sustained speed of approx. 0.8 to 0.9 L_{fish}/s. The sustained swimming speed of the sea lamprey is 0.9 to 1.7 L_{fish}/s according to BEAMISH (1979).
- The relation between swimming speed and body length is dependent on the size of the fish: Whilst the sustained swimming speed of adult fish of most species amounts to approximately 5 L_{fish}/s, young fish below a length of 10 cm achieve up to 10 L_{fish}/s, and the values for frys are often even higher (PAVLOV, 1989).
- Also the condition of the fish plays an important role. The swimming performance deteriorates remarkably in case of food shortage, for instance. If zander, as an example, get caught in the turbines of hydropower plants, the portion of the undernourished fish is exceedingly high (PAVLOV, 1989). Unfavourable chemico-physical environmental conditions like oxygen deficits, high ph-values, etc. have an adverse effect on the condition. The relevant limit values, however, differ species-specific. Salmon, for example, slacken their swimming performance already at a reduced oxygen content of 5 mg/l, Cyprinids, however, only at a value below 2 mg/l (TURNPENNY et al., 1998).
- Fish are poikilotherms, of which the efficiency is dependent on the temperature of the water and their adjustment to specific temperature conditions. The activity of the muscles is greatly reduced at temperatures near freezing point and the fish get into torpor. The efficiency becomes enhanced with rising temperature, but will be impaired for cold water species like salmon and brown trout through high summer temperatures of the water. The temperature of the water during the migration season of the target species is to be accounted for when determining the approach velocity for hydraulic structures. These are for example the temperatures of the spring season for salmon and sea trout smolts, the summer temperatures for the juvenile allis shad and the autumn temperatures of the water for silver eels. Hence, the lowest possible temperature of the water in winter time is relevant to the most unfavourable case for potamodromous species.

Table 2.8 gives bibliographic references for the swimming speed of fish of different species and sizes, on which the exemplary representation of the critical speed is based which is shown in figure 2.16 to 2.18.

However, the situations are much more complex in reality, as the real swimming speed of a fish and its perseverance, also the duration over which it is able to maintain this speed, is the result of multi-factorial interactions between the above mentioned parameters. According to TURNPENNY et al (1998) it would be ideal, therefore, that the swimming speed of fish be assessed precisely for each target species and -stages under realistically occurring environmental conditions. These authors recommend that the permitted approach velocity of hydraulic structures should be less than 50 % of the assessed swimming speed. Figure 2.19 gives an idea of how greatly dependent swimming speed and perseverance are on species, length of fish and temperature.

Table 2.8: Swimming speed of fish of different species in dependence of the total length (L_{fish})

species	L_{fish} [m]	V_{sprint} [L_{fish}/s]	$V_{sustained}$ [L_{fish}/s]	$V_{critical}$ [m/s]	Source
Eel	0.07		8.6	0.60	SÖRENSEN, 1951
	0.10		7.0	0.70	SÖRENSEN, 1951
	0.16		2.9	0.47	JENS et al., 1997
	0.40		2.1	0.83	JENS et al., 1997
	0.60	1.9		0.51	BLAXTER & DICKSON, 1959
Brown Trout	0.13	10.5		0.62	BLAXTER & DICKSON, 1959
	0.20	10.0	4.0	0.80	GEITNER & DREWES, 1990
	0.34		2.7	0.92	JENS et al., 1997
	0.35	10.0	2.9	1.00	GEITNER & DREWES, 1990
	0.37	8.2		1.37	BLAXTER & DICKSON, 1959
Perch	0.05		9.3	0.42	PAVLOV, 1989
	0.05		8.8	0.44	PAVLOV, 1989
	0.06		8.0	0.48	PAVLOV, 1989
	0.22	5.5		0.55	BEAMISH, 1978
Bream	0.22	4.2		0.42	JENS et al., 1997
	0.30	4.3	3.3	1.00	GEITNER & DREWES, 1990
	0.50	4.2	3.0	1.50	GEITNER & DREWES, 1990
Goldfish	0.07	11.5	6.3	0.42	BAINBRIDGE, 1958
	0.09	11.1	5.4	0.50	BAINBRIDGE, 1958
	0.12	10.0	5.1	0.60	BAINBRIDGE, 1958
	0.14	9.8	4.6	0.62	BAINBRIDGE, 1958
	0.15	9.5	4.3	0.64	BAINBRIDGE, 1958
	0.16	11.9	4.1	0.66	BAINBRIDGE, 1958
	0.21	9.4	3.2	0.68	BAINBRIDGE, 1958
Bullhead	0.02		9.5	0.19	PAVLOV, 1989
	0.03		9.0	0.27	PAVLOV, 1989
	0.04		8.5	0.34	PAVLOV, 1989
Gudgeon	0.12		4.7	0.55	STAHLBERG & PECKMANN, 1986
Dace	0.10	12.0	5.0	0.50	BAINBRIDGE, 1958
	0.10	11.0	4.6	0.46	BAINBRIDGE, 1960
	0.10	11.5	5.3	0.55	BAINBRIDGE, 1958
	0.15	11.0	4.3	0.62	BAINBRIDGE, 1958
	0.15	11.8	5.3	0.80	BAINBRIDGE, 1958
	0.17	12.0	4.8	0.80	BAINBRIDGE, 1958
	0.18	9.3		0.77	GRAY, 1953
	0.20	11.3	4.0	0.80	BAINBRIDGE, 1958
	0.21	11.2	4.2	0.90	BAINBRIDGE, 1958
	0.21	11.2	4.5	0.96	BAINBRIDGE, 1960
Pike	0.12		1.6	0.19	BEAMISH, 1978
	0.62		0.8	0.47	BEAMISH, 1978
Carp	0.35	6.7		1.06	BEAMISH, 1978
Crucian Carp	0.02		13.0	0.26	PAVLOV, 1989
	0.03		14.0	0.42	PAVLOV, 1989
	0.04		12.0	0.48	PAVLOV, 1989

species	L_{fish} [m]	V_{sprint} [L_{fish}/s]	$V_{sustained}$ [L_{fish}/s]	$V_{critical}$ [m/s]	Source
Salmon	0.15		4.7	0.70	BEAMISH, 1978
	0.20		5.0	1.00	BEAMISH, 1978
	0.47		2.8	1.33	PAVLOV, 1989
	0.75	5.7		1.93	DENIL, 1937
	0.85	7.1		2.70	DENIL, 1937
Sea Lamprey	0.15		1.1	0.17	BEAMISH, 1978
	0.39		1.1	0.41	BEAMISH, 1978
Moderlieschen	0.03		12.0	0.36	PAVLOV, 1989
	0.04		13.8	0.55	PAVLOV, 1989
	0.05		7.6	0.39	STAHLBERG & PECKMANN, 1986
Roach	0.03		12.0	0.36	PAVLOV, 1989
	0.04		11.0	0.44	PAVLOV, 1989
	0.15	5.1		0.35	GEITNER & DREWES, 1990
	0.22	3.8		0.37	JENS et al., 1997
	0.30	5.1		0.69	GEITNER & DREWES, 1990
Burbot	0.12		3.0	0.36	BEAMISH, 19..
	0.62		0.7	0.41	BEAMISH, 1978
Tench	0.02		8.3	0.19	PAVLOV, 1989
	0.03		8.3	0.25	PAVLOV, 1989
	0.04		7.8	0.31	PAVLOV, 1989
	0.05		7.2	0.36	PAVLOV, 1989
	0.06		6.7	0.40	PAVLOV, 1989
	0.26	5.4		0.62	BEAMISH, 1978
Loach	0.02		9.6	0.22	PAVLOV, 1989
	0.03		9.7	0.29	PAVLOV, 1989
	0.04		9.3	0.37	PAVLOV, 1989
	0.10		5.9	0.61	STAHLBERG & PECKMANN, 1986
Loach (*Cobitis spp.*)	0.00		75.8	0.25	PAVLOV, 1989
	0.04		7.3	0.29	PAVLOV, 1989
	0.05		6.8	0.34	PAVLOV, 1989
	0.06		6.2	0.37	PAVLOV, 1989
	0.07		5.9	0.41	PAVLOV, 1989
Stickleback	0.05		7.4	0.36	STAHLBERG & PECKMANN, 1986
Bleak	0.02		17.0	0.34	PAVLOV, 1989
	0.03		17.3	0.52	PAVLOV, 1989
	0.03		16.3	0.52	PAVLOV, 1989
Russian Sturgeon	0.04		5.5	0.22	PAVLOV, 1989
	0.05		5.0	0.25	PAVLOV, 1989
	0.06		4.5	0.27	PAVLOV, 1989
	0.07		4.1	0.29	PAVLOV, 1989

species	L_{fish} [m]	V_{sprint} [L_{fish}/s]	$V_{sustained}$ [L_{fish}/s]	$V_{critical}$ [m/s]	Source
Vimbra Abream	0.04		9.8	0.39	PAVLOV, 1989
	0.05		8.4	0.42	PAVLOV., 1989
	0.06		7.5	0.45	PAVLOV, 1989
	0.07		6.7	0.47	PAVLOV, 1989
Zope	0.03		10.7	0.32	PAVLOV, 1989
	0.04		9.8	0.39	PAVLOV, 1989
	0.05		9.2	0.46	PAVLOV, 1989
	0.06		8.3	0.50	PAVLOV, 1989
Where no details were given for $V_{sustained}$, $V_{critical}$ was calculated according to the formula $V_{critical} = V_{sprint} * L_{fish} * 0.45$					

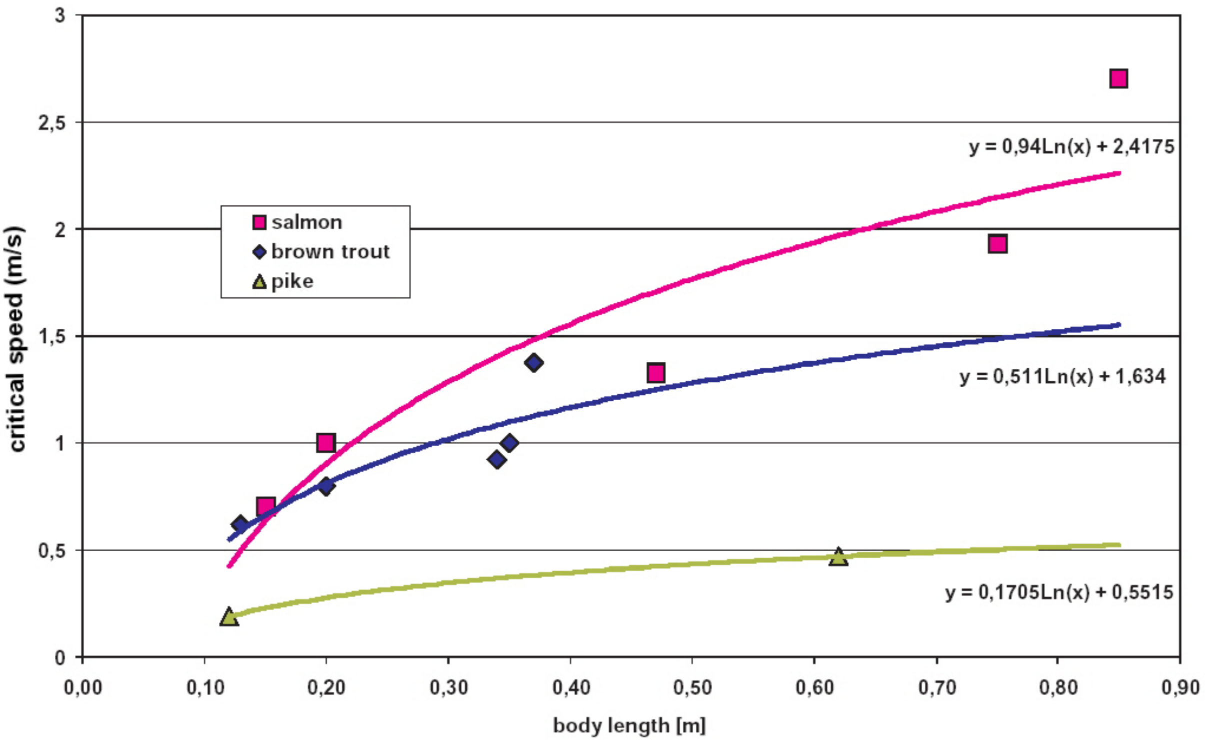


Figure 2.16: Critical speed $V_{critical}$ of salmon, brown trout and pike in dependence of the body length (data basis: table 2.8)

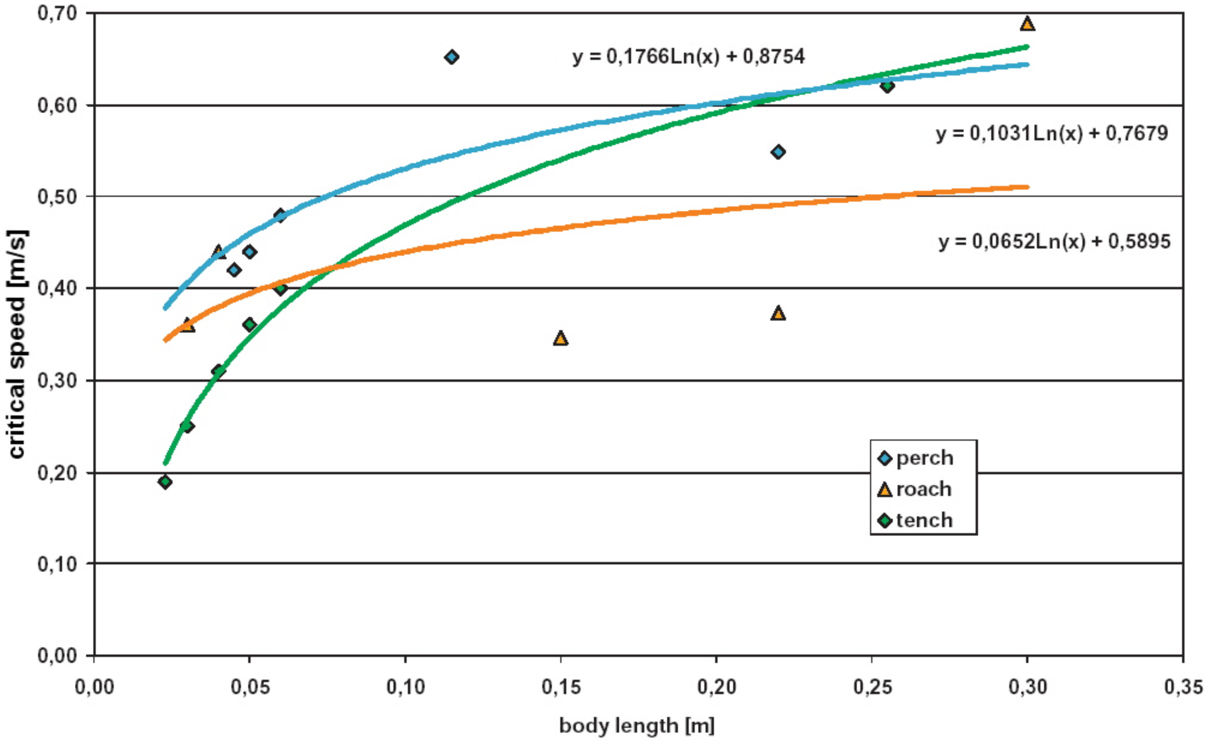


Figure 2.17: Critical speed $V_{critical}$ of perch, roach and tench in dependence of the body length (data basis: table 2.8)

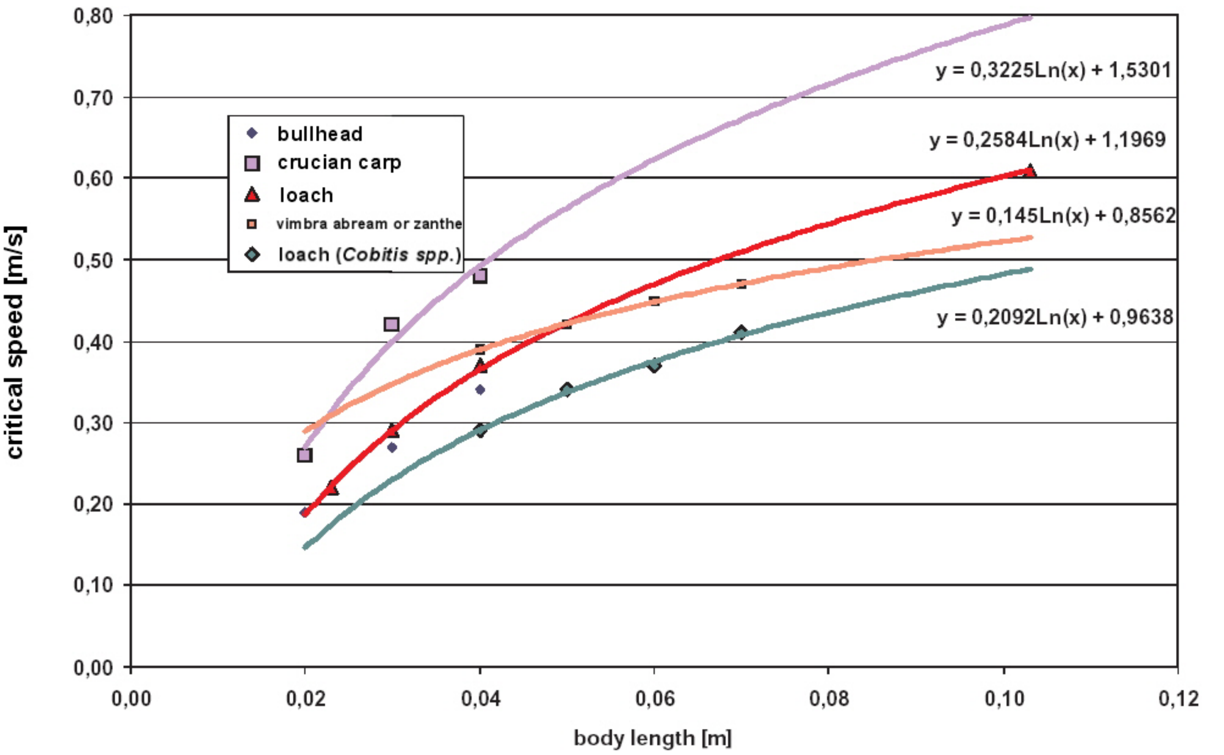


Figure 2.18: Critical speed $V_{critical}$ of small and young fish in dependence of the body length (data basis: table 2.8)

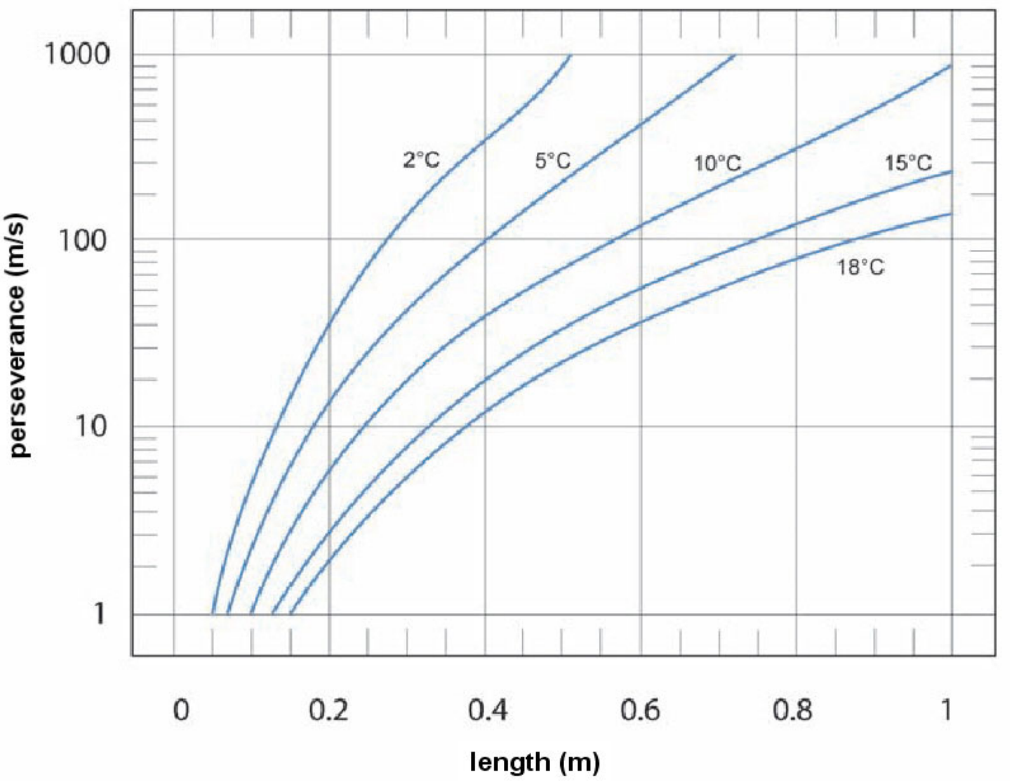


Figure 2.19: Darting swimming speed of Salmonids in dependence of body length and temperature (according to LARINIER, 2002)

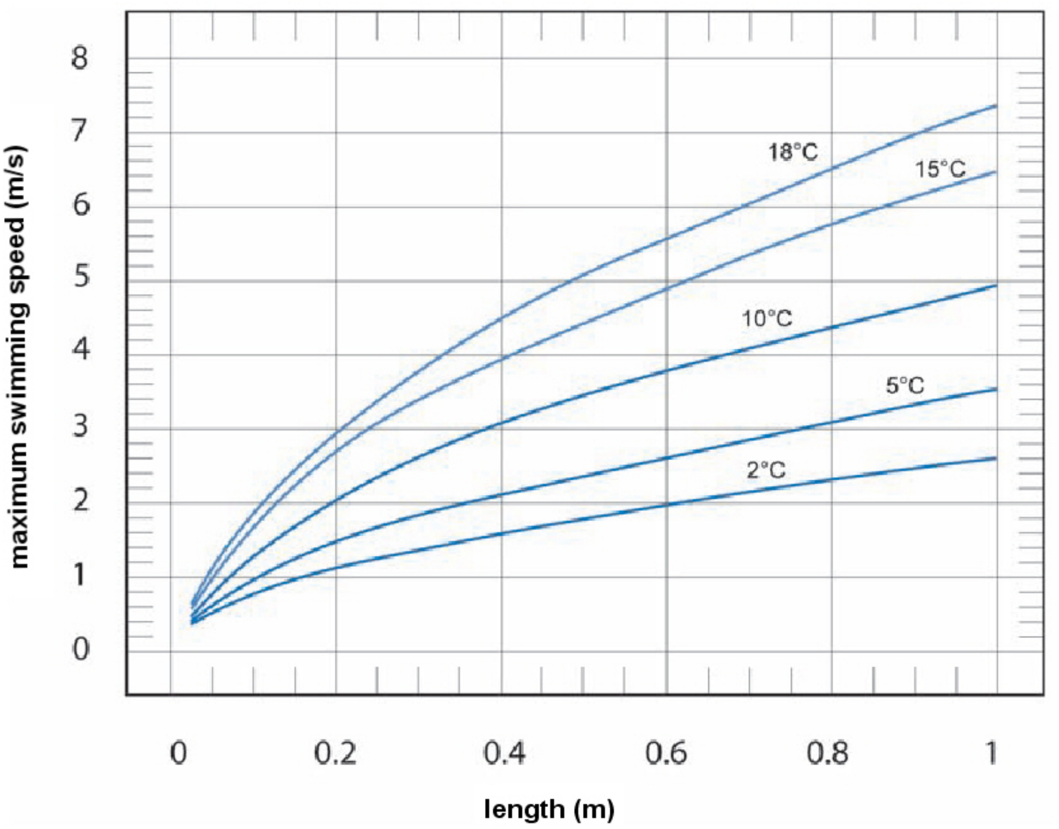


Figure 2.20: Perseverance of Salmonids at maximum speed in dependence of body length and temperature (according to LARINIER, 2002)

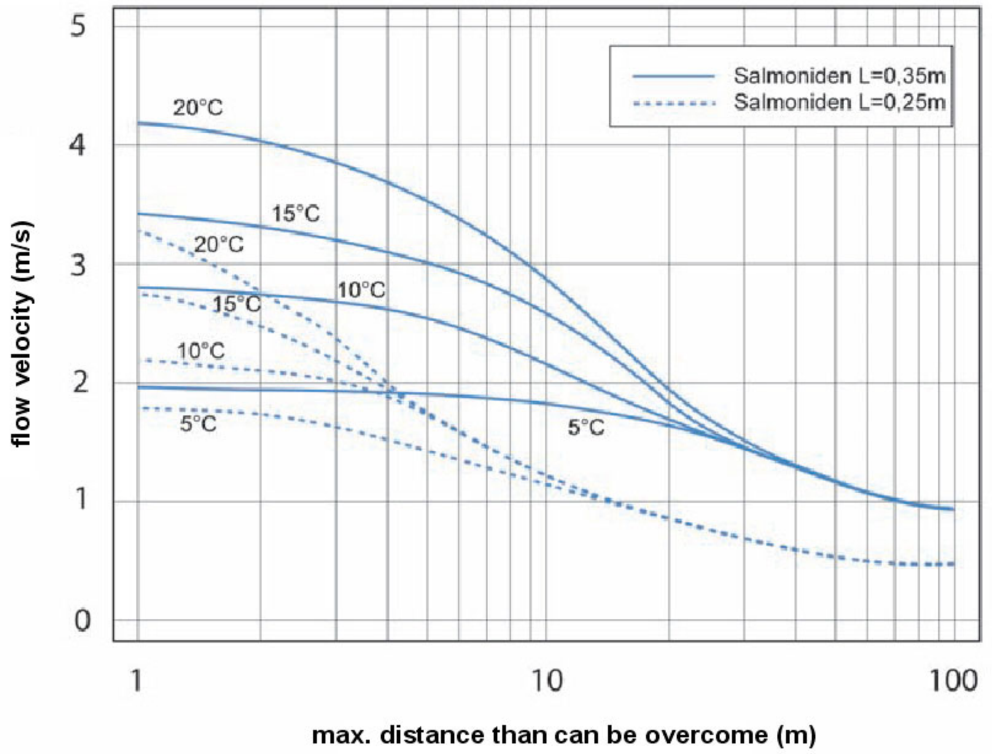


Figure 2.21: The maximum distance overcome by Salmonids of various sizes in dependence of flow velocity and temperature (according to LARINIER, 2002)

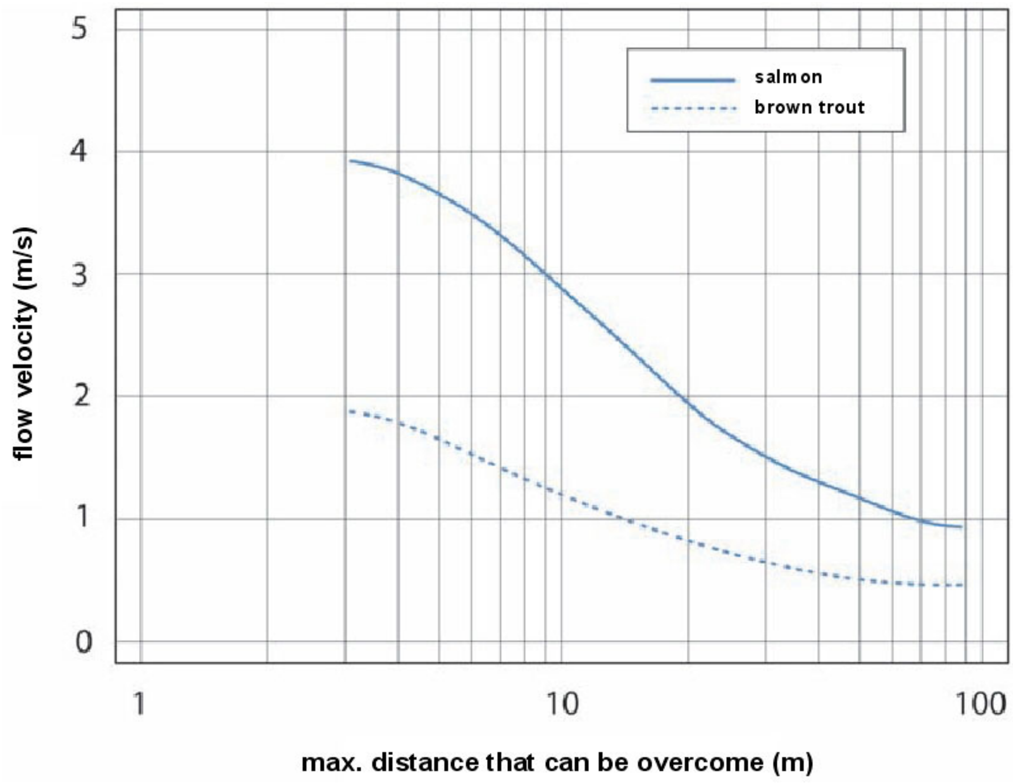


Figure 2.22: The maximum distance overcome by adult salmons and brown trouts in depen-dence of the flow velocity (according to LARINIER, 2002)

2.6.4 Migration speed

Statements on migration speeds and distances of the various migrating fish species can differ greatly as per individual author. It is hereby apparent, however, that the fish is directly dependent on the flow velocity of the water body (table 2.9).

Table 2.9: Speeds and distances of migrating fish

species	migration speed and distance	water body	author
Atlantic Salmon	8 km / day (maximum)	Thurso (Scotland)	ALLEN, 1944
	13.5 km / day (average)	model channel	FÄNGSTAM, 1993
	20 km with 6 weirs in 5 days	Lahn (Rhineland-Palatina)	SCHWEVERS, 1999
Pacific Salmon	2.5 km / h (average)	rivers on Vancouver Island (Canada)	WOOD et al., 1993
	up to 54 km / day	Snake River (USA)	RAYMOND, 1979
Eel	3.0 to 3.7 km/h 36 to 72 km / day	Elb	TESCH, 1994
	maximum: 4.7 km in 0.32 h = 14.8 km/h 31.5 km in 4.00 h = 7.8 km/h 74.6 km in 13.57 h = 5.5 km/h 170.6 km in 36.05 h = 4.7 km/h	Maas	according to data from BRUIJS et al., 2003
	2 km/h	Baltic Sea	TESCH et al., 1990
potamodromous species	5 to 8 km / day (average)	Rhine system	STEINMANN, 1937

2.7 Mortality during migration

Migrating fish are subject to a significant natural mortality. This specifically refers to spawn of anadromous species, which are heavily exhausted, as LEONHARDT (1905) vividly describes: *"The masculine salmon often [have to] cure severe wounds which they suffer during their spawning battles. It is therefore not surprising that here and there one can find such dead animals, as decaying Saprolegniaceae [parasitic funguses] populate the wounds and lead to a quick death of the concerned animal."* The sensitivity to diseases and parasites is increased after the spawning period and thus the mortality through unfavourable environmental conditions, as can sometimes be observed in eutrophicated impoundments (TRAVADE & LARINIER, 1992).

Another natural cause for mortality is the feeding pressure through predators or fish-eating birds, effecting a reduction of migrating young fish in particular. This effect is often intensified through storage level regulations of water bodies, as accumulations of predators can be noticed in reaches and in the tailwater of weirs and hydropower plants. Appropriate investigations were carried out in Denmark where mortality rates of 81 to 85 % respectively 99 % of salmon and sea trout smolts have been assessed. These smolts had to pass through two rivers with shallow impounded lakes that were extensively populated by pikes and zander (RASMUSSEN et al., 1996).

The exploitation through fishing migrating fish plays a role especially for the eel. In previous times the fishing method with fyke nets was purposely used to catch migrating silver eels. Additionally were so-called stationary eel traps operated at many mills. The organic loads in rivers which increased rapidly during the years after the war, however, resulted in such a heavy move of sewage funguses (*Sphaerotilus natans*) in the flowing wave, that fyke net fishing was no longer possible in many places, and most of the eel catches have been stopped. Subsequently since the sixties, fishery as a cause of mortality of migrating fish, especially the silver eel, is of minor significance in most river systems. An exception for example is the Dutch Maas, where more than half of the migrating eels are caught through intensive professional fishing by means of anchored stow nets and bow-nets (BRUIJS et al., 2003).

3 Technical principles

The flow conditions along a river change naturally by gradient changes, blocking rocks, ravine stretches, and by human interference. Centuries ago weirs were installed in rivers to power water mills of flourishing trades (figure 3.1). At the beginning of the 19th century the technical engineering of water body developments evolved to meet the demand of a growing population, the fast increasing requirement for energy of a growing industrialization and the urgent demand for traffic routes, which is mirrored by the following examples:

- The longitudinal corrections for the purpose of land reclamation and flood protection.
- Protection of the river bottom by means of structures to prevent erosion.
- Since 1830 hydropower plants with turbines were put into operation to generate mechanical energy.
- Development of larger rivers to provide all-year-round navigation.
- Since 1890 construction of hydropower plants for electric power generation.

In Germany, 75 % of the total of about 400,000 km of rivers has been altered artificially. Approximately 5,000 km refer to river sections of federal waterways. An overview of the intensity at which flowing waters have been developed is exemplified by several rivers in table 3.1. Hydraulic structures, especially impounding structures and water intakes, can impair the downstream migration of fish, of which the most important installations are described in the following.

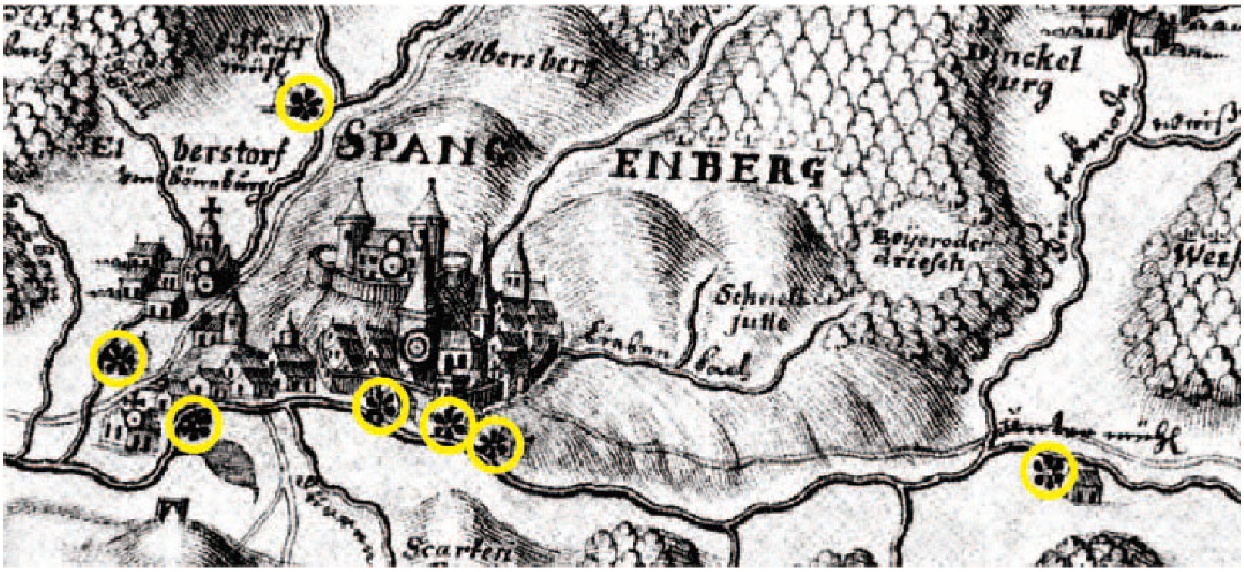


Figure 3.1: The extract from the Schleenstein'sche Karte (map of Schleenstein) of the years 1705 to 1710 (reprint, LANDESVERMESSUNGSAMT HESSEN) shows a section of the Pfieffe river, a tributary of the Fulda river (Hesse, Land of the Federal Republic of Germany) and documents the former density of mills.

Table 3.1: Impounding structures in selected river reaches (Germany)

water body	river length [km]	number of cross con-struc-tions	mean dist-ance [km]	function						author remarks
				B	E	K	S	Si	So	
Danube (Bavaria)	378	22	17.2		22		6			209 km federal waterways
Elb (Germany)	727	1	-				1			
Fulda (Hesse)	219	86	2.5	4	27	47	5	3		SCHWEVERS et al., 2001
Havel (Brandenburg)	341	19	18.0		3		18		1	GOERLACH & KRUEGER, 1996
Jagst (Baden-Wuerttemberg)	114	34	3.4	1	31				2	SILIGATO et al., 200
Lahn (Hesse/Rhineland-Palatinate)	165	56	2.9	17	25		3		11	SCHWEVERS & ADAM, 1996
Lech (Germany)	166	39	4.4	3	30			1	13	
Main (federal waterway)	381	35	10.9		31		35			BORN, 1995
Main (Oberfranken)	167	31	5.4		21	5		2	3	STROHMEIER, 1998 Red Main & Main up to Viereth
Moselle (federal waterway)	245	12	20.4		12		12			
Neckar (federal waterway)	203	27	7.5		26		27			
Rhine	170	13	13.1		11		2		2	Constance to Basel
Rhine (upper Rhine)	164	16	10.2		10		10		16	Basel to Iffezheim, incl. Grand Canal d'Alsace
Ruhr (North Rhine Westphalia)	219	85	2.6	7	45	33	11	3		DUMONT et al., 2002
Spree (Brandenburg)	308	34	9.1			1	14		19	GÖRLACH & KRÜGER, 1996
Stepnitz (Brandenburg)	86	15	5.8	4	2	6		1	2	LESKE & STRUNCK, 1993
Weser (federal waterway)	227	8	28.4		6		8		1	ARGE-Weser
Wupper (North RhineWestphalia)	113	32	3.5	6	10	16				DUMONT et al., 2002

Legend:
Bdischarge of industrial water, cooling water, irrigation, etc.
Eenergy generation
Kno recognizable function, left vacant
Snavigation development
Sisecuring constructions (bridges)
Soriver bottom protection, elevation of groundwater

3.1 Bottom constructions

According to DIN 4047, part 5, bottom constructions are structures which are arranged transverse to the flow direction and shall prevent an erosion of the river bottom. Dependent on the structural shape and height above the river bottom, it is differentiated between sills like ground- and bottom sills, and bottom steps like bottom ramps and bed drops (figure 3.2, figure 3.3). All bottom constructions are constantly under flowing water, so that they do not present an obstacle for downstream migrating fish.

If for the protection of the river bottom it is also necessary to elevate the water level, this requires supporting weirs of which the overflow crest lies above the upstream river bottom. The structure projects out from the bottom at supporting steps or supporting weirs so high that a flow transition takes place over its crown. The overflowing water, however, normally creates a sufficiently deep water cushion so that a harmless passage for migrating fish is facilitated.

3.2 Barrages

Barrages are impounding structures, which basically block only the river off and not the entire width of the valley (DIN 4048, part1). Its dam constructions are weirs with impounding dams or dikes. Depending on the objective, further constructions like hydropower plants, navigation locks or canal inlets are incorporated.

3.2.1 Weirs

A weir is a dam construction that serves for the elevation of the water level and is often also used to control the discharge (or flow) (DIN 19700, part 13). The construction of weirs can look back to a long tradition. One of the oldest struc-tures in Germany is the Weir Hameln on the Weser river, which was built around 1000 AC and in its present form goes back to the year 1900 (DVWK, 1996). Numerous construction types evolved during the course of time, of which the most common types are described in the following.

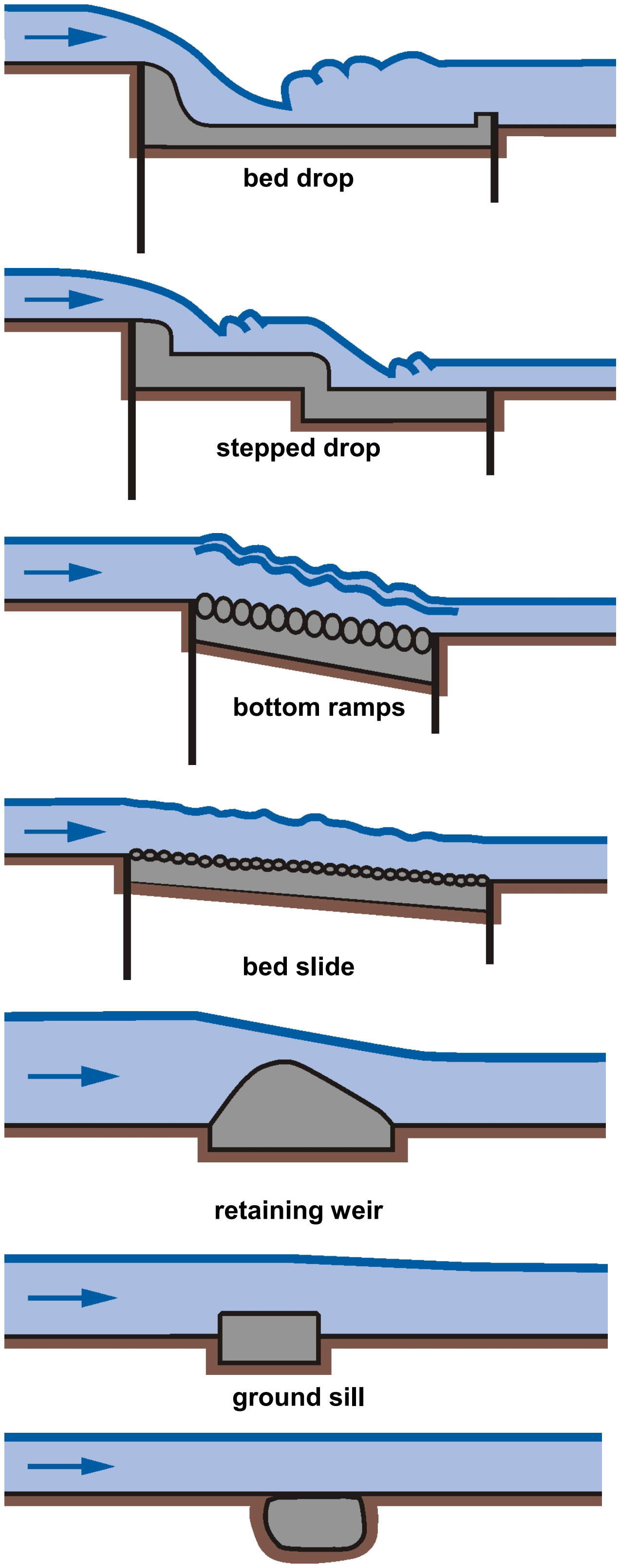


Figure 3.2:
Types of Bottom Constructions (according to DIN 4047, part 5)

Engineering differentiates primarily between fixed and movable weirs. Fixed weirs have no movable locks. Movable weirs are structures with adjustable locks, which assist in adjusting the water level and controlling the discharge. The structure is called “check” (weir) if the water level of a weir primarily controls the corresponding groundwater flow (figure 3.4).

Figure 3.3:
Stepped Drop on the Lech river south of Augsburg (Bavaria)

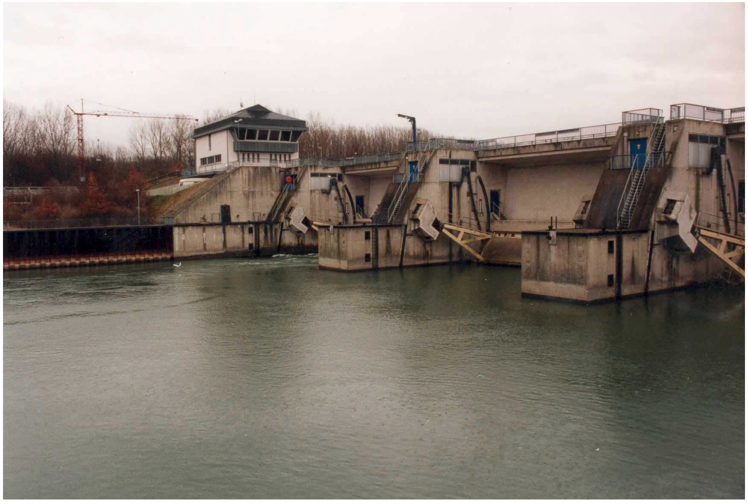


Figure 3.4:
Weir Kehl on the Rhine (Baden-Wuerttemberg)

Sliding-Panel weirs belong to the simplest types of movable weirs (figure 3.5). The gates are plane gates made of wood, steel or concrete, which are lifted by means of hoisting gears. They present the common construction type amongst old and smaller weirs.

Figure 3.5:
Sliding-Panel Weir Egeln on the Bode river (Saxony-Anhalt)

If greater discharges are to be controlled, the weir will be divided into several weir sections thereby limiting the dimensions of the locks, to optimize the actuating forces and to enhance the operating reliability. The locks must be lowered or pulled out of the water if the flow has to be regulated. The result is in an overflow or underflow of the weir lock.

Gates, drum gates, drum weirs and double flaps (bear-trap gate) belong to the group of lowerable weir locks (figure 3.6). Roller weirs which are equipped with immerse rollers can also be lowered below the standard position for the release of ice and flotsam (figure 3.7, figure 3.8). This also applies to two-piece crest-wicket gates which consist of a basic element and a lowerable element placed on top (figure 3.9). Examples are pressure and tension segments with a gate placed on top (figure 3.10), hook double gates and double gates.

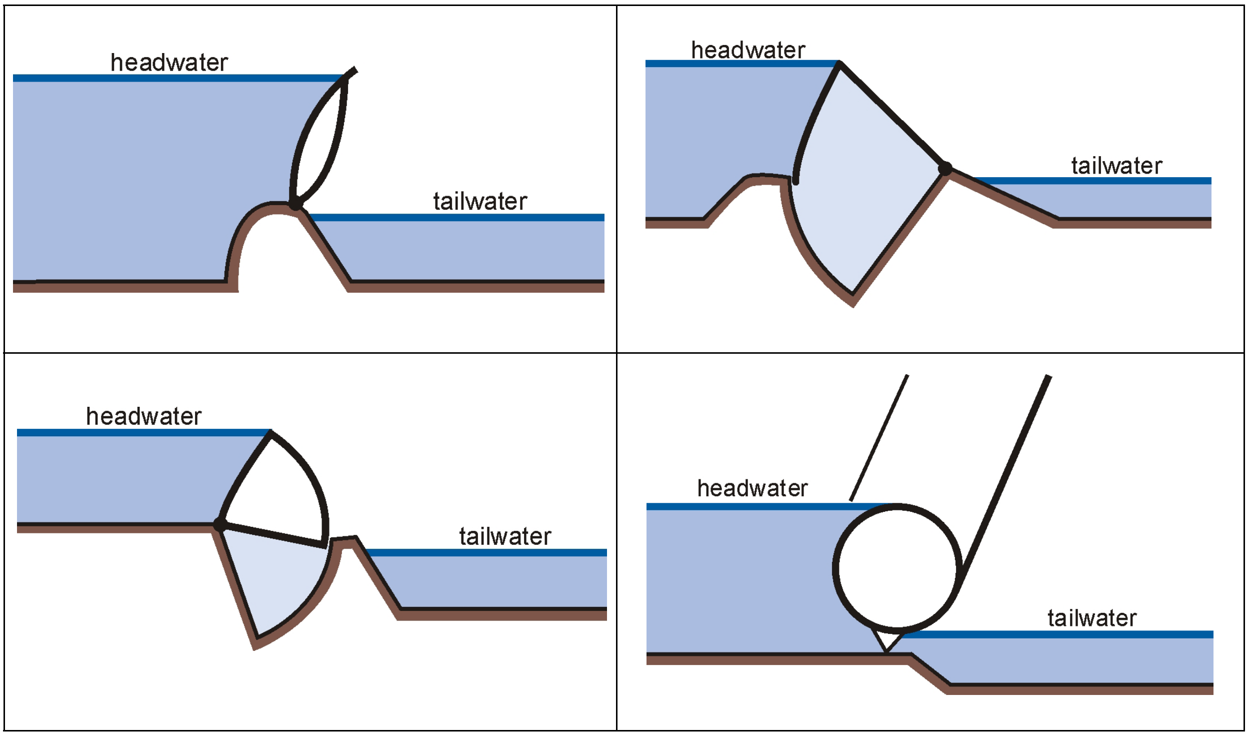


Figure 3.6: Single Crest Wicket gate (according to DIN 4048, part 1)

Figure 3.7:
Drum gates are installed in the outer fields of the weir of the Main barrage Garstadt (Bavaria), in the centre field a gate on which a gate is placed

Figure 3.8:
Drum gate of the Moselle barrage Lehmen (Rhineland-Palatina)

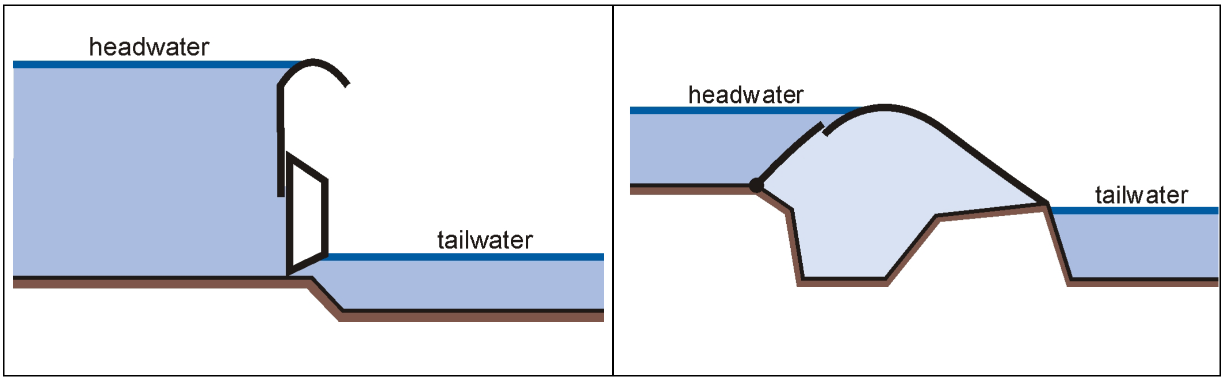


Figure 3.9: Two-piece crest-wicket gate (according to DIN 4048, part 1)

The gate of segment weirs with or without top flap must be lifted out of the water for complete discharge (figure 3.11).

A newer kind of construction is the inflatable weir (figure 3.12). Inflatable weirs are a type of movable weir. A rubber fabric is anchored on a fixed concrete structure in such a way that a dense flexible interior like a “hose” is created. The hose will be filled with air or water and the impounded head is regulated by the filling ratio.

During the many years of experience in hydraulic constructions, planners and operators have developed various combinations of structures. Two-piece or lowerable gates are generally employed at large rivers, which had been developed as waterways. At least one of the weir fields will be equipped with an element that assumes precise regulation, so that the water level required for navigation can be maintained as exact as possible (see figure 3.7). Movable weirs are operated according to instructions, which regulate the maintenance of the level of the impounded water in dependence of the inflow. The operation instructions are normally verified and approved by the regulatory authorities. Smaller weirs may be controlled automatically.

Figure 3.10: Danube barrage Vohburg (Bavaria): pull segments with gate placed on top

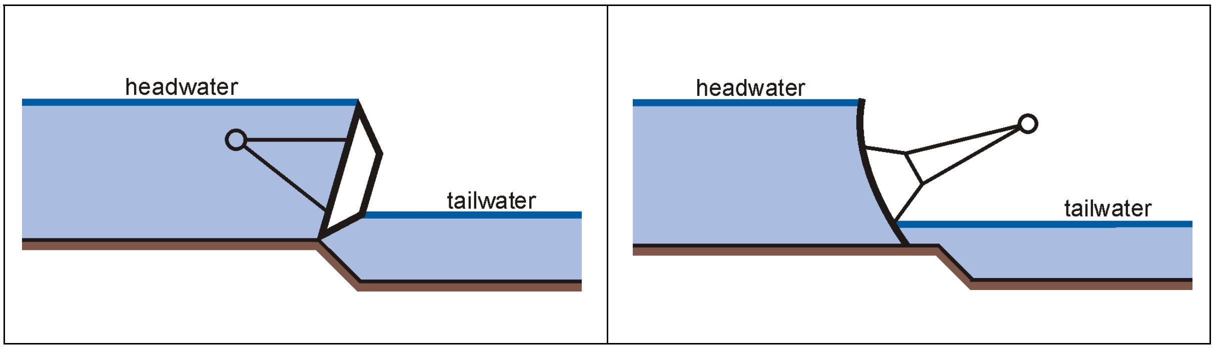


Figure 3.11:Radial gates (according to DIN 4048, part 1)

Figure 3.12:
Inflatable weir Thierbach on the Zwickauer Mulde (Saxony)

3.2.2 Navigation locks

Navigation locks are installed at barrages in waterways for ships to overcome height differences between headwater and tailwater (figure 3.13). Ship hoists are used in the case of greater height differences. When filling the lock, the water streams into the lock chamber through flooding openings in the upper gate or below the lifted gate. The locks can alternatively be filled through canal systems located in the chamber floor or in the chamber walls. When emptying the lock chamber, the water in the lock will be drained through comparable ways into the tailwater. The appropriate lock gate can be opened as soon as the water levels in the lock chambers, and in the head- and tailwater have been equalized. The operating hours of navigation locks are, except for ice and flood occurrences mainly dependent on the traffic volume (table 3.2).

Navigation locks for boats exist additionally at many barrages, enabling fishing and sport boats to pass the barrage. The construction principle is equal to navigation locks for ships but of smaller dimensions. The size of the navigation lock for boats at the Danube barrage Bad Abbach (Bavaria) for example, is only approximately 1/30 of the volume of the navigation lock for ships.

Fish can get into the lock or into the tailwater with the lockage water, or can pass the open lock gates depending on the operating hours.

Table 3.2:Examples of operating hours of locks

waterway	operating hours
Danube, Main, Moselle, Rhine, Saar	24 h-operation, throughout the year
Neckar	daily operation, throughout the year
Lahn	daily operation, closed from 01 Oct.- 31 March

3.3 Dams and reservoirs

Dams and reservoirs are impounding structures which beyond the cross-section of the watercourse block off the entire profile of the valley (RISSLER, 1998, figure 5.1). Dam constructions are differentiated by impounding dams and retaining walls. The reservoir creates a completely new water body. Fish can only reach the tailwater through the intake structure or in case of a flood through the spillways.

In Germany, there are more than 300 structures with impounding heads above 15 m or an impounding volume exceeding 1 mio. m^3. The majority of these installations serve for the supply of drinking water, flood protection or low-flow augmentation. Only a small portion is utilized for the generation of energy. Intake structures and spillway are available for the operation of the reservoirs:

- Intake structures for the management of stored water
- Bottom outlets to drain the reservoir

- Spillway for a safe diversion of floodwater

Numerous solutions to the design of operation facilities can be derived from the type of dam construction, the purpose for which the reservoir was created, the local conditions like hydrology, topography, etc. (RISSLER, 1998).

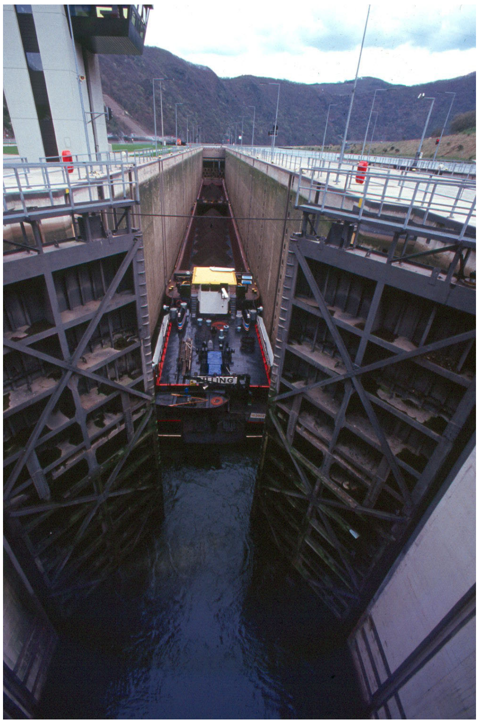


Figure 3.13: Chamber lock Serring on the Saar river (Saarland)

3.4 Hydropower

Hydropower generates from the ability of heading water to work through gravitational forces. It was one of the first sources of energy man has discovered. Hydropower was first of all employed as mechanical energy in mills, hammer works, etc. After WERNER v. SIEMENS has discovered the dynamo-principle in the year 1867, it became possible to convert hydropower by means of turbine and generator into electric energy on an industrial production basis. Hydropower is nowadays almost exclusively used for the generation of electric power. It is an inexhaustible energy that is constantly regenerated through solar radiation. The electric power generation through hydropower today constitutes the best developed and most important regenerative energy source. About 5 % of the electric power used in Germany is supplied from that source; the portion that hydropower covers in the generation of energy worldwide, and its ratio in selected countries can be taken from the tables 3.3 and 3.4. The construction of new hydropower plants and the modernization of existing installations help to enhance the generation of energy from regenerative sources. However, other fields of interest in the utilization must also be considered, like discharge regulation, drinking water supply, flood protection, leisure and recreation, and fishery.

Table 3.3: Proportion of hydropower used for the generation of electric power in the Federal States of Germany in the year 1995 (from: VDEW, 1996)

Federal State	total of generated electric energy [GWh/a]	portion of hydropower [GWh/a]	proportion of hydropower [%]
Baden-Wuerttemberg	55,182	5,571	10.1
Bavaria	65,783	10,654	16.2
Berlin	10,237	-	-
Brandenburg	17,683	5	0.03
Bremen	4,319	-	-
Hamburg	1,339	-	-
Hesse	20,286	969	4.8
Mecklenburg-Vorpommern	2,075	3	0.15
Lower Saxony	50,991	389	0.8
North Rhine-Westphalia	126,554	598	0.5
Rhineland-Palatina	5,106	1,026	20.1
Saarland	5,609	64	1.1
Saxony	31,051	1,062	3.4
Saxony-Anhalt	2,616	113	4.3
Schleswig-Holstein	26,235	140	0.5
Thuringia	1,136	569	50.0
Total in Germany	**426,202**	**21,163**	**5.0**

Table 3.4: Proportion of hydropower used for the generation of electric power worldwide (from ASE, 1997)

County	total of generated electric energy [GWh/a]	portion of hydropower [GWh/a]	proportion of hydropower [%]
USA	2,755,000	275,500	10.0
Japan	902,200	92,100	10.2
Russia	810,700	167,000	20.6
France	494,000	69,200	14.0
Germany	426,200	21,200	5.0
Canada	465,100	293,000	63.0
India	266,000	71,700	27.0
Brazil	240,000	228,000	95.0
Sweden	140,900	73,300	52.0
Norway	112,100	111,700	99.6
The Netherlands (1999)	83,800	110	0.1
Switzerland	51,600	31,500	61.0
Austria	48,200	34,000	70.5
Total worldwide	**12,081,100**	**2,147,310**	**17.9**

3.4.1 Hydropower plants

Hydropower plants consist of the following main components, which are graphically presented in figure 3.14 and figure 3.15:

- Storage of an artificial or natural lake or an impounded river.
- Intake structure with shut-off device, overflow and mechanical barriers (chapter 5.2).

GIESECKE & MOSONYI (1998) suggest that hydropower plants can be summarized in groups on the basis of varying points of view (table 3.5).

Table 3.5: Grouping of different types of hydropower plants

Technical (river training and structural engineering) and topographical criteria	
run-off river hydropower plants	in rivers or canals
storage power plants	in reservoirs with natural inflow
pumped storage power stations	in reservoirs without or with natural inflow
effective head	
low pressure plants	head < 15 m
mean pressure plants	head 15 - 50 m
high pressure plants	head > 50 m
installed capacity	
small hydroelectric power plants	capacity < 1 MW
middle size hydropower plants	capacity < 100 MW
large-scale hydropower plants	capacity > 100 MW
energy management related criteria	
base load power stations	permanent operation
mean load power stations	temporary, long-term operation
peak-load power stations	temporary, short-term operation
water management criteria	
hydropower plants that serve exclusively for the generation of energy	
hydropower plants for several water-management objectives (multi-purpose plants)	
hydropower plants that mainly serve other objectives and only secondarily are used for the generation of energy	

However, it is very difficult to establish a systematic differentiation, as on the one hand there are flowing transitions between the groups, and on the other hand numerous special forms of how hydropower are utilized.

Beside the criterion of the effective head there are additional parameters of a location to be accounted for when defining the type of power plant (table 3.6). Specific characteristics of a construction result from the turbine flow, which together with the relative construction elements, and characteristic differences will be looked at more closely in the following:

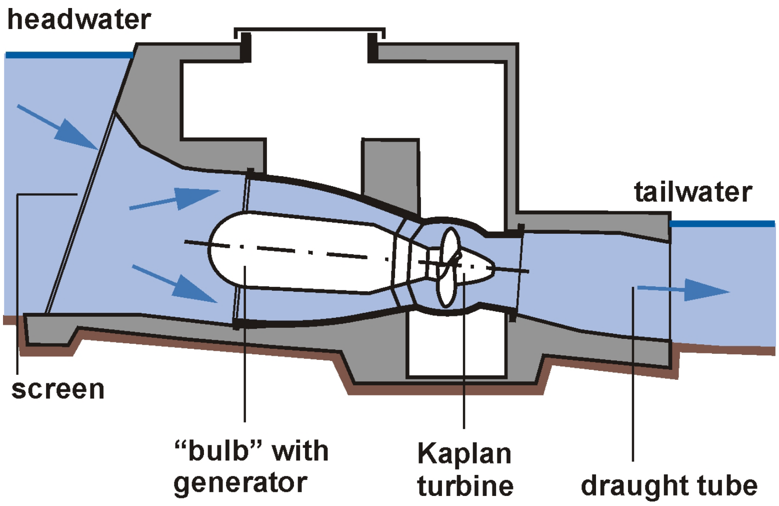


Figure 3.14:
Schematic diagram of a low-pressure power plant

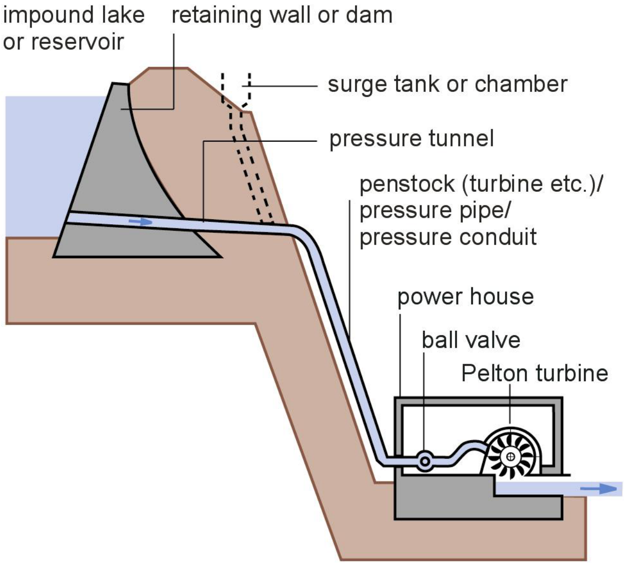


Figure 3.15:
Schematic diagram of a high-pressure power plant

Table 3.6: Typifying hydropower plants (from GIESECKE & MONSONY, 1998)

	low pressure plants h, <15 m	mean pressure plants h, = 15 to 50 m	high pressure plants h, > 50 m
type of landscape	lowlands and low mountain range	low mountain range	low / high mountain range
turbine flow	large	medium	small
substratum	mainly loose rock	compact rock	compact rock
impounding constructions	fixed and movable weirs	reservoirs (dams or retaining walls)	reservoirs (dams or retaining walls)
power conduit	river power stations or	diversion power	diversion power plants

	diversion power plants	plants, more seldom river power stations	or power plants with penstock
important construction elements	inlet, machine house, outlet	inlet, penstock or tunnel, machine house, outlet	inlet, pressure tunnel, surge tank, penstock, machine house, outlet
water turbines	Kaplan-/propeller-tubular-turbines or Francis turbines	Francis turbines or Kaplan- / propeller-turbines	Francis turbines or Pelton turbines
	at same machine capacity: units of large dimensions	units of mean dimensions	units of small dimensions
	horizontal and vertical arrangement of shafts (inclined at tubular-turbines and partly at propeller turbines)	vertical arrangement of shafts	mainly vertical arrangement of shafts (horizontal only for smaller hydroelectric generating sets)
generators	generators with high number of poles	generators of standard design	generators of standard design
	directly coupled generator (gear)	directly coupled generator (gear)	directly coupled generator or with gear
storage volume	water operated power plants or daily storage	daily or weekly storage	daily storage to storage over the year
prevailing energy generation	fluctuating and possibly interrupted	minor fluctuations, steady	adjusted to demand
load operation in interlinked operation	base load power station in interlinked operation	base load power station in interlinked operation	base-, mean or peak power station

3.4.1.1 Low pressure power plants

Low pressure power plants work at heads of up to 15 m and a relatively great flow-through. They are designed as river or run-off river power plants with propeller, Kaplan, tubular or direct flow turbines, especially where the topography does not provide significant storage possibilities when large areas of the river banks are flooded. Francis-turbines are only employed for this kind of power plant in the exceptional case. The number of hydroelectric generating sets used in a power plant, depends primarily on the flow-through volume and the annual discharge characteristic of the individual water body. Low pressure power plants are either singly used or operated as a flow storage in a chain of power plants, and often also in combination with other utilization objectives like for example navigation or drinking water extraction.

This type of power plant is preferably used as a river power station in rivers and streams with a gravity smaller than 2 ‰ and is built transverse to the streamline. Storage and power plants hereby create an additional reservoir of minor capacity. In most cases weir and powerhouse are located side by side. This arrangement proves best especially where the maximum flood water flow can be discharged over the dam construction and does not involve a further widening of the river cross-section. A lock is additionally installed in rivers used for navigation.

Arranging river power stations in rows, the so-called staggered or chain-arrangement can decisively enhance the utilization of the head. Staggered river power stations can be operated as water operated power plants or as a succession of river power stations with flow storage. In this case water operated power plants utilize the natural water supply continuously over the day without any significant storage, and thereby provide base load energy. River power units are operated in flow storage in order to adjust the generation of electric power to a fluctuating demand. The existing hydroelectric generating sets are controlled in dependence of need. A precondition for this operation mode is that each individual barrage of the power plant chain has a sufficiently large storage volume that can be utilized if needed in addition to the natural discharge.

The flow storage of a power plant can generally be performed as a tipping or surging operation. Tipping operation means that all hydropower plants are taken into operation with the same turbine flow, so that the water level “tips” out of its neutral position. This mode of operation activates instantly the full capacity of the entire chain. Surging operation means that the individual hydropower plants are taken into operation successively in accordance with the discharge. This operation mode achieves an effective utilization of the head and an increased capacity over a longer period.

Power plant chains like those on the Rhine, Moselle, Neckar, Danube and Drau are nowadays increasingly automatically controlled. Complex control and simulation models are employed that exceed requirements for an optimized energy generation, and take also the interests of the inland waterway transport, management of water flow, environmental correlations into consideration, as well as those of leisure and recreation.

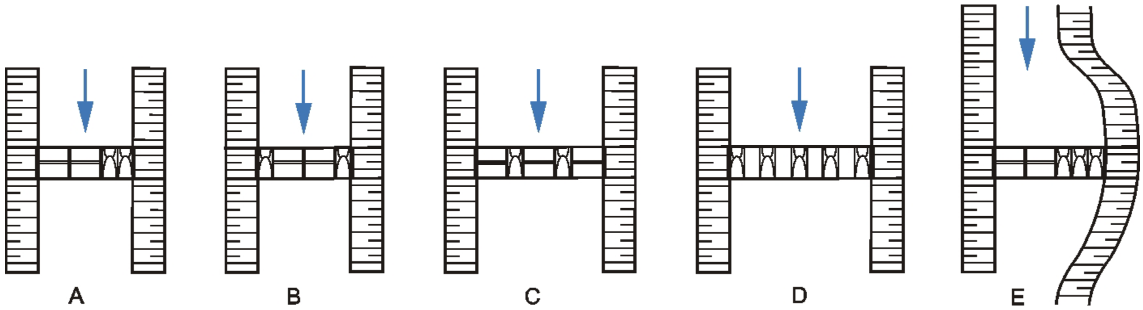


Figure 3.16: Arrangement of river power stations
A: modular construction, B: twin construction, C: buttress construction,
D: overflowable power plant, E: bay power plant
(changed according to GIESECKE & MOSONYI, 1998)

There are three construction designs of hydropower plants that can be defined in dependence on how power house, weir structure and a possibly existing navigation lock are arranged in the cross-section of a water body:

Compact construction

a) **Modular construction** (figure 3.16 A): The powerhouse shall preferably be located at banks with minor silting. In order to improve the often unfavourable approach velocity and flow conditions, it may be necessary to build guide walls to prevent cross currents and the formation of still pond zones which tend to become silted.

b) **Bay power plant** (figure 3.16 E): Bay power plants are a specialized form of modular construction, where the power plant is located along the original course of a river in an artificially created bay. Compared with the modular construction, the flow-through cross-section of the water body is only slightly reduced or not at all, thus allowing that flood water to remain where there are no obstructions.

Incompact construction

a) **Twin construction** (figure 3.16 B): Construction of the power plant in two parts may be sensible for water bodies with great discharges but a small head, in order to house a greater number of machines on the one hand, and on the other to prevent disproportion between the length of the powerhouse and the original width of the river. A symmetrical arrangement of both powerhouses offers advantages in respect of approach velocity and flow conditions.

b) **Buttress construction** (figure 3.16 C): Weir fields and turbine buttresses alternate in the cross-axis of the weir structure at buttress power plants. Turbine buttresses also serve as abutment for the weir fields, which results in a very steady approach velocity for both parts. A powerhouse is not required for this type of power plant, because the operational premises can be arranged alongside the turbines. The hydroelectric generating sets can be maintained via a gantry crane installed on the roof of the structure.

Overflowable construction (figure 3.16 D): Overflowable hydropower plants, also called submerged power plants, are of one homogeneous structure, which houses the hydroelectric generating sets, and serves for the impoundment generation as well as the delivery of water when exceeding the design flow. The crown of the structure normally bears a weir crest consisting of several gates, which is turned in the event of a flood, so that the water can be discharged via the weir power plant and will be overflowed. The first submerged power plant was taken into operation at the Patapsco Weir Ilchester (USA, Baltimore) in 1907. In Germany, the first submerged power plants were built on the Persante (Pomerania, today Poland), Iller and Lech (Bavaria) rivers (figure 3.17) during the years 1936 to 1945.

Submerged power plants require only little space, and it is possible to integrate these structures comparatively well in the landscape (figure 3.17). The 40 m wide weir "Karlstor" (Charles' gate) on the Neckar river (Baden-Wuerttemberg) that is located in the historical old town of Heidelberg, has for this reason been equipped with a submerged power plant (figure 3.18) (LIENING, 1996). This inundated run-off river hydropower plants power plant consists of two Kaplan-tubular turbines and achieves a total capacity of 3.1 MW at a head of 2.6 m and a flow rate of 140 m^3/s.

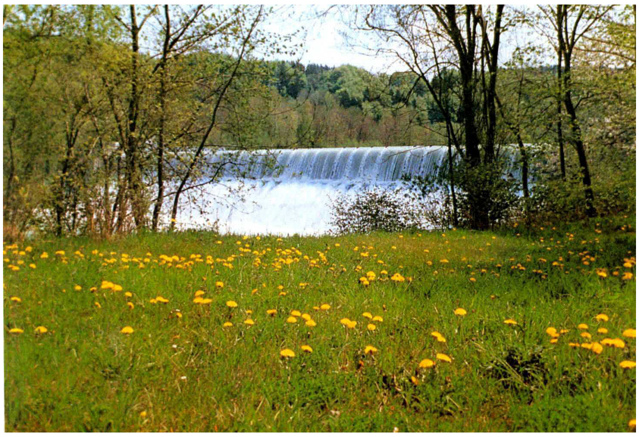


Figure 3.17:
Overflowable hydropower plant Lechblick on the Lech river (Bavaria, Germany)

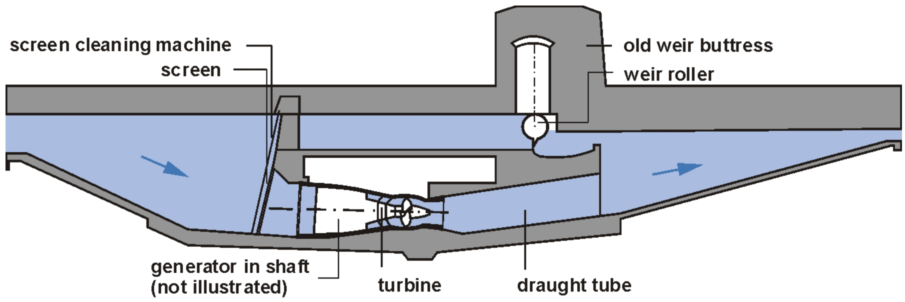


Figure 3.18:
System profile through the submerged power plant "Karlstor" in Heidelberg on the Neckar river (Baden-Wuerttemberg, Germany) (changed according to LIENING, 1996)

3.4.1.2 Mean pressure power plants

Mean pressure power plants are those hydropower plants which utilize a head of 15 to 50 m. These are mainly located at low-lying reservoirs in the form of storage power plants or as run-off river power plants on higher situated weirs, whereby the required flow rate is adapted by the reservoir management. The construction of the powerhouse is one of the characteristic features of the mean pressure power plant next to the head range, and consists of the following components:

- intake with screen and turbine gate
- power conduit
- intake spiral, hydroturbine and suction tube

The machines installed are mainly Francis turbines. Pelton or Kaplan turbines are rarely used.

3.4.1.3 High pressure power plants

High pressure power plants utilize heads above 50 m for energy generation at relatively low flow rates (figure 3.15). The losses that occur in the frames and feed pipes because of the great heads are of minor importance. More significant are the energy losses caused by fluctuations of the available discharges in relation to the size of the catchment area and storage capacity. Therefore quite often neighbouring catchments are included, whereby the compensation of fluctuating inflows is accomplished through a purposeful management of several reservoirs. Pelton turbines and Francis turbines are employed for heads up to 300 m.

Pumped storage power stations belong basically to the group of high pressure power plants. Therefore, any cheap excess current from the network is used during light load periods to pump water from a lower storage basin, river or lake into an upper storage basin. The upper storage basin will be emptied again at periods of peak demands, and the stored water powers the turbines of the plant. Pumped storage power stations have the advantage that their power generation can be immediately adjusted. They are therefore primarily employed as a flexible means to compensate load peaks and to make available a spare capacity that can quickly be utilized in case of a temporary breakdown of other power plants.

3.4.1.4 Diversion hydropower plants

When first hydropower plants were constructed, the power plant was preferably placed outside the water body for constructional and operational reasons. The powering water is hereby discharged from the impounded weir into the headwater channel (figure 3.19), which feeds the diversion hydropower plant. This type of plant is also called discharge power plant or canal power plant. Its design may alternatively be a low pressure power plant or mean pressure power plant.

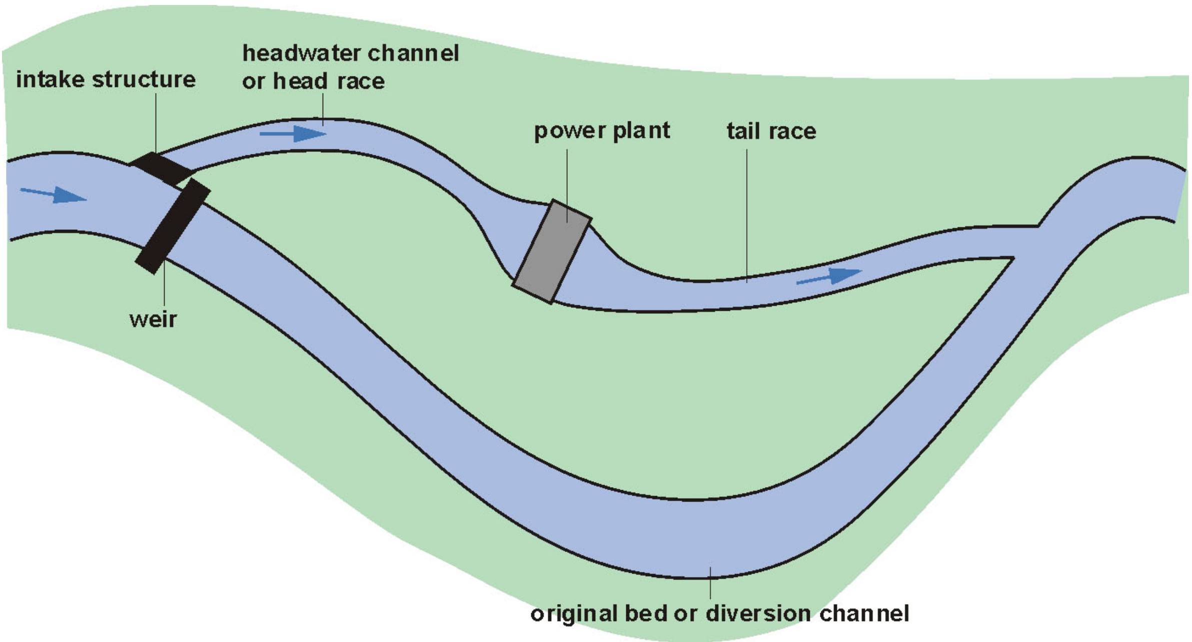


Figure 3.19: Schematic diagram of a diversion hydropower plant

Often there is an intake structure installed at the outlet of the headwater channel (figure 3.20), which consists of the following components:

- skimming wall to reject flotsam, drift ice, etc.,
- coarse screens to protect against driftwood
- river bottom sill to reduce silting

- shut-off devices like gates to drain the canal stretch
- admission of rafts or boats to navigate on the canal

Bed loads in rivers are continuously or temporarily washed back into the river bed from the inlet through bed load channels.

Only the minimum discharge that is not used for the generation of energy, and the discharge that exceeds the development dimension of the hydropower plant remain in the tailwater of the impoundment structure, i.e. in the original bed at diversion hydropower plants. The volume of the minimum discharge is especially important for fish to pass the discharge reach. Concerning the problems connected with downstream migration, care must be taken that migration corridors like the passage over the weir and through the diversion channel are made available to fish.

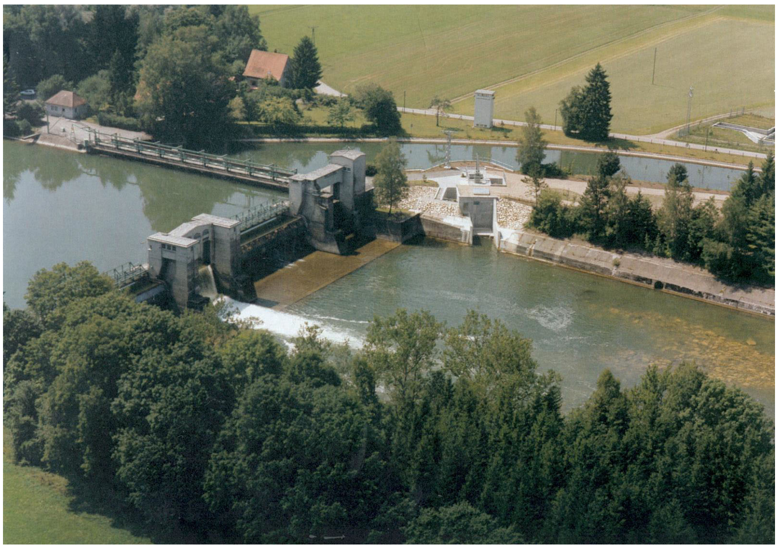


Figure 3.20:
Intake structure Illerkanal (Iller Canal) on the weir Moos-hausen (Baden-Wuerttemberg, Germany)

3.4.2 Turbine technologies

The various types of hydropower plants are operated with different types of hydroturbine. Dependent on head and defined design flow, there are turbine types available, which by their design are most favourable and suitable for a specific location and fulfil construction criteria, like for example the shape of runner, rotary speed, diameter and installation height (figure 3.21). Such considerations are always based on long-term measurements of discharge and water level required for the evaluation of head and discharge.

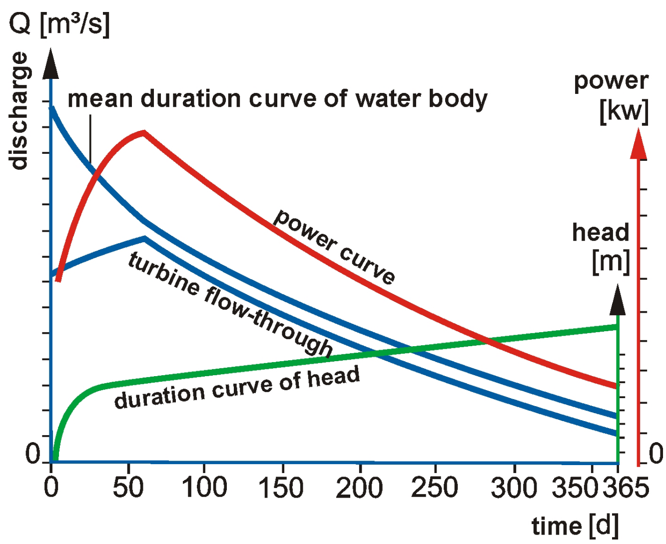


Figure 3.21:
Duration curve of flow, power curve and duration curve of head (changed according to WBW, 1994)

The design flow stands for the flow of water that is taken for the dimension of the hydropower plant. The design capacity of a hydropower is not solely dependent on the discharge characteristic of the water body, but also on the purpose for which the hydropower plant shall be built, as well as other uses of the water body and finally on the cost-benefit-ratio.

It has been learned that the design flow of a turbine lies between 80 and 120 days p.a., but can also reach values of up to 180 days p.a. The nominal value of head and design flow are defined by the design flow selected. Figure 3.22 demonstrates the application fields for the different hydroturbines depending on head and water flow.

The choice of turbine to be used is guided by the most economical solution. Pelton turbines are basically employed for great heads, mean heads require Francis turbines and small ones the Kaplan type. Sometimes application fields of turbines overlap, the following views listed below are a quotation of some which should be considered when selecting the right turbine type for a specific application.

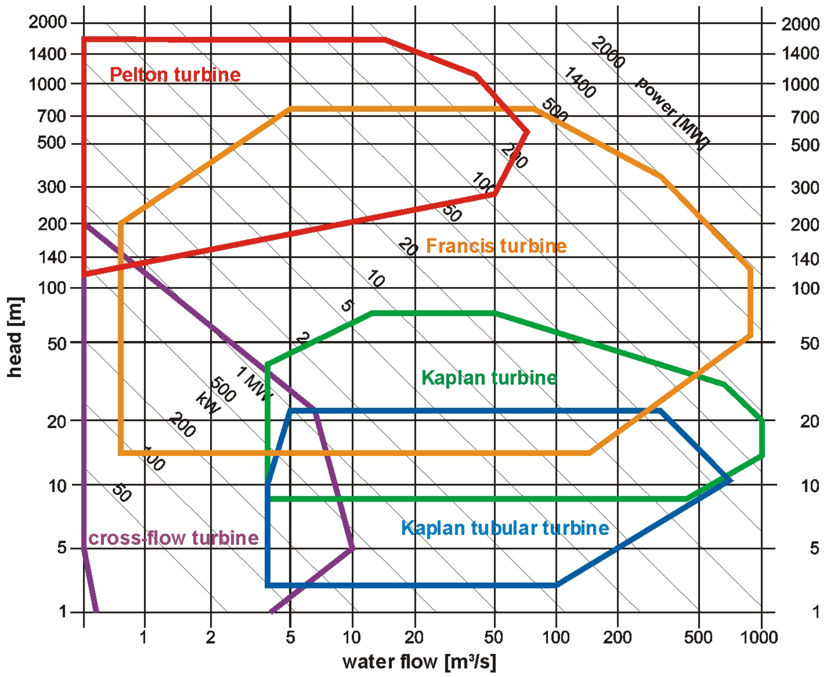


Figure 3.22: Application fields of various types of hydroturbines and ratings in dependence on head [m] and water flow [m^3/s](changed according to GIESECKE & MOSONYI, 1998)

Overlapping range
Pelton and Francis spiral turbine:

The advantages of a Francis spiral turbine in comparison with a Pelton turbine are that of smaller dimensions and greater rotary speeds. Also there are lower costs involved for a Francis spiral turbine that is more suitable for an application at strong fluctuations of the tailwater level.

The Pelton turbine shows a flatter progress of the efficiency ratio in comparison to the Francis spiral turbine. This means that this type of turbine covers a power range of 20 to 100 %, while the Francis turbine only achieves 40 to 100%. The Pelton turbine therefore accomplishes a greater annual working capacity especially where water supplies are fluctuating. This type of turbine is also preferred if an application in sandy water is required, as the small number of wear-and-tear parts is repaired or exchanged quickly and economically.

Overlapping range
Vertical Francis-turbine and Kaplan turbine:

The advantages of a vertical Francis turbine in comparison to a Kaplan turbine are to be seen in the simpler and thus more economical erection of turbine and powerhouse. Furthermore, it is possible to operate vertical Francis-turbines at heights of up to 6 m between rotor axis and tailwater level

However, Kaplan turbines can obtain a greater annual working capacity especially at fluctuating water supplies, because of higher rotary speeds and better efficiency, provided runner and discharge ring are adjustable. For horizontal turbines it is also feasible to have low-built powerhouses installed which can better be harmonized with the surrounding landscape.

The decision on the turbine type to be employed is always dependent on local conditions. Previously, the geared tubular turbines were more readily used because of lower price, small structure and ease of installation. The turbine types most employed shall be described in more detail hereunder:

3.4.2.1 Water wheel

The water wheel (figure 3.23) is a primitive form of hydropower machine. The history of water-powered water scoops can be traced back to the 3rd century BC. Water wheels were mainly employed as irrigation installations and as actuators for corn mills. Even today they are still used by following their original construction principle. Since the 9th century in Central Europe water wheels have been used for manual work like forging, tumbling, stamping, grinding, sawing, turning etc. The National Trust today intensifies its efforts in preserving historical water mills as impressive witnesses of traditional crafts and as a technological cultural asset of the pre-industrial world of professional occupation.

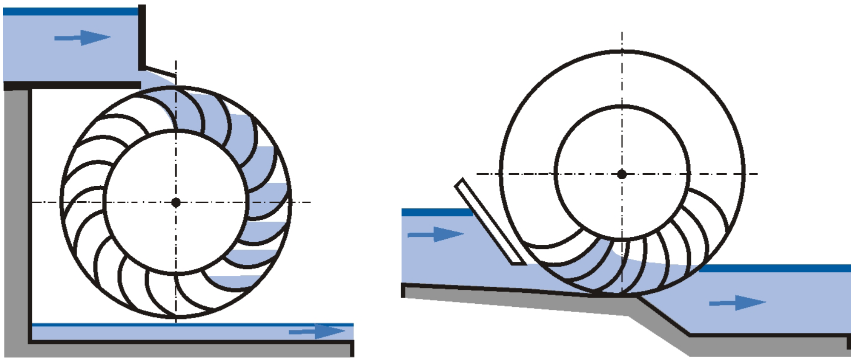


Figure 3.23:
Water wheel typesleft: overshot bucket wheelright: undershot bucket wheel

Over thousands of years has the water wheel been maintained for its purpose to power mills. They were in parts gradually replaced by the more effective hydroturbines for the generation of electric power. Nowadays, water wheels of newer constructions are in operation which may yield an efficiency of up to 75 %, provided specific frame conditions are fulfilled, and water supply and gradient are low.

3.4.2.2 Archimedean screw

The water-lifting screw is since ancient times known as Archimedean screw. Almost forgotten during the first half of the 20th century, it was then revived with its application in waste water technology. The Archimedean screw is an energetic reversion in comparison to the water-lifting screw known from waste-water technology (figure 3.24).

The Archimedean screw is not a turbine, but could possibly be related to water wheels, as like an overshot water-wheel it takes full advantage of the potential energy of water under atmospheric pressure. However, this power converter with an absorption capacity of 0.04 to 5.5 m^3/s and heads of 0.5 to 8.0 m goes beyond the classical spectrum of water wheels and under specific conditions is capable of adjusting itself to varying water levels. The Archimedean screw cannot obtain the peak efficiency of turbines of > 90 %; but values of 84.25 % have been measured at full load (KLEEMANN, 2003).

Figure 3.24:
Archimedean screw with a capacity of 20.5 kW at a head of 2.0 m and an design flow of 1.2 m^3/s (mills in Taufers/South Tyrol)

3.4.2.3 Francis turbine

The Francis turbine was first taken into operation in 1873. It is a machine that is suitable for a wide range of applications, but in some fringe ranges overlaps with the Pelton and Kaplan turbine. Heads between 15 and 720 m and water flows of up to 900 m^3/s can be managed by this turbine type, achieving a machine capacity of up to 1,000 MW.

The water is guided to the runner (figure 3.25) over a concrete or steel spiral and the adjustable wicket gate (figure 3.26). The water hereby flows radially onto the fixed, spacially curved runner blades and axially out. It is solely regulated by the wicket gate which in comparison to the Kaplan turbine results in a less favourable partial load behaviour. The Francis turbine, like any other low pressure turbine, holds a draught tube where the pressure within is artificially reduced behind the runner and thus achieves a higher efficiency of the turbine.

Prior to the development of the Kaplan turbine have Francis turbines also been employed where Kaplan turbines are presently used for their better efficiency. Many of this type of installations are still in operation today.

Figure 3.25: Runner of a Francis turbine

3.4.2.4 Vertical Francis turbine

A smaller, simpler and therefore more economical construction of the Francis turbine is the vertical Francis turbine or chamber turbine, which is mainly employed in small hydropower plants (figure 3.27). It is used for heads of up to approximately 5 m and therefore does not need to have the spiral housing. The spiral housing is replaced by a simple turbine chamber of rectangular profile. This type of turbine is only equipped with adjustable guide vanes, runner and draught tube. The regulating rods of the discharge ring are located open in the headwater.

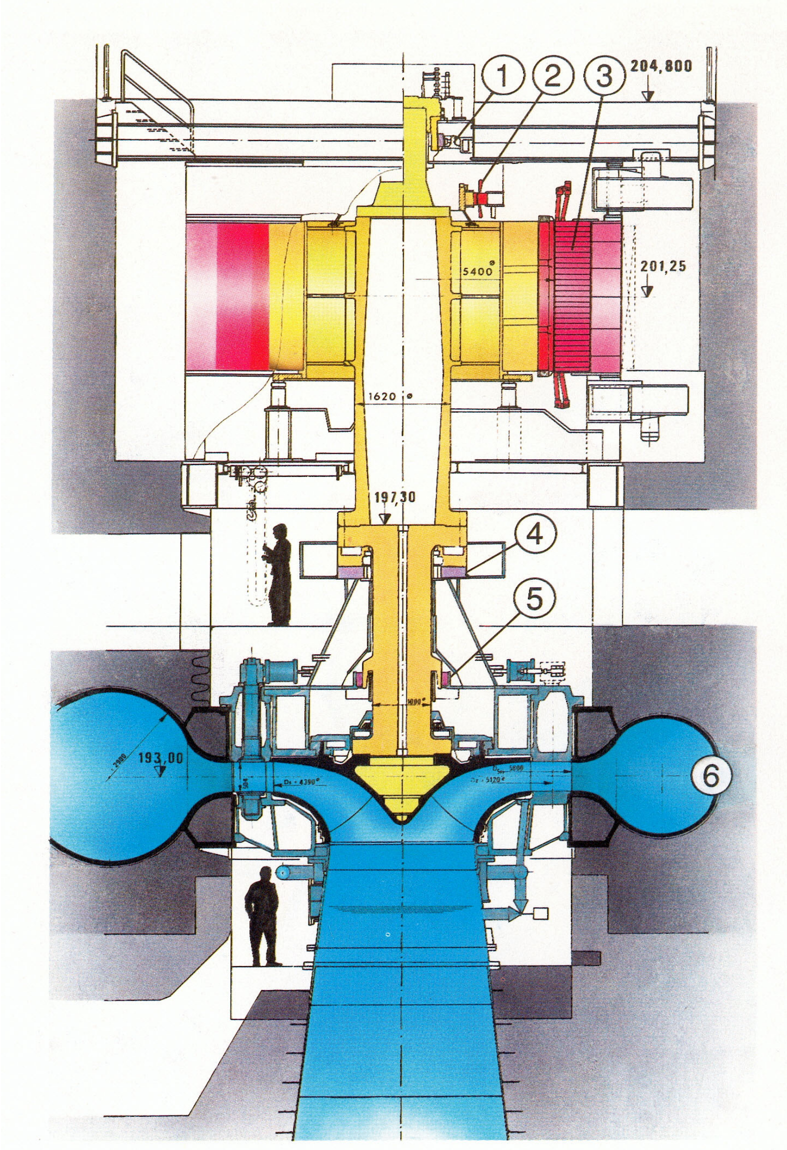


Figure 3.26:
Installation of a Francis turbine in a storage power station (mean pressure plant) (changed according to EnBW ING, 2000)

1 upper guide bearing
2 exciting device
3 generator
4 supporting bearing
5 lower guide bearing
6 scroll case

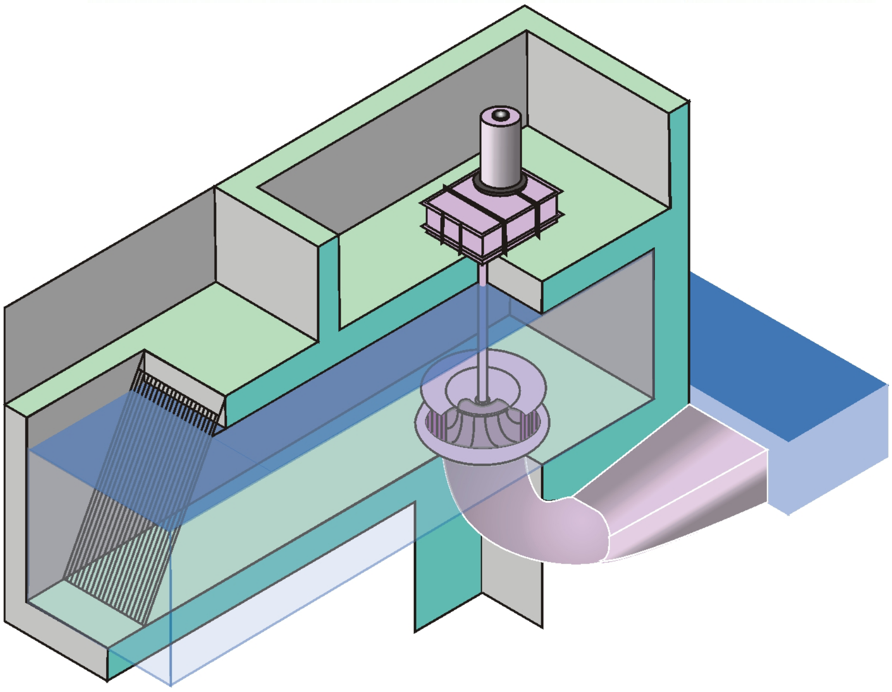


Figure 3.27:
Schematic diagram of a vertical Francis turbine with vertical shaft, gear and generator

3.4.2.5 Pelton turbine

The Pelton turbine was first built in the year 1892. It is also known as open jet turbine. This type of turbine belongs to the group of high pressure turbines that are employed at heads of > 100 m and a flow of water of < 80 m^3/s. Classical application fields for this turbine type are for example Alpine storage power stations with heads of up to 2,000 m. The water is hereby guided from a reservoir to the power station via a penstock. The water is then led to a runner with mounted bowls by means of one or several jets (figure 3.28). The water jet that hits the runner blades at high speed will be diverted and so effects a rotation of the runner. The rotating turbine shaft in this case can be arranged vertically or horizontally. An adjustable needle inside the jet body forms the controlling device. Pelton turbines can be designed with one or several jets in dependence of the flow of water. If an emergency closure takes place, for example in case of a power failure, the turbine can be stopped quickly by means of a jet deflector. A valve plug, for example a ball valve, is arranged in front of the turbine for revision purposes.

Figure 3.28: Runner of a Pelton turbine

3.4.2.6 Cross-flow turbine

The water that at this type of turbine is tangentially fed from the wicket gate flows through the cylindrical runner from the outside to the inside, and after having crossed the interior of the runner from the inside to the outside. The cross-flow turbine was developed in the thirties of the last century and is particularly well suited for the application at heavily fluctuating inflows, as it is possible to admit the runner only partially in dependence of the available powering water. The multicell design (standard partioning 1:2) facilitates the efficient utilization of minor water flows through small cells, mean water flows through large cells and the full flow of water at a combination of both (figure 3.29). This feasibility to adjust the performance to the fluctuating water supply results in a very flat, but lower curve of the turbine efficiency in comparison to other types of turbines. The cross-flow turbine has lately been installed at small hydropower plants for ease of adjustment to heavily fluctuating inflows and its simple construction. The application applies to heads between 1 and 200 m.

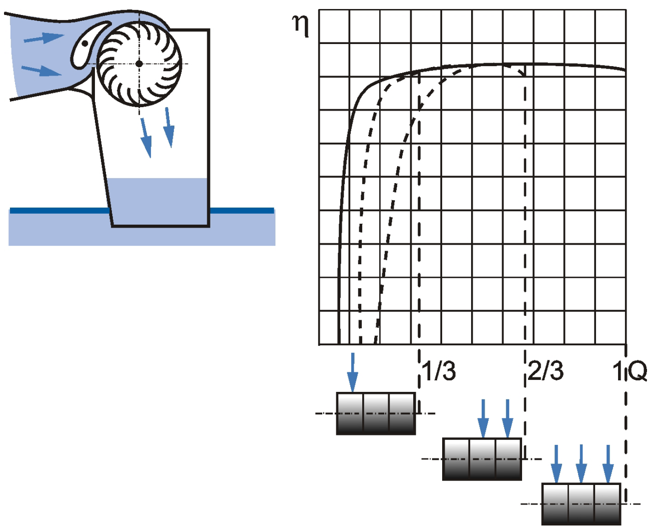


Figure 3.29:
Course of flow at a cross-flow turbine (changed according to GIESECKE & MOSONYI, 1998) with a horizontal inflow (left) and efficiency curve at a 1:2-partioning (right)

3.4.2.7 Kaplan turbine

The first application of a Kaplan turbine goes back to the year 1919. Kaplan turbines are axial hydroturbines equipped with only a small number of blades (figure 3.30). The main application field refers to heads between 8 and 70 m and a water flow of up to 1,000 m^3/s. This turbine type is particularly suitable for river power stations, where fluctuating heads and varying water supplies occur, because of its good adjustability and flat efficiency curve. At the classical design of the Kaplan turbine with a vertical shaft the water flows over a concrete spiral and the adjustable wicket gate onto the runner, which is equipped with runner blades that are also adjustable (figure 3.31). The outflow takes place via a draught tube elbow.

As Kaplan turbines are more adjustable, they are given preference to Francis turbines in application fringe areas. The disadvantages of the Kaplan turbine, however, exist in loss of efficiency through the double flow diversion. Also, there are higher construction costs involved with the large depth required for the construction and the following draught tube elbow because of the vertical position of the shaft.

A simplified form of the Kaplan turbine is the propeller turbine, which is of identical design with the exception of non-adjustable runner blades. It is more favourable in price than the Kaplan turbine because there is no need of the otherwise required hydraulic adjustment mechanisms and the appertaining wicket gates. A disadvantage, however, is the lack of adjustability to changing hydraulic conditions, and therefore minor efficiency.

Figure 3.30:
Runner of a Kaplan turbine

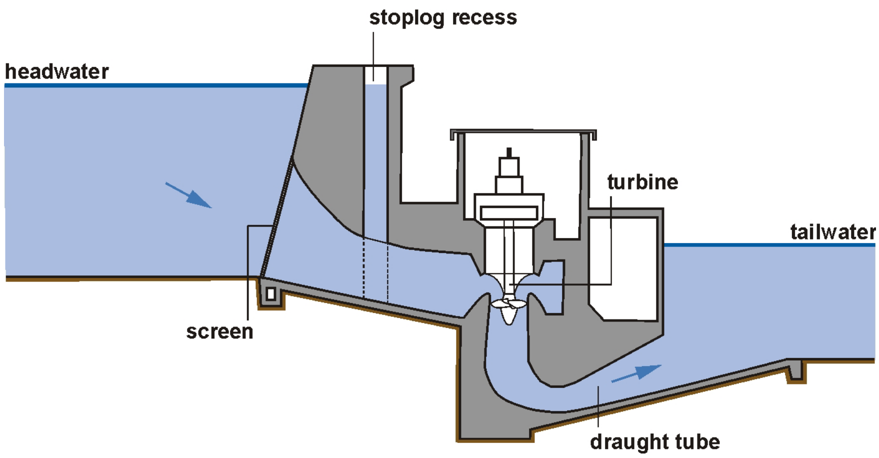


Figure 3.31:
Kaplan turbine in a run-off river hydropower plant

3.4.2.8 Kaplan-tubular turbine

The Kaplan-tubular turbine presents a special design of the Kaplan turbine. Its application field lies at heads between 2 and 22 m and water flows between 4 and 750 m^3/s. This type of turbine today is one of the most used types of equipment for run-off river power plants. The Kaplan-tubular turbine is directly installed in the tube with a horizontal or slightly inclined shaft. The water flows around the turbine housing with turbine shaft and generator, and flows via the adjustable wicket gate through the also adjustable blades of the runner (see also figure 3.14). The water flows out through the following draught tube. An increased efficiency by about 3 % is obtained in comparison to the Kaplan turbine of classical design as the water flows straight through the turbine. Furthermore, there are lower costs possible since the Kaplan-tubular turbine is very compact and does not require spiral housing and draught tube elbow

An outstanding feature is the so-called outside ring tubular turbine, where turbine and generator build a direct coupled aggregate without a drive shaft. The generator is positioned on the same vertical level as the runner, but arranged outside the flown-through tube. The runner can be designed with movable or fixed runner blades. The advantages of this type of construction result from a reduced construction and plant volume and thus the savings in costs involved. The higher maintenance works incurred with the operation, however, constitute disadvantages.

3.5 Water intakes

Intake structures are built for the discharge of drinking and industrial water. They are either located directly on the bank or are approached by the flow through an offset canal of varying length. The lateral water extraction, mostly concerning only a minor portion of the total discharge, does not require the water body to be impounded. Figure 3.32 presents a schematic design of an intake structure.

In the simplest form curtain wall and debris screens prevent flotsam being washed in. If there are higher requirements on the purity of the industrial water, several fine screens, band screen machines and other filter systems are connected. Silt is extracted from the water via screen cleaning and band screen machines.

A special form of the so-called Tyrol weir that, when appropriately aligned, is also employed for control examinations of fish protection facilities and downstream fishways (chapter 6, figure 6.8): This kind of construction is a stationary hydraulic installation where a screen is installed in the river bottom at an inclined angle of maximal 25° to the flow direction. The water that is flowing through the screen will be extracted via a diversion channel, whilst the excess discharge volume and flotsam will remain in the water body.

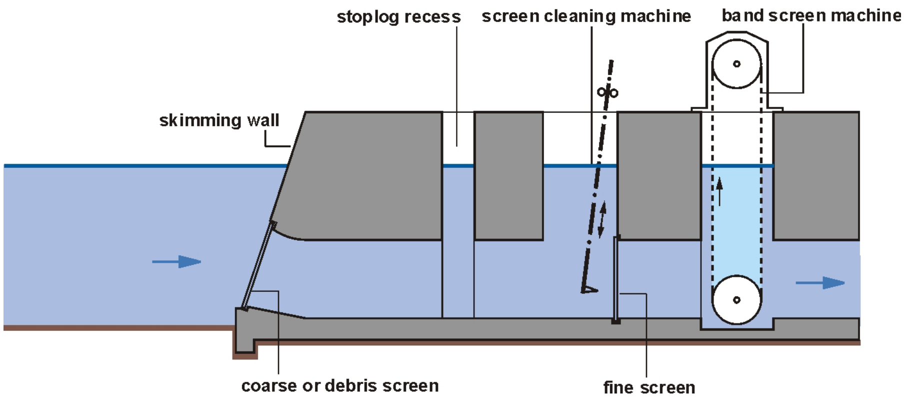


Figure 3.32: Schematic diagram of an intake structure

3.6 Culverts, bridges, floodgates and pumping stations

According to DIN 19661, part 1, cross-constructions are divided into conduit and estuarine structures. Conduit structures are constructions like bridges, culverts, pipelines and dive culverts, which are necessary where water bodies cross other installations like traffic ways, dams, dikes and watercourses.

Estuarine structures comprise outlets, inlets and flood gates as well as pumping stations according to DIN 1184, part 1. These structures can be of an entirely different design and dimension in dependence of the size of the water body, position and function. As they are generally dimensioned and designed as required under hydraulic, operational and static views, possible impacts and restrictions of a free passage of the water body for the fish fauna cannot generally be excluded.

4 Harmful impact on migrating fish

Basically, fish damage may occur in any water body where free passage is obstructed. This especially applies to regulated rivers where hydropower plants are installed and water courses that are utilized for water extraction by means of appropriate structures. The kind and impact of the damage depend on the local conditions and can vary to a great extent. A high degree of mortality of migratory fish can possibly be crucial to the sustainability of a particular species from an ecological point of view, as damaged fish will irretrievably be withdrawn from reproduction.

With regard to the damage of fish populations, species used for fishery are also considered under economical aspects. Within the frame of ichthyo-biological examinations by means of an anchored stow-net (figure 6.4, figure 6.5) in the tailwater of the Frankel barrage on the Moselle river (Rhineland Palatinatete, Germany), the degree of damage to eels due to turbine passage amounted to 23 %. A total annual loss of approx. 500,000 Euro (JOERGENSEN et al., 1999) is estimated for the ten hydropower plants in the German section of the Moselle river. WONDRAK (1989) quotes an annual loss of eels of at least 150,000 Euro for the Bavarian part of the Main river for the same reason. The subsequent deficit in juvenile fish growing up ready to be fished as a secondary economical loss to the fishing industry has hereby not yet been considered, though this can hardly be quantified anyway.

Especially in view of the preservation of the eel population, it is of great importance to reduce the mortality rate caused by downstream migration, as the morphology of the eel makes it especially prone to turbine damage. Due to its reproduction biology the eel is an obligatory migratory fish, and thus to a high degree endangered by turbine damage in hydropower plants. The eel is furthermore subjected to a number of other hazardous factors: Being a popular cooking fish, the eel is exposed to excessive leisure and professional fishing. Great infestations of nematodes *Anguillicola crassus* which were introduced from Asia, and live parasitically in the air bladder of the eel, lead to the conclusion that the function of the air bladder as a hydrostatic organ is thus disturbed. Therefore, a great number of the infested eel cannot reach their spawning area, the Sargasso Sea, and thus is also lost for reproduction. KUHLMANN (1997) considers this factor next to the loss through damage caused by turbines the most significant for the population maintenance.

Contrary to most of the other fish species, the eel spawns only once and with it completes its lifecycle (figure 2.3). Each pubescent eel that does not reach the spawning area in the Sargasso Sea is hence withdrawn from maintaining the population of its species. The eel population is exclusively recruited in a natural way. It has until now not been possible to increase the population of the eel artificially for the aqua- and mariculture despite intensive research. In subsequence thereof it is not possible to support the population of the eel.

Damage caused by turbines additionally concern juvenile anadromous species and potamodromous fish which migrate into the sea. Table 4.1 demonstrates mortality rates of such fish species which have been caught by HOLZNER (1999) by means of nets in the tailwater of the Dettelbach hydropower plant on the Main (Bavaria). The power station consists of two vertical Kaplan turbines with runner diameters of 3.54 m, and together they achieve a maximum flow of 120 m^3/s. The head amounts to 4.55 m. A conventional screen with a bar spacing of 90 mm is installed at the intake.

Besides the subsequent risks to which migratory fish are exposed when overcoming impounding structures or turbine and water intake passages, fish can also be damaged in installations which in fact are installed for their protection. This regularly happens when necessary frame conditions have not been complied with, like the approach flow against screens with small spacings. Such damages observed at fish protection facilities are quite similar in their damage characteristic and rate to those caused by turbines.

The effectiveness of preventive measures is to a high degree dependent on the variability of the frame conditions such as run-off, flow velocity, turbidity and temperature. The behaviour of the fish in dependence on species, age, size and development phase plays an additional role.

Table 4.1: Total number and average rate of mortality of fish registered over 111 days of netting examinations at the Dettelbach hydropower plant on the Main river (taken from HOLZNER, 1999)

species	number of species	mortality in [%]
eel	2,840	27.0
brown trout	244	15.0
barbel	56	15.0
bream	594	48.0
perch	2.846	25.0
crucian	33	45.0
white bream	54	46.0
dace	51	31.0
pike	28	16.5
carp	33	20.0
ruffe	975	17.0
roach	1,626	34.6
asp	63	14.2
rainbow trout	31	13.0
tench	49	11.0
bleak	308	22.0
catfish	33	6.0
zander	20,860	21.0

4.1 Damage during impoundment / dam / weir passage

Reservoirs with their relatively large water volumes and rather low flow velocity normally show a fish population that is not typical for flowing waters, and is generally distinguished by a greater biomass, and often also by a high population of predators. Migrating fish cannot avoid passing the reservoirs where they are exposed to a higher predation risk.

Whether fish can surmount dams is dependent on the water flow. As soon as a weir overflow is provided by sufficient discharge volumes, it can be assumed that for example smolts of salmon and sea trout that are migrating near the surface can pass the dam with the overflowing water.

A sufficient depth of immersion must hereby be ensured. Damages should be of minor significance, if the difference in height (see below) is not too great and the water depth below the dam amounts to at least a quarter of the head, but by no means lower than 0.9 m. In order to prevent excessive gravitational forces, the stilling basin must have a minimum volume of 10 m^3 per 1 m^3/sec discharge (or run-off) (ODEH & ORVIS, 1998).

The impingement speed of the fish in the tailwater is of decisive importance for the cause of mortality. Investigations of BELL & DELACY (1972) have proven that independent of the size of the fish, serious injuries like damaged gills, eyes and inner organs occur when the impingement speed on the water surface exceeds 15 to 16 m/s. The impingement speed of the fish is solely dependent on the head if the fish is embedded in the water body of the weir overflow. The speed of 15 to 16 m/s that is crucial to fish will hereby be achieved after a fall from a height of approximately 13 m. The damage and mortality rate rises quickly with greater falls, so that a mortality rate of 100 % will apply to heads between 50 and 60 m. However, the risk of damage will be small, should the impingement speed be lower than 13 m/s, provided that a reduction of the speed of the nappe takes place without a major diversion and that a sufficient depth of the tailwater is guaranteed.

The impingement speed is, when isolated from the water body not only dependent on the head, but also on the size of the fish. Fish of a total length of 60 cm, for example, reach the critical impingement speed after a free fall from a height of 13 m. Smolts of salmonids of a total length between 15 and 18 cm, however, not before a free fall from a height between 30 and 40 m. Fish of a length lower than 10 to 13 cm do independent of the fall normally not suffer from any damages when they bump onto a water surface, as they will never reach the critical speed of 15 to 16 m/s. The situation for small fish is therefore always more favourable, when they pass the weir overflow isolated from the water body. For large fish, however, the risk within the nappe remains. In consequence of these correlations have the sluices of the Bonneville Dam (Columbia River, USA), for example, been arranged like ski jumps, so that the water body will be dispersed and the migrating smolts of salmonids bump into the tailwater isolated from the water body. This system will significantly reduce the risk of damage (figure 4.1) to fish.

Figure 4.1:
Dispersion of the weir structure through a ski jump-like design of the sluices at the Bonneville Dam (Columbia River, USA) for the purpose of reducing the mortality of migrating smolts of sal-monids

An increased mortality can occur when fish drift over high drops or passage of culverts like undercurrents at crest wicket gates because of sudden pressure fluctuations or changed velocities of flow. In this respect Salmonids are clearly more robust than Clupeids like twaite shad and allis shad. This species of fish is prone to pressure changes, especially to pressure drops, conditioned by the position and expansion of the air bladder, which on Clupeids spreads into the back of the head, where it is located in contact with the brain (STOKESBURY & DADSWELL, 1991). The air bladder expands during a pressure relief and thus squeezes the brain, which often has a lethal effect.

At times of high run-offs and an overflow of the weir, it is possible that at great heads the water will be significantly oversaturated with atmospheric gases, which for fish lead to symptoms of the so-called gas bubble disease (figure 5.70) and can result in a fatal end (RAYMOND, 1979). The reasons for mortality deriving from the impact that a free fall, pressure fluctuations and gas oversaturations in the tailwater may have, can be considered to be unimportant at European hydropower plants, as they mainly hold a low storage level.

Influencing elements or other built-in elements for the purpose of energy conversion are often installed in the tailwater of weirs or at spillways of dams. It is possible that fish collide with these structures and can get killed.

Another, although difficult to quantify secondary mortality occurs in the tailwater of dams through predators, which chase especially weakened, injured, dazed and disoriented fish (figure 4.2).

Figure 4.2:
A brown trout has captured an eel that was damaged in a turbine in the tailwater of a mill on the Doersbach river (Rhineland-Palati-nate, Germany).

4.2 Damage at water intakes and screens

Water is extracted from many rivers to be used as industrial water, although there is no impoundment involved. Significant flow velocities quite often occur in the area of water intakes, but also in the feeding offset canals, which can be perceived by the fish and interpreted as guide flow. As migrating fish normally follow the main flow, they are particularly jeopardized to enter such water intakes. If the relation between the water current in the original bed and the intake volume is unfavourable, this may result in high structure-specific damage and mortality rates (TRAVADE & LARINIER, 1992).

Examinations of screenings at thermal power plants, where water is withdrawn as cooling water, have shown in some instances high occurrence of damaged fish, which vary depending on the season, but the portion of young fish (figure 4.3) is generally outstanding. The mechanisms, to which the occurring damages refer, are demonstrated in chapters 5.1.4 and 5.1.5.

Figure 4.3:
Fish that was killed during one night through the high flow velocity at the drum screen installation Bergum (Bergum Sea, The Netherlands)

WEIBEL (1997) has during examinations of screenings of two thermal power plants at the northern part of the upper Rhine (*Rheinhafendampfkraftwerk Karlsruhe* / Rhine harbour steam-operated power plant Karlsruhe and *Kernkraftwerk Philipsburg* / nuclear power plant Philipsburg) (Baden-Wuerttemberg) determined that the fish discovered reflect the general condition of the populations and the fish fauna in the environment of the power plant. The presumption that fish in a bad condition because of disease, parasitic infestations or malnutrition would over-proportionally occur in screenings could not be confirmed. To some extent more than 50 % of the fish have shown severe mechanical injuries. Whether still living fish that seem to be only lightly injured or outwardly unharmed are able to survive, can only be speculated on since advanced examinations are lacking. RAUCK (1980) arrived at similar results despite existing electric barriers when examining screenings at the cooling water inlet of the nuclear power plant Brunsbuettel (Schleswig-Holstein), where the average intake and flow-through volume accounted to 33.0 m^3/s. The major portion of fish is killed during high approach velocities from which a strong squeezing pressure results, and also through screens in operation. 25 species were represented in the screenings. The loss of eels amounting to 6.5 tons in average per year is especially important to the economy of the fishing industry. To categorize these results in relation to the absolute fish population of the Elb river, however, is impossible as there is no appropriate data available.

Most fish can master flow velocities of 0.5 m/s (BEAMISH, 1978). Percids and Cyprinids are in a position to resist flow velocities of 0.8 m/s, but already flows exceeding 1.0 m/s cause an irregular swimming performance (KAUSCH, 1972). Furthermore to be considered is the increased swimming speed, which may have to be performed over a longer distance or for a longer period to escape upstream from the entire hazardous area depends on the body length and the swimming capacity of the fish (chapter 2.6.2).

Decisive in this connection is also, whether the buoyancy of the fish suffices the strength needed to avoid or to flee from the close vicinity of the screens. If a fish enters this hazardous area, then owing to its wave resistance it requires a considerable amount of energy to release itself from the screen. The consequence is that the approach velocity of the screen must be distinctly lower than the flow velocity that can be mastered by the fish when swimming freely. Also to be accounted for is the fact that the heavier the screen is covered by fish and flotsam, the higher is the squeezing force, and thus the fish at risk to be damaged.

4.3 Damage during turbine passage

The storage level regulation of larger rivers aiming to render the water body navigable and to utilize the water power causes a massive impediment to migrating fish. Damage to migrating fish through turbines passage became a new phenomenon since power plants were introduced at the end of the 19th century. Even at small rivers small power plants were erected or water wheels on existing plants successively replaced by turbines. Meanwhile, there is extensive literature available that deals with the problems concerning damage to fish during turbine passage. Publications were first limited to only a detailed description of appropriate findings, but soon also comprised topics that involved tasks concerned with the prevention or minimization of such damage. Additionally, trials implemented on the turbine passage of fish enhanced the knowledge so far available inasmuch as the input quantities and output quantities became known. Whatever happened inside the turbine, however, remained undiscovered. This situation, nevertheless, led to a legal appreciation through amended fishery laws (chapter 8).

Although there are no concrete results on hand on the examinations carried out, the possibility for fish to migrate over water wheels, specifically at the overshot type, should be possible without problems in most situations. Also the fish damage caused by Archimedean screws is comparatively low. SPAEH (2001a) examined Archimedean screws of 0.7 m diameter and 8.4 m length in respect of damage occurrences on fish. After the passage have 7, or 4.4 % of the total of 158 test fish species of a length between 36 and 58 cm shown losses of scales or haematomas. Lethal injuries were not recorded. GERHARDT (1893) on the other hand has already identified multiple fractures of the vertebrae or even cut through species after turbine passage, which was proven by pieces of eels that were found in the tailwater (figure 4.4). The knowledge gained from these examinations was directly accounted for in the year 1916 by an amendment of the Prussian Fishery Law, which stipulated that the owner of new plants could be made obliged to prevent the entry of fish through suitable devices at his own expense.

The mortality caused by turbine passage is dependent on the fish species and their length, as well as the turbine type and dimension, the head and the individual operational conditions. Although turbines are designed for a specific increased water volume, they can nevertheless be adjusted to varying discharge conditions, and so create favourable or less favourable situations for fish in respect of a harmless passage. Consequently, the results of examinations on the mortality during turbine passage vary significantly: The mortality rates of juvenile salmonids, for example, that were assessed at Francis turbines in run-off river hydropower plants differed from less than 5 % to over 90 %, and at Kaplan turbines between 5 % and 20 %. These greatly varying results reflect the different location- and plant-specific conditions. The mortality rates of other fish species may be significantly higher. Particularly at risk are eels for example, because of their body length, and physoclists for their greater sensitivity towards pressure fluctuations. Under equal conditions it is noted that the mortality during passage of Francis turbines is higher than that of Kaplan turbines.

Figure 4.4:
Cut through eel in the tailwater of a hydropower plant on the Maas river (The Netherlands)

MONTÉN (1985), EICHER (1985) and LARINIER & DARGIGUELONGUE (1989) have unanimously arrived at the conclusion that the survival chance for fish passing a Pelton turbine will be equal to zero, that means a mortality rate of 100 %. The direct flow turbine also involves a high damage rate. GLOSS & WAHL (1983) established mortality rates of 10 to 72 % or 8 to 53 % for juvenile salmonids during examinations at cross-flow turbine. LARINIER & DARTIGUELONGUE (1989) defined mortality rates between 59.3 and 100 % at a direct flow turbine of 820 kW nominal capacity.

A more detailed analysis of the findings leads to three basic causes for mortality during turbine passage:

Direct injuries through contact with fixed or movable turbine parts:

Decisive are injuries caused by collisions between fish and blades (MONTÉN, 1985, figure 4.5) as the latter move transverse to the approach velocity and so separate the flow into sections of specific lengths. The length of the fish shall consequently not exceed the length of the water section, or else it will be hit by the blade edge. This assumption is confirmed by the damage rate that rises with the length of the fish. A distinct correlation between fish length and damage rate was also confirmed by HADDERINGH & BAKKER during their examinations at Dutch hydropower plants. However, RABEN (1957 a) is of the opinion that guide vanes are harmless, as they are stationary and only divide the flow into longitudinal courses in flow direction. Flow velocities of far beyond 2.0 m/s often occur in turbines. Under such conditions it is not possible for the fish to react, instead it will be passively exposed to the flow (MONTÉN, 1985).

Pressure fluctuations:

The fish is subjected to strong and abrupt pressure fluctuations during turbine passage. A rapid rise of the pressure is followed by a quick drop under atmospheric pressure. The changes, which take place within the shortest time and with great amplitude, especially negative pressures, can effect a bursting of the air bladder. Salmonids are in this respect less endangered, as MUIR (1959) and others have proven with their trials: Rainbow trout have been exposed to a water pressure of up to 13.8 bar, which was abruptly lowered to the atmospheric pressure. The fish remained unharmed, although they were immovable during the high pressure phase.

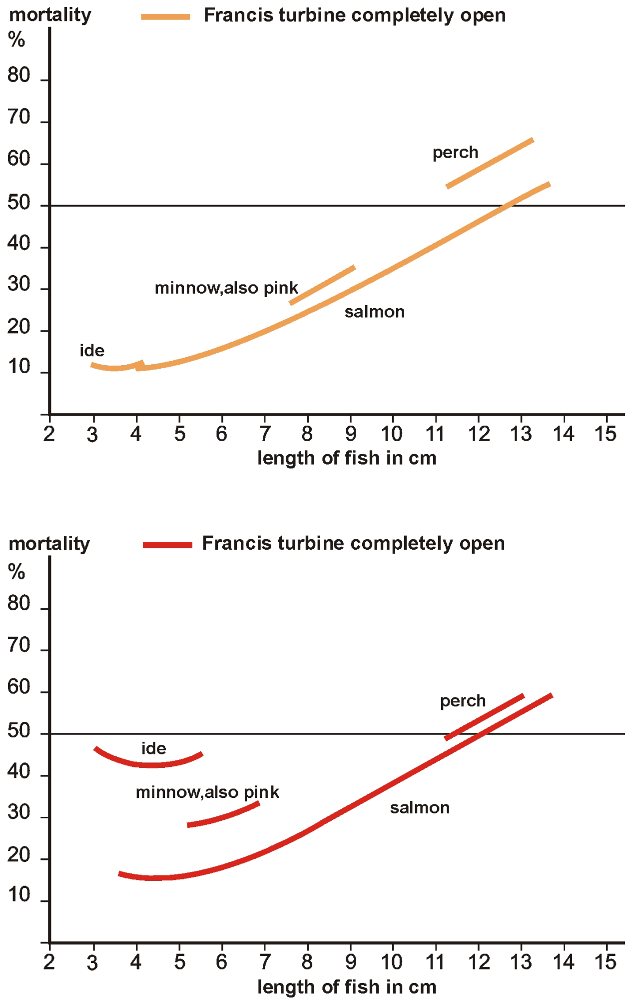


Figure 4.5:
Fish losses assessed by MONTÉN (1985) for various species during passage of a Francis turbine (1.4 m³/s flow-through, 0.60 m diameter of the runner, 19 blades, 381 rtm) and a Kaplan turbine (0.81 m³/s flow-through, 0.64 m diameter of runner, 6 blades, 598 rtm) at a head of 14.6 m in dependence on the length of the fish

Cavitation:

Gas bubbles which develop through cavitation can reach a significant size. Pressure waves of up to 10,000 kPa (PAVLOV et al., 2002) evolve during their implosion, and can lead to damages of the air bladder and the vascular system and can also cause gills to bleed (MUIR, 1959; MONTÉN, 1985).

Other problematic areas

Design characteristics and operating conditions of turbines are to be seen in a causal relation with the damage and mortality rates observed: Thus, the number of damaged eel rises with decreasing discharges, since the angle of the guide vanes as the variable quantity and therefore the gap between the runner blades in the Kaplan turbines becomes narrow at low discharge volumes to obtain a constant speed (RABEN, 1955). Similar results were achieved by BERG (1987) during examinations on the Neckar river: The damage rate at angles of attack < 20° amounted to approximately 50 % in comparison to rates of 20 to 30 % at angles of attack of 25 to 30°.

Also, there is a direct relation between damage rate and speed and the diameter of the turbine (HEMSEN, 1960: CRAMER & OLIGHER, 1964): The smaller the diameter of the runner and the greater the rotary speed, the more severe damage is caused by the turbine. The damage rate also increases when the water in the turbine is diverted and will not hit the runner blades in the direction of the rotation axis (CRAMER & OLIGHER, 1964). The consequence is a greater risk for the fish to collide with parts of the installation.

From the numerously available literature concerning these problems (e.g., ANONYMUS, 1899; RABEN, 1955; BUTSCHEK & HOFBAUER, 1977; RAYMOND, 1979; BARUS et al., 1984; TAYLOR & KYNARD, 1985; DARTIGUELONGUE & LARINIER, 1987; TRAVADE et al., 1987; BERG, 1988; MATHUR et al., 1994; HADDERINGH & SMYTHE, 1997; HADDERINGH & BAKKER, 1998) it becomes clear on the one hand that this topic has since been dealt with, and on the other hand how greatly the results from outdoor studies vary. Meanwhile, quite a number of literary studies exist with respect to the mortality of fish caused by turbines. Especially to be noted are surveys of MONTÉN (1985), EICHER (1985), LARINIER & DARTIGUELONGUE (1989), CHRISTEN (1996) and HOEFER & RIEDMUELLER (1996).

The most recent results of assessed fish damage caused by hydropower plants refer to the hydropower plant Dettelbach on the Main river (Bavaria) that has been taken in operation in 1959 (HOLZNER, 1999). Various outer and inner injuries, which were already known from earlier examinations, were discovered on fish that have passed the turbines at this location. The spectrum of damage covers a total cut through and cuttings in parts (figure 4.4, figure 4.6), damages to the skin with scale losses (figure 4.7), damages to eyes and fins and also damages to the skeleton (figure 4.8, figure 4.9), the tissue and the inner organs.

Considering the ecological and ichthyo-economical extent of fish damage caused by turbine passage, attempts were made to develop an assessment procedure that would allow an advanced estimation of damage rates for Salmonids and eels. RABEN (1957a), for example, has established a formula for the calculation of the contact frequency which includes the length of the fish and the length of the water sections between the runner blades. The values resulting from such calculations however, clearly exceeded the assessments from control examinations. The author thus arrived at the conclusion that injuries occur only at a certain critical impingement speed for which he also developed a formula. A combination of both formulae should lead to realistic damage values. Since this procedure was unable to supply satisfactory results, the formula was extended by a correction factor in another publication (RABEN; 1957b), to obtain accordance between calculated and empiric values. A similar approach was pursued in France under consideration of the fish length and the construction characteristics of the turbine (TRAVADE & LARINIER, 1992).

Figure 4.6:
Decapitated roach from the tailwater of the hydropower plant Lahnstein/Lahn (Rhineland-Palatinate, Germany)

Figure 4.7:
Salmon smolt with skin damages and scale losses after turbine passage at the hydro-power plant Lahnstein/Lahn (Rhineland-Palatinate, Germany)

Figure 4.8:
Multiple fractures of the vertebra of an eel that outwardly seemed unharmed caught in the tailwater of the hydro-power plant Wahnhausen/Fulda (Hessen, Germany)

Figure 4.9:
Fractures of the vertebra and haema-tomas alongside the vertebra of an eel caught in the tailwater of the hydro-power plant Wahnhausen/Fulda (Hes-sen, Germany)

5 Techniques to safeguard downstream fish migration

To prevent any damage to migrating fish and to safeguard their downstream passage requires solutions appropriately aligned to the individual conditions of a location and the specific behaviour of the targeted species. A fair amount of techniques have been developed worldwide to meet these requirements, which are described hereafter. Nevertheless, functioning solutions are still not available for all fish species and application fields. For many technologies and procedures, however, which for example have been developed in the USA, it is not clear whether and under which frame conditions they can be applied to Central European conditions. Therefore, it will be necessary in future to test techniques used in other places under local conditions, and to develop new solutions independent thereof.

According to EICHER (1970) the behaviour of fish shall be examined first. Based on the findings, small-scale trial plants shall be installed. Only when these prove successful in practice, the preconditions are fulfilled to employ the specific system for a large-scale application.

The necessity for a migration barrier is to be verified prior to employing a technique to ensure a safe downstream fish passage. In this connection, HANSON et al (1977) point out that for example closed cooling systems in thermal power plants are the most effective technology for the prevention of fish damage, as only the evaporation loss must be compensated and the water withdrawal volume can be significantly reduced.

The following techniques refer as much as possible to existing installations in Germany, or at least in Europe, and are taken as an example. Many systems, however, have been developed in the USA and Canada, and some of them are in operation in these countries only.

When classifying the different fish protection facilities and downstream fishways, the following functions and procedures can be differentiated:

- Mechanical barriers are installations that prevent fish entering hazardous areas. Nevertheless, they influence the behaviour of fish in their approach, and whether the fish can be guided in direction of a bypass is dependent on the combination of both functions.
- Behavioural barriers guide or repel fish through stimuli or other disturbing sources which result in avoidance, timidity or escape reactions.
- Fish collection systems mechanically remove fish from hazardous areas and transport them to installations for further downstream passage.
- Bypass systems are installations to avoid hazardous areas or parts of an installation and guide fish safely into the tailwater of a migration obstacle.
- For fish transportation systems, fish are caught in the headwater of a migration obstacle. They are then loaded into a means of transportation and taken downstream, where they are released into the river.
- Fish damages can be avoided or at least reduced by means of a targeted installation management, which accounts for migration periods of specific target species.
- Presently, there are trials carried out in different research laboratories to develop fish-friendly turbines, which to a great extent would avoid fish being harmed during passage.
- In some places combined downstream fishways are in operation, consisting of several different techniques. Bypasses are often combined with mechanical or behavioural barriers in order to improve attraction.
- It is possible to position intake structures for the withdrawal of water where the density of the fish population is naturally low, which would subsequently reduce the risk of fish losses.

5.1 General requirements

The general requirements described hereunder constitute basic preconditions for the best possible arrangement and design of fish protection facilities and downstream fishways. They account for biological necessities and behavioural patterns of migrating fish and are therefore important planning criteria independent of the individual construction type. At this place however, it is to be noted that the knowledge of biologically effective mechanisms which cause or influence the migration behaviour is presently still insufficient and extensive research is yet required.

The general requirements comprise different individual aspects which are to be considered to ascertain operatability when planning new constructions of barrages and water intakes, but also for the assessment of existing installations and a supplementary incorporation of fish protection facilities and downstream fishways.

Fundamental biological differences exist between upstream and downstream migrations of fish: Any upstream impassable obstruction will lead to an isolation of habitats located above from other river systems and result in the loss of spawning and maturing biotopes especially for diadromous but also potamodromous species. This is why upstream fishways are generally required at all impassable obstructions (DVWK, 1996). Of decisive difference is the situation for downstream migrations: A downstream migration of fish still takes place at locations which lack specifically installed downstream fishways, although the fish are jeopardized to become damaged or even killed during their passage.

The function of upstream and downstream fishways refers to different biological patterns. Therefore, completely different criteria play an important role in the design of the inlet of an upstream fish pass in comparison to the construction of a downstream fishway. Upstream located inlets of fish passes are therefore basically not suitable for downstream migrating fish as they will not be found in a sufficient number. However, the discharge needed to operate downstream fishways can also be utilized as guide flow and enhance the traceability of an upstream fish pass. It is possible that several downstream fishways are required to guarantee a downstream migration at a dam, of which each is to be arranged to suffice the specific behavioural pattern of different target species.

As each dam and each water intake represents special features with regard to their construction and incorporation in the water body, it is not possible to offer generally applicable standard solutions. Moreover, the type of fish protection facility and / or downstream fishway chosen for the target species must be suitable to sufficiently ensure the protection of the downstream migrating fish under location-specific technical and topographic conditions.

5.1.1 Application fields for fish protection technologies and downstream fishways

Especially for ethical reasons and those concerning legislations on animal protection, but also in respect of the economy of the fishing industry, it is to be demanded that all migrating fish are to be protected against damage through barrages etc., hydropower plants and water intakes disregarding their development stage and species.

The continuity of all rivers which originally have been passable is required (DVWK, 1996). The EU-Water Framework Directive claims that this condition must be restored to such extent that the achievement of the “good ecological status” of the river system will not be forestalled (EU-WFD, 2000). The aim of a guaranteed free migration is therefore not only to be looked at from a location-specific point of view, but also in the context of the entire river system. The following conditions must therefore be established:

- all species of the potential natural fish fauna must be enabled to create populations (chapter 2.2), which will not be jeopardize,
- the abundances of species in view of the status specific for the water body, i.e. the potential natural status will only be reduced to a negligible extent, and
- interruptions in the age structure of the population shall only be tolerated for a few individual species, where some age stages may be missing.

Eventually, the efficacy of fish protection facilities and downstream fishways is to be assessed for each location on condition that the above mentioned hydro-ecological objectives can be achieved for each river system. In subsequence thereof, different requirements of fish protection are to be applied to individual locations. Taking hydropower plants in the Columbia River (USA) as an example, the occurring losses of Pacific salmon cannot be reduced as needed for the water ecology despite enormous technical and financial expenditure. For this reason a survival rate of 100 % for all migrating development stages is aimed for all small inflows of hydropower plants and water intakes. Such measures will assist in reducing the losses of Pacific salmon species in the entire water system to such an extent that their population will become stable (DUMONT, 2000).

The supplementary construction of fish protection facilities and downstream fishways is generally limited to locations where the downstream migration will not be feasible without such specific installations and populations will be impaired. These are in particular:

- barrages with hydropower utilization
- barrages where migration is impossible or damages could occur because of the relevant head and / or type of construction
- water intakes where organisms would be damaged by technical parts of the structure or chemicophysical changes of the water body etc.
- water intakes where the withdrawn water will be used (irrigation, industrial water, etc.)

Considering the partly high costs involved with the protection of downstream migrating fish and the partly lacking technologies it is presently deemed unrealistic to demand fish protection facilities and downstream fishways for all above mentioned structures. Furthermore, many methods are employed for the protection of individual target species and are thus only effective in specific cases. The following procedure is therefore recommended when planning fish protection facilities and downstream fishways:

- First of all is to be assessed whether populations of fish species would be impaired by a specific hydraulic structure. If quantification is impossible, the actual damage rate can only be evaluated through control examinations. Whether fish protection facilities are necessary is then to be decided on the appropriate findings.
- The potential of fish willing to migrate is to a high degree restricted to the fish population contained in the impounded water especially in reservoirs of upper river reaches. A technology that will guarantee free downstream migration can by all means be neglected according to presently available estimations, when there are no stocks of eel in the reservoir, and the upper reaches are neither actually nor potentially populated by anadromous species.
- Should measures to guarantee fish protection and downstream migration be deemed necessary because of high damage rates, it is to be decided whether all species shall be protected or whether it would be sufficient to protect specific target species only.

Figure 5.1:
Whether downstream fishways are neces-sary to guarantee a free passage at dams has to be evaluated in individual cases (Wupper Dam, North Rhine Westphalia)

5.1.2 Target species and target stages

If the demand for fish protection refers to all species, this will restrict the selection of fish protection facilities and downstream fishways to those types which will not be species-specific. This according to the latest state of the art is in particular not feasible at larger hydropower plants and water intakes. Hence, the protection of migrating fish will in practice inevitably be limited to specific target species.

The selection of target species is based on considerations to guarantee the survival of populations of potential natural fish species through functioning fish protection facilities and downstream fishways. Most at risk during migration are diadromous species, as they are relying on a free passage of all obstructions in fresh water and the sea between their spawning and maturing biotopes. Particularly endangered in this respect is the migrating adult eel, whilst downstream migrating development stages of anadromous species are exposed to a lower damage risk because they are smaller in body length. The eel consequently is the primary target species for fish protection in potamon river systems that drain into the North and Baltic Sea. Anadromous species like the salmon, sea trout, river lamprey and sea lamprey are also to be considered, provided they belong to the potential natural fish fauna in a specific water body system.

In order to preserve their own kind potamodromous species are not stringently dependent on downstream directed migrations that involve great distances. Their populations are therefore able to survive even if a free passage is not feasible at all barrages. In such cases damages are tolerable at some points, provided they have no significant impact on the abundance and age structure of the species concerned within a water body. To which extent potamodromous species are therefore to be considered as target species to be protected, shall be decided on the basis of water- and location-specific conditions.

The requirements for fish protection installations and downstream fishways are also dependent on the body length of the migrating fish: mechanical barriers must be designed of such narrow mesh size, gap width and perforation diameter that the specific target species and -stages will physically be prevented from a passage (chapter 5.1.5). Also the flow velocity occurrences must be aligned to the swimming capacity of the fish (chapter 5.1.4).

The risk to collide with runner blades during turbine passage on the other hand will be reduced the smaller the body sizes (chapter 4.3), leading to the conclusion that the protection of fish fry is at least at hydropower plants not of prime importance. However, the best possible protection of fish fry is to be aimed at for water intakes, where fish is at risk to be damaged through band screen machines or other filter systems, or where the water is used or heavily chemicophysically affected and the survival of the animals unlikely. Only one-summer young fish, especially migration stages of anadromous species are to be fully accounted for when guaranteeing free downstream passage at hydropower plants.

Invertebrates drift with the flow. Any damage through turbines or screens in hydropower plants has so far not been recorded. Also damage during downstream directed passage over weirs would only be likely in the case of extreme heads. On the other hand, however, the damage to invertebrates caused by water intakes can rise to a significant extent. So far no procedures have been established which would assess these ecological or ichthyo-economical losses. It is therefore disputed whether protection facilities must also be designed to be effective for invertebrates.

The effectiveness of fish protection facilities is decisively influenced by the flow conditions before the migration obstacle or the protection installation. The following flow vectors are hereby of relevance (figure 5.2, figure 5.3):

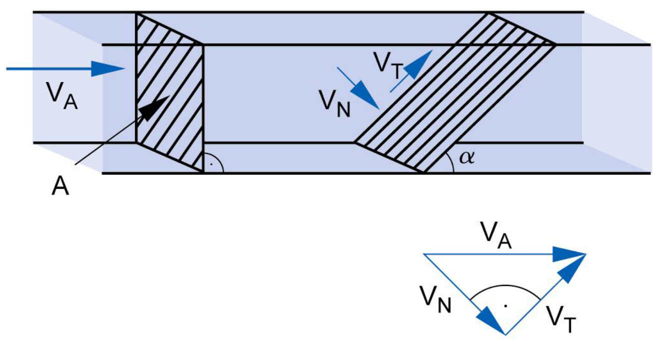


Figure 5.2:
Vectors of the approach velocity at a ver-tical protective screening and a screen that is installed inclined at an angle (α) to the bottom

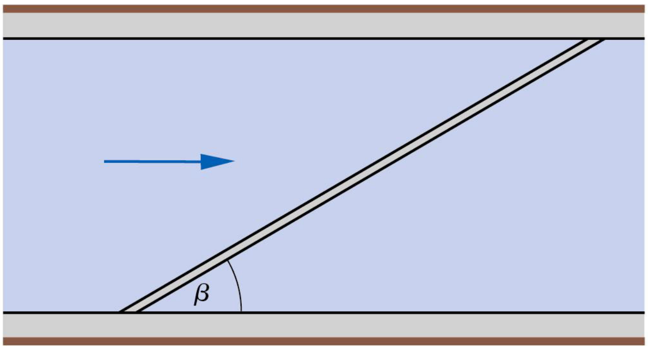


Figure 5.3:
Angle (β) at vertically, inclined to the approach velocity installed screens or protective screens (top view)

- The approach velocity V_A is the flow speed of the water in an imagined vertical cut through the inflow channel in front of a migration obstacle, e.g. a screen (figure 5.2). The approach velocity is measured directly before the screen. The possibility that the flow vectors may distribute over the surface of the screen in an inhomogenous way is hereby to be considered. Consequently the actual approach velocity may deviate from the calculated mean value.

- Flow velocities (V_d) occur between the screen bars and in the meshes or perforations of protective screenings which are distinctly higher than the approach velocity, to which the following applies:

$$V_d = {V_A}/{\rho}$$

with □ = obstructing degree of the protective screening, i.e. the ratio of the flow-through area of the protective screening to the total area

- The flow vector parallel to the screen surface is called sweeping velocity or sweeping velocity.

$$V_T = V_A \cdot \cos\alpha \text{ or } V_T = V_A \cdot \cos\beta$$

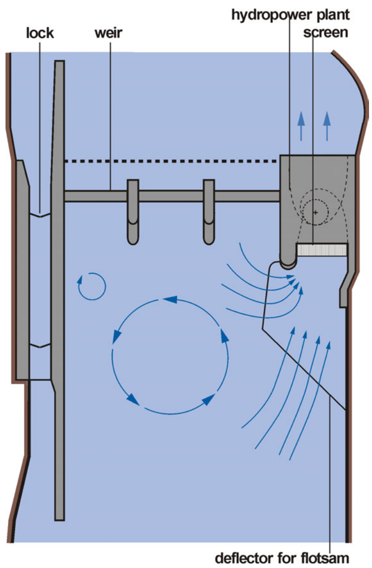
- The flow vector vertical to screen and protective screening is called normal velocity VN, to which the following applies:

$$V_N = V_A \cdot \sin\alpha \text{ or } V_N = V_A \cdot \sin\beta$$

The normal velocity for vertically arranged protective screenings is equal to the approach velocity.

The approach velocity vectors of screens of run-off river power plants are only rarely homogenous. Especially at separation buttresses the approach velocity towards the weir is higher than in the area of the banks as has been proven by model experiments (figure 5.4, figure 5.5). These different velocities must be considered not only when determining the losses through screens but also in respect of their effect on fish that approach the screen.

Figure 5.4: Intake of the hydropower plant Wahnhausen on the Fulda river (Hesse, Germany)



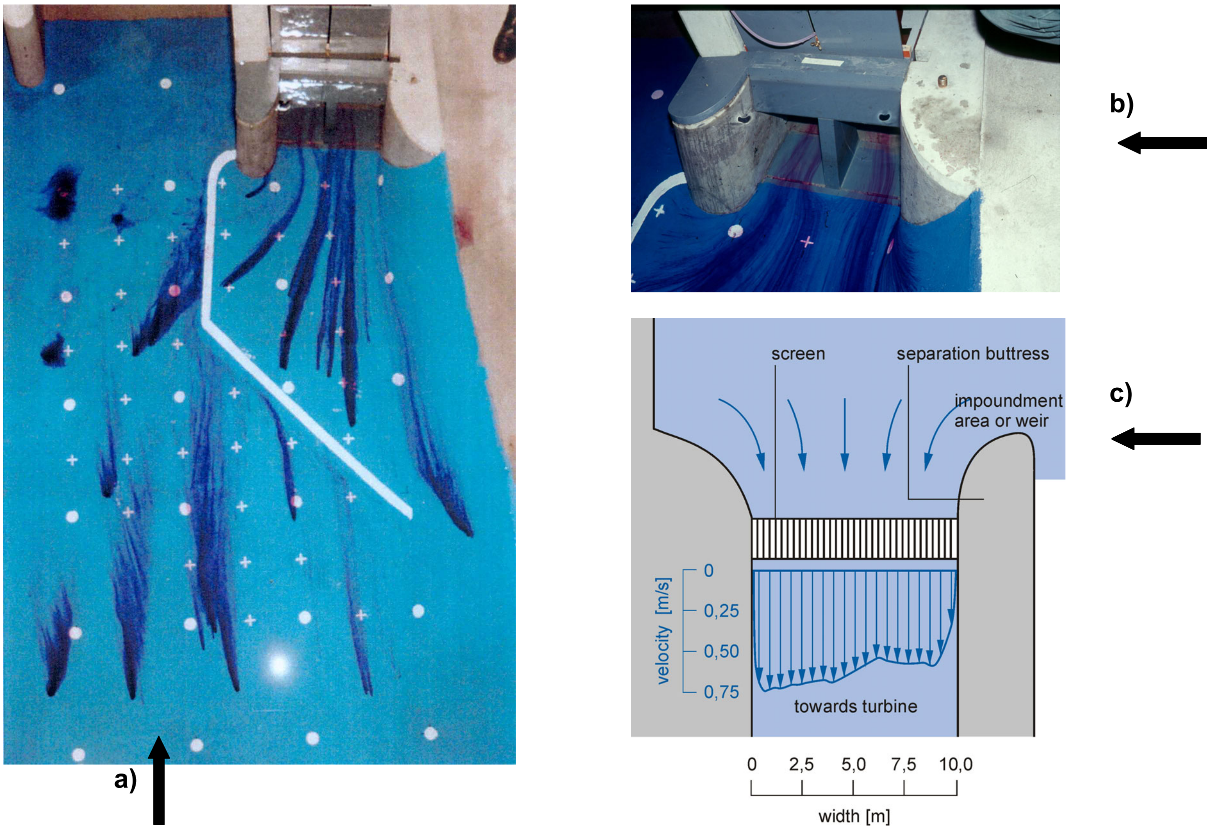


Figure 5.5: Model experiment with the approach velocity of the hydropower plant Wahnhausen on the Fulda river (Hesse) (ZANKE, 1997)

a) and b): View in flow direction, arrangement: weir on the left hand side, hydropower plant on the right hand side

c) Mean flow velocity taken during a model experiment at the screen of the hydropower plant Wahnhausen on the Fulda river(arrangement: separation buttress on the right hand side towards the weir, levee on the left hand side).The velocity at the separation buttress is lower than in the other areas.

5.1.4 Influences of barriers on migration behaviour

5.1.4.1 Perception of obstructions

The reaction of fish to obstructions of whatever kind is comparably identical for all indigenous species according to present knowledge: Fish normally swim with their head in upstream direction against the current. If their swimming speed $\vec{V}_{rel}$ is lower than the approach velocity they will be drifted downstream:

$$\vec{V}_{abovebottom} = \vec{V}_{rel} + \vec{V}_A$$

$(\vec{V}_{abovebottom}$ in flow direction$)$

Should obstructions be perceived by fish as a threat, this will delay their migration since the fish will increase its swimming speed $\vec{V}_{rel}$ against the flow direction. If the swimming speed of fish reaches the amount of the approach velocity ($|\vec{V}_{rel}| = |\vec{V}_A|$) this will interrupt the drift ($\vec{V}_{abovebottom} = 0$). A further increase of $\vec{V}_{rel}$ affects an upstream directed escape.

This escaping behaviour, however only occurs at massive obstructions and will only be possible if the approach velocity is lower than the critical swimming speed $V_{critical}$ of the fish:

$$\vec{V}_{abovebottom} = \vec{V}_{rel} + \vec{V}_A$$

$(\vec{V}_{abovebottom}$ against flow direction)

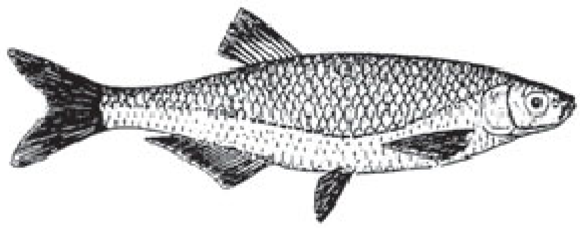
with $\left|\vec{V}_A\right| < \left|\vec{V}_{rel}\right| \leq \left|\vec{V}_{critical}\right|$

Such a reaction can be released by various stimuli, e.g,:

- Visual, acoustic and electrical stimuli, like they are employed for behavioural barriers.
- Chemicophysically changed water bodies, e.g. through inflows but also through introductions of waste water, surplus heat, etc.
- Obstructions of all kind, like mechanical barriers

Obstructions will generally be visually perceived by fish. However, fish are also able to react very sensitively to flow changes, which are influenced by a changed cross-sectional area of the flow that may result from a narrowing or widening or caused by bottom steps and buttresses, but also through mechanical barriers. Consequently mechanical barriers have next to their purely physical filtering effect in general also the effect of a behavioural barrier.

The typical impact of small-scale flow changes through mechanical barriers can be exemplified by the conventional bar screen: A standing wave is formed at the head of a screen bar as described by NAUDASCHER (1992) for the surge around buttresses (figure 5.6, figure 5.7, figure 5.8). Numeric simulations carried out by the Versuchsanstalt fuer Wasserbau of the ETH Zuerich (research institute for hydraulic engineering) for the screen of the hydropower plant Wahnhausen on the Fulda river (Hesse) indicate that furthermore *"starting at both front corners of the bar [...] two zones of strongest eddies develop diagonally to the back, the so-called Bloor-Gerrard-wake"* (VAW, 1999).



	undisturbed migration	interrupted migration in case of alarm	upstream directed escape in case of massive obstructions
$\vec{V}_A$	←	←	←
$\vec{V}_{rel}$	→	→	→
$\vec{V}_{abovebottom}$	←	0	→

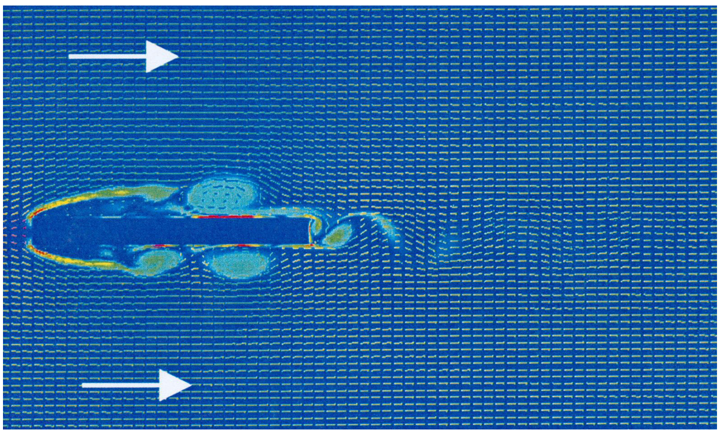


Figure 5.6:
2 D-simulation of a develop-ing wake at a single bar (VAW, 1999)

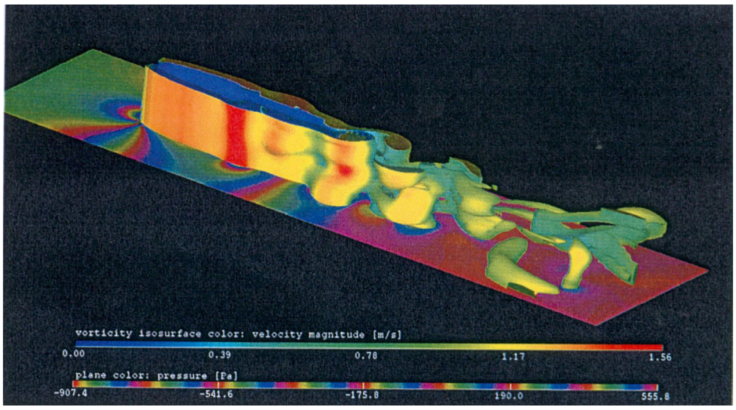


Figure 5.7:
3 D-simulation of a momen-tary velocity around a single bar (VAW, 1999)

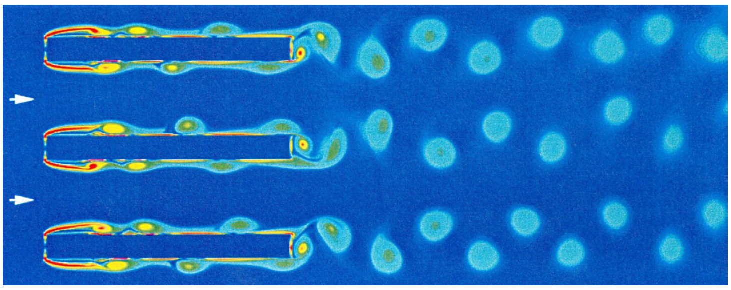


Figure 5.8:
Flow situation at a screen made of flat steel: The eddies expand over a specific portion of the free and not obstructed cross-section. Decisive for the development of the wake is the proportion of the obstructing degree ρ of the bars in comparison to the total surface of the screen. The bars lose their hydraulic independence at ρ < 0.31, i.e. the eddies of neighbouring bars influence each other (VAW, 1999)

The formation of velocity vectors at a conventional screen as shown in figure 5.8 will be very sensitively perceived by fish approaching the barrier. They are therefore not dependent on visual perceptions, and leads to the conclusion that mechanical barriers often achieve a similar effect whether in complete darkness or in daylight.

The stronger the hydraulic interferences which evolve from individual elements of a barrier, the better they are perceived by migrating fish and the greater is thus their efficiency. Louver (chapter 5.2.3) therefore offer a better efficacy than conventional screens (chapter 5.2.2), as they have a stronger influence on the flow pattern. According to PAVLOV (1989) barriers of cylindric elements and plates of L-shape are particularly effective, for which however, there are no experiences available outside the former Soviet Union.

It is possible that other physical effects like vibrations of the screen may also influence the behaviour of the fish, although this has so far not been closely looked at scientifically.

5.1.4.2 Reaction to rectangular arranged barriers

The reaction of migrating fish (with the exception of eel) when approaching barriers which are arranged rectangular to the flow (□ = 90°) is greatly independent of the inclination of the barrier, i.e. the angle towards the bottom (□): They accelerate their swimming speed to the extent that is equal to the approach velocity:

$$\vec{V}_{abovebottom} = \vec{V}_{rel} + \vec{V}_{A} = 0$$

The fish is hereby enabled to keep its position before the barrier and not get in touch with it. This has for example been observed for salmon smolts at the screen of the hydropower plant Soeix on the Gave d’Aspe (France). The fish avoided a passage of the screen, although the clearance between the bars was distinctly greater than their body length (LARINIER et al., 1993). Brown trout, roach, darting swimming and dace approached screens of various designs in the model channel as described above. The fish remained positively rheotactically aligned in a constant distance of a few centimetres to the migration obstacle (figure 5.9). In case of an occasional contact with the tail fin, the fish accelerated only slightly but solely in order to regain their original position (ADAM et al., 2001). It is hereby of no relevance whether the barrier is arranged vertically or flat inclined to the bottom.

Furthermore, the fish perform sideways movements in search for a migration corridor where the approach velocity is low. If a bypass does not exist or cannot be traced, the fish remain in this dead ended location for several minutes or even hours until they finally increase their swimming speed V_{rel} and escape into the headwater. This, however requires an approach velocity V_A that is significantly lower than the critical swimming speed $V_{critical}$ If the approach velocity is too high ($V_A > V_{duration}$) this will fatigue the fish over a longer period. It will slow down in its swimming speed, and thus will not be able to withstand the drift. Consequently the fish will be pressed against the impassable barrier and get killed.

Figure 5.9:
Salmon smolts remain in a position only a few centimetres before mech-anical barriers - the photograph shows a 20 mm-screen arranged flat inclined to the bottom - by adjusting their swimming speed exactly to the approach velocity (ADAM et al., 1999)

If the barrier is passable, e.g. if the clear width of conventional screens d_{St} exceeds the circumference of the fish D_{fish} (chapter 5.1.5), they will finally be passed by migrating fish after a moment of hesitation. The less passable the barrier, the longer the fish hesitate. However, at least the migration stages of diadromous species cannot permanently be hindered in their passage of mechanical barriers. If they cannot find any other migration corridor, they will eventually drift through the barrier by reducing their swimming speed V_{rel}, even if the approach velocity V_A is lower than their cruising swimming speed $V_{duration}$. This has been documented for salmon smolts during examinations in a model channel (ADAM et al., 1999, figure 2.21) and similar outdoor observations have also been recorded (LARINIER et al., 1993).

Behavioural observations in model channels have proven that eel react totally differently to mechanical barriers than other indigenous species (ADAM et al., 1999; ADAM et al., 2001; AMARAL, 2000): When approaching a mechanical barrier they do not perform the same avoidance reaction like other species, not even at an approach velocity of < 0.3 m/s.

They generally do not accelerate their swimming speed but collide brakeless with protective screenings and obstacles during their migration. Hence, the previously outlined interactions between flow, the arrangement of the barrier and the behaviour are not applicable to eel

The eel always performs a similar attempt to escape after a collision (figure 5.10): Immediately upon hitting screens with clear spacing of 5 to 20 mm, they carry out a 180°-turn and try to align the front of their body against the flow, to push themselves off the screen with the back of their body and to escape against the approach velocity. Where flow velocities do not exceed 0.5 m /s most eel can free themselves from the screen by means of this method. An increasing approach velocity and the resulting higher pressure force against the screen requires much greater energy and involves a significantly longer time for the fish in its attempt to escape.

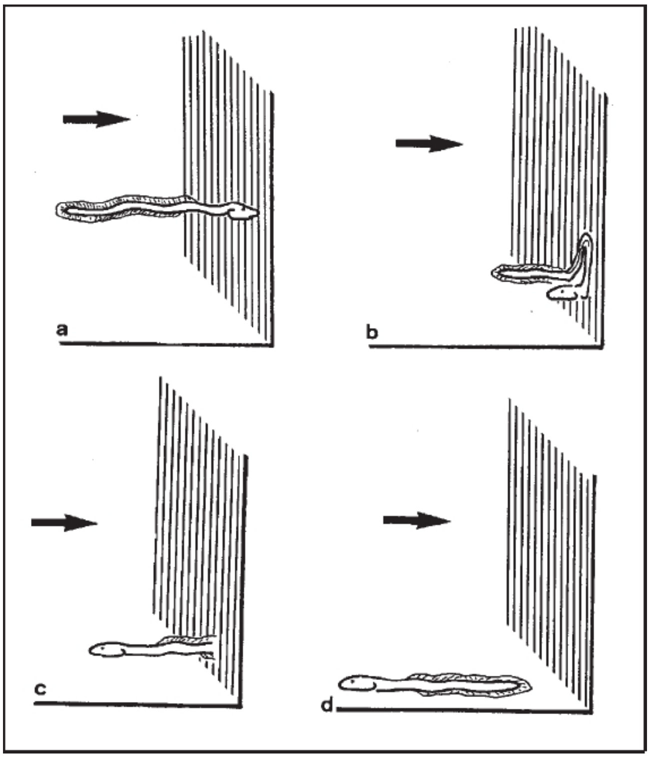


Figure 5.10: Stages of escape reactions of eel before a mechanical barrier (according to ADAM et al., 1999):

a. collision

b. 180°-turn

c. alignment against the flow

d. escape into the headwater

Outdoor examinations also provide evidence of such return reactions at impassable barriers, which could be closely observed and documented (figure 5.11, ADAM & SCHWEVERS 2003) at the flat inclined 5 mm-Wedge-Wire-Screen of the Floecksmuehle on the Nette river (Rhineland-Palatinate). Whether eel, however, generally first react after a collision with a screen, or whether they partly interrupt their migration beforehand to escape upstream could until present not be clarified in a reliable way (chapter 5.1.5.2).

Fiugre 5.11:
An eel escaping into the head-water in reaction upon contacting the screen at the flat inclined Wedge-Wire-Screen of the Floec-ksmuehle on the Nette river (Rhineland-Palatinate) (ADAM & SCHWEVERS, 2003)

5.1.4.3 Permitted approach flow against rectangular arranged barriers

Mechanical barriers can only be classed as fish protection facilities if their approach velocity is sufficiently low to prevent migrating fish from being pressed against the barrier and become damaged. Rectangular, almost vertically arranged barriers (□ = 80° to 90°), as they are typical for conventional screens of hydropower plants, are hereby hydraulically distinguished because their normal velocity approximates the approach velocity.

With regard to fish protection this arrangement represents the most unfavourable of all possible constellations: Migrating fish will swim in front of the screen with $V_{rel} = V_A$ against the flow for as long as they either have traced a migration corridor and can thus continue their migration, or can escape into the headwater. Migrating fish, especially the migratory stages of diadromous species, will hereby repeatedly return into the hazardous area whilst searching for a migration corridor. This especially will occur in cases where no traceable bypass exists.

Fish can only be saved from damage if their cruising swimming speed is higher than the approach velocity of the barrier. To avoid damage to fish at rectangular arranged barriers with no traceable bypass the following applies:

$$V_A < V_{duration}$$

Under these conditions the fish is able to swim against the flow for hours if required and will not be drifted into the hazardous zone. In this instance the cruising speed of approximately 2 L_{fish}/s is to be applied (chapter 2.6.3). Exactly these magnitudes are taken as the basis for assessments in foreign countries. PAVLOV (1989) for example quotes 2 L_{fish}/s as the generally permissible maximum approach velocity. The same value is stated by TURNPENNY et al. (1998) for salmon smolts, whereby different approach velocities are demanded in dependence of the size of the smolts:

- In England, Wales and Northern Ireland smolts are of a size of approximately 15 to 20 cm. The permitted approach velocity is max. 0.30 m/s.
- The smolts in Scottish water bodies of sizes between 12 and 15 cm are obviously smaller, so the permissible approach velocity is restricted to 0.25 m/s.

The permissible approach velocity is generally higher where well traceable bypasses are available to migrating fish, as the time the fish remain in front of the barrier will be reduced under such conditions. If optimal arrangements are provided, the approach velocity can be calculated on the basis of the sustained swimming speed of the specific target species and -stages rather than on the duration.

Examinations of French salmon rivers have proven that approach velocities of 0.5 to 0.6 m/s can be permitted if well traceable bypasses are arranged laterally beside rectangular arranged mechanical barriers (LARINIER & TAVADE, 2002, chapter 5.6.1.1). This is approximately equal to the sustained swimming speed of the smolts. The following speed values are taken for calculations at the West Coast of the USA, where smolts of the Pacific salmon species are significantly smaller:

- max. 0.25 m/s for young fish > 6 cm and
- max. 0.15 m/s for young fish < 6 cm.

The relation between swimming speed and approach velocity is not decisive for the prevention of damage in respect of migrating eel and their deviating behaviour (chapter 5.1.4.2). It is more important that the fish is able to align itself against the approach velocity that exists on the screen surface and to push itself off the screen and then escape upstream (figure 5.10, figure 5.11). In order to facilitate this return reaction also under unfavourable frame conditions, it is important that the approach velocity of rectangular arranged mechanical barriers will not exceed 0.5 m /s (ADAM et al., 1999).

Table 5.1 gives an overview of the maximal permissible approach velocities of rectangular arranged mechanical barriers.

Table 5.1: Permissible approach velocities at almost vertical, rectangular to the flow arranged mechanical barriers (α = 80 - 90°, β = 90°)

target species	without bypass	with well traceable bypass
general	□ $V_{duration} = L_{fish}$/s	$V_{duration}$ to $V_{sustained}$ = 2 to 5 L_{fish}/s
salmon smolts	total length 12 - 15 cm: 0.25 m/s total length 15 - 20 cm: 0.30 m/s	0.5 - 0.6 m/s
silver eel	0.5 m/s	

The effect that barriers shall have on the behaviour of fish will fail in all cases, independent of the kind and force of the stimuli employed, if the limit values shown in table 5.1 are adhered to. Hence, in case these biological limit values are exceeded, a protective screening can no longer function as an effective behavioural barrier. Smaller specimen will pass the barrier and get into power plants or into water outlets and thus will be exposed to the risk of damage. Larger specimen, however, will be pressed against the screen surface and will have no chance to escape (figure 5.12). In such a situation, they will be damaged through the water pressure or caught by the screen cleaning machine and become damaged. High damage and mortality rates occur in both cases. Under conditions like this 1,000 kg of eel and other fish species have been killed in only one night at the hydropower plant Wahnhausen on the Fulda river (Hesse), because the approach velocity of the 20 mm-screen that was purposefully installed for the protection of fish has been too high (figure 5.13, figure 5.14).

Figure 5.12:
An eel that was pressed against a 20 mm-screen at an approach velocity of 0.5 m/s (laboratory examination, ARBEITSGEMEINSCHAFT GEWAESSERSANIERUNG, 1998).

Figure 5.13:
Eel that were killed during one night in 1991 at the 20 mm-screen of the hydropower plant Wahnhausen on the Fulda-river (Hesse) and carried into the debris container by the screen cleaning machine.

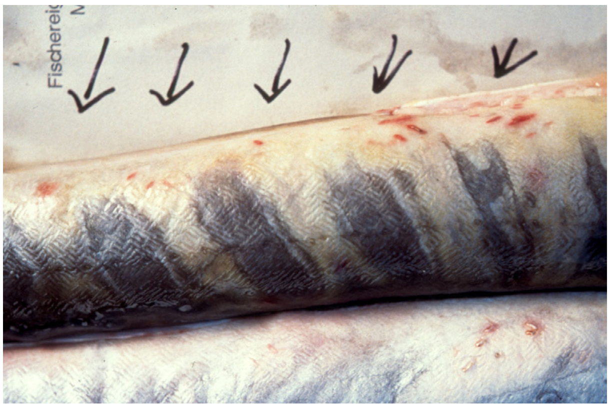


Figure 5.14:
Detailed picture: The pressure marks prove that the eel have been pressed against the screen by a too high approach velocity.

The severity of injuries caused by screens is directly related to the duration of the contact pressure and the normal speed (HANSON et al., 1977), which are equal to the approach velocity (chapter 5.1.3) in the case of vertical protective screenings (α = 90° and β = 90°) that are arranged rectangular to the flow. The contact pressure hinders the fish in its breathing, which is especially crucial for exhausted animals and will lead to a further weakening.

Examinations of Salmonids have shown that bleeding in tissues occur at a normal speed of 0.46 m/s. Already 10 % of the fish show bleeds at 0.61 m/s and a duration of 30 seconds. This rate will be increased to 33 % at a contact pressure that exceeds 60 seconds. Damaged gill covers and lost eyes have been recorded as well. Also fish which are able to free themselves from the protective screening will often be injured. Damage to the skin and scale losses interfere with the osmotic balance between body fluid and the surrounding water. This consequently leads to a changed behaviour and increases the proneness to disease and parasites. The compliance with the limit values of permissible approach velocities as listed in table 5.1 is therefore a decisive precondition for the prevention of damage through mechanical barriers. The following aspects are hereby to be considered:

- The flow distribution on the surface of a protective screening may be irregular. Results obtained from a model experiment carried out for the hydropower plant Wahnhausen on the Fulda river (Hesse) indicate an approach velocity that varies on the screen surface by around 25 % (figure 5.5). The normal speeds can therefore be much higher in some parts than the calculated average value. The area where the fish will most likely hit the screen is in the range of the maximum approach velocity
- If fish get in contact with a protective screen, they will be pressed against it with their flank. That part of the body that is exposed to the flow will thus be considerably enlarged. In order to free itself from the screen the fish must first take a position against the water pressure where it will be enabled to swim against the flow. The pressure forced onto the fish body is hereby determined by the following factors:

Flow pressure:

Size and shape of the fish body cause a flow resistance (F_w), which acts as a force on the fish. The capacity of this force will be determined by measuring the speed considered vertically through the projected area of the fish body (A_{FP}), by the flow resistance coefficient (c_w) and the rate of the relative velocity (v) between flow and moving fish. The flow resistance coefficient (cw) depends on the shape of the fish body in relation to the direction of the relative velocity. The following refers to the force acting on the fish:

$$F_W = c_W \cdot \left(\rho \cdot {}^{v^2}\!/_2\right) \cdot A_{FP}$$

with

ρ= specific density of water

c_w= flow resistance coefficient, will be determined by trial

Assuming that the cross section of a fish body is almost elliptic / oval then (c_w) is approximately 0.4 to 0.8 in dependence on the approached side and exact shape of the fish for normal velocities at protective screenings. Some flow resistance coefficients of geometric bodies are quoted in the following table for low Reynold's numbers:

cone, approached at the top	c_w = 0.34
ball	c_w = 0.47
regular cylinder, approached diagonally	c_w = 0.63

The flow resistance (F_w) of a fish before a mechanical barrier must be looked at separately for the normal and the tangential velocity. Not only the different velocities but also in each case the effective projected areas and if applicable different c_w-values are hereby to be taken as basis.

Static pressure difference at the protective screen:

A pressure drop (figure 5.11) generates through hydraulic losses at a clean screening and the additional losses caused by their soiling. Dependent on the dimension of the protective screening, e.g. depth (t) of the screen bars, either the total or a portion of the pressure drop becomes effective on the fish body in addition to the flow resistance. Normal loss rates at clean screens of hydropower plants are between 2 and 10 cm for approach velocities lower than 0.7 m/s. The losses can rise to 30 cm or beyond if the approach velocities are higher. The appropriate force resulting from the pressure difference reads:

$$F_P = A_{FP} \cdot \Delta\rho$$

with

$\Delta\rho$= hv * g * ρ = effective pressure difference

h_v= difference in water level at the screen in [m]

g= 9.81 m/s^2 (acceleration due to gravity)

ρ= 1,000 k/m^3 (specific density of water)

The height of the static pressure difference independent of the inclination of the screen is α or β (figure 5.15).

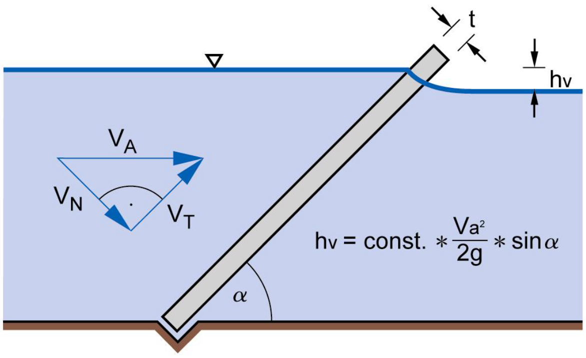


Figure 5.15:
Static pressure difference at a screen

- The swimming speed a fish can achieve in a free water body therefore is not relevant to a successful escape, but the force that becomes effective through the flow resistance and the static pressure difference. Damage is thus already to be expected where the approach velocity is significantly lower than the swimming capacity of the fish. Hence, the limit values stated for the permissible approach velocity are for eel in particular considerably lower than the maximum swimming speeds. Eel, for example, can reach a cruising swimming speed of approximately 0.7 m/s (JENS et al., 1997). Nevertheless, the risk to get killed remains at rectangular arranged protective screens already at an approach velocity of V_A = 0.5 m/s, as once specimen have been pressed against the screen they have no chance to free themselves.
- Since fish belong to the group of poikilotherms they fatigue quickly and their efficiency is also strongly dependent on the temperature of the water. Therefore, if the water temperature is outstandingly low or if the fish had to swim against the flow over a longer time, they may already be at risk of damage at protective screens if the approach velocity is low.

Specifically problematic is the situation in the inflow area of intake structures. Here, there are band screen machines or other rotating protective screens of such small mesh width in operation that fish larvae will be pressed against the screen surface and get killed. The mortality caused by the fish being pressed against mechanical barriers is related to a time factor. Thus, the damage rate of fish larvae at rotating protective screens (chapter 5.4.2) can be reduced when increasing the rotating speed to a value at which the animals will be exposed to the water pressure for a short time only.

At vertical rotating protective screens larger larvae and young fish often fall back into the water as soon as they have been transported above the water surface. It is hereby inevitable that they will immediately be pressed against the installation again and eventually get killed. This can be avoided if the protective screen is installed inclined or equipped with troughs that are filled with water and receive larvae and young fish to be safely transported and finally emptied into a bypass through which they reach the tailwater (chapter 5.4.2).

5.1.4.4 Reaction to flat inclined barriers

If the limit value of the approach velocity is exceeded (chapter 5.1.4.3), the danger for migrating fish to become damaged through being pressed against the screen can be reduced by arranging the screen flat inclined and maintaining a pressure difference at the screen as low as possible. This however, requires larger screen surfaces, but the greater the inclination the smaller the portion of the approach velocity applicable to the vector of the tangential flow. The result is that the vector of the normal velocity will be reduced, and consequently also the risk of damage to migrating fish caused when being pressed against the protective screen.

Such arrangement works mainly to the benefit of eel (figure 5.16), which, as much as is known, normally first reacts upon contact with the screen to escape upstream.

Figure 5.16:
Behavioural observations on eel on a very flat inclined Wedge-Wire-Screen: the normal velocity is significantly reduced with an approach velocity of approx-imately 1.0 m/s. The fish will hence not be pressed against the screen, but kept away from the mechanical barrier with no risk of damage (ADAM et al., 1999)

A flat inclination effects a reduction of the normal velocity and thus the flow pressure from which the eel must escape. The eel is hereby enabled to avoid the danger of being pressed against the installation and to escape upstream, provided the approach velocity does not exceed their cruising swimming speed of approximately 0.7 m/s. A precondition however, is a sufficiently small clear spacing of the protective screen, as eel in particular tend to squeeze themselves actively through the gaps of flat inclined screens.

Other species avoid collisions with the screen and are generally not pressed against the installation unless the approach velocity has exceeded their swimming capacity. Hence, it is not the normal velocity that is decisive, but the approach velocity. The limit values stated in table 5.1 are therefore also to be applied to flat inclined protective screens for all species with the exception of eel.

Should the tangential velocity at an approach angle << 45° be increased to such extent that it exceeds the swimming speed of fish, it will function as a transporting flow and the fish will drift alongside the surface of the protective screen. In order to achieve this effect, the tangential component of the force resulting from the flow resistance must be greater than the frictional force between protective screen and fish. The frictional force is dependent on the roughness of the surface of the protective screen and the force it normally affects on the fish. This force however, derives directly from the normal velocity and the pressure drop that occurs at the protective screening.

The function of flat inclined screens is based on this mechanism, like the Eicher-Screen or the Modular Inclined Screen (chapter 5.6.3), where a bypass orifice is located at the downstream end to accept the fish. This principle therefore, although contrary to other protection facilities is very suitable and its effectiveness will be even greater where the approach velocity exceeds the swimming capacity of fish, so that they will drift alongside the screen.

However, a smooth screen surface is required if this principle is to be applied at high approach velocities, so that the frictional force generated will be low and damage to fish that contact the protective screen prevented. These factors were fulfilled by a Wedge-Wire-Screen (chapter 5.2.6) where tangential velocities of up to approximately 3.0 m/s (AMARAL et al., 1994) were evident.

5.1.4.5 Reaction to inclined arranged barriers

There are in principle no hydraulic differences between a flat inclined screen with □ < 45° and a vertical, but inclined to the approach velocity arranged screen with β < 45°. Hereby as well there will not only be a decrease of the normal velocity and consequently a reduction of the normal component of the flow resistance, which is influential on the fish (figure 5.2, figure 5.3). The flow vector that runs parallel to the screen surface can furthermore assist specific fish species in their downstream directed migration. This effect is utilized for combined downstream migration facilities (chapter 5.6), where for example Louver, drum screens, stationary or rotating protective screenings etc. are inclined arranged and equipped with bypasses at the downstream end. Such combined downstream migration facilities are very effective especially for smolts of migratory salmonids.

Fish behave differently at barriers arranged inclined to the approach velocity than at rectangular ones. These too indicate to fish that there are hazards, but a collision can on the one hand be avoided if the fish increases its swimming speed V_{rel} against the approach velocity, and on the other hand through traverse directed evasive movements. The fish will generally perform combined avoidance reactions. An overall downstream directed drift alongside the barrier will be effected, provided that the swimming speed V_{rel} is hereby lower than the approach velocity V_A. Bypasses which are arranged at the downstream end can thus be traced reliably. This reaction has been proven many times in laboratory and outdoor examinations. This principle however, now serves as basis for routine arrangements of fish protection facilities and downstream fishways for anadromous species mainly in the USA, but also in European countries (TAFT, 1986; PAVLOV, 1989; TURNPENNY et al., 1998; LARINIER & TRAVADE, 1999, and many more). Whilst fish stay for at least 10 minutes but possibly also for hours in the close vicinity of barriers which are rectangular arranged to the flow, they remain for just some seconds before inclined arranged barriers with an ideally traceable bypass until they have found the downstream fishway.

BATES & VISONHALER (1957) state that the swimming movement V_{rel} assumed by the fish to swim against the flow in order to avoid a collision with an inclined arranged barrier is equal to the amount of the normal velocity V_N, but in an opposite direction. Consequently would the velocity V_{dis} that drifts the fish parallel to the barrier be identical with the tangential velocity V_T (figure 5.17).

The actual behaviour of the fish in the vicinity of inclined arranged barriers does not contain just one individual linear reaction, but a combination of a complex succession of different behavioural patterns and changing swimming speeds and directions. HAEFNER & BROWN (2002) have hereby identified the following stages (figure 5.18):

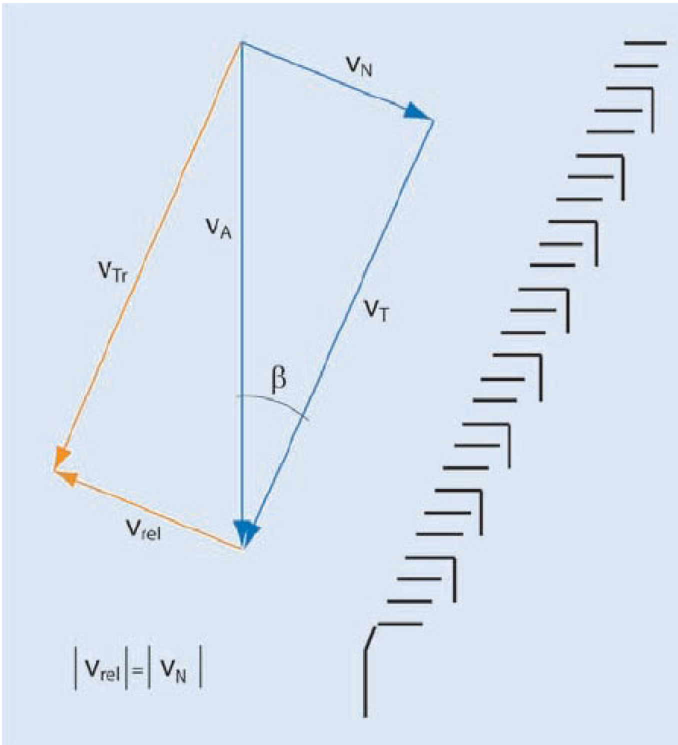


Figure 5.17: Illustration of how fish move in the vicinity of a barrier arranged inclined to the approach velocity by BATES & VISONHALER, 1957)(blue vectors = water; yellow vectors = fish)

V_A = approach velocity
V_N = normal velocity at the barrier
V_T = tangential velocity at the barrier
V_{rel} = swimming speed of the fish in relation to the water
V_{Tr} = transportation speed of the fish above bottom
b = angle of the barrier to the approach velocity (VA)

Stage 1: The fish migrates passively / actively downstream, whereby its body axis is aligned parallel to the approach velocity. It does not sense any jeopardy and moves at a maximum cruising speed: $V_{rel} \leq V_{duration}$.

Stage 2: When in close vicinity, the fish will perceive the barrier visually and / or hydraulically. The fish will be alarmed and enhance its swimming speed up to the sustained speed: $V_{rel} = V_{sustained}$. It hereby reacts on both, the approach velocity and the barrier, and changes its body axis to the flow accordingly to enlarge the angle towards the barrier. This reaction will suffice in avoiding a collision with the barrier where the approach velocity is appropriately low.

Stage 3: The fish will nevertheless drift towards the barrier during this manoeuvre if its swimming speed V_{rel} stays below the normal velocity V_N. In an effort to avoid this happening, the fish will accelerate its speed and assume the darting swimming speed: $V_{rel} = V_{sprint}$, whereby it will align its body axis rectangular to the barrier and swim against the normal velocity VN (BATES & VISONHALER, 1957). The further progress is dependent on the relation of the darting swimming speed to the normal velocity.

- There is no escape possible, if the normal velocity exceeds the darting swimming speed of the fish. It will drift further and be pressed against barriers if they are impassable. However, if barriers are passable for the fish it will then enter the hazardous zone.
- The fish will be able to evade the barrier in cases where the normal velocity is lower than its darting swimming speed, and will drift downstream by means of the tangential component of the approach velocity.
- velocity.

Stage 4: f the fish has accomplished a sufficient distance to the barrier and feels safe, it will realign its body axis parallel to the approach velocity and resume its cruising swimming speed: $V_{rel} = V_{duration}$. The fish has hereby re-established stage 1, but as soon as it gets nearer to the barrier again, this complex motion will start anew.

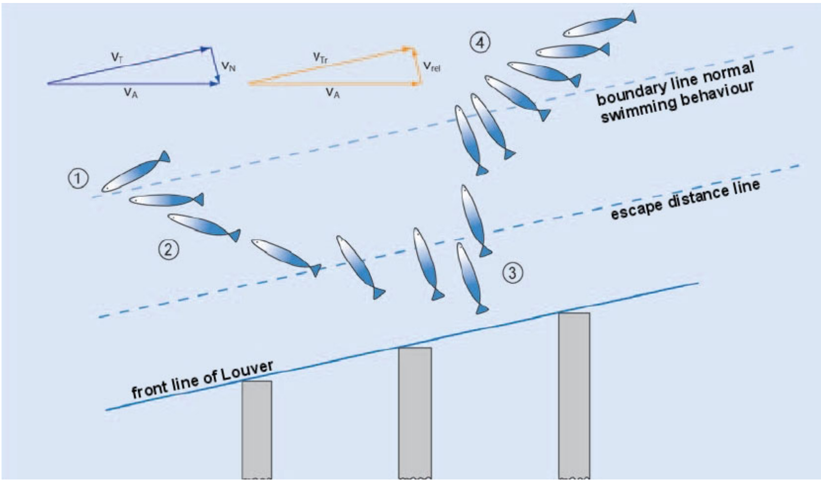


Figure 5.18:
Behaviour of fish in the vicinity of an inclined arranged barrier, exemplified by a Louver (according to HAEFNER & BOWEN, 2002)(blue vectors = water; yellow vectors = fish)

When following this procedure the fish will be guided alongside the screen surface in "wavelike" manoeuvres to a bypass located at the downstream end of the screen (figure 5.19).

The darting swimming speed and the perseverance of a fish are related to its size, which has the following consequences on the success of the manoeuvres described above (figure 5.20):

- The amplitude of the entire motion is greater for large fish than for small fish. The distance large fish can swim alongside the screen by the same number of sprints is subsequently greater. They therefore reach the bypass that is arranged at the downstream end of the screen much faster than small fish.
- Since the white musculature fatigues quickly, there is a limit to the number of times this motion can be repeated, as the swimming capacity of the fish will be reduced successively.
- When combining both these effects it becomes obvious that the size of the fish is the decisive factor for the protective effectiveness of inclined arranged barriers.

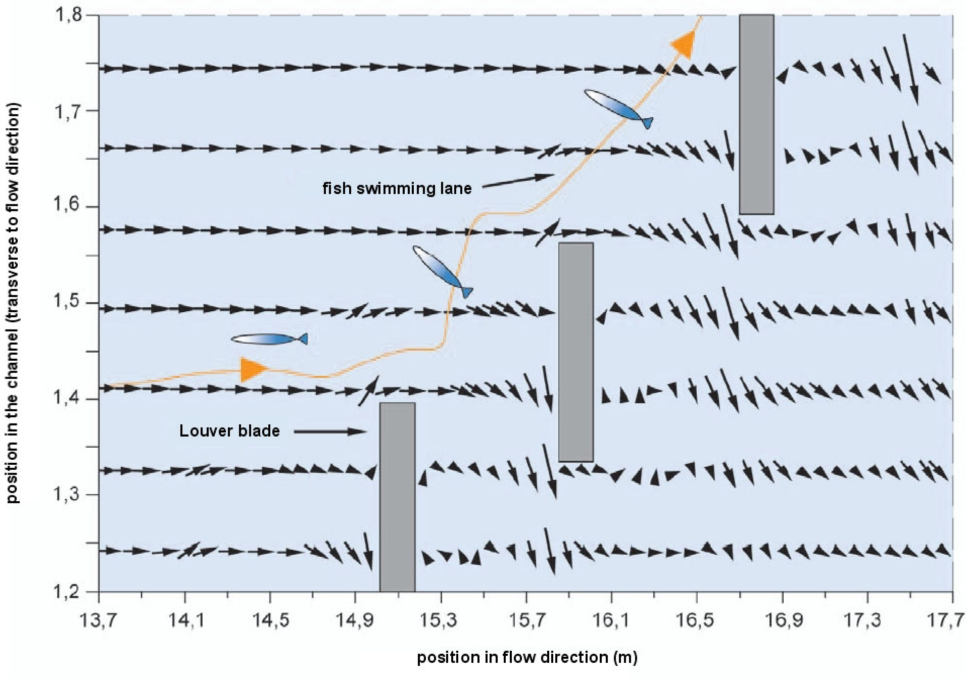


Figure 5.19: wimming lane of a fish alongside an inclined arranged mechanical barrier (according to HAEFNER & BOWEN, 2002)

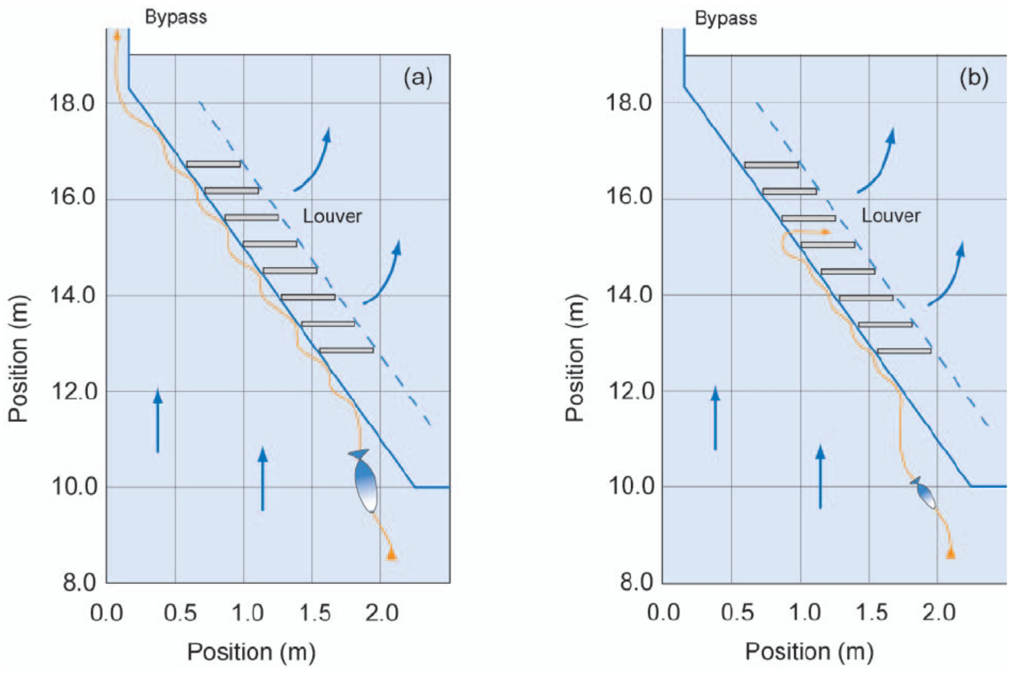


Figure 5.20: wimming lanes of small and large specimen of the same species which meet an inclined arranged barrier at different places, schematic diagram (HAEFNER & BOWEN, 2002): Large fish (a) keep a greater distance to the barrier and the amplitude of their swimming manoeuvre is greater. They are in a position to follow the total length of the screen and finally find the bypass (shown in the schematic diagram on the left hand side above). However, the amplitude of the swimming manoeuvre of small fish (b) is significantly lower. Small fish can only follow the surface of the screen for a specific distance until they fatigue and will be pressed against the screen surface or will drift through it.

5.1.4.6 Permitted approach flow against inclined arranged barriers

The motion that fish perform in their avoidance reaction towards inclined arranged protective screenings was analyzed in detail by HAEFNER & BOWEN (2002) and has earlier already been identified by PAVLOV (1989). He took the analysis for a mathematic model that he developed to calculate the speed at which a fish moves alongside the barrier and the time it needs to reach the bypass.

The hereby resulting motional system in connection with the behavioural reaction of the fish is presently the most complete model that describes the interaction of fish (with the exception of eel) with fish protection facilities. It combines the hydraulic characteristics of the protective installation with the behaviour of the fish, which previously was only approached empirically. This leads to concentrated consideration of the conditions, under which the fish is able to reach the bypass. The correct arrangement of mechanical barriers and bypasses according to chapter 5.5 and 5.6.1 refers mainly to these correlations.

PAVLOV (1989) idealized the wavelike swimming manoeuvre of the fish to a straight line and divided the shunning and avoidance reaction into two components:

- The reaction towards a flow (R_{rel}) in order to avoid a drift and
- The shunning reaction towards the obstacle ($R_{shunning}$) to prevent a collision.

If in greater distance to the barrier, the migrating fish reacts solely to the approach velocity. Its swimming speed V_{rel} is lower than V_A and it moves exactly in the opposite direction to the approach velocity.

The reaction to the flow will partly be suppressed and the avoidance reaction will become dominant when the fish approaches the barrier. Its subsequent reaction to the approach velocity deviates by an angle □ from the flow direction and the escape reaction takes place in a pointed angle to the barrier (figure 5.21). Based on empiric examinations, especially on juvenile Cyprinids, PAVLOV (1898) indicates for □ an angle of approximately 25° as a rough reference point.

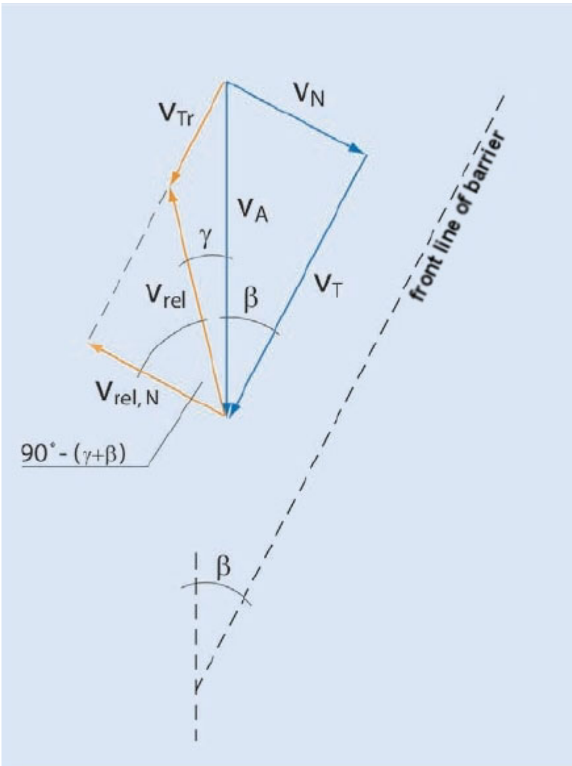


Figure 5.21:
Schematic diagram of fish movements in the vicinity of a barrier according to PAVLOV (1989)(blue vectors = water; yellow vectors = fish)

V_A = approach velocity
V_N = normal velocity at the barrier
V_T = tangential velocity at the barrier
V_{rel} = swimming speed of the fish in relation to the water
V_{dis} = drifting speed of fish above bottom
β = angle of barrier to the approach velocity
γ = angle of fish to the approach velocity (V_A)

Based on PAVLOV's (1989) mathematic formulation, the swimming speed V_{rel} that must be achieved by the fish to avoid a collision with the barrier can be assessed as follows:

$$V_{rel} = V_N \cdot \left[\sin(b + g)\right]^{-1}$$

with:

V_N= normal velocity of the barrier

γ= angle of the fish towards the flow direction

β= angle of the barrier towards the flow direction

The speed at which the fish moves alongside an inclined arranged barrier is calculated as follows:

$$V_{dis} = \sqrt{V_{rel}^2 + V_A^2 - 2 \cdot V_{rel} \cdot V_A \cdot \cos\gamma}$$

It is feasible by means of this calculation method to establish the best possible hydraulic dimensioning of fish protection facilities for specific species and stages if the swimming capacity is known. The angle of the barrier and the approach velocity must hereby be synchronized in such a way that the required swimming speed of the fish V_{rel} is lower than its sustained swimming speed $V_{sustained}$. The traceability of a bypass at the downstream end of such a barrier will in this case be supported by high approach velocities, as a distinct searching behaviour is not possible, hence, the amount of fish trying to migrate through passable barriers will evidently be reduced.

Taking a barrier that is arranged at an angle of 15° as an example, the approach velocity calculated for migrating salmon smolts would be based on the following:

$$V_{rel} = V_N \cdot [\sin(b+g)]^{-1} \text{ or } V_N = V_{rel} \cdot x \cdot \sin(b+g)$$

The result for β hereby reads = 15°,

γ (according to PAVLOV, 1989) = 25°

and V_{rel} = 0.5 m/s:

V_N = 0.5 x sin (15° + 25°) = 0.5 x 0.64 = 0.32

The following formula is applied to calculate the approach velocity on the basis of the normal velocity:

$$V_A = V_N / \sin\beta = 0.37 / \sin 15° = 0.37 / 0.26 = 1.42 \, m/s$$

In this case therefore, the approach velocity with regard to the protection of migrating smolts shall never exceed 1.42 m/s. An optimization in respect of this target species would be possible at a slightly lower approach velocity. PAVLOV indicates a factor of k = 0.95 for the best possible relation between $V_{critical}$ and V_{rel}, which results in an approach velocity of V_A = 1.35 m/s. If the approach velocity has already been defined, it would then be possible to establish optimal conditions by adjusting the angle accordingly.

However, the consequence arising from an optimized arrangement and dimensioning of barriers for a specific target group is that the swimming capacity of other species will be neglected and can lead to damage.

Many of the fish protection facilities that exist in foreign countries comply with the above mentioned criteria. In Germany however, the results of the before mentioned calculation methods have never been realized in practice.

5.1.5 Clear spacing of mechanical barriers

- The fact that mechanical barriers with clear spacing of a dimension in line with the technical requirements outlined in chapter 5.2.2, or on the basis of technical standards applicable to fishery can only insufficiently assist in preventing fish from entering hazardous installation areas and has been comprehensively documented on examinations carried out in German-speaking regions:
- Examinations in the Main and Moselle rivers where conventional screens with the usual clear spacing of approx. 90 mm are in use have shown that they can only keep extremely large fish from entering the turbine intake (HOLZNER,1999).
- The results of examinations which RAUCK (1980) has carried out at the cooling water intake of the nuclear power plant Brunsbuettel (Schleswig-Holstein, Germany) prove that also a screen with a clear spacing of 40 mm was only able to keep breams of a size from 50 cm onward away. Any other fish will pass the screen, then be pressed against the fine screen and get killed.

- Behavioural observations in a model channel indicate that even eel of 70 cm body length will pass a 20 mm-screen (ADAM et al., 1999, figure 5.22). Outdoor examinations implemented by BERG (1988) at the hydropower plant Letzter Heller on the Werra river (Lower Saxony) confirm these findings. On this occasion it could further be observed that a 25 mm-screen fails any protective effect on large silver eels.
- Even screens with a clear spacing of 18 mm will be passed by eels of a weight of 250 g and a body length of 45 to 50 cm (JENS, 1987).

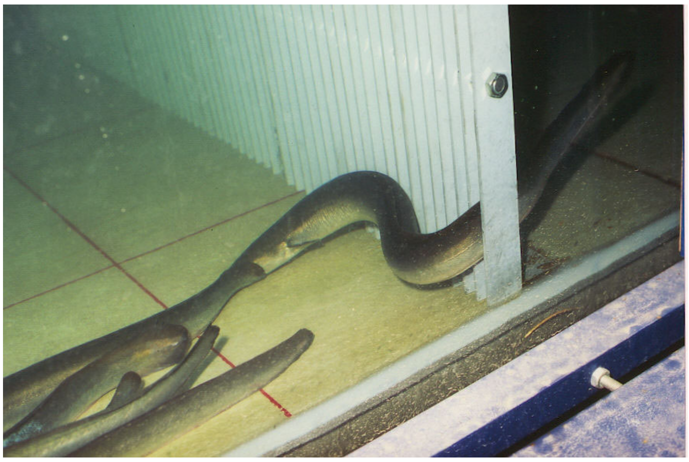


Figure 5.22:
A 70 cm long eel passes a 20 mm-screen (ADAM et al., 1999)

These examples outline that the protective function of mechanical barriers is dependent on their clear spacing in relation to the size of the fish. The smaller the target species or -stages, the smaller the clear spacing that is required to guarantee effective protection. PAVLOV (1989) defines three degrees in passable screens with regard to their protective function:

- **impassable**: The clear spacing is lower than the body size of the fish, so that a passage will not be feasible.
- **passable**: The clear spacing is greater than the size of the fish.
- A special situation arises from passable barriers which are avoided by fish because of their behavioural reactions. PAVLOV (1989) has classified such barriers as **impassable due to behaviour**.

5.1.5.1 Impassable mechanical barriers

Whether mechanical barriers are passable for a fish depends on the following sizes and proportions of a fish:

L_{fish}: The total length of a fish from the tip of its mouth to the end of its tail.

H_{fish}: The maximum height of the fish body

D_{fish}: The maximum bigness of the fish body.

K_{high}: The relative height of the fish body in relation to the total length:

$$K_{high} = H_{fish} / L_{fish}$$

K_{thick}: The relative bigness of the fish body in relation to the total length:

$$K_{thick} = D_{fish} / L_{fish}$$

These dimensions and proportions are stated in table 5.2 as an example for juvenile and adult specimen of different body shapes. In comparison, larvae and frys are generally remarkably slimmer, to which the values K_{high} = 0.09 to 0.15 apply.

Protective screens with meshes or perforations

The relation of the mesh width (d_M) or the diameter of the perforation (d_L) to the maximum diameter of the fish is the decisive parameter for mechanical barriers with meshes or perforations to be passable for fish ($P_{M/L}$), and normally refers to the body height of the fish (H_{fish}) (figure 5.23). The relative passage results from:

$$P_{M/L} = \frac{d_M}{H_{fish}} \; or \; \frac{d_L}{H_{fish}}$$

In the case of impassable barriers, the mesh width or the diameter of the perforation of the barrier is smaller than the height of the fish body (H_{fish}), the value $P_{M/L}$ is therefore lower than 1, and for passable barriers greater or equal 1. Thus, the following applies in order to offer an effective protection:

$$P_{M/L} < 1$$

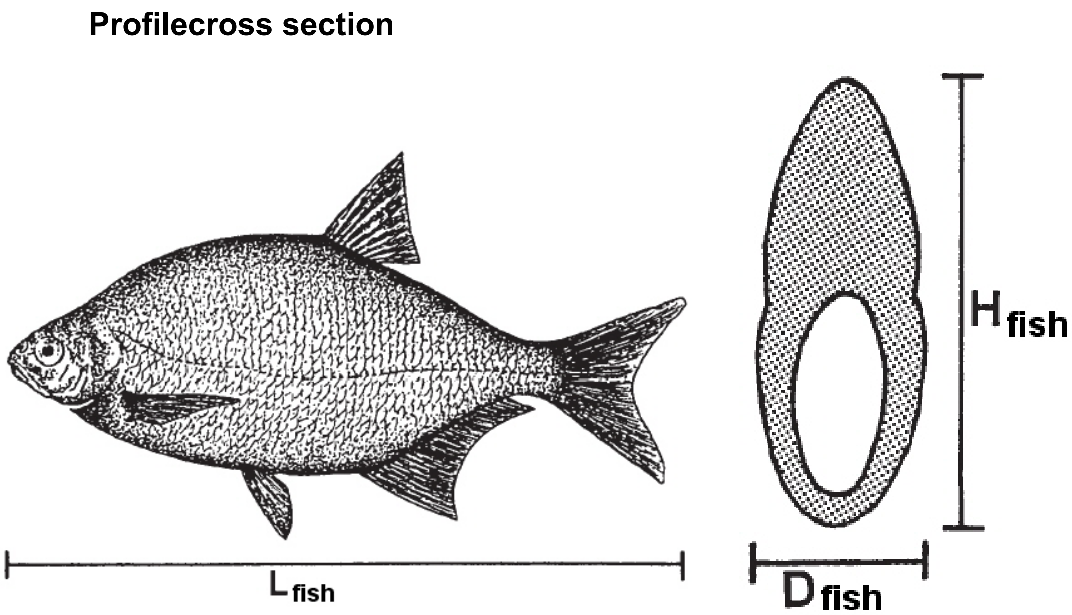
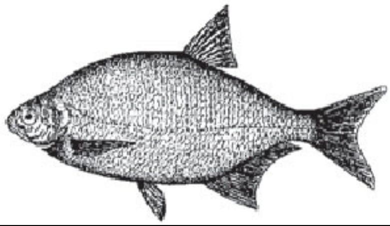
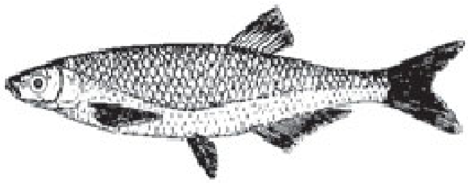
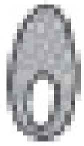
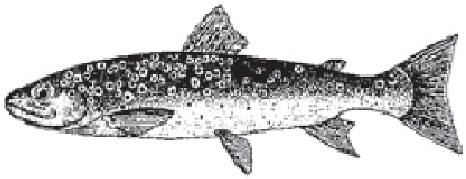
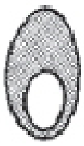
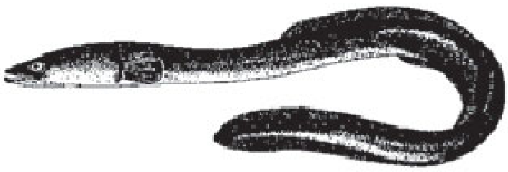
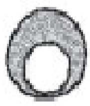


Figure 5.23: Relevant body dimensions of fish

Table 5.2: Relevant body dimensions and proportions of fish of different body shapes (SCHWEVERS, 2004)

body shape	example	profile	cross section	K_{high}	K_{thick}
high back	bream			0.30	0.10
long-stretched to torpedo shaped	bleak			0.23	0.10
	brown trout			0.17	0.10
eel shaped	eel			0.05	0.05

Hence,

$$d_M < H_{fish} \text{or} d_L < H_{fish}$$

is to be applied to the mesh width or diameter of the perforation of impassable mechanical barriers.

The value H_{fish} is normally expressed in relation to the fish length like:

$$H_{fish} = K_{high} \times L_{fish},$$

whereby L_{fish} is the total length of the fish and K_{high} the relation between body height and total length. The required mesh width or diameter of the perforation of an impassable mechanical barrier is therefore calculated as follows:

$$d_M < K_{high} \times L_{fish} \text{or } d_L < K_{high} \times L_{fish}$$

According to PAVLOV (1989) K_{high} is 0.17 to 0.23 for fish with long-stretched or torpedo shaped bodies, and 0.3 for species with high backs like bream and white beam. Larvae of most species however, with values of K_{high} = 0.09 to 0.15 are remarkably slimmer. A K-value of approximately 0.05 applies to eel and other eel shaped species like lamprey (ADAM et al., 1999). From this follows the correlation between body length of fish and limit value of the mesh width of impassable mechanical barriers as illustrated in figure 5.24.

Bar screens

The clear spacing between the bars of the screen is of a long-stretched shape. Hence, the maximum bigness of the body D_{fish} and not the height of the fish H_{fish} is decisive for the passage feasibility.

$$P_{St} = \frac{d_{St}}{D_{fish}}$$

The following formula applies if protection effectiveness of bar screens is to be provided:

$$P_{St} < 1$$

Accordingly

$$d_{St} < D_{fish}$$

is the clear spacing of impassable mechanical barriers

The value D_{fish} is normally expressed in relation to the fish length like:

$$D_{fish} = K_{thick} \times L_{fish},$$

whereby L_{fish} is the total length of the fish, and K_{thick} the relation between the bigness of the fish and its total length. The required clear spacing of impassable bar screens is therefore calculated as follows:

$$d_{St} < K_{thick} \times L_{fish}$$

According to HOEFER & RIEDMUELLER (1996) the relative body bigness of Salmonids with their torpedo shaped body in relation to the total length is approximately $K_{thick} = 0.10$. The relative body bigness for many other species has been assessed by HOLZNER (1999) through a systematic measuring of fish in the Lower Franconia stretch of the Main river. The species-specific values for K_{thick} as shown in table 5.3 are calculated on the basis of these data. These, however, exhibit some dispersion in dependence on the nutritional condition, but a linear relation between L_{fish} and D_{fish} has nevertheless been established for all examined species, so that K_{thick} is a species-specific constant which will only be lower for the comparatively slimmer larvae and frys.

Table 5.3: Relative bigness of the fish body K_{thick} of various species

K_{thick}	fish species	authors
0.05	eel	HOLZNER, 1999
0.07	pike	
0.09	white beam, dace, bleak	
0.10	bream, asp, zander	
0.10	asp	
0.10	zander	
0.11	barbel, perch, nase, roach, rud	
0.12	chub	
0.13	ruffe	
0.13	burbot, tench, catfish	
0.15	crucian	
0.24	carp	
0.10	salmonids	HOEFER & RIEDMUELLER, 1996

The clear spacing of impassable bar screens in dependence of the fish size is calculated as follows:

$$d_{St} < K_{thick} \times L_{fish}.$$

The correlation between the limit value of the clear width d_{St} and the length of the fish L_{fish} for impassable bar screens is exemplified by some species in figure 5.25 and is based on the values indicated in table 5.3. For all other species can d_{St} be calculated according to the above shown formula. The clear width of bar screens must therefore be distinctly smaller than those of mechanical barriers with square, rectangular or round openings.

The eel represents a special case, as it will actively squeeze itself between the bars of the screen also where the clear width is clearly less than their body bigness. According to ADAM et al. (1999) therefore, the limit value of the clear width of impassable bar screens for eel is to be calculated on the value K_{thick} = 0.03 (ADAM et al., 1999).

Figure 5.24 and 5.25 illustrate the relation between the total length of a fish and the limit value of the mesh width or clear spacing of impassable bar screens and explain why mechanical barriers have to be dimensioned to the size of the specific target species if they are to be effective. Fishery regulations of most of the federal states of Germany demand the use of 20 mm-screens, which however, guarantee a reliable protection of the carp of a size of 8.5 cm and more, the tench of 16 cm and pike of 30 cm total length and larger, but migrating salmon smolts and silver eels will not be prevented from their passage. The limit values of the clear spacing of impassable mechanical barriers in respect of salmon and eel as displayed in table 5.4, are calculated on the basis of the before mentioned formulae.

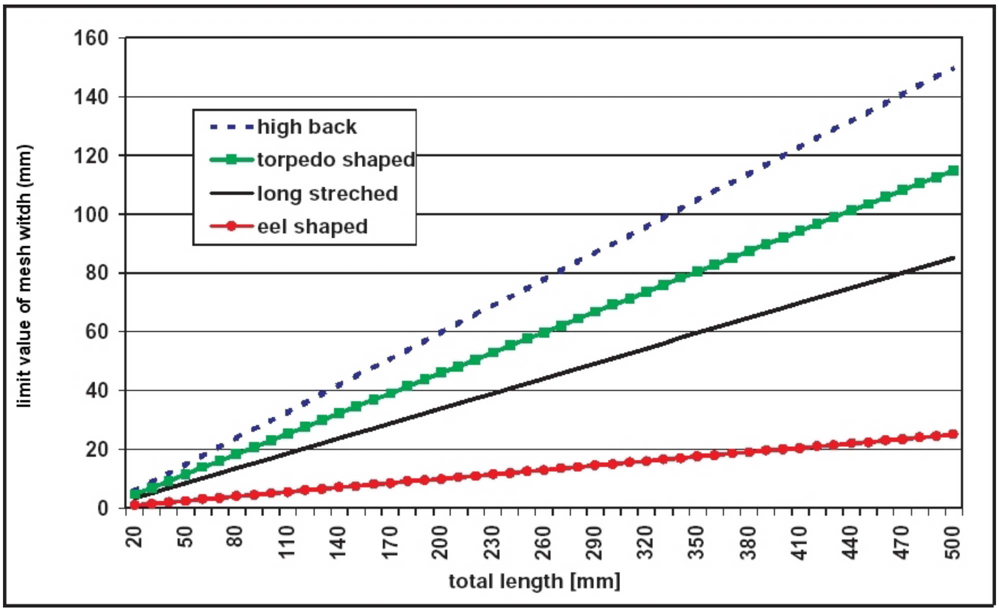


Figure 5.24: Dependence of the limit values for the mesh width or diameter of the perforation of impassable barriers from the body length and shape of a fish

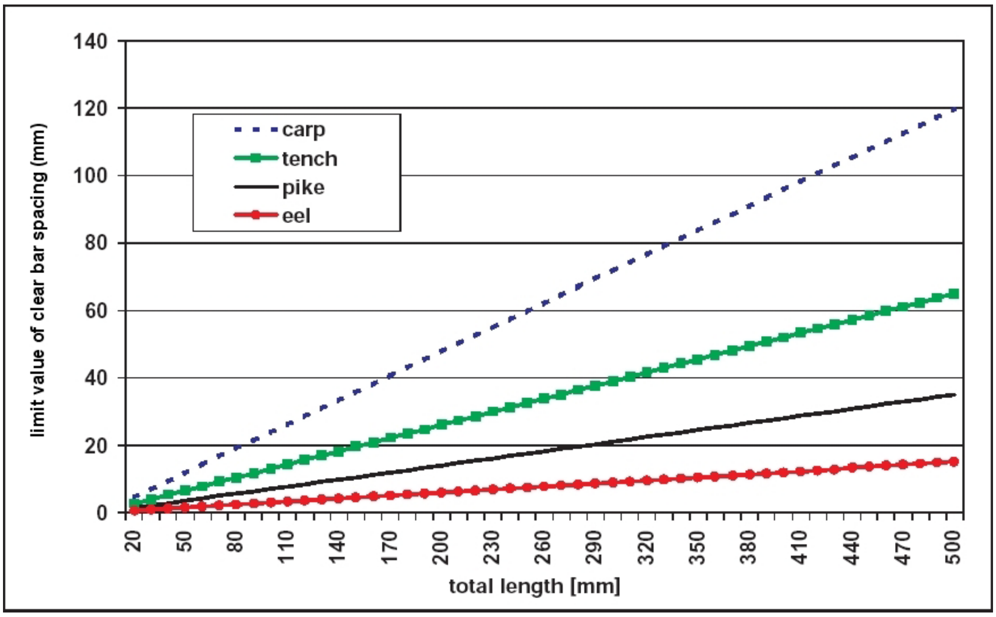


Figure 5.25: Dependence of the limit value for the clear width of impassable bar screens from the body length of a fish

Table 5.4: Limit values of the permissible clear width of impassable mechanical barriers in dependence on the target species

species	relevant length [mm]	proportions		permissible clear width [mm]	
	L_{fish}	K_{high}	K_{thick}	d_{M+L}	d_{St}
salmon smolt	> 120	0.17	0.10	20	12
silver eel (♀)	> 500	0.05	0.03	25	15
silver eel (♂)	> 300	0.05	0.03	15	9

5.1.5.2 Passable mechanical barriers

Whilst the free passage coefficient $P < 1$ is to be set up with 100 % for the protective function of mechanical barriers, passable barriers with $P > 1$ however, will no longer offer a perfect protection, but neither will they immediately lose their entire function as a fish protection facility: Under certain conditions they are effective as impassable barriers in relation to behavioural patterns, and according to PAVLOV (1989) can achieve an efficacy between 70 and 95 % in the most favourable case.

Their effect depends on how the fish perceives visual, tactile and hydraulic stimuli. If illuminated, all barriers will be perceived visually, but in darkness hydraulic stimuli become more important, like sudden changes of the flow structure and flow direction and also changing frequency patterns of pulsating flows. Such hydraulic stimuli are generated by any object in the flow. Especially in darkness the efficiency of passable barriers is the better the stronger the stimuli. The efficacy of passable mechanical barriers is therefore primarily dependent on the clear spacing, but also on various other factors.

Clear spacing: The maximum efficiency of passable barriers will be obtained according to PAVLOV (1989) at a relative free passage of $P < 3.0$, and is in line with data established by LARINIER & TRAVADE (2002), who have stated that conventional bar screens keep a greater rate of salmon and sea trout smolts off at a clear width between 2.5 to 4.0 cm ($P = 1.4$ to 3.3). Clear spacing in excess of these values will soon reduce the protective effect, thus screens with a clear width between 6.0 and 7.0 cm will not comply with the function intended. This clear spacing equals a relative free passage of $P = 3.3$ to 5.8 for smolts of a length between 12 to 18 cm.

How migrating eel behave at passable mechanical barriers is still not sufficiently known. The restricted protective function of passable barriers was proved by BERG (1988) at the hydropower plant *Letzter Heller* on the Werra river, where more than 200 silver eels have passed the conventional screen of 25 mm clear width within one week. The free passage coefficient of $P \approx 1.7$ equals a minimum size of 50 cm. There is evidence, however that screens of significantly greater clear spacing will in general not be passed by eel, but that some will perform a return reaction as already described for impassable barriers (BRUIJS et al., 2003). Telemetric examinations at the Moselle river have also led to the conclusion that some eel will instantly interrupt their migration and escape upstream before contacting the screen (BEHRMANN-GODEL, 2000). Professional fishermen on rivers like the Weser, Main and Moselle take advantage of this behaviour, and traditionally expose their fyke nets in a small distance to screens of a clear width between 80 and 120 cm in such a fashion that the opening of the fyke net is laid out in downstream direction. The catches made with fyke nets arranged in such a manner reflect the upstream directed escape reaction of eel in front of the screen of the hydropower plant, which even happens at values of $P = 5.3$ to 8.0. The eel nevertheless, will eventually pass the screen if there are no alternative migration corridors available.

Telemetric examinations carried out at the hydropower plant Cabot Station on the Connecticut River (Massachusetts, USA) by HARO et al. (1999) give evidence of comparable parallels of escape reaction and screen passage: Here, migrating American eel of a length between 0.7 and 0.9 m swam into the forebay of the hydropower plant up to 15 times prior to finally passing the screen of 102 mm clear spacing that is equal to a free passage coefficient of $P = 3.8$ to 4.9.

On the one hand these findings confirm that screens of P-values of slightly above 1.0 will indeed be passed by eel and therefore constitute a reduced protective function. On the other hand, however, the unrestricted free passage does obviously not apply to values below $P > 0.8$. Hence, there is evidently a wide range of P-values at which passable barriers will be passed by a number of migrating eel, but a return reaction as described for impassable barriers will still happen to some extent. It is possible that this behaviour is owed to the long-stretched body shape of the eel and the variable alignment of its body to the approach velocity.

Angle of the barrier to the approach velocity: If a barrier is arranged in a pointed angle to the flow direction, the local hydraulic disturbances, which are caused by each element, will induce the fish to move alongside the barrier from one element to the next (chapter 5.1.4.5). Inclined arranged barriers produce a flow gradient along their surface in addition to local hydraulic disturbances. This also assists in diverting the fish into a bypass.

The efficiency in this respect is the greater the smaller the angle □ at which the barrier is arranged to the flow. The optimal angle at Louvers is 10° to 16° according to BATES & VISONHALER (1957). PAVLOV (1989) states that these values are also suitable for other types of passable barriers.

Inclination of the barrier towards the bottom of the water body: Flat inclined passable barriers are similarly effective for salmon smolts and potamodromous species like vertical barriers. The eel, however is a bottom-orienting species and any kind of disturbance will cause it to seek protection at the bottom of the water body, but will be induced to escape into the headwater as described in chapter 5.1.4.2 by a greater inclination of the screen and will more often be led to a different behavioural reaction: The fish pass the screen by squeezing themselves either with their head or their tail ahead actively through between the bars of the screen (ADAM et al., 1999, figure 5.26).

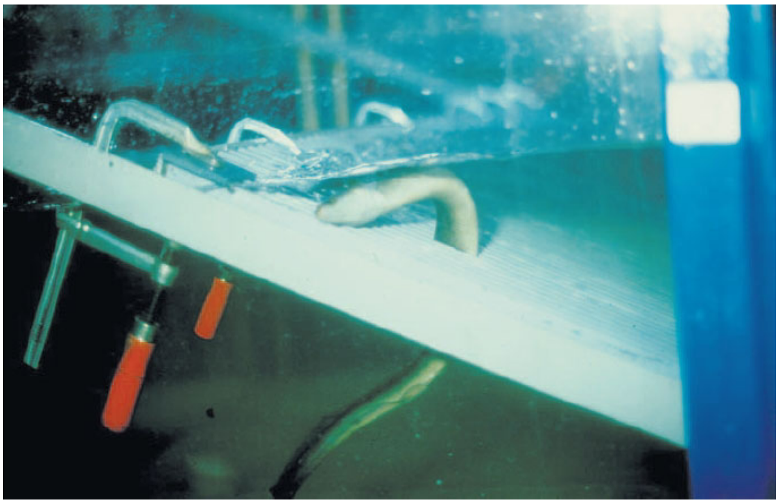


Figure 5.26:
Active passage of an eel through a flat inclined 20 mm-screen in a model channel.

Approach velocity: The progressing movement of the fish into a narrower intake zone leads to more intense panic reactions and subsequent search for possibilities to escape the crucial situation. Consequently, the fish will most likely pass the passable barrier where low approach velocities allow intensive search behaviour. A rise of the approach velocity (V_A) up to the critical speed of the fish ($V_{critical}$) results in an increased suppression of the search behaviour of the fish and enhances the protective effect by a reduced free passage in relation to behavioural patterns. However, if the approach velocity (V_A) exceeds the critical speed of the fish ($V_{critical}$), this will increase the probability for the fish to drift through the barrier, this means that the physical passage takes place and consequently leads to a reduced protection efficacy. Hence, there is an upper and lower limit of the permissible flow velocity to be observed for passable barriers. In practice the effective operation of such facilities is only guaranteed for a relatively restricted spectrum of flow velocities. According to preliminary statements by PAVLOV (1989) the best effectiveness can be obtained at a relation of V_N / $V_{critical}$ between 0.14 and 0.33.

5.1.6. Operational hours

Should fish protection facilities and downstream fishways not be designed and used for the entire spectrum of species of a water body, but to guarantee the migration of specific target species, their operation can then be adjusted to meet the migration periods of these species.

The migration of Atlantic salmon and sea trout smolts Europe-wide can be relatively exactly determined for the period mid of April to end of May (SCHWEVERS, 1998). Bypasses in French salmon rivers are therefore solely operated over this specific period. The migration of smolts, however, normally taking place over night is less distinct: During the course of the migration season smolts extend their activity more and more into the daytime. The diurnal rhythm of the migration of smolts should therefore be assessed in the appropriate water body (chapter 2.5) over the course of a day prior to any restriction of the operational hours of salmon bypasses.

The migration season of eel can only roughly be limited to the months August to January, so that it is needed to operate eel bypasses over a period of at least 5 months to safeguard their migration. However, the operational hours can normally be restricted to the night time, as eel are bound to migrate in darkness and only exceptionally during the day if there is a strong turbidity of the water (chapter 2.5.2). A further restriction of the operational hours might be implemented on the basis of early warning systems, provided they permit a reliable definition of the migration period of the target species (chapter 5.8).

To confine the operational hours of downstream fishways to the migration periods of target species implies that the migration possibilities for all other species or development stages will be limited in time:

- If the operation mode of bypasses near the surface is adjusted to the migration periods of salmon smolts and sea trout smolts, then the migration of Kelts will not be guaranteed.
- Neither will the bypasses be available to the migratory stages of other anadromous species during their migration season because of their different annual rhythmic.
- Potamodromous species will also be neglected, especially since their migration periods could not reliably be defined until present.

Consequently bypasses must be operated throughout the year if they are intended to guarantee the downstream passage of all fish species. Only strong frost periods during which only a minor migration activity would take place anyway, could become an exception if technical problems, especially iced-up barriers, would impede the operation of fish protection facilities.

5.2 Mechanical barriers

Mechanical barriers are installed in front of intake structures of hydropower plants, irrigation and drainage systems or cooling water withdrawal systems of thermal power plants etc.. They comprise screens of various types or perforated plates. Such systems will be dealt with in the following, of which the openings are so small that they hinder the penetration of fish like a filter. Additionally, mechanical behavioural barriers will be described, of which the function as a physical obstruction becomes secondary in comparison to the effect they have on the behaviour of migrating fish. The main problem of almost all mechanical barriers is their high tendency of clogging caused by flotsam in the water and icy conditions. This situation necessitates special cleaning requirements.

5.2.1 Hydraulics of mechanical barriers

Hydraulic loss occurs at all mechanical barriers, which become noticeable through differences in the water level or pressure. At hydropower plants, these screen losses result in a reduction of the utilizable head. Losses incurred by the screen will be influenced by:

- the geometry of the barriers: dimension of the clear opening of the barriers (clear spacing (d_R) at conventional screens, clear mesh width of nets, hole diameter of perforated plates), the bar profile, and the ratio of the clear opening to the total surface of the barriers.
- the approach velocity and -direction of the barrier.

The hydraulic loss will increase the smaller the clear spacing and also with a rising approach velocity. In order to lower the loss at a certain flow-through it is necessary to reduce the approach velocity and / or enlarge the screen surface. At a given cross-sectional approach velocity it is also possible to enlarge the screen surface by inclining the screen horizontally or vertically against the direction of the approach velocity. The screen loss is calculated on the basis of the following formula:

$$h_R = \xi * \chi * V_A^2/2g$$

with

V_A=approach velocity

g=final acceleration

χ = coefficient that accounts for the loss arising through a sideways inclined approach of the velocity to the screen bars at an angle (d). It is additionally depending on the ratio of the bar thickness (s) to the clear spacing (d_R). The values are to be taken from table 5.5.

The loss coefficient (ξ) can be determined by an empiric approach that applies to all shapes of bar screens as follows:

$$\xi = \beta * (s/d_R)^{4/3} * \sin \alpha$$

with

s=bar thickness [m]

d_R=clear spacing between bars [m]

β=experimentally determined form coefficient of screen bars (figure 5.28).

Newer approaches on the calculation of screen losses can be found under GIESECKE & MOSONYI (2003) and VAW (1999).

Table 5.5: Coefficient (χ) in dependence on the approach angle of the velocity (δ) (figure 5.27) and the ratio (s/d_R) (GIESECKE & MOSNONYI, 1997)

a/dR	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2
δ									
0°	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
10°	1.06	1.07	1.08	1.09	1.10	1.11	1.12	1.14	1.50
20°	1.14	1.16	1.18	1.21	1.24	1.26	1.31	1.43	2.25
30°	1.25	1.28	1.31	1.35	1.44	1.50	1.64	1.90	3.60
40°	1.43	1.48	1.55	1.64	1.75	1.88	2.10	2.56	5.70
50°	1.75	1.85	1.96	2.10	2.30	2.60	3.00	3.80	-
60°	2.25	2.41	2.62	2.90	3.26	3.74	4.40	6.05	-

The hydraulic losses so far considered refer to soiled mechanical barriers. However, a clogging of the barrier is caused by flotsam (leaves, wood, waste from affluent society) and leads to further losses.

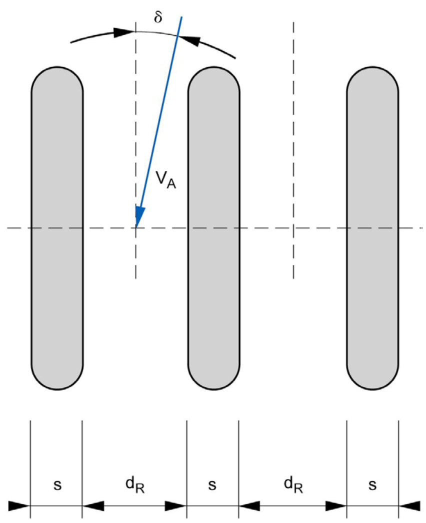


Figure 5.27: Definition of the angle (δ) at an inclined approach of the velocity to the screen bars

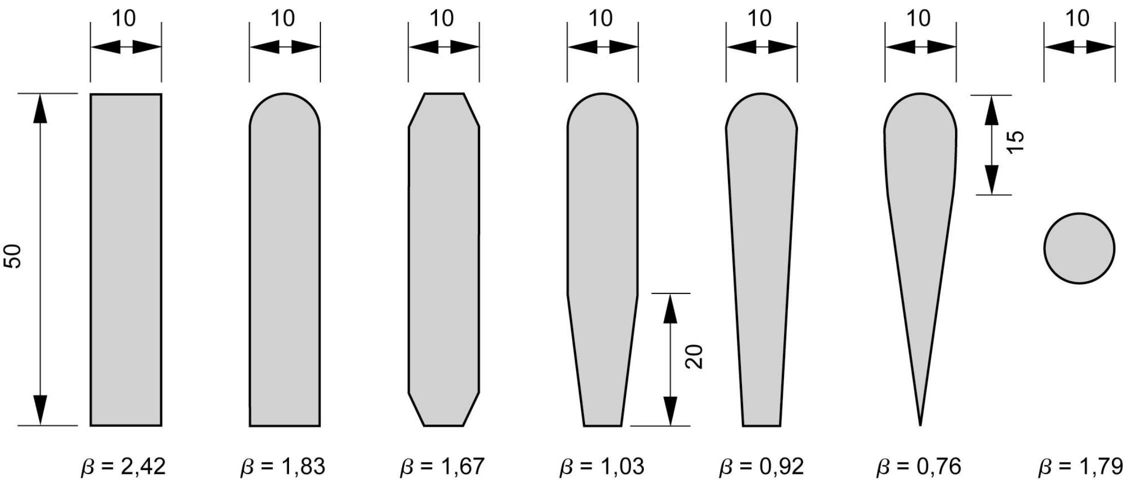


Figure 5.28: Form coefficient (β) for various types of screen bars [mm] (according to BOLLRICH & PREISSLER, 1992)

The smaller the clear spacing of the barrier the greater the portion of flotsam that accumulates at the barrier. The dislocation of the barrier will take place the sooner the more the normal speed (see chapter 5.1.3) rises. Flotsam can heap up on the surface at the barrier and - depending on size and shape - for example be pressed between the bars of a conventional screen. Whilst flotsam that got caught up at the front of the screen can be removed by the screen cleaning machine, material that got squeezed in often presents a permanent clogging which can only be removed manually.

The hydraulic loss of clean and soiled barriers can generally be reduced when decreasing the normal speed (i.e. by enlarging the screen surface and maintaining the same flow-through). Any greater clogging of barriers with small clear spacing can only be controlled through intensive cleaning in the case of an enlarged surface. This presently, though, involves significant technical and economical problems for greater flow-through rates.

5.2.2 Conventional screens

Screens primarily prevent turbines or pumps from becoming damaged by keeping coarse flotsam away from the machines. Screens are generally constructed with flat steel which are kept at a certain distance (d_R) by separators (figure 5.29).

The clear spacing is technically designed to match the construction type and dimension of the turbine or pump, in order to prevent damage to the machine, provided the screen shall not specifically serve as a fish protection facility (figure 5.30, figure 5.31, figure 5.32). Hereby the following applies: the smaller the diameter of the runner or the clear width of flow channels or jets, the narrower the clear spacing of the screen must be. MOSONYI (1966) states as a general rule for Kaplan turbines that the clear bar spacing should not exceed 1/30 of the runner diameter (table 5.6). The smaller the bar spacing the greater the amount of flotsam that needs to be removed by the screen cleaning machine and then disposed of.

The screen bars can be installed vertically or horizontally depending on the direction in which the screen cleaning machine works.

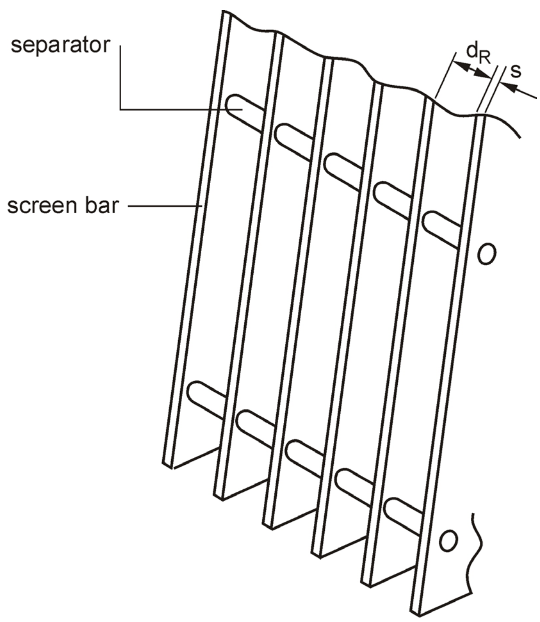


Figure 5.29 Screen made of flat steel

In the beginning screens were exclusively installed for technical reasons but in the past have also been considered as a facility that protects fish from entering machines which are secondarily connected. This has given rise for the demand to install screens with clear spacing as narrow as possible. For this reason, the employment of the 20 mm-screen has become institutional in some Federal States of Germany (chapter 8). The permissible maximum approach velocity however is not defined (chapter 5.1.3 and 5.1.4).

Figure 5.30:
Submerged levelscreen in front of the hydropower plant Obermaubach on the Rur river (North Rhine Westphalia,Germany). The upper edge of the screen will be about 2.0 m below water level if the reservoir is filled

Figure 5.31:
Screen with hydraulic screen cleaning machine in a small discharging power plant on the Dill river (Hesse, Germany)

Figure 5.32:
Screen with rope driven screen cleaning machine at the power plant Ahl on the Lahn river (Rhineland Palatinate, Germany)

Table 5.6 Technically conditioned maximum screen widths at hydropower plants (Details according to RWE POWER AG and INGENIEURBUERO FLOECKSMUEHLE, verified on the basis of data available from MOSONYI (1966))

turbine type	runner diameter [m]	permissible maximum clear bar spacing [mm]	standard approach velocity of conventional screens without any specific protective function for fish [m/s]
Kaplan turbine	0.8 to 1.3	20 to 30	up to 0.7
	1.3 to 2.0	30 to 60	up to 0.8
	> 2.0	60 to 200	up to 1.0
Francis turbine	up to 1.5	20 to 30	up to 0.7
	1.5 to 2.5	30 to 50	up to 0.8
	> 2.5	50 to 150	up to 1.0
cross-flow turbine		15 to 30	0.5 to 0.7
water wheel (under-shot / middle-shot)	5 to 7	50 to 150	up to 0.7

5.2.3 Louver systems

If conventional screens are approached by the flow sideways inclined at an angle □ < 90°, the flow at the barrier will then be diverted in dependence of the arrangement of the screen bars. Higher hydraulic losses will generate and the standing wave being built up near the head of each screen bar will be stronger than at a vertical approach flow of the screen (chapter 5.1, figure 5.33). It can be further intensified by positioning the screen bars vertically to the approach flow, and thus enforce a diverted flow direction of the water. Such screen type is called Louver.

The changed flow direction in form of a standing wave in front of the Louver can be perceived by approaching fish, and lead to species-specific behavioural reactions. They can be taken advantage of in order to guide fish (chapter 5.1.4).

Louvers are mainly employed in order to guide salmonids to bypasses. For this purpose, the row of lamellar will be arranged in a flat angle to the approach flow (chapter 5.6, figure 5.34). The clear spacing between the bars ranges between 20 and 50 mm. Guiding plates are often placed behind in order to achieve an orderly approach flow.

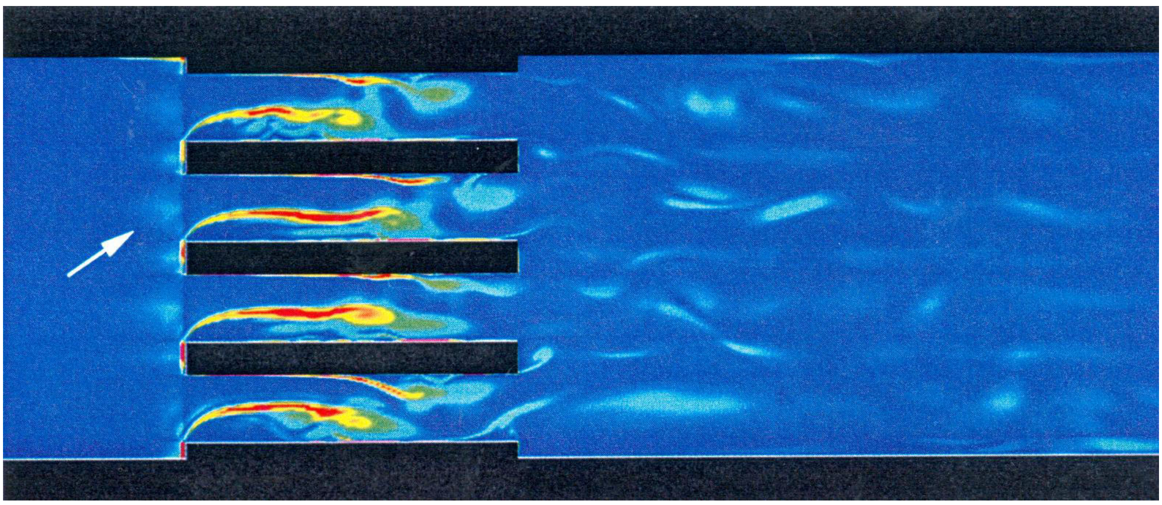


Figure 5.33: Creation of eddies at conven-tional screens with an approaching flow below 30° and an obstructing degree of ρ = 0.45 (VAW, 1999)

Louvers show high hydraulic losses because of their specific approach flow, requiring a limit of the approach velocity to between 0.4 and approx. 1.0 m/s. The inclined arrangement of the lamellar and the generally great length of the entire facility furthermore incur cleaning problems. It is therefore necessary to place a coarse screen in front. The lamellar are combined to units of approx. 2 m width, and at most installations it is possible to lift them out of the water in winter time and also for cleaning purposes, for which the required lifting equipment must be made available.

Louvers can be of a continuous design down to the bottom of the water body or of an immersion depth that is adjusted to a specific target species. Because of the static load of the lamellar and the required bridge-like construction, Louvers are comparable to conventional screens.

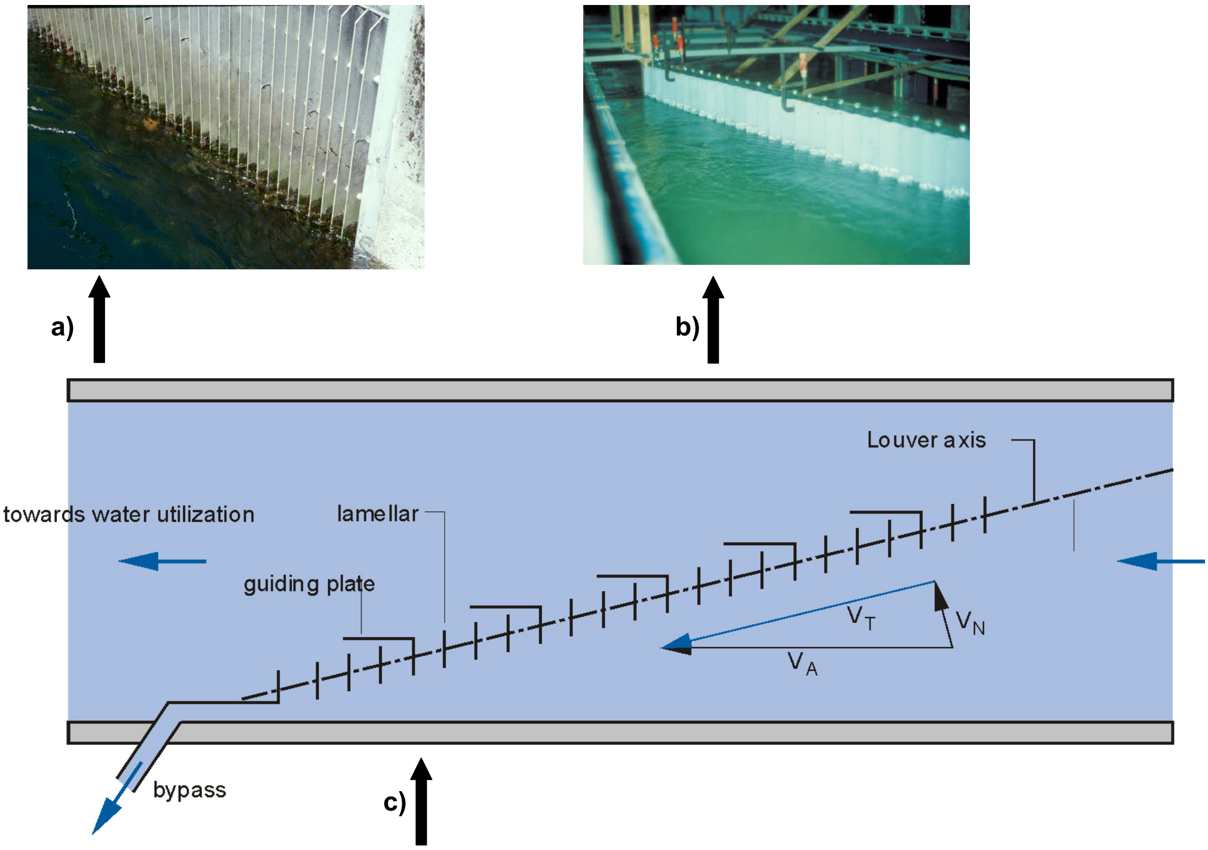


Figure 5.34: Louvers are principally built of flat steel like conventional screens, but the approach flow is vertical to the screen bars.

a.Louver (Collwitz Falls, USA, Washington State)
b.Flow that is running parallel to the Louver towards a bypass, model channel
c.Construction and approach flow of a Louver (diagrammatic view)

Operatability:Numerous examinations of the operatability of Louvers have been carried out in the USA, which also in outdoor operation have partly confirmed high deterrent rates (table 5.7). In order to guarantee an efficiency as high as possible, the following key features apply:

- The angle between the axis of the Louver and the main flow must be between 10° and 20°; an angle of 15° is applied as a rule (BATES & VISONHALER, 1957; PAVLOV, 1989).
- The smaller the target species the lower the distance between the individual lamellar must be. Normally, the lamellar are arranged with a distance between 5 and 15 cm (TRAVADE & LARINIER, 1992).
- The optimal approach velocity is also species-specific. TAFT (1986) states an optimal flow velocity of 0.46 to 1.1 m/s for King Salmon-smolts, but emphasizes that it must be remarkably lower for other species.

- The flow velocity in the bypass must exceed the approach velocity by a significant degree (chapter 5.6).

Laboratory examinations on silver eel could not prove any guiding effect on these species; on the contrary the eel passed the Louver effortlessly (ARBEITSGEMEINSCHAFT GEWAESSE-RSANIERUNG, 1998).

Table 5.7: Results of selected control examinations of the effectiveness of Louvers

species / length	flow rate [m/s]	angle [°]	lamellar-distance [mm]	effective -ness	author / water body
Rainbow trout		20.0	100 - 50	> 60	BATES & JEWETT, 1961 Umatilla River
King Salmon 10 cm *Roccus saxatilis* 1 cm American allis shad 2 cm		11.5	25 - 50	> 84	BATES & VISONHALER, 1957 Scaramento River
Salmon 15 - 17 cm		12.0	51	57 - > 80	DUCHARME, 1972 East River, Nova Scotia
King Salmon 7 - 10 cm Perch 10 - 17 cm	0.9 - 1.1 0.3 - 0.7	15.0		46.8 47.6	KARP et al., 1995 Sacramento River
Salmon 15 - 17 cm		15.0		91.6	RUGGLES, 1990 Connecticut River
Perch < 2 cm 2 - 3 cm 3 - 4 cm 4 - 10 cm		15.0		15 - 60 33 - 90 52 - 92 88 - 95	SKINNER, 1974 Sacramento River
King Salmon 5 - 15 cm	0.46 - 1.1	15.0	25	65 - 90	TAFT, 1985 Sacramento River
King Salmon 6 - 9 cm Coho-salmon 8 - 12 cm	0.3 - 1.2	12.0	51 - 152	85 - 95	TAFT, 1986 Puntledge River
18 American fish species	0.61	20.0	25	95 - 100	TAFT, 1985 model channel

5.2.4 Skimming walls

Skimming walls are of two-dimensional structure. They are arranged before intake structures and project more or less deep from the surface of the water into the water body (figure 5.35), thereby enforcing a change of the flow pattern. Skimming walls can be installed in the water body vertically or inclined to the flow direction. They consist of stationary concrete-steel or wood constructions which are stretched between the river walls, or they are designed like a bridge. Another possibility is to mount skimming walls to floating bodies like pontoon bridges, which are permanently or temporarily in working position.

Skimming walls are used for many purposes in order to keep flotsam away from intake structures, but also to divert fish migrating near the water surface. The effect is dependent on the following factors:

- Absolute immersion depth. According to currently available knowledge smolts migrate in water depths of up to 2.0 m. The walls must be immersed appropriately deep if they are to fulfil their purpose of influencing the behaviour of fish.
- Relative immersion depth in comparison to the depth of the water body.
- Approach velocity and angle of the approach flow.
- Portion of the bypass-discharge in comparison to the total discharge.

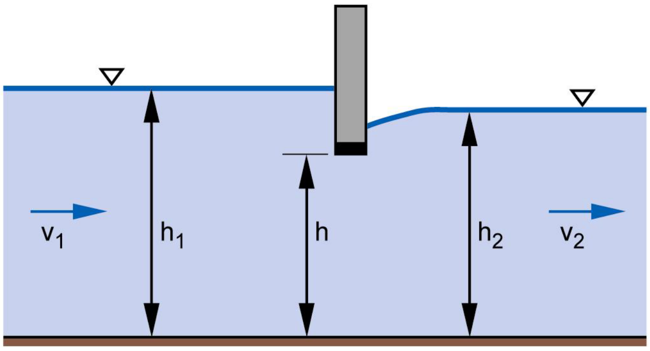


Figure 5.35: Working principle of a skimming wall

The static of the skimming walls must be designed to meet the forces generating from the water pressure. The hydraulic losses at skimming walls can be calculated for a vertical approach flow on the basis of the following formula according to PRESS & SCHROEDER (1966):

$$h_{TW} = \xi * v_2^2/2g$$

with

v_2 = velocity behind the skimming wall

ξ= loss coefficient, which results from:

$$\xi = h_2^2 / h^2 - 2 * (1 - 2 * Fr_2^2 * (h_2/h - 1))^{1/2} / Fr_2^2 - 1$$

with

h_1= depth of the water before the skimming wall

h_2= depth of the water behind the skimming wall

h= clear passage height below the skimming wall

$Fr_2 = v_2 / (g * h_2)^{1/2}$ (Froude number behind the skimming wall).

A further calculation approach is given in SCHROEDER (1994).

Skimming walls are primarily employed to guide migrating smolts of salmonids to a bypass. A skimming wall of a length of 63 m and an immersion depth of 4.6 m that is inclined installed in the turbine intake of the hydropower plant Bellows Falls at the Connecticut river / USA for example, achieves an efficacy of 84 % (ODEH & ORVIS, 1998).

Turbine intakes and water intakes, which are installed deep below the water surface show a similar effect like skimming walls. This way migrating salmon smolts only occasionally enter the turbine intake at the dam Poutès on the Allier river (France), which is positioned at a depth between 7.5 to 13.0 m depending on the filling ratio of the reservoir (BOMASSI & TRAVADE, 1987, figure 5.66 and 5.67).

5.2.5 Chain barriers

Chain barriers are made of metal chains which are set closely side-by-side and block the entire cross-section of the flow in front of intake structures. In comparison, such barriers can only be approached with a slow flow, as otherwise they would be dislocated by the flow and lose their effect as a more or less close curtain.

Whereas chain barriers in model trials with Salmonids according to TAFT (1986) could deter 71 % of fish at an approach velocity of 0.46 m/s and an approach angle of 45°, these results could not be achieved in outdoor trials. Presently there are no installations known to be in operation, for which the reason next to the lack in efficiency could most likely also be referred to significant technical problems, since the chains need to be suspended on bridges or pontoon constructions which generate the occurrence of coarse flotsam.

5.2.6 Wedge-Wire-Screens

The conventional screen made from flat steel has further been developed for the protection of fish in the USA, whereby the main focus of the efforts referred to the diminution of the clear spacing between the bars and the minimization of the losses incurred by screens. The hereby created Wedge-Wire-Screen consists of wedge-shaped stainless steel screen bars and has first been used in 1980 at the T.W. Sullivan power plant in the Willamette Falls (USA, Oregon) (WINCHELL & SULLIVAN, 1991). At this type of screen the broad side of the bars forms the screen surface that faces the flow, so that the bars become smaller in flow direction while the clear spacing widens in a wedge-shape (figure 5.36, figure 5.37). The dimension of the bars is very small in comparison to conventional screens (table 5.8). Owing to the small clear spacing of the bars, the position of the broad side of the triangular shaped cross-section against the approach flow and the use of stainless steel, the Wedge-Wire-Screen forms a very smooth surface, which significantly reduces the risk of injuries to fish. Evidence of these advantages could be provided in laboratory tests with silver eel and other fish (ADAM et al., 1999).

An extremely small clear spacing of the bars of up to 1.0 mm can be realized with this extra-fine screen type, so that high deterrent rates can even be achieved for fry, provided the approach conditions can be aligned to the biological requirements.

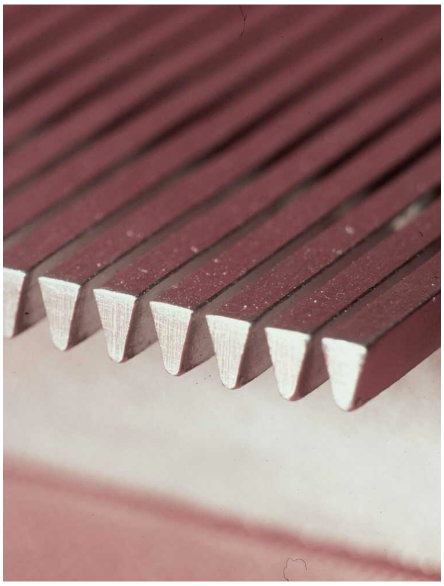


Figure 5.36: Wedge-Wire-Screen with a clear spacing of 1.0 mm

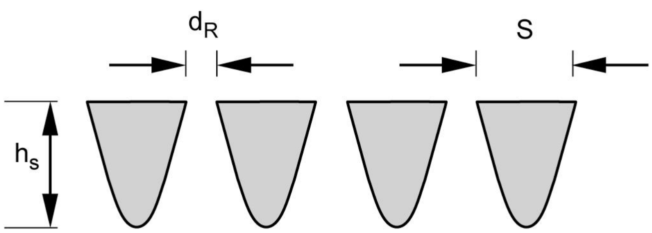


Figure 5.37:Dimension of Wedge-Wire-bars

Table 5.8:Typical dimension of Wedge-Wire Screens

thickness of bar s	between 2 and 10 mm
height of bar h_s	between 6 and 10 mm
clear spacing of bar d_R	between 1 and 10 mm

The consequence of the small cross-section of the bars is that the inherent stability of this type of screen is of a minor degree only, but generally requires a special supporting structure. As in the case of conventional screens, the static and dynamic carrying capacity of each bar and the supporting structure must be examined in each individual case. The installation of this type of screen may be restricted in dependence of the maximal occurring pressure difference at the screen being either partially or entirely clogged. For new constructions it is possible to solve this problem to some extent by designing a suitable intake structure and limiting the depth of the water.

The hydraulic loss at a Wedge-Wire-Screen is higher than at conventional screens (table 5.9). These losses, which are mainly generated by the supporting structure, must also be accounted for. The replacement of a conventional screen by a Wedge-Wire-Screen would therefore involve remarkably greater hydraulic losses if the installation conditions were not changed and would thus result in noticeable economical losses particularly at hydropower plants with low slopes. The use of Wedge-Wire-Screens in the low-pressure range therefore seems only feasible if the standard velocity will be kept low. This can be realized by an enlargement of the inlet cross-section or by an inclined positioning of the screen in horizontal direction or an inclined arrangement in the channel.

The amount of flotsam accumulating on the screen surface grows the smaller the clear spacing. However, the remaining clogging of the Wedge-Wire-Screen between the screen bars is lower than to be expected according to experiences made with conventional screens: According to TAFT (1986), thicker flotsam will be retained by the smooth surface of the screen and can easily be cleaned. Flotsam which has passed the screen gap can easily be washed out because of the clearance that widens in triangular shape with the flow direction and will not get stuck between the bars. These findings however, are based on experiences made at rivers in the west of the USA, which carry only minor amounts of flotsam.

Table 5.9:Measured screen losses at a Wedge-Wire-Screen without clogging

thickness of bar s [mm]	clear spacing d_R [mm]	angle of screen α [°]	approach velocity v_A [m/s]	amount of loss h_v [mm]	form coefficient β	author
2	2.0	15	0.6	30	6.5	WEBER et al., 1993
5	5.3	25	1.0	60	8.0	DUMONT, 2000
For comparison: The form coefficient □ of conventional screens is around 2.4						

In Europe the Wedge-Wire-Screen has not been used on a large scale so far and consequently there is little information available whether it would also be suitable for water bodies carrying greater amounts of flotsam, and how it reacts on very small organic particles and aquatic plants etc. First tests with a Wedge-Wire-Screen with d_R = 5 mm at a small water body in the German low mountain region have proven that a permanent clogging of approximately 10 % of the clear opening surface is to be expected after one year in operation. This permanent clogging which is mainly due to small twigs, plant fibres and plastic foils must be removed manually for as long as there are no screen cleaning machines of advanced development available (figure 5.38). It turned out that the cleaning frequency of the screen cleaning machine needed to operate the turbine without any significant loss of the head was double or triple the amount of a 20 mm-screen (DUMONT, 2000). The use of a Wedge-Wire-Screen incurs appropriate higher costs if a more efficient screen cleaning machine is to be employed. The operating costs rise as a higher cleaning frequency of the cleaning machine is required and the permanent clogging must be removed manually at certain intervals. If the temperatures are very low, icy conditions will soon occur if the clear spacing of the bars is very small and subsequently will create a blockage of the screen. In such weather conditions Wedge-Wire-Screens will be pulled out of the water. Examples of the layout of Wedge-Wire-Screens and details on permissible approach velocities for different target species are given under chapter 5.6

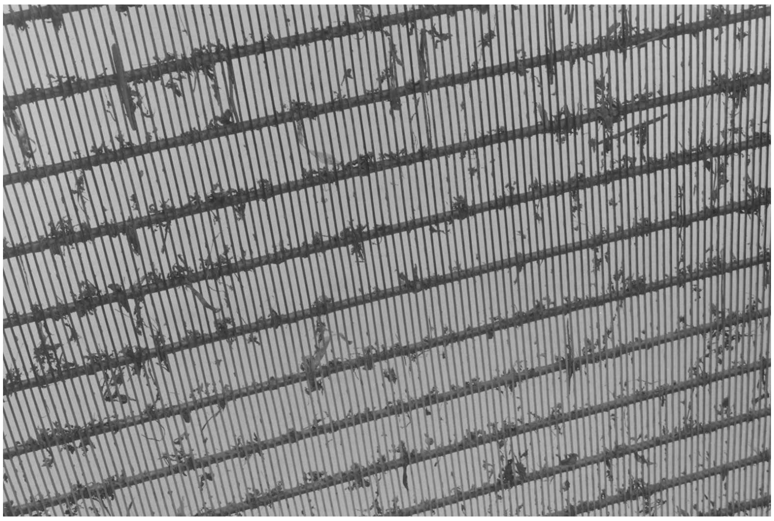


Figure 5.38:
Permanent clogging of a Wedge-Wire-Screen after approximately 9 months of operation (approach velocity 0.5 m/s, screen inclination approximately 40°, clear spacing 5.3 mm) (DUMONT, 2000)

5.2.7. Other stationary screens

Next to various types of screen construction, plane screens like perforated plates, woven wire cloth and grid with small sized openings can be used (figure 5.39). The diameter of the mesh or hole must be chosen in such a way that the target species and development stages to be considered will be unable to pass through. In the west of the USA a clear spacing between 1.5 and 3.0 mm is employed to protect frys of Pacific salmon species. Correctly arranged stationary screens will thus have a high protective effect, but a very large screen surface is required because of the generally low approach velocity (chapter 5.6). Like for screens with small clear spacing the main problem of such screens lies in the fact that they will quickly be clogged. Motor-driven brush-systems are generally installed which continuously clean the surface of the screen and at the same time will shift any screenings into the bypass that is created for migrating fish. In order to manage coarse flotsam like branches, trees etc. coarse screens with a clear spacing between 100 and 200 mm which are equipped with conventional screen cleaning machines are additionally connected in front of the above described plane screens.

Figure 5.39:
Stationary screens with perforated plate (d = 3.0 mm) at a withdrawal point for irriga-tion purposes in the catch-ment area of the Yakima River (Washington State, USA)

Stationary screens are most suitable for rivers in Alpine or arid regions that carry only poor amounts of flotsam. In Central European rivers where significant volumes of flotsam occur the maintenance expenditure is comparatively much greater. Stationary screens are therefore only installed at small power plants, e.g. at several locations in Switzerland (ENGEL & WEBER, 2003). An overflowable hydropower plant with a maximum flow rate of $10 m^3/s$ that is equipped with a flat inclined 10 mm-perforated plate screen (figure 5.40) has been operated since 2001 in Wetzlar on the Lahn river (Hesse). The screen is cleaned by means of a conventional chain cleaning machine equipped with a plastic lip (figure 5.41). The gate will be laid down during each cleaning process and any screenings will hereby be fed into the tailwater.

Figure 5.40:
Overflowable hydropower plant at the Lahn river in Wetzlar (Hesse, Germany) with a flat inclined 10 mm-perforated plate screen

Figure 5.41:
Detail of figure 5.40: screen cleaning machine in operation at a perforated plate screen

5.2.8 Travelling screens

Travelling screens, which are often also called band screen machines, refer to a technology developed some time ago. In isolated cases they are presently used at American hydropower plants and are placed as standard equipment at cooling water intakes of thermal power plants where water needs to be filtered because of secondarily connected technical facilities.

Travelling screens consist of a band which runs over two deflection rollers (figure 5.42). They are either made of flexible plastic, wire fabrics, perforated plates or grid elements which are connected by joints. Different hydraulic losses occur depending on the material and the clear spacing of the band (table 5.10). If a fabric is used at small plants, this can convey the driving power itself. At larger facilities, chains are installed at the sides and connected to the fabric. In order to ensure a safe static condition against the forces resulting from the hydraulic pressure difference at the screen, fabrics must be stiffened or run on a substructure. The section of the band that faces the approaching water is called upper boom. The bottom boom is flowed through in opposite direction, which facilitates a certain self-cleaning process. Most installations are equipped with special facilities like spray systems to clean the band. The band rotates at a speed between 0.1 and 5.0 m/min depending on the amount of flotsam carried by the river.

The mesh width or diameter of the perforation of travelling screens lies between 1.0 and 6.0 mm (table 5.3). Although the protective effect for fish is consequently very high, these installations however provoke the following risks of damage:

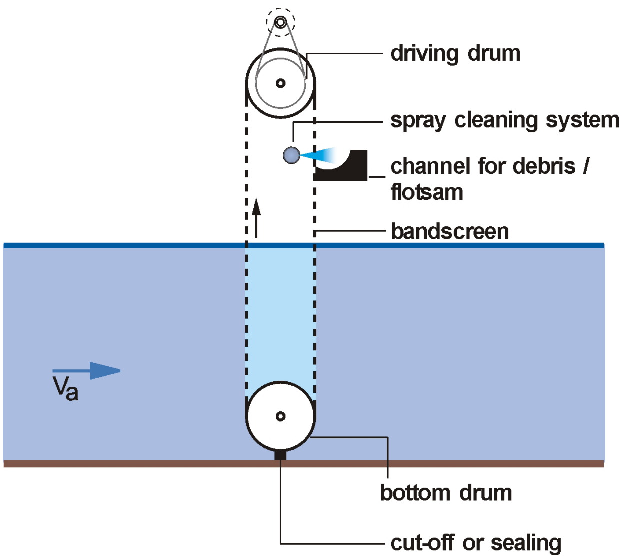


Figure 5.42: Schematic diagram of a travelling screen

- If the normal component of the approach velocity (table 5.1) is too high, the fish will be pressed against the screen.
- Fish that cling to the screen will be transported beyond the surface of the water by means of the rotation movement. The fish may suffocate if it has to remain outside the water body for a longer time, especially if the screen operates in an intermittent mode.
- Some fish, which have been transported by the screen above the surface of the water will fall back into the water because of a lacking squeezing pressure. They will then be pressed against the screen anew and may consequently suffer from losses of scale and grazes.
- In most cases conventional travelling screens are cleaned by the water jet from high pressure nozzles at a pressure between 4.0 and 6.0 bar, which however, leads to high damage rates amongst small fish that cling to the screen, larvae and fry. A reduction of the pressure of the water jet to between 0.3 and 1.4 bar to account for the structure of the screen and the target species to be protected may help to lessen damage rates (TAFT, 1986).

The combination of these effects will cause mortality rates of up to 100 % amongst fish being pressed against vertically travelling screens (FLETCHER, 1990). Transportation troughs which are mounted to the rotating band (chapter 5.4.2) present a means to reduce the damage to transported fish and fry that occurs if they were kept outside the water body for too long, or if they repeatedly fall back onto the screen.

Table 5.10: Loss coefficient at screens made of wires

thickness of wire s [mm]	2.0	2.0	2.5	3.1
clear width [mm]	20	25	25	25
loss coefficient ξ	0.34	0.27	0.32	0.39

If travelling screens are to guide fish to bypasses they must be arranged in the water body in such a way that they will suffice the species-specific orientation and behavioural pattern of the target species concerned. This requirement is very similar to that of other mechanical barriers.

Basically there are two cleaning mechanisms of travelling screens possible:

- Removal of flotsam:
  Flotsam will be pressed against the band by the standard component of the approach velocity and then transported to the surface of the water (figure 5.43, figure 5.44). Coarse flotsam falls into a container at flat inclined, vertically rotating screens. In any other case cleaning takes place by the band being flowed through in opposite direction on the reverse side of the screen and will thus loosen any adherent flotsam

- Transportation of flotsam:
  For this purpose the bands are installed vertically and admitted with a very low standard speed of approxi-mately 0.1 m/s. Adherent flotsam will be transported out of the water by means of the band and removed through a backwashing. The instal-lation will be mounted at a very flat angle of 15 to 25° to the flow, which generates a high tangential compo-nent of the approach velocity by which fish and flotsam are transported into a bypass and then into the tailwater (figure 5.45).

As a rule, a coarse screen with a clear spacing between 50 and 200 mm is additionally connected before travelling screens to gather flotsam of greater dimensions that could not be handled by such installations.

The following points have to be considered when designing travelling screens:

- If travelling screens are installed for a continuous rotation, all movable parts must be of suitable heavy duty design; otherwise there will be high maintenance expenditure involved. Either condition will increase the costs of the installation. Moreover, elongations of the band and a high degree of wear and tear, also of possibly existing driving chains are to be expected. It is known that such wear-and-tear symptoms occur at cleaning machines of chain screens which are installed at hydropower plants, and they are therefore increasingly replaced by other structures.

Figure 5.43:
Travelling screen at a water intake structure of the fish hatchery d'Augerolles (France). It serves for the removal of flotsam from the inflowing water

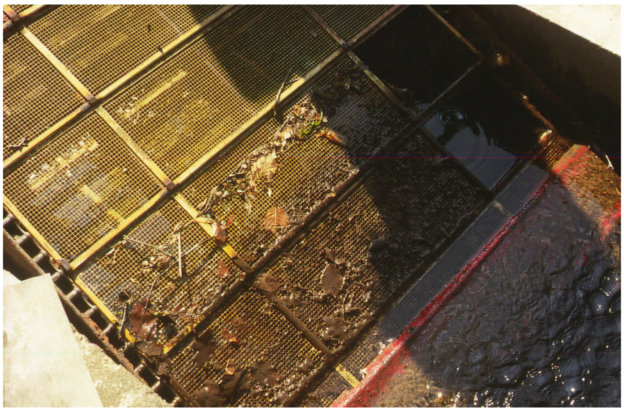


Figure 5.44:
Detail of figure 5.43: The screen consists of individual foldable sections of close meshed grids that lean on a supporting construction. Identifiable are driving chain and stiffening material

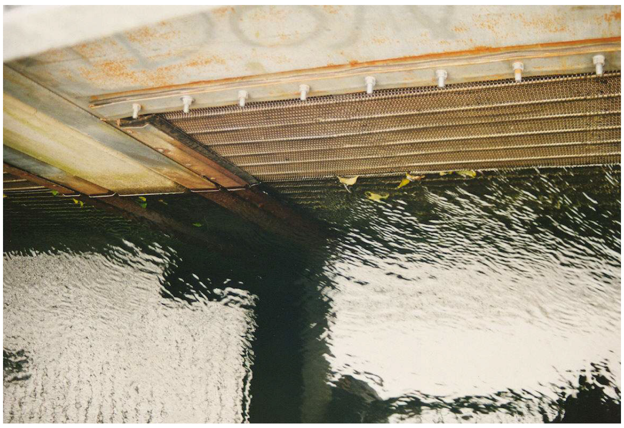


Figure 5.45:
Vertically travelling screen of stain-less steel fabric with a clear width of 3 mm at the hydropower plant Winooski (USA, Washington State). Flotsam and fish will be transported by the tangential component of the approach velo-city. The screen is sealed against the structure with rubber lips at the bottom and the sides.

- Screens must be designed in such a way that they can be lifted out of the water together with drive for the purpose of maintenance work.
- As the screens would ice up at low temperatures in the winter season and could not be operated, it must therefore be possible to lift them out of the water.
- Sealings must be provided at the sides and the bottom in order to prevent the passage of fish.
- Depending on the clear width and design of the sealing it is to be expected that fine flotsam will pass the upper boom and accumulate between the booms and possibly on the driving drums. This will increase the susceptance to failure of such systems.
- Careful examinations for which difference in the water level the static of the travelling screen is to be designed, from which additional limitations for the use of this technology will derive, especially where there are greater discharges.

5.2.9 Drum screens

The function of drum screens is very similar to travelling screens. The filter, however, does not consist of a flexible band but is made of fine meshed wire, perforated plate or is produced of bent flat steel bars or Wedge-Wire-bars (figure 5.46, figure 5.47). The hereby created drum rotates slowly around a horizontal axis (figure 5.48). This way, the adherent flotsam will be transported to the back side of the drum screen and because of the flow-through of the screen will be washed out at the back (figure 5.49). Drum screens are installed behind coarse screens and must be located below the surface of the water at a rate of 70 % to 80 % of their diameter, thus allowing the utilization of a sufficiently great flow cross-section. The dimensions are dependent on the discharge. Drum screens in front of smaller water intakes have a typical diameter between 0.8 and 1.5 m, whilst large installations have a diameter greater than 6.0 m (figure 5.49, figure 5.50).

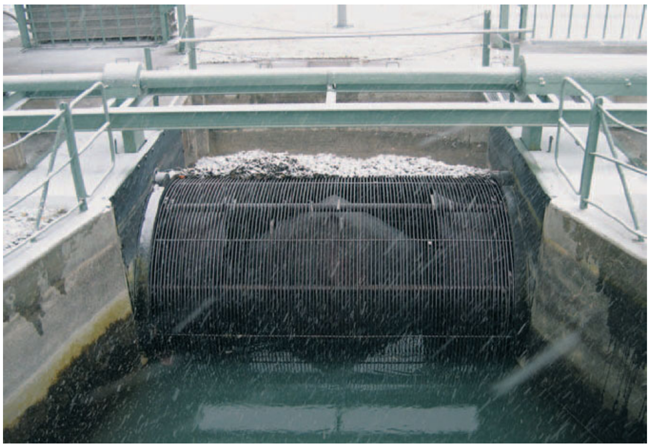


Figure 5.46:
Since 1953 operated drum screen at the hydropower plant Gluringen on the upper reach of the Rhône river (Oberwallis/ Switzerland) with a clear spacing of 25 mm

Drum screens generally work without great problems in water bodies with poor flotsam. They are though only restrictedly employable in frosty conditions as the surface of the screen will ice up (TAFT, 1986). If the water body carries great amounts of flotsam, however, there is a risk that this might accumulate inside the drum and the creation of algae would also be likely. Sealings must be provided at the sides and at the bottom for the protection of fish (figure 5.48). Depending on the approach flow it is possible that the flotsam will be forwarded tangentially or transported into the tailwater of the installation by the movement of the drum. In this case, the water withdrawn from the water body will only be cleaned to a reduced extent. Actuation is normally effected by electric motors and appropriate step-down gear units which guarantee a circumferential speed of approximately 1.0 to 2.0 m/min.

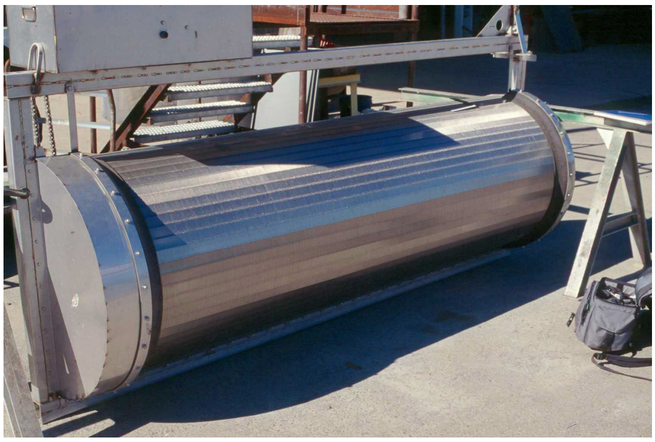


Figure 5.47:
Drum screen with a diameter of 1.0 m and a Wedge-Wire-Screen surface with drive unit (workshop view, USA, Washington State)

Although drum screens are operated in Europe in some isolated cases (figure 5.46, figure 5.50), they are mainly used as special fish protection facilities in the Pacific area of the USA, and here they are often installed at water intakes in order to prevent frys and fish from entering irrigation ditches (figure 5.47, figure 5.49).

Drum screens involve intensive maintenance work and for this purpose must be lifted out of the water complete with drive, which sometimes requires large-scale devices. The operation falls under the same frame conditions as for travelling screens.

The mesh width is dependent on the target species and development stages which shall be deterred, and ranges between 3.0 and 6.0 mm as a rule. This achieves a deterrent rate of almost 100 % (table 5.11).

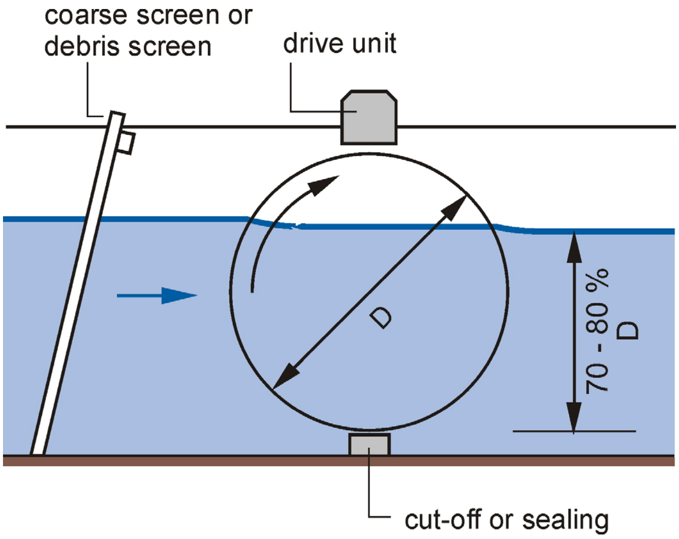


Figure 5.48:
Schematic profile of a drum screen (changed according to TAFT, 1986)

Standard velocities of 0.1 to 0.3 m/s to a great extent prevent young fish from being pressed against the screen and getting killed. The damage rate however, rises significantly already at standard velocities of 0.5 m/s (table 5.12).

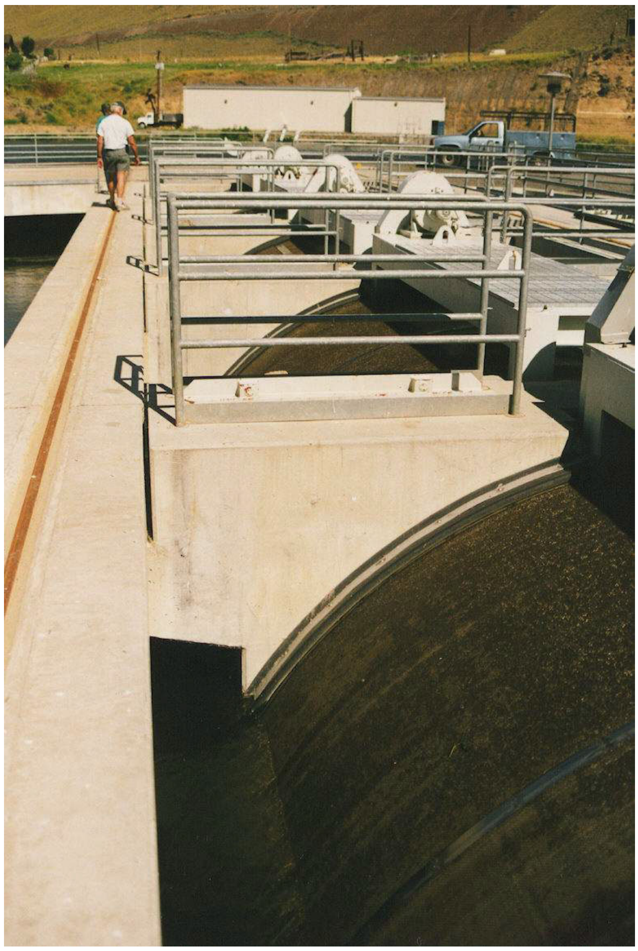


Figure 5.49:
Drum screens on the Yakima River (USA, Wash-ington State) with a drum diameter of 6 m in front of a combined hydropower plant and discharge installation for irrigation purposes

Table 5.11: Efficiency of drum screens in the USA assessed with frys and smolts of Pacific salmon species as target species. Since the velocity indicated is not clearly defined, it is to be assumed that the standard velocity has been taken as basis.

location / State	standard velocity [m/s]	mesh width [mm]	deterrent rate [%]	mortality [%]	author
Yakima River	max. 0.15		> 98	< 2	NEITZEL et al., 1990
Woodbridge / California	0.18	6.3	insufficient		TAFT, 1986
Rogue River / Oregon	0.6 - 0.9	6.0			
Naches River	< 0.3			only significant in case of larvae	
Sacramento River	0.2	4.3			
San Joaquin River	0.1	3.0	very high		
White River	0.5	6.0		0^+ smolts: 90 1^+ smolts: 10	

Table 5.12: Mortality rate of different fish species in the drum screen Bergum (The Netherlands) at an approach velocity of 0.7 to 0.8 m/s and a mesh width of 5.0 mm (HADDERINGH, 1978)

fish species	length of fish [mm]	mortality [%]
smelt	38 - 73	95
zander	24 - 66	67
perch	4 - 40	65
ruffe	38 - 76	65
bream / white bream	40 - 79	64
roach	39 - 78	25
three-spined stickleback	27 - 42	3
eel	30 - 80	0

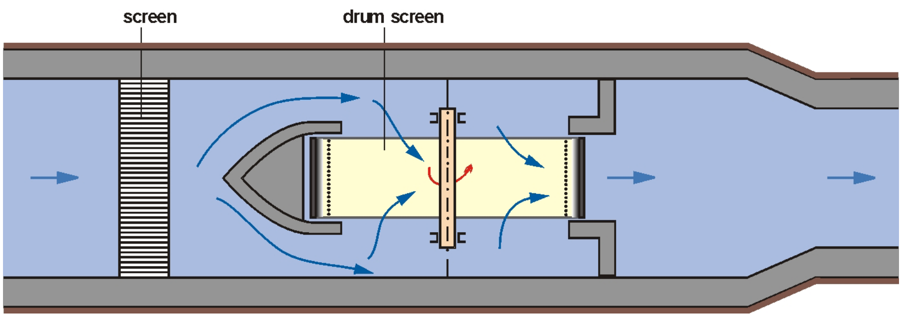


Figure 5.50:
Drum screen Bergum on the Bergum Sea (The Netherland). 4 drum screens that are open on both sides with a total flow-through of 27.8 m³/s, which are installed in front of a cooling water withdrawal system. The diameter of the drum is 12.0 m, the mesh width 5 mm. The inflow takes place from both sides into the inner drum. The water leaves the drum from the inside to the outside, and hereby accomplishes a 100 % filtering of the water. The drum is cleaned by jets in the area of the vertex. Fish are transported out of the water by means of troughs arranged inside and then into a funnel-shaped basin from where they reach the water body via a bypass pipe (changed according to USF HUBERT)

5.2.10. Gravel bed filters

Water will be led over a gravel bed filter through a porous medium at an extremely low speed and will be withdrawn afterwards. Such filter systems protect all life stages of fish and even plankton organisms. In the long run, however, the suspended matters carried by the water will lead to congested interstices and thus to an increased hydraulic resistance of the gravel bed filter. Its area is therefore generously dimensioned in order to achieve longer operating periods before the layers of gravel have to be replaced. Water is normally withdrawn via drainage systems below the gravel bed, which may for example be conducted into a pump pit. The applicability of gravel bed filters is limited to intake structures with minor flow-through rates.

5.2.11 Cage filters

Cage filters are used to protect pumps at water withdrawal points. The cages are of box or pipe shape from which the water they contain is pumped out (figure 5.51). They are made of wire mesh, perforated plate or Wedge-Wire-Screens. If the surface is sufficiently large and the approach velocity of a minor rate, they can even protect fish eggs and fry.

A congestion of openings through sediments, overgrowing algae etc. presents the biggest problem with cage filters. The Wedge-Wire-Screen has once more proven itself reliable as it is significantly less prone to congestions in comparison to wire meshes or perforated plates. Backwashing systems have proven to be the most efficient cleaning method (TAFT, 1986).

5.2.12 Shut-off nets

Shut-off nets have occasionally been used in the intake area of hydropower plants and intake structures in order to deter fish. However, this method has not proven itself in practice, as the nets are generally not strong enough to withstand the stress of continuous operation that is mainly caused by flotsam. On the other hand, in some special cases it is possible to catch migrating fish in net- and fyke-net constructions and to carry them downstream by means of fish transportation systems.

A high deterrent rate will generally be achieved with a mesh width of less than 10.0 mm. The approach velocity shall not exceed rates between 0.12 and 0.15 m/s.

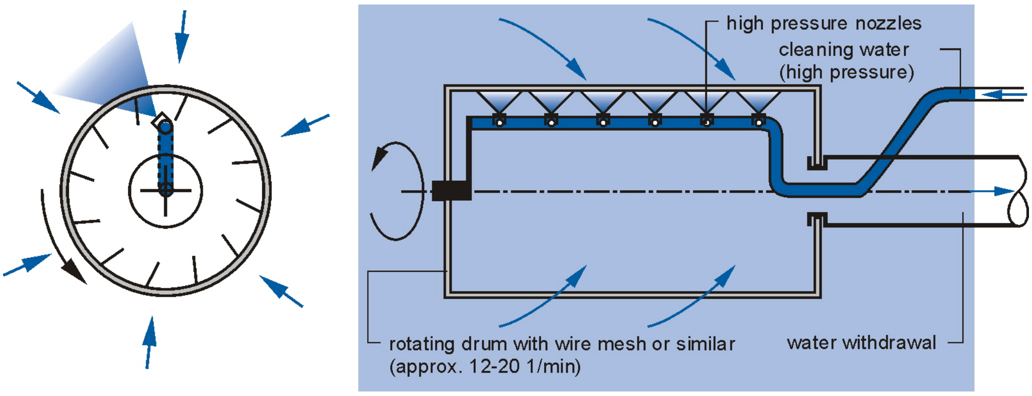


Figure 5.51: Cage filter made of wire mesh with flushing system

5.3 Behavioural barriers

The following chapter deals with the effects of behavioural barriers only and not with mechanical components (chapter 5.2). Behavioural barriers induce fish to change locations through well-aimed stimuli which influence the behaviour of fish. The objective is to attract the fish, deflect or guide them in defined directions. The following technologies are employed for this purpose:

- air-bubble and water-jet curtains
- electric fields

- light
- sound or pressure waves
- hybrid-behavioural barriers, where a higher effective degree is aimed at through a combination of different stimuli.

Behavioural barriers are particularly attractive because their technologies are much more favourable in price and require only minor cleaning and maintenance expenditure in comparison to mechanical barriers. This is why visual, acoustic, electric and hydro-mechanical behavioural barriers have been tested in laboratory and outdoor experiments. When estimating the operatability of behavioural barriers, however, basic problems arise which make a reliable judgment of the various technologies more difficult. The effectiveness will be decisively influenced by the local conditions:

- As fish after all orientate themselves visually, their reaction to visible barriers during daytime differs from that at night. Furthermore, turbid water can also influence the reaction to behavioural barriers.
- Since fish belong to the group of poikilotherms their physiological capability is substantially influenced by the temperature of the water. Therefore, in so far as physical efforts are required by behavioural barriers, the temperatures prevailing at a certain location will influence the effectiveness of the technology employed.
- Flow conditions are also of significant influence: The fish needs a specific reaction time to behavioural barriers. If migrating fish drift by the flow too fast in the direction of the hazardous source, then no escape is possible and the behavioural barrier fails.

The effectiveness of behavioural barriers is furthermore dependent on the specific biological requirements of the individual fish species and their different development stages in dependence of their body size and corresponding capability. The individual motivation of the fish will eventually also be a decisive factor concerning their reaction to behavioural barriers.

Behavioural barriers are particularly effective where local movements of fish are nondirective or aimless. Under laboratory conditions with no flow, or in stagnant or slowly flowing water bodies fish can be influenced if the area that is screened by a behavioural barrier is of no or only minor attraction. This is why behavioural barriers for example in front of an intake structure achieve a comparatively good effect, provided the volume of water withdrawn is low in comparison to the total discharge of the water body. However, if fish are migrating downstream they will always move with the main flow of the river, and at dams with water power utilization they will inevitably arrive in the inflow area of hydropower plants. In such situations fish show only little willingness to be influenced by behavioural barriers and to interrupt their biologically targeted migration or to leave their migration corridor. Behavioural barriers may in this case perhaps be effective under certain frame conditions and it is necessary that the stimuli coming from the barrier must be stronger to induce a shunning- and escape reaction.

When assessing the efficacy of behavioural barriers it is of decisive importance that the following conditions are considered:

- Fish outdoors will react differently or insufficiently to behavioural barriers than in laboratory tests,
- the local conditions must be described as precise as possible, e.g. with respect to flow velocity and temperature of the water,
- when looking at the findings it must be differentiated between species and development stage.

Based on these requirements, all presently known details on the operatability of behavioural barriers are very uncertain, particularly since many statements originate from the manufacturers and have so far not been reviewed scientifically in an independent way. On the basis of knowledge available it is therefore not yet possible to make any recommendations for the employment of behavioural barriers which are effective in a reliable way. In consequence thereof it is necessary and useful to develop behavioural barriers further.

The function of the behavioural barrier should be fully examined when deciding to build such a facility. There is a risk that the installation may fail and will have to be retrofitted with for example mechanical barriers. The installation of behavioural barriers is generally useful if the basic frame conditions are complied with. In many cases the approach velocity of 0.5 m/s must not be exceeded in order to ensure effectiveness of the behavioural barrier. Depending on the fish species and the conditions prevailing at the time of migration, like run-off conditions, turbidity and water temperature, it may be necessary to set an even lower approach velocity. Before this background, an approach velocity of 0.3 m/s is to be considered a safe value.

5.3.1 Water jet curtains

Construction mode / acting mechanisms: Water jet curtains will be generated by means of water jets which emerge parallel from small openings of a pressurized pipe system. These jets cause strong flows or turbulences in a specific area and shall have a deterring effect on fish. During test series carried out by the US BUREAU OF COMMERCIAL FISHERIES, 75 % of fish on average have been diverted in a model channel. The water jet curtain has been graded as unsuitable despite these good results (TAFT, 1986), as the jets tend to become congested and the maintenance work involved to keep the installation operative is enormous. Additionally, the requirement of water or energy is very high with approximately 50 l/s * m^2 area of curtain.

5.3.2 Air-bubble curtains

Acting mechanisms: The air-bubble screen provokes a shunning reaction of the fish through a visual or / and contact stimulus. Air-bubble screens can be combined with stroboscope lamps to improve the visual perception, the light they emit will be reflected by the bubbles.

Construction mode: Air-bubble screens will be produced by means of a pipe, that is designed with appropriately arranged ejection nozzles. The pipe will be admitted with compressed air and normally is fixed to the bottom of the water body. A very similar technology is used in front of barrages for example, in order to keep them free of ice in winter time. It is important that the air pressure will not decrease with an increasing length of the ejector and that the ejector is made of corrosion-proof material.

Estimation of operatability: Experiments with air-bubble screens have proven that their operatability is generally low, although in model tests a certain reduction of fish passages was to be noticed. Air-bubble screens at numerous withdrawal points of cooling water in the USA have been replaced by other constructions because of their lack in efficiency (TAFT, 1986). During experiments with eel in model channels it could be seen that the fish first performed a shunning reaction but soon became familiar with the ascending air-bubbles and reacted no more (ADAM et al., 1999).

An effective operatability of the air-bubble curtain could neither be proven with laboratory and outdoor experiments that were carried out with other fish species in the Netherlands. A test with juvenile perch in a channel has shown that they performed a shunning reaction only at the beginning of the test. The fish were soon accustomed to the air-bubbles and swam through the screen without hesitation (HADDERINGH et al., 1988). An air-bubble screen of 24.0 m length at an angle of 45° to the flow direction was inspected in the Vechte river (The Netherlands). The screen was intended to divert silver eel to a bypass (KEMA, 1992). The screen has been switched on and off alternately over 24 nights. The flow velocity of approximately 0.05 m/s was very low. The visibility depth was between 1.0 and 1.4 m. A total of 726 silver eel of a medium length of 47.0 cm has been caught. Behind the switched-on air-bubble screen there were 9 % more eel caught than behind the screen that was switched off, which means that the air-bubble screen had not achieved a positive effect.

The use of air-bubble curtains is generally restricted to low flow velocities, as the ascending air-bubbles will be drifted with the flow, so that the curtain would already be dislocated by 45° at a flow velocity of 0.5 m/s (ADAM et al., 1999).

The consequence is that air-bubble screens cannot be used as effective protective and deterrent facilities in front of hydropower plants and intake structures, as they are very unreliable in allowing fish to escape.

5.3.3 Electrical barriers

Acting mechanism: Fish like any other aquatic organisms show typical, reproducible reactions to electric fields, which can build up in water bodies by means of electrodes (cathodes and anodes). These electrodes can be admitted with direct-current or pulsed current. Decisive for the effectiveness of the electric fields is which potential difference becomes effective on a fish.

The potential difference grows with the strength of the field and the length of the fish. The fish will be flowed through by a current by means of the potential difference, which causes a physiological reaction. Different reactions occur in dependence of the field intensity (figure 5.52) (HALSBAND & HALSBAND, 1975):

- Galvanotaxis
  The fish displays a directed movement in the distant range of electrodes. Whilst the fish swims with a quick, active movement towards the anode when within its range of influence, it will perform an escape reaction when within the range of influence of the cathode. An electric field that prevents fish from entering an intake structure must therefore be constructed in such a way that fish getting into the distant range of influence of the electrode will be induced to escape upstream in direction of the headwater.

- Electro-narcosis
  The fish will be narcotized in the close vicinity of both, the anode and the cathode, and in the extreme case will even be killed. As soon as the electric field will be interrupted or the fish will be drifted away from the immediate vicinity of the electrode, it will awaken from its electronarcosis. The technique of electro-fishing utilizes the effect of the electro-narcosis. Electrical barriers however, must be designed to prevent fish from entering the close range of electrodes, where they will be narcotized. If an electro-narcosis happens at electrical barriers in front of intake structures, this will hinder fish from escaping and they will drift with the flow.

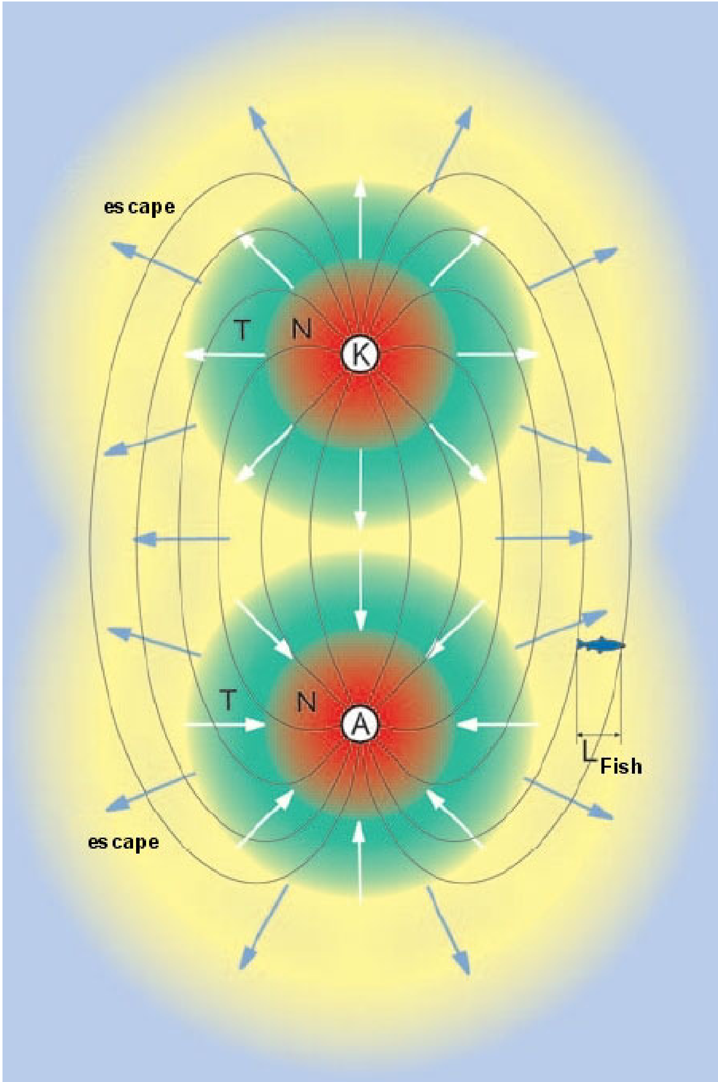


Figure 5.52:
Basic structure of an electrical barrier: The field lines are only drawn in schematically for one pair of electrodes. The different ranges of influence are displayed at the pair of electrodes:

N = close range where the electro-narcosis sets in;
T = range of influence of the galvanotaxis, i.e. fish swim towards the anode and away from the cathode;
F = distant range, where fish escape from the range of a high field intensity into areas with a low field intensity.

The quantity of the influencing difference of the field intensities is determined by the length L_F of the fish.

Construction mode: Electrical barriers are the oldest form of behavioural barriers: The Dane N.D. LARSEN took out a patent on this idea in 1912. The first application in practice was implemented by the American COBB in 1923, but his installation achieved only a minor degree of effectiveness. The usual design is shown in figure 5.53 and 5.54: The arrangement in flow direction is that the main electrode comes first to build up the distant range of influence, followed by the counter electrode placed at a certain distance behind. In order to cover the total width of the intake structure, the appropriate number of main electrodes will be mounted next to one another. In Germany, there are mainly pulse control devices employed (frequency: between 2 and 8 pulses, pulse length: approximately 5.0 ms, voltage: 300 to 900 V). The direction of the current will be changed periodically so that the electrode will act alternately as anode and cathode. The field strength must be adjusted to the conducting capacity of the water. The reaction of fish to electric fields is strongly dependent on the conducting capacity of the water and the species and size of the fish.

Details on the operativeness of electrical barriers or guiding systems refer generally to defined size groups of specific species. If an electrical barrier is designed for a specific target species and / or size, the deterring effect will then be insufficient for other species and / or size groups. Furthermore, other fish may become narcotized very quickly and not be able to develop any directed escape reaction.

Like for most behavioural barriers, fish will become familiar with electric fields, which is attempted to be avoided through a randomized control of the electrical barriers at different pulse rates (MARZLUF, 1985; BERNOTH, 1990).

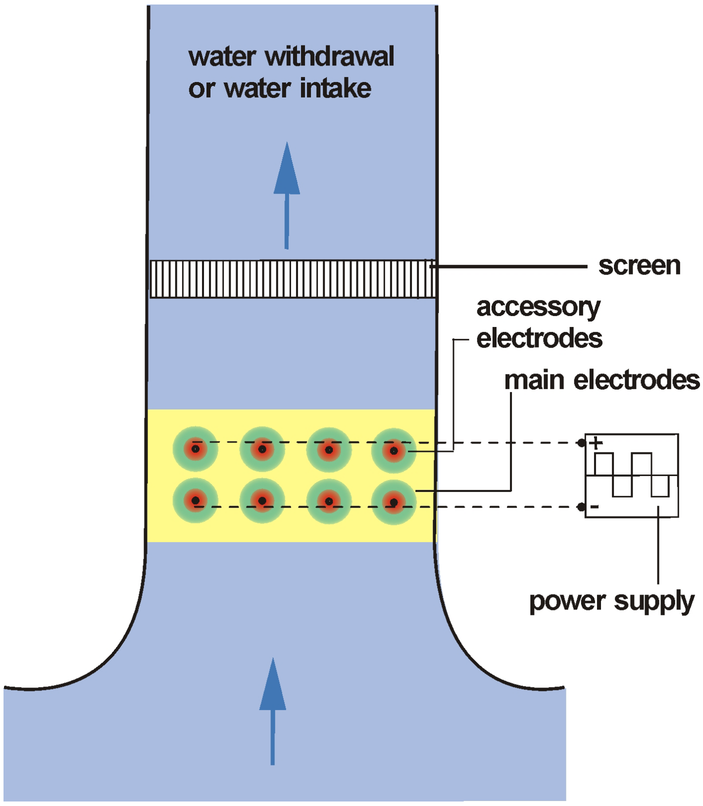


Figure 5.53:
Arrangement of electrodes of an electrical barrier in front of an intake structure.

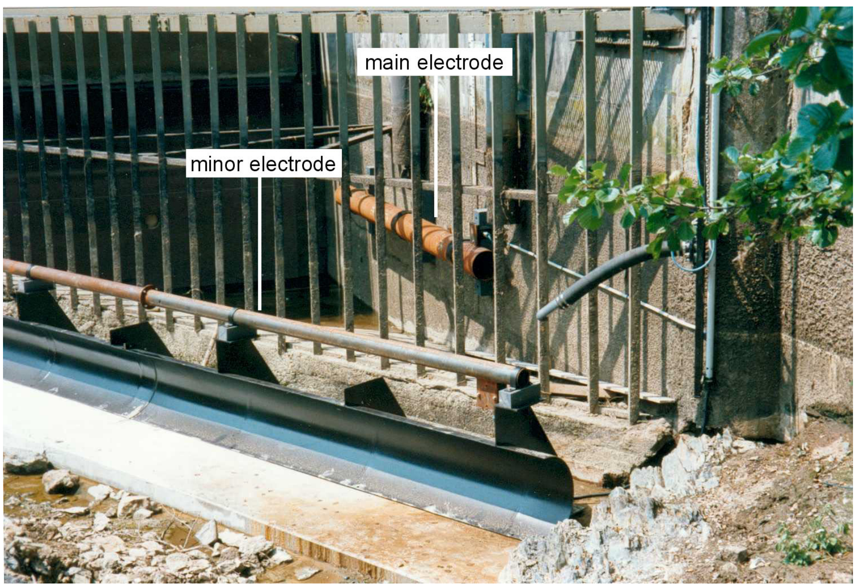


Figure 5.54:
Electrodes in dry condition at the hydropower plant Scheuerfeld on the Sieg river (Rhineland-Palatinate)

The electrical barrier being installed at the hydropower plant Scheuerfeld on the Sieg river (Rhineland-Palatinate, Germany) has been scientifically examined during the years 1994 to 1998. For this purpose all fish passing the turbine have been caught in a large fyke net at the turbine outlet and were examined for damage over 46 trial days. All individual species migrating through the bypass pipe installed in the headwater which was admitted with 300 l/s have at the same time been caught by means of a fyke net in order to be counted. The average number of fish passing the turbine despite the fact that the electrical barrier was switched on amounted to 244 fish / day or 48 kg fish / day. Over the same period however, a maximum of 61 fish, but 1.3 fish in average per day only could be registered in the bypass. The effectiveness of the fish guiding system and the electrical barrier could thus not be proven.

A three-dimensional measuring sensor was constructed by RWTH Aachen specifically for the purpose of examining the electric fields generated by the electrical barrier at the location Scheuerfeld. As expected, the electric field dispersed in an almost elliptical form around the main electrode. Since the distance between the main electrode and the bypass pipe that is shaped like a shell was relatively low, electric fields appeared also in the bypass pipe, which however were not desired. The distance between the electrodes set by the manufacturer therefore was apparently too small.

Parallel to the examinations as above, the flow velocities occurring in the area of the power plant inlet as well as in the area of the electrical barrier have been recorded by the BUNDESANSTALT FUER GEWAESSERKUNDE by means of three-dimensional measuring equipment. At a full-load of the turbine, i.e. 12 m^3/s., the mean flow velocity taken over the depth amounted to max. 0.279 m/s only in front of the electrodes where the water was about 3.0 m deep.

Electrical barriers and guiding systems are employed with different objectives, but mainly to guide fish in direction of fish passes, or to keep fish away from certain areas and also to improve the efficacy of bypasses for fish migration. The operatability of electrical barriers and guiding systems is evaluated very differently in dependence of the application field, but also depending on the location and author. If electric fields are used in order to guide fish from the headwater of a hydropower plant into a bypass, there are various situations to be accounted for:

- Migrating fish, especially the migratory stages of diadromous species, show little willingness to react to behavioural barriers and to interrupt their directed downstream movement because of them.
- Electric fields do not cause any controlled, directed movements, but radial escape reactions that lead away from the electrodes. This is why it is at least with the previous systems difficult to guide migrating fish into downstream migration facilities.
- In order to react, fish needs sufficient time and must be enabled to swim against the flow. PUGH et al (1971) assessed a satisfying deterring effect on migrating salmonid smolts only at approach velocities of 0.2 m/s where the deterrent rate was between 69 and 84 %. The maximum permissible approach velocity of 0.3 m/s which they have indicated seems to be internationally accepted meanwhile (TAFT, 1986; HALSBAND, 1989; BERNOTH, 1990).

As of today however, there are no convincing results available on the operatability of electrical barriers at water-operated power plants that would be better than the findings of PUGH et al (1971). A certain protective function of electric fields is therefore generally granted only where intake structures withdraw comparatively little water from a river or a lake with a low flow velocity at a right angle to the bank line. In cases of such constellation it might be possible to prevent diffuse movements of fish in direction of the water intake and any consequent loss of fish. Concrete examinations of the operatability of electrical barriers in the area of intake structures are rare. GRIVAT (1983) certifies high effectiveness of an electrical barrier at the water intake of the pumped storage power station Weytaux at the Lake Geneva (Switzerland), but does not make available any examination results. According to TAFT (1986, fish of a length in excess of 15 cm could be kept away from the cooling water intake at the Connecticut Yankee Power Plant (USA, Massachusetts) by means of an electrical barrier with an efficacy of 68 to 92 %. However, the same effect was achieved when the plant was switched off: The electrodes which were arranged in a distance of only 19 cm were obviously also effective as behavioural barrier without any electric fields. RAUCK (1980) has proven that the electrical barrier in the cooling water intake of the nuclear power plant Brunsbuettel had no function at all as approximately 6.5 tons of eel had passed over the year.

HADDERINGH & JANSEN (1990) finally have obtained such unsatisfactory results in outdoor examinations of an electrical barrier that this technology has been graded as unsuitable at least for the specific conditions of water bodies in the Netherlands. Examination results which would prove a reliable protective effect of electrical barriers at intake structures do not exist in presently available literature.

Electrical barriers may be relatively low-cost installations, but they require intensive servicing. Constant attention must also be paid to the protection of persons in order to avoid fatal accidents.

Estimation of the operatability: The dissemination of electric fields in water is to a high degree influenced by chemicophysical parameters. Their effect on fish is species-, size-specific and also related to the individual animal. They additionally cause diffuse escape behaviour. Before the background of available literature therefore, a certain protective effect towards the defined size classes of special target species seems to be realizable at approach velocities of max. 0.3 m/s, if at all (table 5.13). This obviously only applies to lateral withdrawals of a partial discharge from a water body, and has so far been achieved in a few individual cases. Behavioural barriers on the basis of electric fields are therefore graded as slightly efficient, unreliable or even completely unsuitable in countries like France, The Netherlands, Canada and the USA. Only in the German speaking region they have repeatedly been propagated until very recently, although no records about a sufficient protective function were made available.

Table 5.13:Reports on experiences made with electrical barriers

author	technical details	details on operatability	method of furnishing proof
GENNERICH, 1954	In the tailwater of the barrage Koblenz on the Moselle river (Rhineland-Palatinate). 200 m long electrical barrier, in order to guide fish that is willing to migrate upstream into fish passes	Tests were abandoned because of technical problems. Statements on the operatability could not be made, as the tests were only carried out over a short period.	Fyke net checks in the fish pass.
MEYER-WAARDEN, 1957	Several techniques are described. The most effective deterrent effect shall be achieved with quarter sine waved pulsed currents.	If migrating fish shall be kept back, the flow velocity in the area of the chain curtain must not exceed 0.3 m/s, so that the animals will not be driven into the electric field by the strong flow.	There are no records available.
KOTHÈ, 1959	In the tailwater of the barrage Lahnstein on the Lahn river (Rhineland-Palatinate). Fish willing to migrate upstream shall be guided into the fish passes by means of dipped electrodes connected to chain curtains.	Usable results could not be obtained despite high expenditure.	Fyke net checks in the fish pass.
HATTOP, 1964	Large surface electrodes are arranged in parallel order and operated with low-voltage alternating current.	No further failures occurred at a cooling water inlet after the deterrent installation was put into operation. The inflow of a carp pond that was blocked by means of a deterrent installation was not passed by fish first; the later presence of fish in the fyke net is explained with failures of the deterrent installation.	There are no records available. Box fish trap in the pond inlet. There are no details on the duration of the checks provided.
BRUSCHEK, 1965	0.3 to 1.1 Hz	If barriers are arranged “in a clever way”, up to 100 %.	There are no records available.
PUGH et al., 1971	Yakima River (USA). Electrical screen with 125	Deterrent rate of juvenile salmonids in dependence of the	Comparing fyke net checks in the

author	technical details	details on operatability	method of furnishing proof
	V and direct-current pulses of 20 ms duration at a frequency of 15 Hz.	approach velocity: at 0.2 m/s 69 to 84 % at 0.5 m/s 40 to 53 % > 0.5 m/s low deterrent rate. A max. permissible approach velocity of 0.3 m/s is derived from these results.	bypass and diversion channel.
STRAHKOV, 1975	Estuary of the Petschora-river (Russia). Electrical screen of 360 m length to guide upstream migrating salmon into fyke nets.	The efficiency of the screen reached almost 100 %. The author nevertheless points out that a similar effect would not be achieved for downstream migrating fish.	Fyke net
GRIVAT, 1983	Water intake of the pumped storage power station Weytaux on the Lake Geneva (Switzerland). A row of 20 electrodes was installed at a distance of 4 m to the intake. Flow velocity < 0.5 m/s, conducting capacity: 260 µS/cm, pulses of 5 ms duration at a frequency of 1 Hz.	The installation was found to be efficient.	There are no records available.
ADLMANNS-EDER, 1986	Approach velocity of 0.34 m/s, current consumption 1.6 kWh/day.	The objective of the test was to judge the risk of an electrical barrier to human beings. Fish-biological results on the function of the pilot installation are not available.	The author waded in the water in front of the installation under medical care in order to prove it harmless.
TIMM, 1987	Pulsed current with 3 to 12 Hz and voltages between 400 and 600 V.	Only a minor percentage of the fish cannot be deterred and get caught in the fyke net.	There are no records available.
HALSBAND & HALSBAND; 1989	Deterrent facilities, which automatically adjust to varying temperatures and conducting capacities. Random controlled pulse rates between 3 and 12 Hz.	An efficacy of more than 90 % can be expected at cooling water intake structures arranged tangentially to the flow direction of the river and at approach velocities of up to 0.3 m/s. A combination with concrete shells on the bottom of the water body is required for hydropower plants in order to guide eel in particular into a bypass.	There are no records available.
MARZLUF, 1985 BERNROTH, 1990	Deterrent facilities, which automatically adjust to varying temperatures and conducting capacities. Random controlled pulse rates between 3 and 12 Hz.	Good operatability if the facility is installed between 5 and 15 m before the turbine intake and at flow velocities of up to 0.3 m/s, provided there is a “diversion” offered to fish.	There are no records available.
KYNARD & O’LEARY, 1990	Pulsed current with 127 V, 64 A at 60 Hz. The installation developed a field with 0.25 V/cm in a	A significant effect of the barrier could not be proven.	Visual observation and telemetry.

author	technical details	details on operatability	method of furnishing proof
	depth of 1.3 and 2 m in front of the electrodes.		
RAUCK, 1980	Cooling water intake of the nuclear plant Brunsbuettel on the Elb river (Lower Saxony).	Approximately 6.5 t of eel annually passed the electrical barrier and got killed by the screen cleaning machine.	Control of the screenings.
HADDERINGH & JANSEN, 1990	Inlet into a drinking water treatment plant in the Netherlands. 24 active cathodes for the deterring effect and 6 inactive anodes at an approach velocity of up to 0.13 m/s, field strength of up to 600 V, pulses of 0.7 ms duration at a frequency of 5 Hz.	The experiments were implemented in the years 1982, 1983 and 1984 with very different results: The eel passages have significantly been reduced by 91 %, but the passage of roach increased to 382 %.	Bow-net (or fyke net) controls in the inlet channel downstream of the electrodes, whereby the electro screen was alternately switched on and off over 24 hours.
GOSSET & TRAVADE, 1999	A 20 m long electrical barrier (130 V, 10 electrodes) at an approach velocity between 0.25 and 1.48 m/s installed at an angle of 40° in the head race of the power plant Halsou/Nive (France).	A diverting effectiveness between 5 and 28 % could be achieved during experiments carried out in the years 1995, 1996 and 1997. The efficacy could be increased to 60 % through illumination of the bypass.	Re-fishing of marked salmon smolts by means of the Tyrolean weir.
EBEL, 2001	Deterrent facility, that automatically adjusts to varying temperatures and conducting capacities. Random controlled pulse rates between 3 and 12 Hz.	No remarkable effect.	Fyke net control of the bypass

5.3.4 Visual barriers

Light is one of the most vital factors in the life of fish. It has a far-reaching influence on physiological processes in the organism itself, but also on the behaviour of fish. Light will be perceived by fish in a wave range of approximately 400 to 700 nm, which is equal to the sensitiveness of the human eye. There are two receptor types in the retina of the fish to perceive the stimulus of the light; they are small rods to see at dusk and dawn and the so-called retinal cones as daylight receptors. The reaction of the receptors to light varies for different groups of fish species. A maximum sensitiveness occurs on cyprinids at wavelengths of 540 to 600 nm, on percids between 540 and 635 nm, on eel between 500 and 560 nm (PROTASOV, 1970) and on brown trout between 300 and 600 nm (BOWMAKER, 1990).

The fish eye reacts extraordinarily sensitively to the intensity of light, i.e. the strength of illumination. Fish that have adjusted to darkness can still perceive light of an intensity of approximately 10^{-7} to 10^{-10} lux (PROTASOV, 1970). For comparison: The human being is only able to recognize pictures at a light intensity of approximately 2 lux.

The sight of fish has a significant influence on their orientation and swimming behaviour as PAVLOV (1969) was able to prove with 53 fish species from entirely different habitats: In order not to become drifted by the flow, the fish always swims so fast against the current that a stable picture of its environment develops on the retina.

However, especially young fish are unable to orientate themselves if the light falls below a certain intensity. As their flow sensory organ, the so-called lateral organ has not fully developed, it is mainly early development stages of a body length of up to 4.0 cm that will be caught by the current and drifted away

(PAVLOV, 1969; PROTASOV, 1970; MANTEIFEL et al., 1978). Adult fish however, are capable of orientating themselves very well also in darkness, as they receive sufficient information about their position in the environment via their fully developed lateral organ and through contact to the bottom of the water body (HARDEN JONES, 1968).

Acting mechanism: Fish perform clear reactions to light, whereby one speaks of a positive phototaxis when they move towards a light source or of a negative phototaxis when they keep away. Both phenomena are already known for some time and are purposefully utilized in fishery to increase the catch. Lamps for example are employed in the Mediterranean to catch the positive phototactic smelt (BEN-YAMI, 1976). But also the American stint, various American species of the allis shad and sticklebacks are attracted by sources of light. In comparison, the eel behaves strictly negative phototactic, which is exploited for commercial fishing of eel by guiding the fish by means of chains of lamps into fyke nets, nets or other fishing tools (DRIMMELEN, 1951; LOWE, 1952; BRAEUTIGAM, 1961, 1962; HOELKE, 19864).

There are different types of lamps used to influence fish through light (table 5.4), whereby the greatest strength of light will incur the maximum possible reaction of fish. The experiences gained with artificial light sources which are to deter fish from hydropower plants will be explained in the following.

Attracting and deterring effects of light: The attracting effect of artificial light has been examined since the 1950ies under laboratory conditions especially in the USA, but also in outdoor experiments in front of hydropower plants with different salmonids as target species. JOHNSON et al. (1958) have observed the significant attraction of filament lamps of very low light intensity between $3 * 10^{-4}$ and $4 * 10^{-2}$ lux on Pacific coho salmon in a small model channel, for which white, red, green and blue light was used. NEMATH & ANDERSON (1992) have proven that chinook smolts are already attracted by poorly shining mercury vapour lamps. Furthermore, sea trout smolts are also attracted by fluorescent lamps of a light intensity of $3 * 10^{-4}$ lux (KEMA, 1994). A comparable attracting effect was achieved with mercury vapour lamps with blue filters (HAYMES et al., 1984).

Various trials have been carried out with the aim to enhance the traceability of bypasses in front of French hydropower plants by means of mercury vapour and halogen lamps and have shown that smolts of the Atlantic salmon will be attracted by the light, but will avoid the direct vicinity of the lamps and only swim into the bypasses after the light sources have been switched off (LARINIER & BOYER-BERNARD, 1991a, 1991b). The examinations have proven that the effectiveness of bypasses can be increased three- to eightfold if fish are attracted by lamps. Decisive for the efficiency of such attracting systems are for example the position, the duration of the illumination and the light intensity of the lamps.

Artificial light in the form of continuous radiation sources as generated by bulbs, mercury vapour and fluorescent lamps or by means of flashlight systems with stroboscope lamps can also be employed for the protection of negative phototactic fish species.

Table 5.14:Identification of usually used lamp types

type	spectrum	wavelength	particularities
filament lamps	continuous	< 400 to > 750 nm	light intensity: max. 1000 W
sodium lamp	discontinuous spectrum	max. values 550 and 675 nm	-
mercury-vapour-lamp	discontinuous spectrum	max. values 400, 440, 550, 580, 625 and 700 nm	light intensity: max. 2000 W
fluorescent lamp	discontinuous spectrum	max. values 430, 550 and 610 nm	light intensity: max. 55 W
stroboscope lamp (KEMA)	unknown	white light, spectrum approx. 400 to 700 nm	frequency: max. 600 per min
stroboscope lamp (Xenon)	discontinuous spectrum	max. values 400 to 570 nm	frequency: max. 66 - 1090 per min

Filament-, mercury-vapour- and fluorescent lamps:

Experiences from professional fishing were the basis for the development of downstream fishways, mainly focussing on migrating eel, where bypass systems have been combined with light sources. Laboratory experiments in aquaria and model channels prove that independent of their spectrum almost all types of lamps evoke the reaction of eel to escape from the light source (HADDERINGH et al., 1992; HADDERINGH, 1993; HADDERINGH & SMYTHE, 1997). A comparable negative phototaxis was also observed on salmonids. It was possible, for example, to effect a significant deflection of one year old coho-salmon even at flow velocities of 0.6 m/s at an immersed chain of bulbs with a light intensity of 4 lux that was arranged at an angle of 20° to the flow direction (FIELDS & FINGER, 1956). In this case it became evident that a continuously illuminated light source is more effective than a discontinuous illumination. Deterring effects on sea trout-smolts were produced by bulbs with 5.8 lux and fluorescent lamps with 1.5 lux in laboratory experiments at flow velocities of up to 0.22 m/s. The efficiency which prompted fish to change their swimming direction rated at 58 % (KEMA, 1993).

Different studies with visual barriers were carried out at Dutch and German hydropower plants, to deflect eels and other fish species from water intakes (HADDERINGH, 1982). Table 5.15 presents a list of the results of such field observations, where different types of lamps were installed above and below the water level. The best results in respect of a reduction of the number of drawn in eels and young fish of the age stages 0+ and 1+ of different species, especially ruffe and perch, zander, roach, bream and smelt were achieved with a direct illumination of the diversion point with mercury-vapour lamps, for which purpose the lamps must be installed below the water. However, the chains of light produced a positive phototaxis on some species, like there were 27 % more sticklebacks swimming into the illuminated discharge structure because of the chain of lights than there were without lamps.

Table 5.15: Deterrent effect of bulbs, mercury-vapour lamps and fluorescent lamps at thermal power plants (T) and hydropower plants (W)

power plant (type) / water body / author	mean flow velocity [m/s]	type of lamp	fish species / age	deflection [%]	method of furnishing proof
The Netherlands					
Bergum (T), Bergum Sea HADDERINGH, 1982	0.30	bulbs / mercury-vapour lamps	eel young fish < 1 year young fish > 1 year	55 19 45	The lamps have alternately been switched on one night and switched off the other night. Those fish were recorded at the screen band machine of the cooling water intake which had passed the visual barrier.
Bergum (T), Bergum Sea KEMA, 1990	0.30	mercury-vapour lamps	eel young fish < 1 year young fish > 1 year	38 73 81	
Amer (T) LUCASSEN & HADDERINGH, 1995	0.50	fluorescent lamps	eel young fish < 1 year	68 25	
Haandrik (W) Vechte HADDERINGH, 1989	0.59	bulbs / mercury-vapour lamps	eel young fish < 1 year	66 58	The lamps have alternately been switched on one night and switched off the other night. The recording of turbine passages was done with fyke net catches at the turbine outlet.

power plant (type) / water body / author	mean flow velocity [m/s]	type of lamp	fish species / age	deflection [%]	method of furnishing proof
Germany					
Guttenbach (W) Neckar BERG, 1994	1.0	fluorescent lamps	eel	< 5	The lamps have alternately been switched on one night and switched off the other night. The recording of turbine passages was done with fyke net catches at the turbine outlet, the bypass was controlled by means of a bow net.
Dietfurt (W) Altmuehl HADDERINGH & SMYTHE, 1997	0.2	fluorescent lamps	eel	8	

The deterrent effect of chains of light is furthermore influenced by different additional factors like the way the chains of light are arranged towards the flow direction and the traceability of a bypass, and above all the flow velocity in the water body. It may be for this reason that the efficiency of a chain of fluorescent lamps installed at the hydropower plant Guttenbach on the Neckar river (Baden-Wuerttemberg, Germany) was low, because the flow velocity was high with up to 1.0 m/s (BERG, 1994). On the other hand, a chain of fluorescent lamps at the hydropower plant Dietfur in der Altmuehl (Bavaria) could only achieve a deflection rate of 8 % for eels, although the flow velocity before the power plant was only 0.2 m/s (figure 5.55, figure 5.56) (HADDERINGH & SMYTHE, 1997). In this case the low effectiveness of the visual barrier was to be referred to the unfavourable position of the bypass and its low admission.

Stroboscope lamps:

Most experiences with the function of stroboscope lamps have been made in America, where PATRICK et al. (1982) have proven in field and laboratory experiments that the American eel reliably avoids the white stroboscope light of a Xenon-lamp. The use of this type of lamp in the intake area of water pumps at the Saunders hydropower plant in the St. Lawrence river has shown that between 65 and 92 % less of upstream migrating eels have entered the water pumps.

Laboratory experiments with stroboscope lamps have provided evidence that also silver eels and juvenile salmonids and a North American species of zander show a distinct negative phototaxis (HADDERINGH & SMYTHE, 1997; BROWN, 1997).

An overview of the results obtained from deterrent facilities with stroboscope lamps at power plant locations is given in table 5.16. Latest field experiments at the thermal power plant Diemen were carried out with the aim to reduce the loss of fish of the age stage 0+ by means of stroboscope lamps in front of the cooling water outlet (KEMA, 1998). The reduction achieved was 41 % on average owing to the induced deterrent reactions, of which the majority belonged to the species perch and zander. The highest values obtained at this location amounted to 69 % for cyprinids and 53 % for the smelt. On the other hand, the employment of stroboscope lamps failed repeatedly at other locations and led to unsatisfactory results. The reasons for these failures in most cases had to be referred to unfavourable topographic conditions of the locations or to a difficult traceability of bypass facilities.

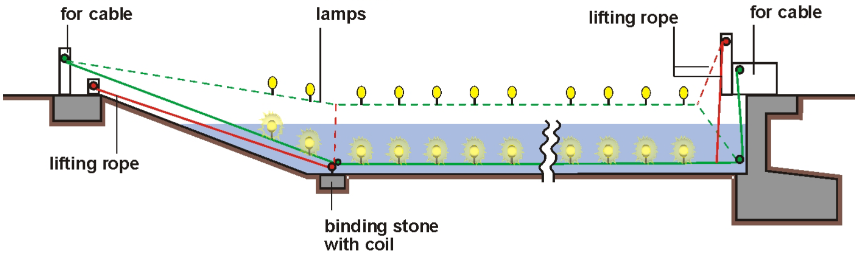


Figure 5.55: Arrangement of a chain of lights installed to guide eels to a bypass at the hydropower plant Dietfurt an der Altmuehl (Bavaria, Germany). The diagram shows the chain of lights in a position of rest and in a position of operation.

Filament- and mercury-vapour lamps with low light intensities have an attracting effect on fish, particularly on salmonids. This can be utilized at hydropower plants to tempt smolts of anadromous species especially to swim into the inflow area of bypasses. Whilst it is possible to evoke deterrent reactions of many fish species with light sources under laboratory conditions, which for example already sets in for eels at a very low light intensity, the efficiency of deterrent facilities where light is used in front of hydropower plants or discharging structures varies very much. The deflection rate of eel fluctuates between 5 and 68 % at facilities with filament-, mercury-vapour- or fluorescent lamps. The effectiveness of stroboscope lamps varies between 0 and 94 %.

Figure 5.56:
Chain of lights in operation at the hydropower plant Dietfurt an der Altmuehl (Bavaria, Germany)

The success gained in practice much too often is not in line with the expectations aroused through laboratory experiments. This can be explained with the existing deficits in the knowledge about the biological/physiological mechanisms like the behaviour of fish in front of power plants in connection with light and current and also about their migration corridors and depths. Additionally however, many questions concerning the site-specific physical/hydraulic conditions are still unanswered, like turbidity conditions and flow distribution or the conditions of the approach velocity, which make an efficient arrangement of deterrent facilities in combination with bypass systems more difficult. It is for these reasons that deterrent facilities are much too often installed under unfavourable conditions which have a negative influence on the efficiency.

Table 5.16: Deterring effect of stroboscope lamps at thermal power plants (T) and hydropower plants (H)

power plant	fish species	deflection [%]
The Netherlands		
Diemen (T) KEMA, 1998	young fish	41
USA		
York Haven (H) MARTIN & SULLIVAN, 1992	American allis shad (juvenile)	94
Handley Fall (H) WINCHELL et al., 1994	American allis shad (adult)	no reaction
Mettaceuunk (H) WINCHELL et al., 1994	Atlantic salmon Atlantic salmon	1988: 78 1990: 15 - 20
Michigan (H) McCAULEY et al., 1996	bullhead catfish	86
Kingsford (H) WINCHELL et al, 1997	walleye rainbow trout yellow perch	good reaction good reaction good reaction
White Rapids (H) AMARAL et al., 1998	diverse species	no reaction

Estimation of the operatability: The arrangement of light sources in principle must fulfil specific criteria, so that the desired effects can be achieved. Furthermore, the light sources must always be adjusted to the behavioural pattern of the target species, like enhancing the attractiveness of bypasses by installing lamps above the surface of the water, which will regularly be switched on and off in order to have a tempting effect on salmon smolts. A chain of lights has to be arranged below the water surface if eels are to be deflected from dangerous installation areas. The chains have to be installed in a pointed angle towards a sufficiently admitted bypass.

Deterrent facilities with light may well be of high efficacy particularly before cooling water intakes of thermal power plants. As a rule, however, they cannot be employed in front of hydropower plants because of too high approach velocities that will not permit a sufficient reaction time to migrating fish.

5.3.5 Visual orientation devices

In order to control their position in the direct environment, fish orientate themselves visually in daytime. Visual reference points are for example water plants, branches which project into the water or prominent points in or outside the water. In darkness, however, fish are mainly dependent on the rheotactical orientation by the main flow, and they are therefore particularly at risk to enter the area of turbine intakes and water intakes during their migration. It would thus be possible to equip areas which are dangerous for fish migrating at night with illuminated visual orientation points (TAFT, 1986). Whilst light in most cases is used to deter and tempt fish, sometimes with good results (chapter 5.3.4), such illuminated visual orientation devices so far exist only theoretically.

5.3.6 Acoustic barriers

Acting mechanism: In principle, the structure of the inner ear is similar to that of higher vertebrate animals, but lacks an outer auditory canal and the sound transmission apparatus of the middle ear. Fish can basically be divided into three categories with regard to their hearing (FAY, 1988):

- Hearing specialists with a high sensitivity for noise of great band width (in average 60 dB re 1µPa): Cyprinids and catfish achieve a better sharpness in hearing through the so-called Weberian ossicles, that consists of small bones which connect the air bladder with the inner ear. For these fish the air bladder serves as sound box that amplifies sound waves which then will be transmitted to the inner ear by means of the Weberian ossicles. Other species like the herring have projections of the air bladder which make contact with the inner ear.
- Non-specialists with an air bladder: Their sensitivity towards noise is moderate and the band width of the perceivable sound pressure is rather low (80 to 100 dB re 1µPa). Species like salmon and perch belong to this group (HAWKINS, 1986).
- Species without an air bladder which show a very low ability to perceive sound (in average 110 dB re 1 µPa): This group mainly comprises ground oriented species, but also mackerel and tuna.

Sounds play quite an important role in the life of fish and the power of hearing, specifically that of hearing specialists, serves for the communication within one group of species and for the perception of danger. However, fish are not capable of localizing sound sources precisely owing to the simple structure of their inner ear.

Construction mode: Sound sources which are installed under water generate noise of certain frequencies and amplitudes with the intention to deflect fish. CHRISTIE (1990) describes devices which transmit vibrations between 20 and 1000 Hz via metal parts into the water, also sound boxes, which produce a sharp tone of very high amplitude. LOEFFELMAN et al. (1991) report about systems where sounds of different fish species are adopted and then translated into new signals which fall into the most sensitive range within fish can hear. A similar method is based on the amplified reproduction of eating noise created by predators (TAFT, 1986). Presently there are two techniques employed to generate acoustic barriers:

- The Sound Projector Array (SPA) uses a series of underwater amplifiers in order to generate a diffuse sound field that has to block the movements of fish. The emitted signals are sounds with frequencies between 20 and 500 Hz. As the deflecting effect of pure tones is low (with the exception of low frequencies of up to 10 Hz or in case of very high sound pressure levels, which however are very expensive to produce), a pulse is generated by a mixture of various frequencies or a frequency mixture that is similar to a chirp. Additionally, the sound level that has to reach a fish at a desired point must be sufficiently high in comparison to the background level.

- The Bio-Acoustic Fish Fence (BAFF®) also utilizes sound of frequencies between 20 and 500 Hz in combination with an air-bubble screen in order to create a spatially contained sound barrier (FISH GUIDANCE SYSTEMS Ltd. & HYDRO ENERGY DEVELOPMENTS Ltd., 1996; WELTON et al., 1996). It serves for the precise guidance of fish, e.g. into a bypass. The BAFF®-System which proves to be effective where the approach velocity of 0.5 m/s will not be exceeded, not even locally, will mainly be used to deflect fish from intake areas of intake structures, but not to obstruct fish migration in rivers or in front of hydropower plants.

Estimation of the operatability: Various examinations of the effect that sound has on fish have been carried out in the USA which arrived at contrary results. The reactions differed in dependence on the capability of the organ of hearing of the species. Laboratory experiment recordings document some distinct deflection reactions. KYNARD & O'LEARY (1990) have not been successful in outdoor experiments where they tried to deflect allis shad by means of an acoustic barrier of a frequency of 161.9 kHz from the turbine inlet of the Holyoke Dam in the Connecticut River (USA, Massachusetts). Neither could KNUDSEN et al. (1992) define any reactions of salmon to sound of a frequency of 150 Hz, despite the fact that this is the most sensitive range of hearing of this species. CHRISTIE (1990) however, reports about deterrent rates of up to 75 % by acoustic barriers.

Most promising seem to be experiments with low frequency noise. KNUDSEN et al. (1992) in laboratory experiments have observed escape reactions of salmon smolts to a low frequency sound of 10 Hz. Field observations have confirmed this behaviour not only for the Atlantic salmon (KNUDSEN et al, 1994) but also for smolts of the Pacific King-Salmon and rainbow trout (KNUDSEN et al., 1997).

SAND et al. (2000) have examined the reaction of silver eel to low frequency noise of 11.8 Hz in the laboratory and outdoors. Laboratory experiments have evoked panic and stress reactions by fish with an increased pulse. A sound source was installed between the bank and an eel trap for outdoor experiments and it could be observed that the catches were significantly lower when the sound source was switched on. In how far this shunning reaction could also be of use for the construction of effective deflection facilities at hydropower plants and intake structures has until present not been examined in practice.

Already in 1991 LOEFFELMAN et al. have reported about a deflection rate of 66 to 70 % of all fish in the test area through signals they have artificially created on the basis of fish noise. They stated a deflecting effect on migrating salmonid smolts of even 83 to 100 %. The actual results achieved with SPA and the BAFF®-system are summarized in table 5.17. Therefore, it is possible to obtain deflection rates between 56 and 98 % with the SPA-system and between 74 and 88 % with the BAFF®-system. According to the knowledge available these systems are most effective for salmonid smolts and herring.

High frequency behavioural barriers of 122 to 128 kHz have been accepted by authorities in the USA for the nuclear plant James A. Fitzpatrick and a hydropower plant in Main with the aim to deflect clupeids (TAFT et al., 1999).

The results available so far on the effectiveness of deflection facilities that are based on sound differ very much and reach from an entire failure to efficiencies between 50 and 100 %. This extreme variation of the results may have to be referred to specific features of the techniques applied and how experiments were arranged, but also to species-specific behavioural patterns. However, these differences cannot be explained comprehensively on the basis of published information. Although the efficacy of acoustic barriers apparently is not equally reliable for all species because of the different physiological perception abilities, they nevertheless offer general possibilities by means of sound sources to prevent salmonids and clupeids in particular, and also eel if low frequency sound is used, from entering dangerous areas.

Table 5.17: Results achieved with experiments with acoustic barriers

water body / facility	installation	frame conditions	effect	author
River Foss (United Kingdom), intake structure	SPA with 6 underwater amplifiers in front of the pump intakes, approach velocity	withdrawn discharge 32 m^3/s	chub: 88 % dace: 76 % bream: 74 % bleak: 72 % roach: 68 % perch: 56 %	WOOD et al., 1994

water body / facility	installation	frame conditions	effect	author
	approx. 0.5 m/s installed: 1994		total reduction: 80 %	
estuary of the Tee river (United Kingdom) nuclear power plant Hartlepool	SPA with 12 underwater amplifiers in front of 8 "onshore" cooling water intake structures, experiment: 1995	withdrawn discharge 34 m^3/s	herring: 80 % sprat: 60 % total reduction: 56 %	TURNPENNY et al., 1995
estuary of the Schelde river (Belgium) nuclear power plant Doel	SPA with 20 underwater amplifiers in front of 2 "offshore" cooling water intake structures, approach velocity approx. 0.48 m/s installed: 1997	withdrawn discharge 25 m^3/s	herring: 98 % sprat: 97 % sea perch: 89 % diverse types of gudgeon: 75 % total reduction: 80 %	MAES et al., 1999
Farmoor Water (United Kingdom) pump station for the withdrawal of water	SPA with 8 underwater amplifiers in front of the intake in 4 intake structures installed: 1998	mean discharge: 3.6 m/s water withdrawal during tests 1.5 m^3/s	different species, mainly perch: 80 %	TURNPENNY et al., 1998
River Frome (United Kingdom) research facility at the Institute of Freshwater Ecology	24 m long BAFF®-system to guide smolts into a bypass, counting of fish by means of a "fish counter", experiment: 1995	discharge distribution: discharge: 75 % bypass: 25 %	salmon: 88 % sea trout: 88 %	WELTON et al., 1996
River Clyde (United Kingdom) hydropower plant Blantyre	24 m long BAFF®-system, approach velocity approx. 0.75 m/s experiment: 1996	discharge distribution: turbine: 95 % bypass: 5 %	salmon: 74 % sea trout: 74 % other species: 92 %	FISH GUIDANCE SYSTEMS Ltd. & HYDROENERGY DEVELOP-MENTS Ltd., 1996
Nive (France) hydropower plant Halsou	30 m long BAFF®-system in the headwater canal of the power plant; 60-600 Hz: approach velocity approx. 0.25 - 1.44 m/s	discharge distribution: heavily fluctuating	During experiments in 1997 no provable effect on salmon smolts.	GOSSET & TRAVADE, 1999
Saale river (Thuringia, Germany), hydropower plant Jaegershof	sound of frequencies between 100 and 450 Hz, at a sound pressure of 140 to 160 dB	installation at the intake structure of a diversion power plant	No deterrent effect obtained for most fish species. Distinct deflection effects only detectable on brown trout.	SCHMALZ, 2002a

5.3.7 Poppers

Acting mechanism: The acting mechanism of poppers refers to the ability of fish to perceive sound (chapter 5.3.6).

Construction mode: Poppers are sound generating facilities, which release explosions of oxyhydrogen gas under water, or where short thrusts of compressed air will be directed into small pressure chambers. The “pops” hereby produced shall frighten the fish and induce deflecting or escape reactions.

Evaluation of the operatability: In various laboratory experiments it has been proven that poppers evoke reproducible shunning reactions for different fish species. Distinct protective effects have been established at “offshore” cooling water intakes and in stagnant water bodies:

- After a popper has been taken into operation which emitted 6 to 12 signals per minute, divers at the Redondo Beach power plant (USA, California) have observed that especially pelagic fish which were within a radius of about 3.6 m have responded with escape. After three hours of continuous operation there were no more fish to be seen in the vicinity of the popper (TAFT, 1986).
- In outdoor experiments at three power plants the frequent occurrence of American allis shad and smelt was reduced by up to 89 % within a radius of 10.0 to 15.0 m around the popper. Yellow perch were located about 13.0 m away from their preferred residential area and could neither be enticed to return by mercury-vapour lamps nor with food. The highest efficiency was achieved by poppers with 15 signals per minute (CHRISTIE, 1990; TAFT, 1986).
- Sun-perch could successfully be kept at a distance of 9.0 m to the popper during tests at the Lennox Generating Station (Canada, Ontario) and have not shown any adaptation effects. However, it could also be observed that salmonids were attracted by the popper (TAFT, 1986).

Even though a distinct deflection effect is described, this is restricted to a maximum distance of 15.0 m and not all species react to the popper in the same way. Additionally, technical problems have to be considered which occur because of wear-and-tear in continuous operation of such facilities (see below).

The use of poppers in the area of intake structures may be sufficient for the protection of fish. In case of hydropower plants however, there are great doubts about the fitness for use of this deflection system. BERG (1993), for example, could not define any protective effect of poppers during experiments in the turbine intake of the power plants Neckarzimmern and Guttenbach on the Neckar river (Baden-Wuerttemberg) (figure 5.57).

BERG (1994) sees the main problem in the approach velocity at power plants which with a rate of approximately 0.9 m/s is too high and the comparably low flow velocity of only 0.4 m/s in bypasses: *“Because of these conditions it is not possible to judge the deflection effect that could maybe be achieved under more favourable conditions for both plants that have been tested by comparison. The existing great doubts whether the oxyhydrogen gas deflection facility would at all function according to the details of the manufacturer could until present not be dispelled.”*

Maintenance: According to the information available, poppers are exposed to high wear-and-tear owing to high energy, which is admitted in small volumes. Because of the high maintenance costs involved, poppers of Ontario Hydro were replaced by acoustic barriers at a cooling water intake despite good test results, because of less maintenance expenditure (CHRISTIE, 1990).

Figure 5.57:
Experiment construction for testing poppers at the power plant Guttenbach on the Neckar river (Baden-Wuerttemberg): 12 oxyhydrogen gas reaction heads have been mounted in front of the intake of a Kaplan turbine with a maximum flow-through of 75 m3/s (on the left hand side of the picture). The second turbine served as bypass during the experiments. Fyke nets were installed behind both turbines for the purpose of counting migrating fish (BERG, 1994).

5.3.8 Chemical barriers

Acting mechanism: Chemicals like toxic substances can cause shunning reactions by fish. On the other hand, fish will avoid areas with low oxygen concentrations and those with extremely high or low ph-values. Furthermore, the skin of loach, minnow (also pink) and other fish species liberates fright substances in case of an injury, which induces fish of the same kind to flee.

Application possibilities and estimation of operatability: Before this background, theoretical considerations were conducted whether chemicals could be employed for the deflection of fish in the sense of behavioural barriers (TAFT, 1986). Because of the enormous quantities of chemicals which would presumably be required, the costs would be appropriately high. Questions in respect of the degradability of the substances used and their impact on the environment have also not been clarified. Any research work has meanwhile been stopped. The conclusion therefore is that chemicals are not suitable for the deflection or guidance of fish.

5.3.9 Hybrid-behavioural barriers

Acting mechanism: Hybrid-behavioural barriers are a combination of various systems, which develop a greater effect through the application of different stimuli. TAFT (1986) quotes examples for combinations and application fields which can be imagined and realized:

- Improvement of the visual perception of air bubbles or chain barriers by stroboscope light.
- Combinations of stroboscope chain of lights and mercury-vapour lamps have been employed for the purpose of keeping fish away from turbine inlets and also to entice fish to move into a bypass.
- Mercury-vapour lamps in the area of bypass openings are used to attract salmonids in particular, and thus support the effect of Louvers, conventional screens, etc.

Operatability: Hybrid-behavioural barriers generally evolve from the attempt to improve the insufficient operatability of a behavioural barrier through a combination with other techniques. BRETT & MACKINNON (1953) discovered that juvenile salmon of the Pacific King Salmon would not react to air-bubble screens. The deflection effect however, could be enhanced by illuminating the air-bubble screen and was most effective with stroboscope light.

During behavioural observations of eel in a model channel a shunning reaction of fish to an air-bubble screen was noticed initially, but the eel soon became familiar with the ascending air-bubbles and ignored them. An additional illumination with mercury-vapour lamps or stroboscope light has not caused a reproducible shunning reaction (ADAM et al., 1999).

Evaluation: In principle it seems quite possible to enhance the effectiveness of behavioural barriers by a combination of other techniques. However, it is difficult to judge from an experiment, especially in outdoor experiments, whether the effect obtained is to be referred exclusively to one of the two techniques employed, or whether in fact the combination itself leads to an improvement of the effectiveness. There are not many secured findings available that would allow a reliable judgement of the effectiveness of different hybrid-behavioural barriers. Previous experiences, however, indicate that the efficacy basically is equal to that of the more effective component and cannot significantly be enhanced through a combination with other behavioural barriers.

5.4 Fish collection systems

Fish collection systems remove fish mechanically from areas where they are at risk and transport them to bypasses or collection vessels, to facilitate a continued safe downstream migration. Therefore, fish collection systems cannot generally be used as a single protective installation, but as part of combined downstream fishways. It is to be differentiated between the following types:

- fish pumps
- travelling screens with troughs
- collection nets.

Since collection nets are not suitable for a continuous operation, they will not be dealt with further.

5.4.1 Fish pumps

Fish pumps are mainly employed at intake structures in connection with mechanical barriers in order to remove fish from dangerous zones as well as from areas with a high density of individuals, and to transport them to proper downstream fishways by means of transportation facilities like pipes or channels. Fish pumps are mainly in use in the USA, where the target species are young fish of anadromous species of comparatively small body length, e.g. American allis shad and smolts of Pacific migratory salmonids.

The operation of pumps is restricted to such types which would not injure fish, or if, only to a minor extent.

- jet pumps
- pneumatic airlift
- screw-impeller
- spiral pumps.

Jet pumps: Jet pumps function as follows: the water within a pipe will be accelerated by admitting a "powered flow-through" at a high speed in tangential direction to a ring-shaped nozzle (figure 5.58). The advantage is that fish will not get in contact with any rotating mechanical system. The mortality of young fish has been examined in laboratory tests: A bypass was arranged at a barrier. The approach velocity was between 0.31 and 0.61 m/s. Any fish that had entered the bypass was transported further by the jet pump. The speed inside the pipe of the jet pump was between 1.5 and 2.7 m/s. The injection speed chosen was between 9.1 and 15.2 m/s. The mortality of fish within the entire system amounted to 11.8 % (TAFT, 1986).

Table 5.18: Results of examinations on the mortality of fish in screw-impeller pumps (TAFT, 1986)

technical data	species and size [mm]	mortality [%]
number of revolutions 430 1/min diameter of impeller of pump 30.5 cm	American allis shad< 102	1.25
number of revolutions 430 1/min diameter of impeller of pump 12.7 cm	rainbow trout< 200 American smelt< 200	0.8 0.9
number of revolutions 430 1/min diameter of impeller of pump 10.2 cm	American allis shad 12.4 American allis shad 9.6 American allis shad 6.1	46.2 12.4 8.3

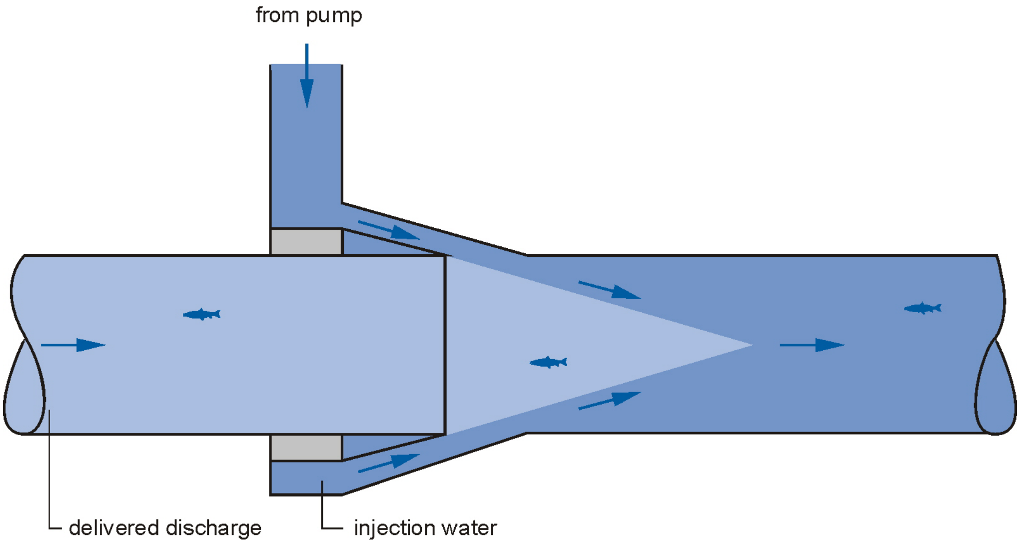


Figure 5.58: Schematic diagram of a jet pump (changed according to TAFT, 1986)

Pneumatic airlift: The method is that air-bubbles are blown into a vertical pipe. The uplifting force of the air-bubbles accelerates the water column, and fish contained in it will be transported. Such facilities have been employed in some individual cases at the Columbia river (USA) before more efficient installations had become available for the diversion of fish from stoplog recesses.

Screw-impeller: Such pumps are hydraulically more effective than jet pumps and can be used at greater height differences (figure 5.59). This risk of injury to fish through screw-impeller refers to similar causes as in turbines, e.g. by contacting the runner, differences in the pressure, turbulences, etc. The examination results indicated in table 5.18 however show that screw-impeller can be operated with mortality rates far below 10 %. The mortality next to species-specific differences is dependent on:

- the type of pump
- the proportion in size of fish : diameter of pump
- the revolution number of the pump

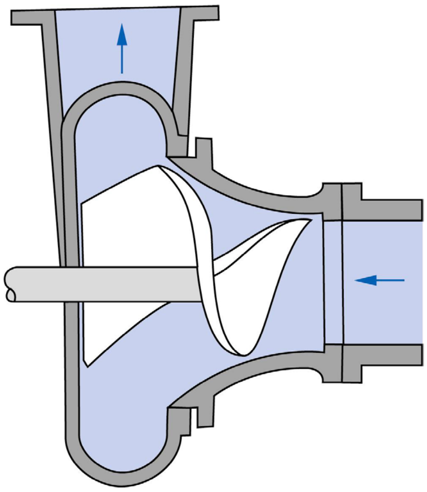


Figure 5.59:
Schematic diagram of a screw-impeller (changed accor-ding to TAFT, 1986)

Spiral pump: The principle of the Archimedean screw, which in many ways is used in sewage engineering, can also be employed as fish pump. The screw will be arranged slantingly and its length must be adjusted to the height to be overcome. Comparatively large dimensions will thus be involved, especially since the diameter of the screw is to be designed as required for the fish species and the necessary water volume. Typical dimensions are diameters of above 1.0 m and lengths of 3.0 m and more. Spiral pumps which are used for the raising of water differ insofar as when applied as fish pump the spiral is wrapped outside by a simultaneously rotating cylindric jacket (figure 5.60, figure 5.61, figure 5.62). This construction prevents fish from entering a gap between screw and the usually stationary trough. The revolution numbers are in the range of 10 1/min. Examinations of TAFT (1986) have resulted in a mortality of 13.8 %.

5.4.2 Travelling screens

The rotating screens described in chapter 5.2.8 will only protect those fish whose swimming performance exceeds the approach velocity of the facility. All fish which are lower in their performances, provided they will not pass the band screen, will be pressed against the screen and get killed. This risk exists especially at such facilities which for technical reasons have only very small mesh widths, so that fish larvae and fry also will be detained.

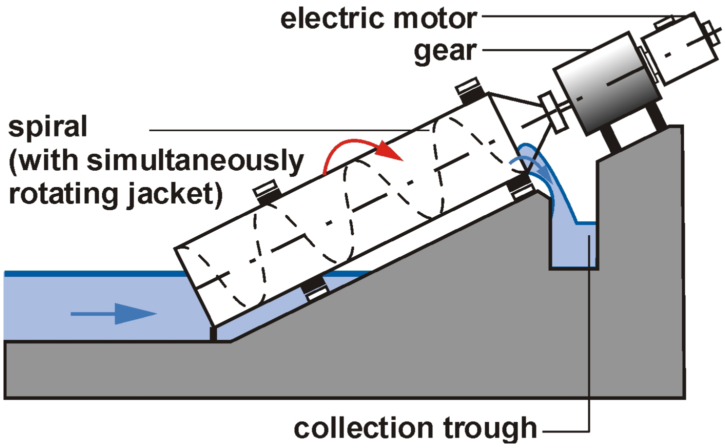


Figure 5.60:
Spiral pump with a simultaneously rotating jacket

Various attempts were made to modify rotating screens with the aim to reduce the mortality of fish. One possibility is to equip the band screen with troughs. Similar facilities are already in use by the fishing industry for some time for clearing fish ponds by chasing fish with nets to the transport facility or by guiding them to the facility by draining the pond water. The prevention of fish damage at travelling screens with troughs is based on two different mechanisms:

- Larger fish whose increased swimming speed is greater than the approach velocity will effectively be hindered from a passage as they are at conventional rotating screens, because their body dimensions exceed the mesh width and they are able to flee from the hazardous area.
- Smaller fish, especially young fish, fry and larvae will be pressed against the barrier, because they are insufficiently capable of swimming against the approach flow. They will however be lifted beyond the

water surface by the rotation of the screen and so escape the pressure force. They release themselves from the band screen and will be received by the troughs which are filled with water through the rotation. At the reverse point of the screen the troughs will be emptied into a bypass, allowing for the fish to return into the river or tailwater unharmed.

The requirements of fish protection and downstream migration will hereby be met and combined with the cleaning of the screen that is possible at the same time because of the travelling band.

Figure 5.61:
Spiral pump of the Tracy Fish Facility at the estuary of the Sacra-mento-River (California, USA)

In order to withdraw fish from the water body and to transport them by avoiding the obstruction, troughs or channels are mounted to the outside of the band (figure 5.63, figure 5.64). However, screens have been construc-ted which are flowed through from the inside to the outside, so that the troughs consequently were mounted to the inside (figure 5.65, similar to the drum screen installation Bergum (The Netherlands), figure 5.50).

It was possible to significantly reduce the damage rate at vertically travelling screens by equipping the band screen with troughs:

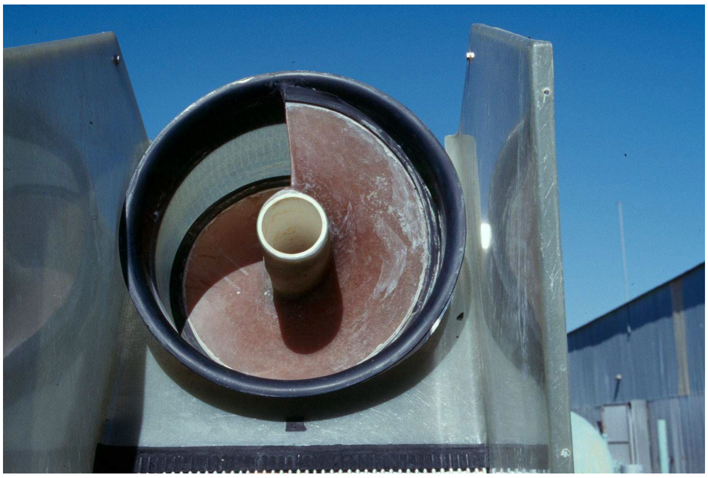


Figure 5.62:
Detail to figure 5.61: View of the inner spiral pump.

- Troughs have been installed inside a travelling screen at the Surry power plant in the James river (USA), which guaranteed a minimum water depth of 5.0 cm during the entire rotation. The cleaning of the band screen is done by means of flush nozzles that work with low pressure. The average survival rate of 58 different fish species amounted to 93.3 % (TAFT, 1986).
- The average survival rate of 13 fish species amounted to 85.5 % on average at the travelling screen of the Hanford power plant at the Columbia river (USA) where fish troughs and flush nozzles were installed at the inner walls (TAFT, 1986).
- 680 fish were registered over 4 days at the travelling screen of the hydropower plant Hadamar at the Elbbach (Hesse, Germany, figure 5.64), which were received by the screwed-on troughs and transported into the bypass channel (HARTVICH et al., 2002). 14 % of these fish have shown injuries, which however were previous damage.

Nevertheless, the positive effects of travelling screens with transportation troughs can only be achieved if specific frame conditions are adhered to:

- Fish can only be transported at low approach velocities of no pressing force, if their behaviour when approaching the screen supports their entry into the troughs. The meanwhile known behavioural pattern of the most important target species eel and salmon (chapter 5.1.4) leaves doubts that healthy and vital fish let themselves be caught and transported by troughs. HARTVICH et al (2002) have almost exclusively registered specimen of a body length of less than 10 cm at the travelling screen of the hydropower plant Hadamar. A significant portion of the fish was weakened by injuries. The consequence is that travelling screens with troughs are effective as fish protection facility for larger fish but cannot function as downstream fishway.

- The probability of fish being transported by the travelling screen with troughs can be enhanced by accelerating the approach velocity, but high approach velocities lead to significant hydraulic losses and can be the cause for static/technical problems. Furthermore, the damage rate of sensitive species and development stages may be increased.
- Sealing of the travelling screen against the bottom of the water body creates technical problems because of the troughs being installed on the screen.
- For small fish, particularly fish larvae and fry, there is the risk that they adhere to the band screen. As for conventional screens, damage to small fish can be avoided by high rotation speeds, so that they will be outside the water body for only a short while. Low pressure flush nozzles can additionally be installed in order to flush adhering specimen into the transportation troughs or bypass. There will be no mechanical damage involved.
- If travelling screens with troughs have to be effective as fish protection facilities and downstream fishways, they must be continuously operated.

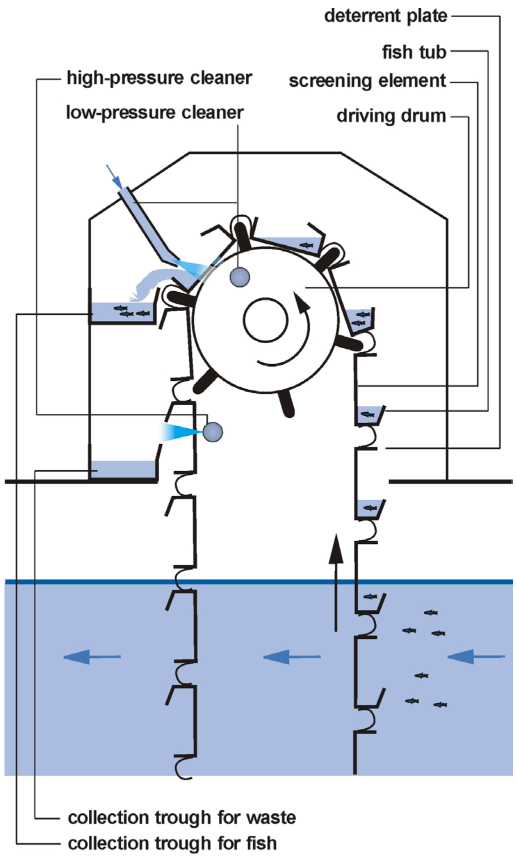


Figure 5.63:
Schematic diagram of a travelling screen with troughs installed to the outside (changed according to CLAY, 1995).

Like other fish protection facilities and downstream fishways, travelling screens with troughs must be designed specifically to the requirements of the individual target species. Although they can achieve high deterrent rates and little damage only if complied with the aforementioned conditions, travelling screens with troughs are rarely used at hydropower plants for the following reasons:

- Similar to travelling screens without troughs (chapter 5.2.8) the operation costs involved are high: The technology is comparatively liable to faults because of a large number of movable parts, and the elongation and wear-and-tear of the band.
- The high portion of flotsam in central European rivers can lead to soiling between upper and bottom boom, which must be removed at great expense.
- The band must be hoisted out of the water during prolonged frost periods similar to other screens with fine openings or bar spacing.
- Great differences in the water level may occur at the screen in case the band screen becomes clogged. The static of the band screen is generally not designed for such loads.
- A continuous operation, which is required for the prevention of damage to migrating fish, implies additional technical problems because of heavy wear-and-tear.

Figure 5.64:
Travelling screen with transportation troughs at the hydropower plant Hadamar in the Elbbach (Hessen, Germany): The troughs with fish being transported therein will be emptied into an irrigated bypass that leads to the tailwater. The instal-lation consists of a 40 mm-screen with screen cleaning machine connected in front. The travelling screen works intermittently.

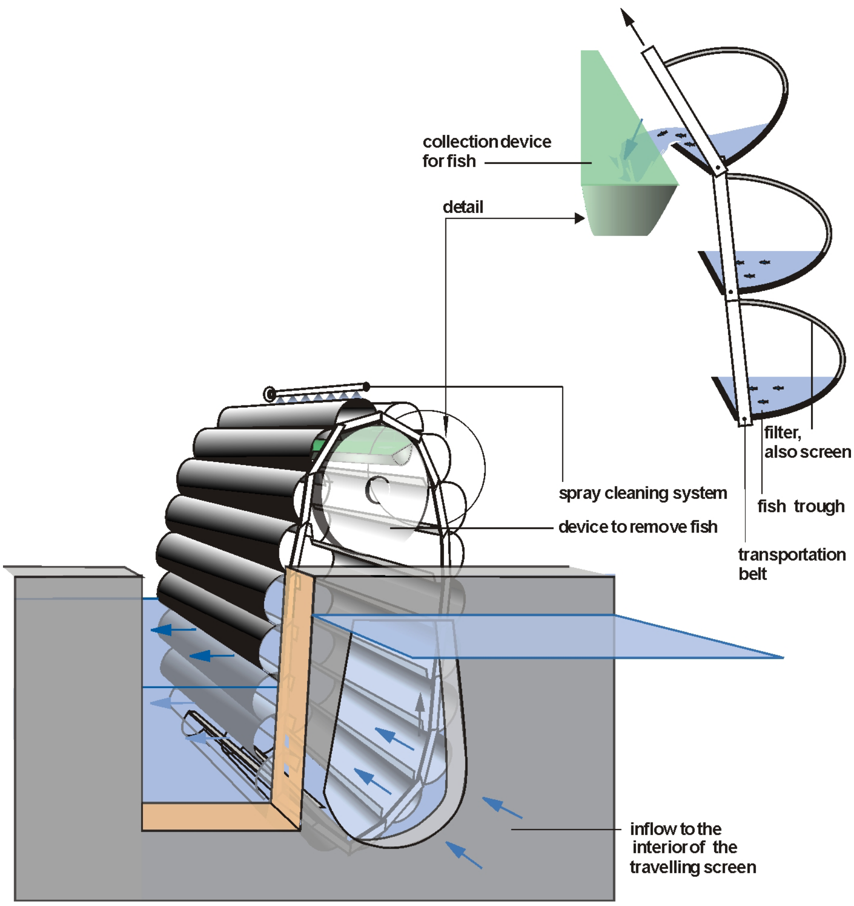


Figure 5.65:
Schematic diagram of a vertically travelling screen with troughs installed to the inside wall.

5.5 Design of bypass systems

Alternative migration ways must be offered to fish not only in order to avoid damage through migration obstacles but moreover to facilitate their safe passage into the tailwater. Such facilities are described as bypasses, which can be of entirely different construction.

Bypasses in the narrower sense are flowed-through pipelines or channels, which connect the headwater with the tailwater of the migration obstruction. Additionally, it is possible that other, permanently or temporarily open connections between headwater and tailwater resume the function of bypasses, e.g.:

- partially or completely opened weir fields
- weir overflow
- bottom outlets
- sluices, ice and flotsam gates
- fish passes
- overflowable power plants
- navigation locks.

Position, intake design and hydraulic are the main decisive factors for the effectiveness of bypasses. They must be arranged to meet the requirements of specific species, since construction principles which have proven suitable for salmon smolts must not necessarily be right to guarantee the migration of eel.

Almost all bypass constructions described in literature are designed to comply with the demands of fish migrating near the surface, especially smolts of salmonids. Comprehensive experiences from the USA for example refer to smolts of Pacific salmon species and to a lesser extent also to smolts of Atlantic salmon. Meanwhile, with regard to the latter species, there is differentiated knowledge available from France on their migration via bypasses which can also apply to German river systems. In accordance with the surface-oriented migratory behaviour of smolts of salmonids, bypasses are arranged immediately at the water surface so that they will only randomly be traced by bottom-oriented species, particularly by eel. According to today's standard of knowledge, bypasses are therefore generally defined by two types depending on their arrangement in the cross-section of the river:

- near-surface arranged bypasses for target species like salmon and sea trout and
- bypasses arranged near the bottom for the target species eel.

Both types will also be passed by other species. However, the examinations on downstream migration via bypasses so far concentrate on diadromous species. Until present, only Russian experiences can be referred to with regard to the positioning of bypasses that have to meet the specific requirements of potamodromous species (PAVLOV, 1989).

5.5.1 Inlet design for bypasses

It is so far solely possible to provide details of the inlet design of near-surface bypasses and mainly those for salmon. Remarks on the arrangement of near-bottom bypasses are given in chapter 5.6.2. Examples of the dimensions of French and American bypasses for Atlantic salmon smolts are summarized in table 5.19.

In French and American literature the following recommendations are given with reference to the minimum dimension of salmon bypasses:

- The width of the intake should at least be 0.5 to 1.0 m depending on the size of the screen (TRAVADE & LARINIER, 1992).
- In case of larger screen dimensions a bypass is necessary for every 10 m of the screen width (LARINIER, 1996).
- The water depth in the bypass must not be less than 0.4 m. Greater water depths improve its effectiveness, so that it may be sensible to increase the depth of the bypass on account of its width in case of a limited availability of water (TRAVADE & LARINIER, 1992). The water depth of a bypass is normally regulated by a lowerable gate or flap gate. At the dam Poutès in the Allier river (France) (figure 5.66), the bypass can be adjusted in height as a complete unit, and thus can be aligned to changing levels of the headwater (figure 5.67).

Table 5.19: Examples of dimensions of the intake of operative bypasses

installation / water body	width [m]	depth [m]	velocity [m/s]	discharge [m^3/s]	author
France					
Halsou / Nive	1.38	0.9	0.2 to 1.0	max. 0.5	LARINIER & BOYER-BERNARD, 1991b
Soeix / Gave d'Aspe	1.00	1.0	0.8 to 1.4	0.5 to 1.9	LARINIER & TRAVADE, 1999
Poutès / Allier	3.60	1.1	no details	max. 10	BOMASSI & TRAVADE, 1987
USA					
Bellows Falls / Connecticut river	2.70	0.9	no details	5.7	ODEH, 1999

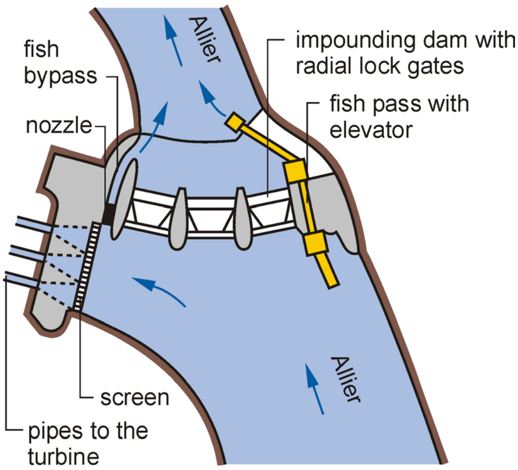


Figure 5.66:
Arrangement of the bypass for salmon smolts that migrate near the surface at the dam Poutès in the Allier river (France) (changed according to BOMASSI & TRAVADE, 1987)

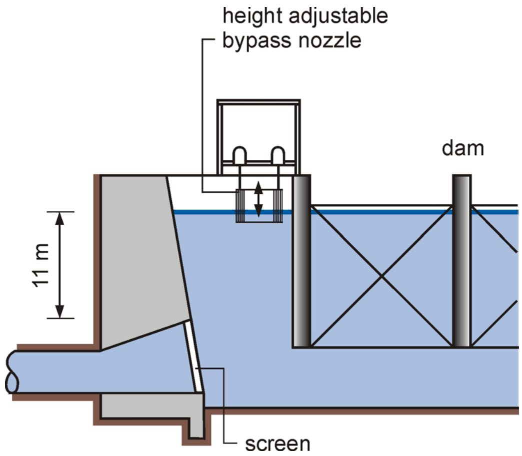


Figure 5.67:
Schematic diagram of the positioning of the near-surface salmon bypass at the dam Poutès in the Allier river (France)(changed according to LARINIER & BOYER-BERNARD, 1991a)

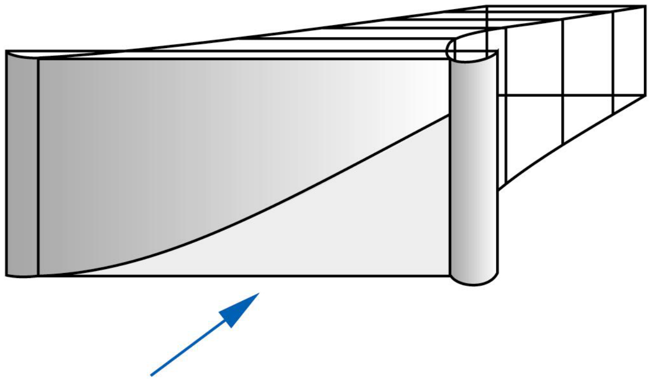
- Operative bypasses can work with a bypass discharge of 2 and 10 % of the turbine flow-through according to French experiences (LARINIER & TRAVADE, 1999). This value should be assessed separately for each location in dependence on the frame conditions, i.e. positioning, hydraulic, characteristic of screen etc. The more unfavourable the other conditions, the higher the discharge required for the bypass will be. The construction criteria applicable to the north-east of the USA are similar to those applied in France: ODEH & ORVIS (1998) calculated a supply to the bypass of 2 % of the absorption capacity of the turbines if an inclined arranged guiding system exists, and up to 5 % if the approach flow impinges rectangularly onto the screen surface. On the west coast of the USA near-surface bypasses are presently more often employed at large hydropower plants in the Columbia river and its tributaries. Although the size and structure of these facilities strongly deviates from those in France, and have been tested on the American east coast, the required discharge of 5 to 10 % of the turbine flow-through is very much the same (FERGUSON, et al., 1998).

According to the sensitivity which salmon develop towards hydraulic conditions, it is of decisive importance for the efficacy of a bypass that turbulences are avoided and that the velocity in the bypass will increase steadily until it has reached a rate that exceeds the swimming capacity of the smolts so that they will be drifted. Any delays of the flow must be strictly prevented. This can be achieved by a suitable funnel-shaped arrangement of the bypass inlet (figure 5.68). Upwelling currents can mask the flow in the bypass and make it difficult for smolts that orientate themselves by the surface drift to trace the bypass. LARINIER & TRAVADE (1999) have proven by means of appropriate examinations that this can effectively be prevented if metal plates are installed below the bypass inlet.

Figure 5.68:
The bypass can be adjusted in height and thus aligned to chang-ing levels of the headwater. It can also be hoisted above the water surface outside the migration sea-son of salmon smolts

A main problem which decisively influences the operatability of bypasses is the danger of clogging the intake. Bypasses therefore must be designed so that coarse particles can be diverted. Although the connection of a coarse screen in front of the bypass is a proven technique to keep flotsam off, but this implies the risk that the screen has the effect of a behavioural barrier and will thus have a negative influence on the efficiency of the bypasses (ODEH, 1999).

Detail of figure 5.68:
The intake of the bypass is shaped in such a way that only minor turbulences can develop and the flow will be in-creased steadily (changed according to BOMASSI & TRAVADE, 1987)



5.5.2 Increase of bypass efficacy with light

Whilst eel avoid light, it is possible to entice other fish species, especially salmonids by light (chapter 5.3). For this reason, trials were carried out at several French hydropower plants to take advantage of this behavioural reaction in order to increase the efficacy of bypasses for the migration of salmon smolts and sea trout. Different types of illuminations were tried out at the bypass of the hydropower plant Halsou on the Nive river (France). It became evident that although smolts were attracted by mercury-vapour-lamps, they shunned a passage of the light cone and did not swim into the bypass (LARINIER & BOYER-BERNARD, 1991a). More intensive examinations were therefore carried out with two different light sources at the dam Poutès on the Allier river (France). After the installation of an 80 W-lamp above the bypass more passages were recorded than at a stronger illumination, but the effect started with some time delay after the lamp had been switched on. This is referred to the fact that the retina of the eye of the smolt requires about 15 minutes to accommodate from darkness to light. The maximum enticing effect on smolts will be achieved after approximately one hour of illumination. Furthermore, it had been observed that fish remain outside of the light source and shun swimming through an illuminated area in order to reach a bypass. LARINIER & BOYER-BERNARD (1991 b) therefore have suggested the following illumination mode in order to increase the effectiveness of the bypass:

- Bright illumination with a 400 W-mercury-vapour lamp upstream of the bypass in order to entice fish into the vicinity of the bypass intake. 30 minutes of illumination will be followed by 15 minutes of darkness, during which phase the fish can swim into the bypass. Additionally, a permanent moderate illumination of the bypass itself with a 50 to 80 W-lamp will be employed for visual orientation.
- As an alternative it is possible to operate the illumination intermittently with only one lamp.

In general it seems possible to improve the effectiveness of salmon bypasses by light. But more essential than light is the influence of hydro-mechanic conditions on the efficacy, like the correct position of the bypass opening in the sense of being traceable, a sufficient dimensioning and admission as well as a continuously accelerating velocity and corresponding flow (LARINIER & BOYER-BERNARD, 1991b).

5.5.3 Design of bypass conduit

The bypass conduit can be constructed like a pipe or open channel. The design must ensure that physical conditions will not cause any damage and injury to fish, which for example can be brought about by a rapid change of pressure and gradual breaking, shear forces, turbulences and power of impact. Scratches and abrasions occur when contacting rough surfaces. The bypass pipe therefore must not have any obstructions or roughness, and an abrupt diversion of the flow has to be avoided. Hence, if the bypass pipe takes a bent course, the radius of the curve must not be below 3 m according to TURNPENNY et al. (1998). In order to greatly exclude injuries, the velocity in the bypass should not exceed 12 m/s (TRAVADE & LARINIER, 1992).

The inflow of the bypass into the tailwater should be above the water surface, as fish which overcome a height difference in a free fall have higher survival rates than fish which are accelerated within the water body and then slowed down which consequently exposes them to high shear forces (TAFT, 1986; figure 5.69). The inflow should preferably be arranged horizontally and be situated 1.8 to 2.4 m above the level of the tailwater according to instructions of ODEH & ORVIS (1998).

The impingement of fish on the surface of the tailwater is to be rated uncritical for minor to medium heights, provided the criteria outlined in chapter 4.1 are complied with. In laboratory tests it was discovered that fish can survive an impingement speed of up to 16 m/s (TAFT, 1986), but American authorities recommend that 7 to 8 m/s should not be exceeded for a reliable prevention of injuries (ASCE, 1995).

Precautionary measures can be taken against the predation of fish which are submerging into the tailwater and will first be disorientated:

- in case of predators by relocating the inflow far below the weir or hydropower plant
- in case of birds by spray-irrigation of the point of inflow.

Bypass pipes should generally allow the installation of control systems in order to implement investigations into downstream migration and the efficacy of the facility.

5.5.4 Migration via alternative corridors

For their downstream passage fish basically use all connections between head- and tailwater. With respect to alternative migration ways, the focal point of concern is not their general suitability as a bypass, but their traceability and whether they can be passed without a risk, and what the possibilities for improvements are.

5.5.4.1 Weir overflow

At barrages without hydropower utilization the migration of fish generally takes place via the weir. A passage is largely uncritical (chapter 4.1), provided the overflow height does not significantly exceed 10.0 m, and a sufficient water cushion and no influencing elements exist in the tailwater. A downstream migration via the weir can also take place at barrages where hydropower is utilized if the discharge of the water body exceeds the design capacity of the power plant. This situation is given approximately every three years at the dam Poutès in the Allier river (France) (figure 5.66) at the time of smolts migration. Many smolts can then be observed in the vicinity of the overflowed spillway of the dam, whilst at the same time only a few specimens will be recorded in the bypass (BOMASSI & TRAVADE, 1987).

Experiences made so far with the downstream migration of salmon from repopulated water bodies in the Rhine-system however, prove that smolts migrate mainly at discharges distinctly below mean water. Since most hydropower plants are designed for this discharge, a weir overflow is to be considered as an exception rather than the rule, so that the downstream migration in most years takes place through the turbines of the power plants (SCHWEVERS, 1999). Also the downstream migration of eel in the autumn season, although primarily released by rising discharges, often happens at discharges below the design capacity of the power plant, and thus makes a downstream migration via the weir impossible.

Figure 5.69:
The inflow of the bypass at the hydropower plant Bellows Falls on the Connecticut river (Con-necticut, USA), is situated approximately 9.0 m above the level of the tailwater

5.5.4.2 Lifted flood control devices

Completely opened weir fields can be passed unhindered by downstream migrating fish and without risk of damage, if the depth of the water is sufficient and no interfering elements exist. A survival rate of 99.6 % was assessed for smolts of the Pacific coho-salmon, which were swept with 850 m3/s water over the laid weir of the Rocky Reach dam (Oregon, USA) (TAFT, 1986).

Whilst the lowering of flood control devices causes a weir overflow, which facilitates especially the downstream migration of surface oriented fish like salmonid smolts, the lifting of flood control devices creates a gap close to the bottom, which especially can be used by downstream migrating eel and other bottom oriented species. A passage at storage levels below 10.0 m will be without risk because of low pressure differences. If the storage levels are greater, it must be examined whether damage can occur depending on the species of fish. Such damage can be conditioned by high flow velocities or the gas bubble disease (figure 5.70). Fish which have migrated and are disorientated might be exposed to growing danger of predators with increasing heads.

With reference to the required discharge distribution, model tests carried out for the hydropower plant Wahnhausen on the Fulda river (Hesse, Germany) have led to the conclusion that 50 % of the discharge of this location would have to be delivered over the opened weir field in order to produce a clear flow in direction of this alternative migration corridor (ARBEITSGEMEINSCHAFT GEWAESSERSANIERUNG, 1998). Similar results were also established through examinations of HOLZNER (1999) carried out at the hydropower plant Dettelbach on the Main river (Bavaria, Germany), where a discharge of approximately 50 % was needed before 26 to 42 % of fish could be recorded in the tailwater of the open weir field. In order to obtain this effect it was necessary to lift the flood control device by at least 10 cm and to ensure that injuries to juvenile perch and zander during their passage of the 25 m wide weir field would be prevented.

Since the Wahnhausen and Dettelbach locations distinguish themselves by specific hydraulic conditions, these results cannot readily be transferred to other dam structures. Nevertheless, it becomes evident that the opening of flood control devices can offer a traceable and safe migration corridor if a high portion of the discharge will be made available for this purpose. Hence, this procedure is obviously not suitable for standard operations, but in combination with a fish-saving management of the power plant it may certainly be a successful method in supporting the downstream migration of fish (chapter 5.8).

Figure 5.70:
Brown trout from the Eder river below the Affoldern reservoir (Hesse, Germany) with symptoms of the gas bubble disease near the eye

5.5.4.3 Sluices

Sluices which are arranged beside the screen of hydropower plants may possibly be used as bypasses for the downstream migration of fish. As exemplified by the power plant Soeix on the Gave d'Aspe river (France), sluices with an overflowed valve can be effectively employed as bypass for salmon smolts if they are optimally positioned (figure 5.71, figure 5.72). Ice gates which for their purpose are arranged near the surface may also be suitable as bypasses if their structure is appropriately aligned.

Underflowed gates with an opening near the bottom are often used as stationary eel traps. For example, during one night in December 1999 more than 500 eel were caught by an eel trap of such design in Dorlar on the Lahn river (Hesse, Germany), which was only admitted with about 1 % of the discharge. Such constructions therefore can also be used as eel bypasses (ADAM, 2000). This kind of utilization is principally also thinkable for bottom outlets of dams; the passage however, can only be graded as safe if the difference in height is low (chapter 4.1). Trials at a dam in New Zealand, where the bottom outlet is located at a depth of 37.0 m and should be used as eel bypass had to be abandoned since a high mortality rate was recorded because of high pressure differences (KLEINSCHMIDT ASSOCIATES, 1997).

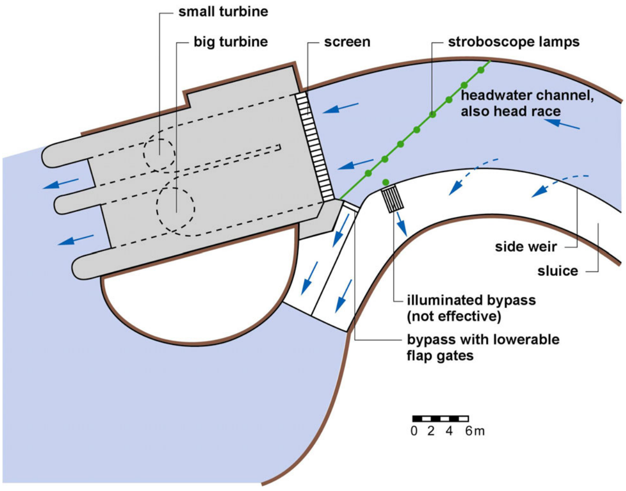


Figure 5.71:
Layout of the hydropower plant Soeix on the Gave d'Aspe river (France) with former by-pass and sluice, which had been converted into a bypass. The stroboscope lamps shown in the diagram have not improved the operatability of the bypass and were not used again for the 2nd bypass (changed according to LARINIER et al., 1993).

Figure 5.72:
The sluice of the hydropower plant Soeix on the Gave d'Aspe river (France) directly above the screen has been successfully converted into a bypass for salmon smolts (view of drained head-water channel)

5.5.4.4 Overflow hydropower plants

Overflow hydropower plants normally consist of a bank up medium placed on top of the power house, which can be laid in case of flood occurrence in order to open an additional discharge section. The arrangement near the surface suggests the use of such shutter as bypass for surface orientated fish. This seems possible under the following conditions:

- The bypass opening must be positioned in such a way that it will be traceable for fish migrating with the main current. The consequence is that the bypass must be located as close as possible to the screen of the hydropower plant. Shutters which are installed far into the direction of the tailwater cannot be traced, unless a significant portion of the discharge is released via the power plant, allowing the generation of a velocity that complies with fish-biological requirements.
- In this case, the requirements for the design of bypass facilities located near the surface as formulated in chapter 5.5.1 must also be fulfilled. It must therefore be possible to lower the shutter by a specific degree. If it covers the entire width of the power house this will produce quite a significant discharge. In individual cases it is to be explored whether a separate bypass is created in or beside the shutter.
- Furthermore it is to be examined whether the section behind the shutter will facilitate a safe passage for fish. The same requirements apply which have already been outlined for the weir overflow (chapter 4.1 and 5.5.4.1).

5.5.4.5 Upstream fish passes

Downstream directed passages via fishways have here and there been documented, which in actual fact serve as upstream fish passes (RATHCKE, 1997 etc.).

When checking the effectiveness of the bypass channel Beckinghausen on the Lippe river (North Rhine-Westphalia, Germany), the downstream migration of fish was detected by means of a separated fyke net (SPAEH, 1999). Also in the fish pass at the weir of the hydropower plant Wilhelmswalze in Sinn on the Dill river (Hesse, Germany) many chub were recorded which have returned into the tailwater via the fish pass several weeks after their upstream migration (ADAM & SCHWEVERS, 1997b, 1997c).

The traceability of the inflow of fish passes in the headwater however is normally restricted, which is why downstream migrating fish cannot be expected to the full extent. Hence, it does not seem realistic to employ fish passes as effective downstream fishways, especially since as a rule the requirements for optimum positioning cannot be combined: The intake of a fish pass must be positioned in front of the screen at a distinct distance in order to prevent fish which changes from the fish pass into the dam will not be drifted towards the screen (DVWK, 1996). This cannot exclude the downstream migration facility opening into the fish pass, or the water which is required for the operation of the downstream migration facility will also be used to enhance the guide flow of the fish pass.

5.5.4.6 Navigation locks

Navigation locks to a great extent are used by fish for their upstream directed passage of dams (SCHMASSMANN, 1924; KLINGE, 1994; SCHWEVERS & GUMPINGER, 1998). It can therefore be assumed that a downstream directed passage takes place as well. However, an extensive downstream migration of diadromous species in analogy to an upstream migration can only be expected if the lock is located favourably, i.e. as close as possible to the power plant and additionally admitted with a significant portion of the total discharge (JOLIMAITRE, 1992; ARBEITSGEMEIN-SCHAFT GEWAESSER-SANIERUNG, 1998). However, concrete examinations of fish migrating downstream via navigation locks are not available.

5.6 Arrangement of mechanical barriers and bypasses

At hydropower plants and intake structures, it is to be ensured that fish are prevented from entering dangerous installations and thus keeping downstream migration safe. For this purpose, mechanical barriers and bypasses are to be arranged in such a fashion that migration corridors can safely be traced. Here, it is important that the guiding effect of the velocity towards the bypass and the mechanical barrier itself can be fully utilized, disregarding whether they are primarily functioning as physical barrier or behavioural barrier. The hydraulic conditions in the vicinity of barriers must also be utilized in order to guide fish to the bypass (chapter 5.1 and chapter 5.2). It is therefore necessary that the species-specific behaviour of fish when contacting these barriers or the flow conditions are known, about which there is insufficient knowledge available. The following considerations also reflect on bypasses in front of conventional screens, i.e. those which have not specifically been constructed as fish protection or guiding facility.

Bypasses must generally be located where downstream migrating fish will concentrate naturally (EICHER, 1985). The optimum position of the bypass opening consequently lies in the area of the main flow of the water body. At weirs with hydropower utilization this is generally the turbine intake, and in the case of diversion power plants possibly also the water intake structure of the headwater channel. If behavioural barriers are in use in order to deter fish from hazardous areas, the bypass opening is to be placed in the area into which fish retreat.

The following instructions apply to the arrangement of mechanical barriers and bypasses for fish species whose behaviour when approximating migration obstacles is sufficiently known:

- smolts of migratory salmonids
- silver eel.

In addition, combined fish protection and bypass facilities will be explained which function is based on the inevitable drift of fish.

5.6.1 Arrangement of barriers and bypasses for surface orientated species

5.6.1.1 Case studies from France

Although bypasses in France are especially designed for salmon smolts, it can be presumed that comparable requirements apply also to potamodromous species, as their behaviour in principle is similar to that of downstream migrating salmon smolts (PAVLOV, 1989).

Examinations of the migratory behaviour of salmon smolts in French water bodies have led to the conclusion that these fish hesitate when approaching the migration obstacle and perform a distinct exploratory behaviour before they decide to continue their migration (LARINIER & BOYER-BERNARD, 1991a). Not only mechanical barriers like skimming walls, coarse screens etc. in the intake area of hydropower plants will induce this behavioural reaction, but any change of the flow conditions. If the fish during its exploration of the migration obstacle finds an alternative migration path in the immediate vicinity, it will accept it, provided the intake is of appropriate design (chapter 5.5). However, if the search is in vain, the intake screen of the power plant will sooner or later lose its effect as behavioural barrier, and even 20 mm-screens will be passed by downstream migrating smolts.

The demands on the optimal positioning of bypasses near the surface can be explained by the example of three French installations:

- The intake of the power plant at the dam Poutès in the headwater of the Allier river (France) is located in a depth of 11.0 m, so that it will be passed by a few smolts only as its effect is similar to that of a skimming wall (figure 5.67). On the other hand, the bypass which is positioned at the water surface will most reliably be traced and accepted, in particular when it is additionally illuminated (LARINIER & BOYER-BERNARD, 1991a).
- The water intake at the power plant Soeix on the Gave d'Aspe river (France), which has a mean annual discharge of 24 m^3/s, is effected via a screen that is arranged rectangular to the flow at the end of the headwater channel (figure 5.72). Both turbines have an absorption capacity of 24.5 and 10.3 m^3/s. At a water depth of 3.5 m the maximum mean approach velocity taken over the screen surface is 0.71 m/s. The original bypass was located approximately 6.0 m above the screen on the bank on the left hand side, had an opening of 1.0 * 1.0 m and was admitted with 0.2 to 0.5 m^3/s. During control examinations of more than 1,000 smolts only 22 % of the specimens could be recorded in the bypass, all others had passed the 35 mm-screen (LARINIER & TRAVADE, 1999). Neither different sources of light nor a higher admission could enhance the effectiveness of the bypass. Radiotelemetric examinations and behavioural observations however, have proven that in the area of a sluice that is located only 1.5 m above the screen, salmon smolts search for migration possibilities. The sluice was therefore equipped with a lowerable flap gate and is since operated as bypass with an admission of 0.5 to 1.9 m^3/s. Control examinations resulted in an efficiency of 50 to 80 % for this kind of arrangement.
- The headwater channel of the power plant Halsou on the Nive river (France) runs diagonally towards the intake screen, so that the tangential component of the approach velocity is comparatively high (figure 5.73). A bypass is arranged directly at the downstream end of the embankment wall. Its flow axis runs in short intervals parallel to the screen surface (figure 5.74). The admission can be adjusted via a lowerable gate. This bypass will mainly be traced by up to 95 % of the downstream migrating smolts when the turbine which neighbours the bypass on the right hand side is in operation. If only the turbine on the left hand side is working, the fish have great difficulties in finding the bypass. The smolts generally show the tendency of concentrating at a point of the screen where the greatest flow velocities occur according to the operation condition of the power plant (LARINIER & BOYER-BERNARD, 1991a).

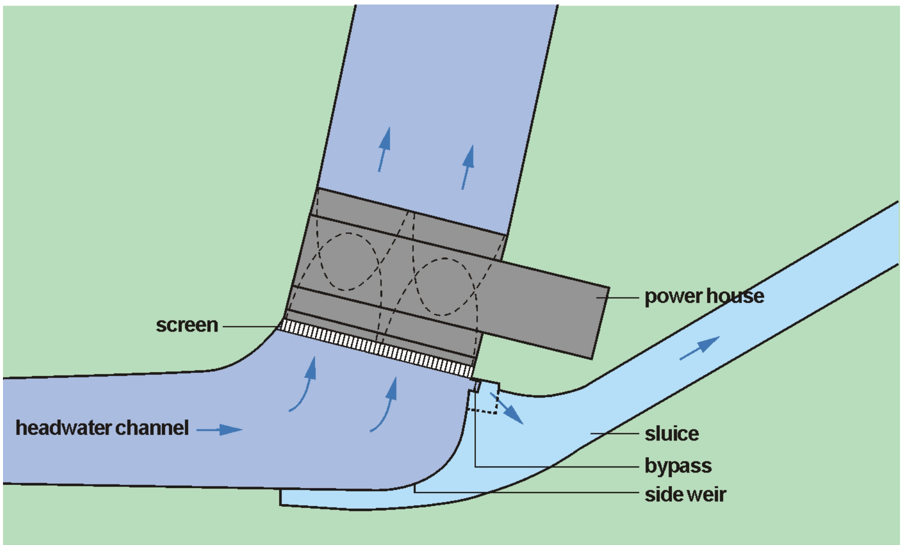


Figure 5.73:
Site plan of the power plant Halsou on the Nive river (France) (changed according to LARINIER & BOYER-BERNARD, 1991b)

A comparison of the arrangement of the bypasses Soeix and Halsou emphasizes the decisive importance which the immediate proximity of the bypass intake to the intake screen has for its traceability. As salmon search for downstream fishways only in the area of the main flow and only directly before the screen, already a relocation of the bypass intake by only a few meters into the headwater will lead to a failure of the downstream migration facility. Experiments which were carried out to compensate for the unfavourable position of the entrance by increasing the admission, installing illumination etc. have not obtained any satisfying results. According to LARINIER & TRAVADE (1999) therefore, the following requirements can be applied to the arrangement of operative bypass installations at existing screens:

Figure 5.74:
The bypass at the power plant Halsou (Nive river, France) directly joins the intake screen that is approached by the flow tangentially

- The approach velocity must be low enough to enable fish to trace the bypass. The velocity must be distinctly lower than the sustained swimming speed of the fish especially at screens that are arranged vertically to the flow. The maximum flow velocity at which salmon smolts can stay sufficiently long in front of the screen is about 0.5 to 0.6 m/s. Greater approach velocities may be acceptable if the hydraulic conditions before the screen are favourable, that means a distinct tangential flow or an inclined arranged mechanical barrier will guide fish to the bypass.
- Conventional screens for smolts of salmon and sea trout of a length of 12 to 18 cm also have the effect of a behavioural barrier, even if the clear width is between 2.5 and 4.0 cm, i.e. at a coefficient of the passage feasibility of P = 1.4 to 3.3. The effect as behavioural barrier, however, will soon be reduced if the clear widths are of greater dimension, so that screens of a clear width of 6.0 to 7.0 cm, equal to P-values > 3.0 will be passed by a large portion of smolts even if a very strong flow vector has generated tangentially to the screen.
- Screens which are arranged far below the water surface have a similar effect like skimming walls.
- A bypass must be arranged as close as possible beside the screen or the migration obstacle. Already distances of 2.0 m will have a negative effect on the traceability.
- The local flow conditions and the operation mode of the hydropower plant are to be considered. In case of tangentially approached screens the bypass must always be positioned in a pointed angle

between approach flow and screen axis. This will lead to an effective utilization of the tangential component of the approach velocity.

- Several bypasses may be required in the case of a very wide screen. LARINIER & TRAVADE (1999) recommend that a maximum width of the screen of approximately 10 m per bypass should not be exceeded, even if the flow conditions are favourable.
- The situation becomes more complex if the intake area consists of several screen fields, which are separated by pillars projecting beyond the screen surface into the headwater. At such arrangement, downstream migrating fish will search for migration corridors in any of the bays which will be created and thus they cannot be guided to a bypass if only one exists. In such cases each screen field must be equipped with a bypass.
- The bypass is to be designed in accordance with the criteria explained previously (chapter 5.5). The discharge required for the bypass in order to have an attractive hydraulic effect must be between 2 and 10 % of the turbine-flow in dependence on the conditions prevailing on site.
- Illumination may enhance the traceability of a bypass.

5.6.1.2 Case studies from the American East Coast

If mechanical barriers are employed purposively for the protection of downstream migrating fish, their positioning can be optimized in respect of the water intake and also with regard to the traceability of a bypass. Next to conventional screens Louver and skimming walls can be used as mechanical barriers for the protection of Atlantic smolts. At the Holyoke Dam on the Connecticut river (Massachusetts, USA) a Louver was installed over the entire width of the headwater channel of the hydropower plant of 40 m and a depth of 6 m, and was fixed to a bridge-like structure, from which point it can be serviced. The Louver is 120 m long and 2.75 m deep, hence covers about 50 % of the water depth. It is constructed with fields of an approximate width of 1.0 m, which run in lateral guide rail (figure 5.75). The Louver lamellae are made of polyethylene and have a bar spacing of approximately 60 mm, which however cannot be kept precisely because of the instability of the material. The installation is arranged at an angle of approximately 30° to the flow direction and runs towards a 2.0 m wide bypass (figure 5.76). The bypass will only be opened during the migration period of the target species, whilst the entire Louver will be hoisted completely in winter time. The approach velocity of approx. 0.5 m/s incurs only a minor hydraulic loss, which however increases with soiling of the Louver. A coarse screen is therefore connected in front of the installation.

Figure 5.75:
Louver in the headwater channel of the Holyoke Dam on the Connecticut river (Massachusetts, USA).

As the installation stretches over the full width of the channel and is admitted with a parallel directed flow, it achieves an efficacy of 86 % for juvenile Clupeids and 97 % for Atlantic salmon smolts (ODEH & ORVIS, 1998).

Figure 5.76:
Detailed view of figure 5.75: Intake of bypass

On the other hand, the Louver of the Vernon Dam being located upstream of the Holyoke Dam on the Connecticut river (Connecticut, USA) has been constructed in front of the approximately 50 m wide power plant, in order to prevent migrating smolts from entering turbines 9 and 10 which are operated preferentially (HANSON, 1999) (figure 5.77). The Louver is also fixed to a bridge construction and leads to a bypass pipe, which runs through the power plant (figure 5.78). The flow over the length of the Louver is not parallel like it is in a channel because of the way the reservoir is arranged. The Vernon Dam is characterised by the following data:

design flow (turbine 9 and 10):	52 m^3/s each
length of Louver:	47.5 m
Louver-lamellar:	10 mm x 50 mm, stainless-steel
distance of lamellar:	76 mm
inclination of lamellar:	60° against Louver axis
immersion depth:	4.6 m
dimension of bypass pipe:	1.2 x 2.3 m
length of bypass pipe:	25 m
discharge of bypass:	9.9 m^3/s

In order to assess the effectiveness of the Louver, various studies have been carried out before and after its installation. For this purpose, between 100 and 200 salmon smolts marked with radio transmitters were released above the dam and their path through turbines, weir openings and the bypass system was traced. The rate of smolts diverted through the bypass pipe which had been installed earlier, could be increased by means of the Louver from 16 % to 54 %. It was essential, however, that the turbines were taken into operation in the sequence 10, 9, 7, 6 and 1 to 4 and were stopped in reverse order, as the most favourable approach flow conditions needed for the function of the Louver could only be achieved by means of this mode. A survival rate of 94.9 % during the passage of the turbines 9 and 10 and 81 % of the other power plants led to the conclusion that 95.5 % of the smolts could safely pass the station in consideration of the downstream migration possibilities at the Vernon Dam. This result complied with the demands established by the CONNECTICUT RIVER ATLANTIC SALMON COMMISSION in 1990.

Figure 5.78:
Louver at the hydropower plant Vernon Dam on the Connecticut river (Connecticut, USA) with a view towards the bypass: The visible coarse screen initially caused shunning and avoidance reactions of downstream migrating smolts when the operation was started. It has meanwhile been removed

The hydropower plant Bellows Falls is located 52 km above the Vernon Dam on the Connecticut river (Connecticut, USA). Contrary to the Vernon Dam the water is fed into the turbines via a 470.0 m long headwater channel, which is why the approach flow of the power house is rather conformable. In order to utilize the head of 19.0 m there are three Francis turbines installed with a flow-through of 99 m^3/s each (HANSON, 1999). A skimming wall made of concrete serves as mechanical barrier for downstream migrating fish, which leads diagonally towards an ice gate, of which the overflowed sliding panel is used as bypass (figure 5.79, figure 5.80, figure 5.81). The fish is then washed downstream through a channel which ends about 9.0 m above tailwater level (figure 5.7). The fish protection facility and downstream fishway at the Bellows Falls on the Connecticut river (Connecticut, USA) are characterized by the following data:

length of skimming wall:	63 m
immersion depth:	4.6 m
height of overflow at sliding panel:	0.9 m
discharge of bypass:	5.7 m^3/s

The effectiveness of the installation has been examined on 152 smolts by radiotelemetry in 1995 (ODEH & ORVIS, 1998). Whilst 84 % of the fish were diverted along the skimming wall and via the bypass, 16 % migrated underneath the skimming wall, of which two thirds found an additional bypass installed beside the screen, so that a total of 6 % of the downstream migrating smolts had passed the turbines. The time the smolts stayed in front of the skimming wall was significantly shorter than before the Louver of the Vernon Dam, and the bypass was traced sooner, which is probably due to the uniform approach flow conditions. The guiding effect of the skimming wall, however, decreases with a rising turbine-flow.

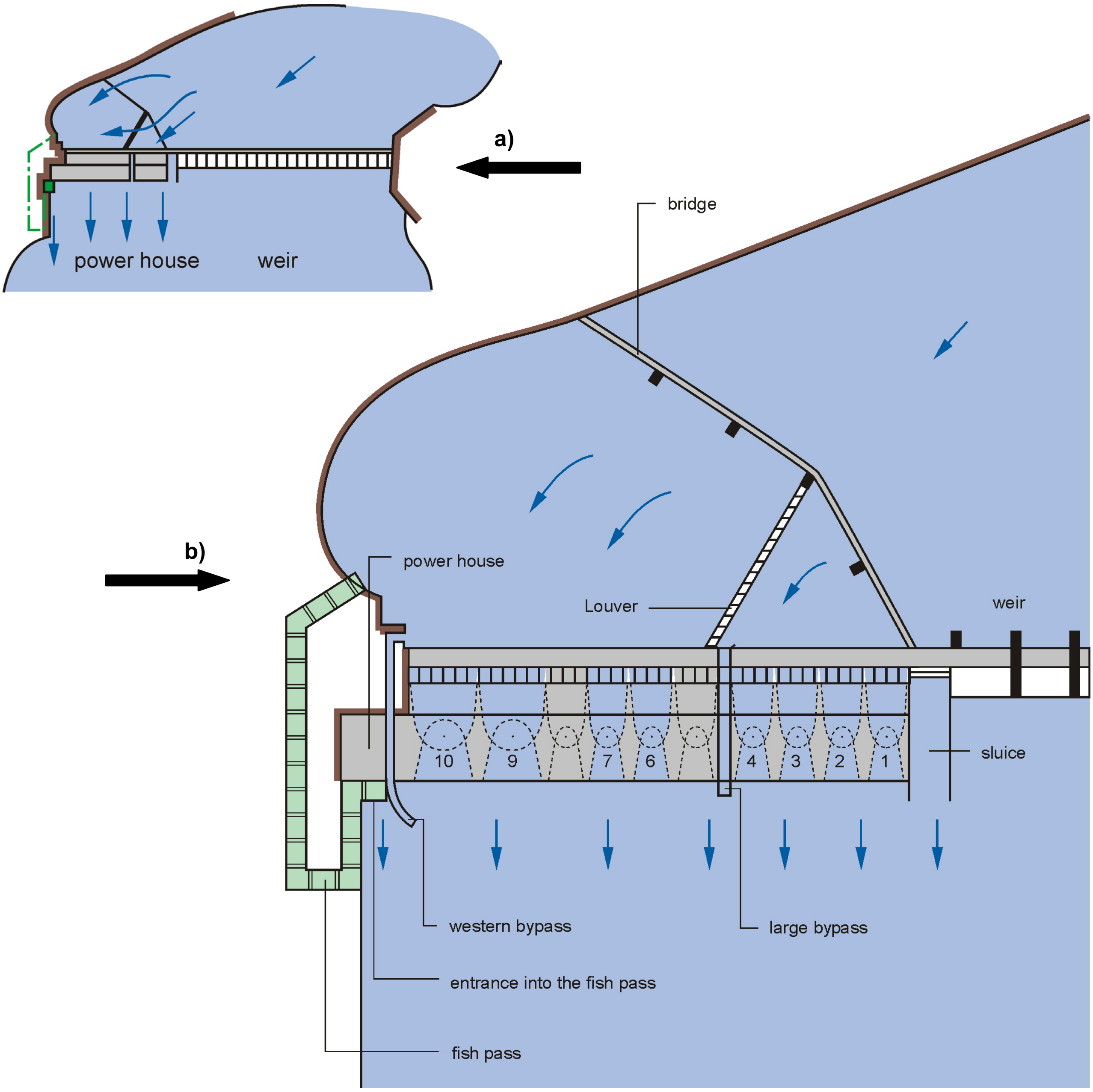


Figure 5.77: Arrangement of the Louver at the hydropower plant Vernon Dam on the Connecticut river (Connecticut, USA):

a): site diagram

b): detailed plan

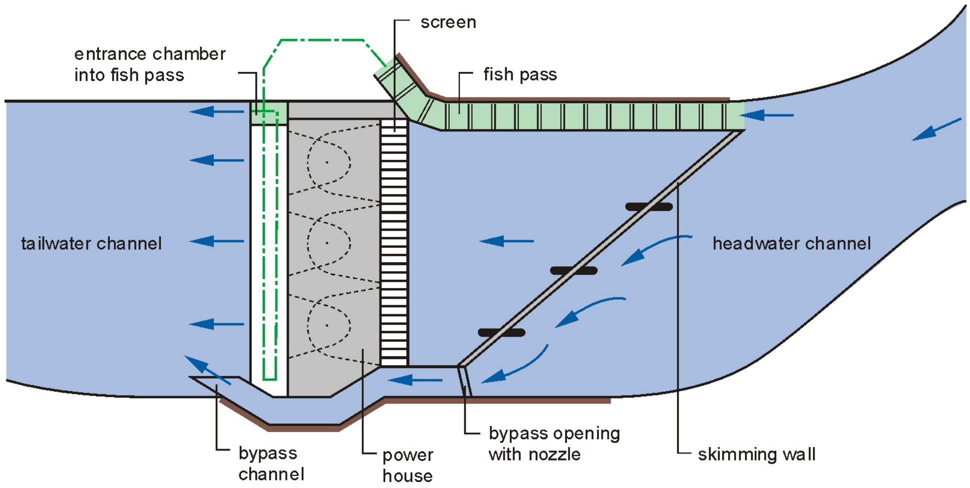


Figure 5.79:
Arrangement of skimming wall at the hydropower plant Bellows Falls on the Connecticut river (Connecticut, USA). There is another bypass beside the screen on the river bank of the right hand side, which is not shown in this diagram (changed according to ODEH & ORVIS, 1998)

Figure 5.80:
The skimming wall at the hydropower plant Bellows Falls on the Connecticut river (Connecticut, USA) has an immersion depth of 4.6 m. The bypass opening can be seen on the left hand side of the picture

Figure 5.81:
Detailed view of figure 5.80: Intake of bypass with actuation to adjust the overflow height

5.6.1.3 Case studies from the American West Coast

Since the beginning of the 20th century significant efforts are being undertaken in the west of the USA to protect smolts of Pacific salmonids and juvenile allis shad from entering irrigation systems, cooling water intakes and hydropower plants. A 100 % protection of fish in water bodies of small and medium size up to 50 m^3/s is aimed at. An important frame condition for the operation of downstream fishways in the north-western States is that the water bodies concerned carry only minor amounts of leaves etc. and that the anthropogenic impact is of minor importance. The standard velocity and clear width of mechanical barriers is very low since the size of the downstream migrating fish of approximately 3.0 to 5.0 cm is small (figure 5.82, figure 5.83). The clear width at new installations is only 1.5 mm.

The behaviour of fish in front of mechanical barriers has been examined in depth and has resulted in standardized structural shapes. Inclined arranged screens are mostly used, where the fish are guided to a bypass by the tangential component of the approach velocity along the mechanical barrier, and can then safely pass into the tailwater or can be transported back into the water body. In this case, any shape of mechanical barrier can be employed. Additionally, mechanical barriers with small gaps (figure 5.83), Wedge-Wire-screens (figure 5.84), drum screens and travelling screens are in use.

Screens can only develop their effect as a guiding structure in the direction of the bypass if the flow vector that runs tangentially to the surface of the screen is at least as great as the standard velocity. The more favourable the relation the better the guiding effect. The responsible authorities of the States of America recommend that the sweeping velocity must be four times the value of the standard velocity (table 5.20, figure 5.90). This will be achieved by arranging the screen inclined to the flow, for which an angle of 20° to 25° has become generally accepted as standard value.

Figure 5.82:
Water intake structure for irrigation purposes (Wash-ington, USA): The water is led through a coarse screen to an inclined screen made of perforated plates (d = 3.0 mm). The bypass is arranged at a pointed angle, and the fish are guided back into the water body through a pipe. The irrigation channel starts behind the sliding panel (on the left hand side of the picture)

Figure 5.83:
Detailed view of figure 5.82: A brush-system is operated horizontally over the perforated plate screen. The bypass inlet can be seen on the right hand side of the picture.

Figure 5.84:
A Wedge-Wire-screen with a clear width of 1.25 mm and a brush-system at a facility with a design flow of 15 m^3/s. The flow pattern illustrates the velocity component (V_T = 0.34 m/s, V_N = 0.12 m/s) that acts tangentially to the screen. Hook river (Washington State, USA)

Figure 5.85:
Fish protection facility at a water intake employed for irrigation purposes in a tributary of the Yakima river (Washington, USA): drum screen made of perforated panels (d = 3.0 mm) with a diameter of 0.8 m arranged inclined to the flow direction; the bypass inlet is arranged at a pointed angle

In order to fulfil these conditions, water is withdrawn in one (figure 5.85), two (figure 5.86, figure 5.87) or even several intake bays (figure 5.88, figure 5.89) via laterally arranged screens while the bypass is located in the pointed angle at the end of the bay. Another possibility offer screens which are arranged in a V-shape towards the bypass (figure 5.91, figure 5.92). At larger installations additional bypasses are arranged over the length of the screen which are equipped with headworks, or alternatively several units are connected side-by-side.

In the USA, two combined downstream migration fishways are occasionally arranged in tandem: Whilst fish are filtered from the cooling water or irrigation water in the first protection facility, the second installation facilitates the concentration of fish in a water volume kept as low as possible so that the bypass water can largely be used as intended (figure 5.75). The results of effectiveness inspections applied to these installations in the USA are listed in table 5.20.

The operation of inclined arranged screens is only possible if a coarse screen with screen cleaning machine, if required, is connected in front. Fine flotsam will be washed back into the water body. Screens with small clear widths are not suitable for operation in the winter season, during which period they will be hoisted entirely or partly. Lifting devices must be made available if needed which can also be used for carrying out maintenance work on the installation.

Table 5.20: Recommendations of various US-States for normal and tangential velocities at inclined arranged screens intended for the protection of fish larvae and young fish. The velocities are measured at a distance of 76 mm to the barrier

State / Authority	maximum normal velocity [m/s] fish larvae	maximum normal velocity [m/s] young fish	tangential velocity
US NATIONAL MARINE FISHERIES SERVICE	0.15	0.30	at least same as normal velocity
CALIFORNIA DEPARTMENT OF FISH AND GAME continuous cleaning intermittent cleaning	 0.10 0.025	 0.10 0.025	at least double the normal velocity
OREGON DEPARTMENT OF FISH AND WILDLIFE	0.15	0.30	double to quadruple normal velocity
WASHINGTON DEPARTMENT OF FISHERIES king salmon and coho salmon pink salmon (or humpback salmon), chum salmon (or keta salmon) and blueback all species	 0.15 0.06	 0.15	double normal velocity
ALASKA DEPARTMENT OF FISH AND GAME coregonids salmonids	 0.03 0.15	 0.03 0.15	no criterion
IDAHO DEPARTMENT OF FISH AND GAME	0.15	0.15	avoid injuries
MONTANA DEPARTMENT OF FISH, WILDLIFE AND PARKS	0.15	0.3	no criterion

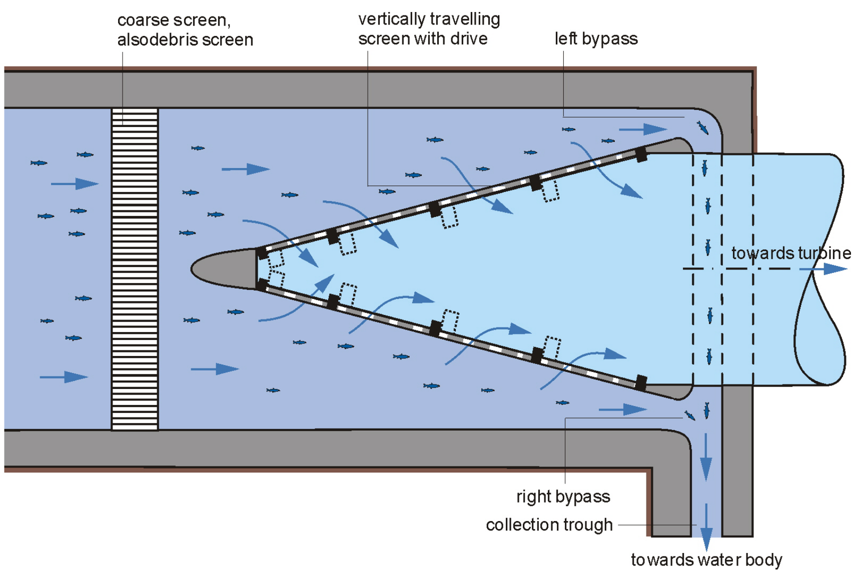


Figure 5.86: Layout of water intake for the hydropower plant Weeles Falls (Washington, USA)

Figure 5.87:
View of water withdrawal (figure 5.86) by vertical travelling screen. Visible are the drives of the screens. The power water is collected in the middle channel. Outside, two bypass inlets are arranged at a pointed angle. Protected fish are guided into the original bed through pipes arranged directly beside the structure.

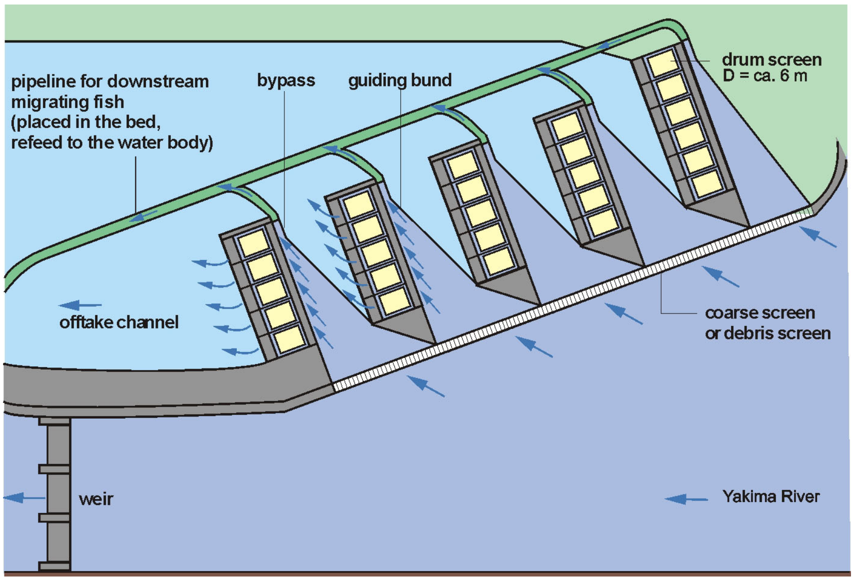


Figure 5.88:
Layout of water intake structure used for irrigation purposes and hydropower utilization (Q = 50 m^3/s) at the Roza Dam, Yakima river (Washington, USA)

Figure 5.89:
Water intake structure at the Roza Dam (figure 5.88) on the Yakima river (Wash-ington, USA): A coarse screen is connected in front of the drum screens. The drum screens are combined in 5 groups and arranged inclined to the approach flow. Each bypass is located at the corresponding vertex leading into a pipe and further to another facility with travelling screens where fish is taken from the discharge of the bypass and guided back into the water body.

Figure 5.90:
Detail of figure 5.89:
Flow pattern at a drum screen

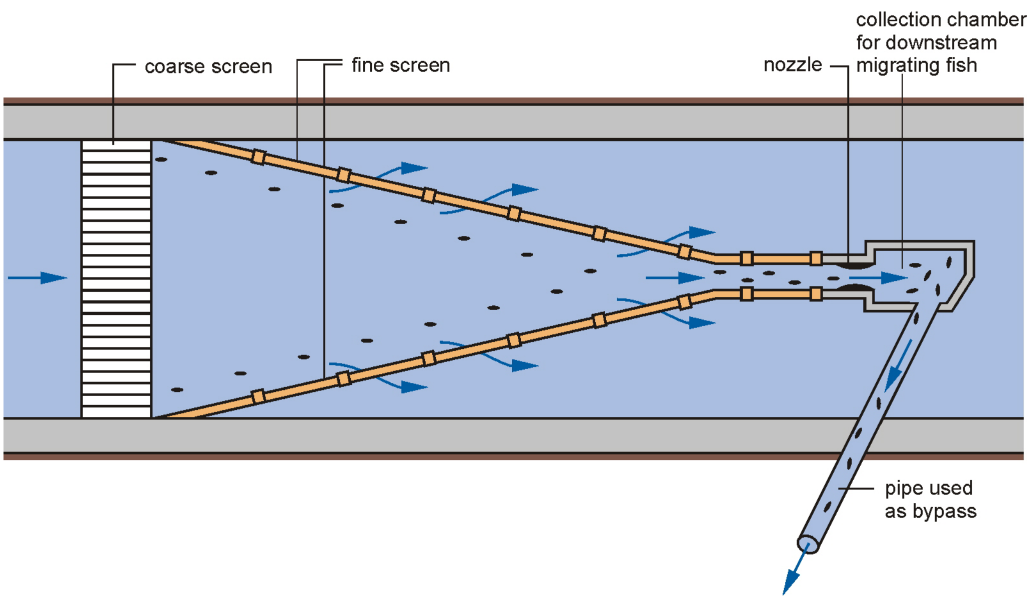


Figure 5.91:
Sketch of fish protection installation and downstream fishway at the White river (Washington, USA). A coarse screen precedes the fine screen. The bypass inflow runs into a pipe

Figure 5.92:
Fish protection facility and down-stream migration fishway of the water intake structure illustrated in figure 5.91 for a hydropower plant (Q = 50 m^3/s) on the White river (Washington, USA):The Wedge-Wire-Screen with 3.0 mm clear spacing is arranged in V-shape. The admission of the bypass is approximately 400 l/s.

Table 5.21:Results of effectiveness inspections on inclined arranged screens in the USA

water body / installation	construction	results	author
Hudson river / pilot installation in front of the cooling water withdrawal of original scale	screen with netting wire of a mesh width of 0.7 or 1.0 mm, 20° in flow direction and bypass of 0.2 m width	deterrent rate for 38 species: fry that can eat: 1.5 % young fish: 82.2 % on average: 84.0 %	MATOUSEK et al., 1988
Brayton Point Generation Station / intake structure	inclined arranged travelling screen with troughs, mesh width 9.5 mm, during drift of larvae reduced to 1.0 mm normal velocity: 0.27 to 0.37 m/s	deterrent rate: 76 %	ANDERSON, 1988
Lake Ontario / cooling water withdrawal	screens arranged in V-shape, which lead to a slot-shaped bypass opening at an angle of 25°. Normal velocity: 0.2 m/s	total efficiency: rainbow trout- smolts:44 - 99 % other species:50 - 100 %	EDWARDS et al., 1988
Kings river / intake structure of an irrigation channel	inclined arranged travelling screens made of perforated plates with a hole diameter of 2.5 mm, speed of screen: 0.1 m/s	deterrent rate: 100 %	TAFT, 1986
Sunnyside Dam Yakima river / diversion channel	17 drum screens arranged at an angle of 26° to the flow direction, diameter: 7.5 m, width of each 3.5 m, additional reduction of bypass water volume by 80 % in an intermediate basin with travelling screens	deterrent rate: 100 % mortality: king-salmon:< 3 % rainbow trout: 0 %	TAFT, 1986

Older installations on the Pacific coast of the USA have initially often been equipped with Louvers. They generally show a similar V-shaped arrangement with a bypass at a pointed angle. These barriers however, are no longer sufficient to meet the today's requirements for the protection of downstream migrating fish and their development stages as comprehensively as possible and are therefore increasingly replaced by close meshed mechanical screens.

5.6.1.4 Partial screening at turbine inlets

Since the 70s of last century, existing large hydropower plants in the river system of the Columbia river (USA) have been retrofitted with partial screens in the intake area as a special form of downstream migration facility, and have continuously been developed further during the course of the last decade.

Figure 5.93:
Louver for Pacific salmonids with a bypass arranged in the centre (Collwitz Falls, Washington State, USA)

Cause for this development has been the fact that considerable accumulations of Pacific salmon smolts were observed in stoplog recesses during maintenance works. This situation has led to attempts to catch fish with collection nets in order to transport them into the tailwater unharmed. However, this method could only prevent 6 % of the downstream migrating smolts from passing turbines (BENTLEY & RAYMOND, 1968). Extended examinations have indicated that between 70 and 80 % of smolts concentrate in the upper 4.5 metres of the turbine inflow. On the basis of this knowledge the development of screens was initiated which divert drifting smolts directly into the stoplog recess. Here, through openings they can reach a bypass which either guides fish alongside the turbine into the tailwater or is connected to a collection system (COLLINS, 1976, figure 5.94).

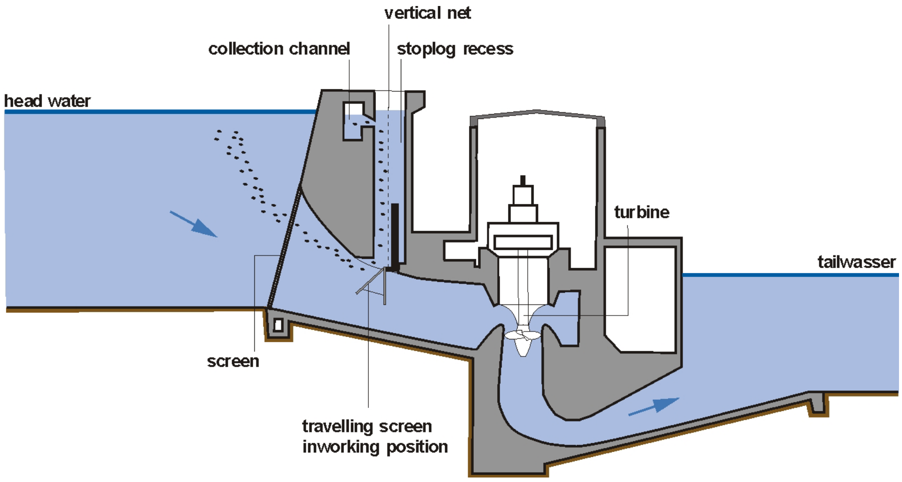


Figure 5.94: Location of a partial screen in the turbine intake of the hydropower plant Bonneville Dam on the Columbia river (Washington State, USA).

For the task of submerging the screens, the same crane systems can be used which are employed for lowering stop logs for maintenance works on turbines. In order to effectively divert fish, the screens must be angled by 35° for which purpose they are equipped with a special hydraulic system. The effectiveness was further enhanced by screens where height was increased to 12 m from the usual 6 m. As the crane systems available were not high enough, telescopic screens had to be constructed, which first were submerged into the stop log and then extended over the full length in order to finally be angled by 35° in flow direction (BARDY et al., 1991).

Different mechanical barriers have been tested (TAFT, 1986; BARDY et al., 1991), where stationary screens which were cleaned by travelling brushes (submerged bar screen) have proven to be better than travelling screens (submerged travelling screen, figure 5.95, figure 5.96). Presently, these two types of screens are gradually replaced by Wedge-Wire-Screens.

The effect of screens in the intake area of hydropower plants differs greatly depending on the conditions of each individual location. Since good experiences were gained with such guiding system at the Little Goose Dam in the Snake river, a tributary of the Columbia river, it was attempted to achieve highest possible effectiveness at the upstream located Lower Granite Dam by a special fish receiving tank. The effect, however, was significantly less and additionally, increased scale losses and other injuries occurred, leading to the conclusion that screens in the stoplog recess were generally more efficient than the fish receiving tank that had been built specifically for this purposes (MATTHEWS et al., 1977). GESSEL et al. (1991) report about similar experiences: After a deterrent rate of 75 % had been achieved in the Columbia river through screens in the inflow area of various power plants, similar screens should be installed at the Bonneville Dam with the aim to reduce the number of 2.25 million smolts being killed every year through turbines. However, an effect of less than 25 % only was obtained by this installation in the year 1983. It was not possible to increase the deflection rate to 70 % despite numerous improvements. Whilst the effectiveness of screens in the inflow area of power plants in the USA is rated unsatisfactory until today, the mortality occurring at such fish protection facilities is generally negligible. Details about deterrent rate and mortality at various power plants in the Columbia river system according to TAFT (1986) are shown in table 5.22.

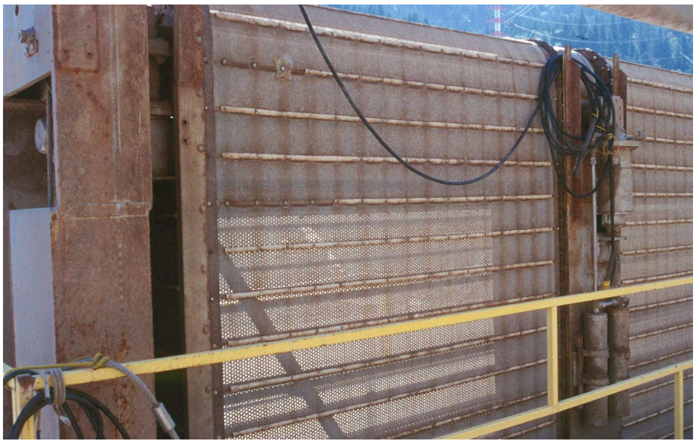


Figure 5.95:
Bonneville power plant (Columbia river, Washington State, USA): Travelling screen made of plastic. The picture shows the entire unit which is pulled from a shaft in the feeding channel to the power house

Figure 5.96:
Detail of figure 5.95: Close-up view of the plastic net of 3.0 mm clear width with traverse rein-forcements and driving chain

Table 5.22: Deterrent rate and mortality of fish at screens in the turbine inflow of hydropower pants in the catchment are of the Columbia river (Washington State, USA) (TAFT, 1986)

installation	species	mortality	deterrent rate
McNary Dam	*Oncorhynchus tshawytscha*, < 1 year *Oncorhynchus tshawytscha*, > 1 year *Oncorhynchus kisutch* *Oncorhynchus nerka* *Oncorhynchus mykiss*	0.9 % 0.3 % 0.1 % 0.6 % 0.2 %	38 % to 74 %
Lower Granite Dam	*Oncorhynchus tshawytscha*, < 1 year *Oncorhynchus tshawytscha*, > 1 year *Oncorhynchus mykiss*	0.7 % 0.4 % 0.1 %	
Little Goose Dam	*Oncorhynchus sp.*	0.7 %	
Bonneville Dam, power house 1	*Oncorhynchus tshawytscha*, < 1 year *Oncorhynchus tshawytscha*, > 1 year		76 % 72 %
Bonneville Dam, power house 2	*Oncorhynchus tshawytscha*		< 40 %

The following conditions should be adhered to (PARK & FARR, 1972; ODGAARD et al., 1988) in order to achieve the maximum effect:

- The admission of the stoplog recess should be as high as possible. The largest portion of the water can return into the turbine inflow via openings which are protected by fine-meshed screens, and thus will not be lost for energetic utilization.
- The dimension of the screen must be sufficient to cover the area of maximum flow within the turbine inflow.
- The flow may be reduced by the screen to a moderate extent.
- The sweeping velocity must be greater than the normal velocity.
- The approach velocity at the screen should be between 1.5 and 2.0 m/s.
- Two openings of a diameter of 15 to 30 cm each per stoplog recess are sufficient for fish to trace bypass systems.
- Illuminated bypasses can more easily be traced by salmon but not by rainbow trout.

The operation of screens in the turbine inflow of hydropower plants involves many technical problems like the removal of flotsam, maintenance works, and inspection of the screen at least every three months, etc. The screen loss amounts to 15 cm on average. According to TAFT (1986), the costs involved are the highest of all available fish protection facilities.

5.6.2 Arrangement of bypasses for bottom orientated species

GERHARDT (1893) already recommended a so-called eel-pass for the protection of downstream migrating eel: "*A channel that rises inclined upward […] is to be installed in the protective grating of a dam in such a way that starting from the bottom of the upper course of the river it will almost reach headwater level […].*" (figure 5.97). Such construction was allegedly first installed at a power plant in Greifenberg on the Rega river (Poland) and its operativeness was proven by a fish box at the bottom exit of the pass. Details about construction and number of downstream migrating fish however, are not known, and the effectiveness claimed by GERHARDT has not been confirmed by any other author.

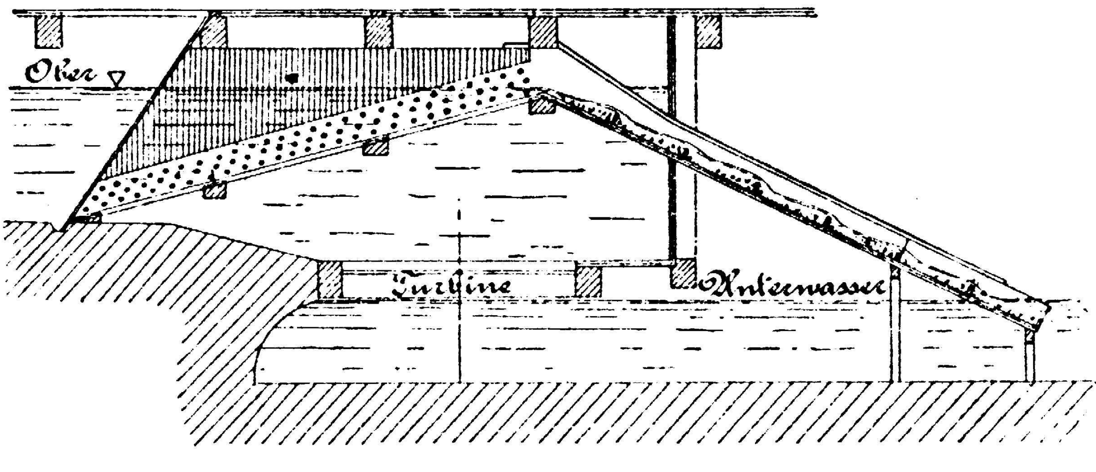


Figure 5.97: Historic schematic diagram of an "eelway" (GERHARDT, 1893)

When constructing new weirs, it was quite common until the 1960s to occasionally install so-called eel-pipes of small diameter, mostly < 100 mm, in any place without taking biological criteria into consideration. Often it was not even clear whether these pipes served for downstream or upstream migration. Any effectiveness inspection has not become known for any of these cases. In the 1990s the construction of such pipes was re-adopted and they were increasingly installed in the area of hydropower plants. The diameter of the pipes was between 200 and 300 mm in general, and they were preferably installed in the vicinity of the screen of the power plant. The results of effectiveness inspections are available for some of these facilities (table 5.23):

Table 5.23: Results of examinations on downstream migrations of eel in the rivers Else, Emmer and Lippe (North Rhine Westphalia, Germany) (BARTMANN & SPAEH, 1998; RATHCKE, 1997; SPAEH, 2001b) in comparison with catches of eel in Dorlar on the Lahn river (Hesse, Germany) (ADAM, 1999)

location	discharge [m^3/s]	discharge in bypass [m^3/s]	number of eel	examination days	eel/day
hydropower plant on the Else river	5.5	0.2	147	213	0.7
hydropower plant at the Emmer Dam	5.5	0.2	27	90	0.3
hydropower plant Dringenauer Muehle (Emmer)	8.3				
eel bypass:		unknown	21	39	0.8
escape pipe:		0.4	64	39	1.6
fish pass:		0.2	19	39	0.3
total:			95	39	2.4
hydropower plant Hamm-Uentrop (Lippe river)	21.0	0.1			
season 1999:			1,348	77	17.5
season 2000:			246	64	3.8
comparison (Lahn river) hydropower plant Dorlar:	5.0				
catch of eel:		0.2	1,386	204	6.8

At the American power plant Cabot Station on the Connecticut river (Massachusetts, USA) a migration corridor was offered especially to downstream migrating eel by lowering and additionally illuminating the flushing gate positioned beside the screen in order to create a bypass (figure 5.100, figure 5.101).

The characteristics of the location are the following:

6 Francis turbines:	Q_{total} = 200 m^3/s
clear width of screen:	100 mm
inclination of screen:	80°
depth of water in front of screen:	9 m
mean approach velocity:	0.9 m/s
bypass opening (surface-near):	2.5 m wide x 0.6 m high
admission to bypass:	approximately 4 m^3/s

For the purpose of examining the function of this bypass acoustic transmitters were implanted in 52 eel. The result was that only 2 specimens had used this migration corridor. The majority of fish had passed the turbine or was never found again (HARO, 2000).

Generally, it can be said that all eel bypasses examined for their operatability have been used by eel and other species for their downstream migration. But assessing the effectiveness of such downstream fishways is only partly possible as little comparable information is available about the migration potential in the water body and the actual passage of eel through power plants.

Even if the conditions of the different locations are not directly comparable with each other, there are indications that bypass openings which are positioned immediately on the bottom of the river cannot be traced reliably. The number of fish migrating downstream via such bypasses is low at all examined installations: Taking the Dringenauer Muehle as an example, there were passages of a similar number registered via the upstream fish pass and three times as many eel took the escape pipe that is installed alongside the screen. This estimation is in line with the knowledge that although eel migrate downstream in great water depths, they nevertheless do not move immediately along the bottom of the water body. There are indications that a lateral arrangement of eel bypasses will also be unfavourable for their traceability:

- Eel follow the main flow and with it inevitably arrive in front of the screens of hydropower plants. According to data of behavioural observations undertaken in a model channel, they do not carry out any sideways search movements at an approach velocity of > 0.3 m/s, but escape upstream against the current if permitted by the conditions of the approach velocity. Laterally arranged bypasses therefore can only be traced if a fish randomly reaches the immediate vicinity of the bypass during its downstream migration (ADAM et al., 1999).
- In order to utilize the escape behaviour of eel and thus to obtain best possible catches, fishermen traditionally position their fyke nets in the headwater of power plants with the fyke net opening in downstream direction. If arranged this way, the catches are especially successful at higher water temperatures, when the increased physiological performance of eel allows them to free themselves from the screen and to escape upstream.
- By means of echo sounding examinations in the intake of the Main (river) power plant Dettelbach (Bavaria, Germany) it could be observed that also under outdoor conditions eel would escape upstream (oral information: HOLZNER, 2001).

Until present there is no evidence on operative eel bypasses available. According to actual knowledge however, the following possibilities exist to arrange bypasses in such a way that they can quite reliably be traced by downstream migrating eel:

- Provided that eel are physically capable of migrating through a screen, and the normal velocity before the screen is so low that the fish can free themselves, the likeliness will be enhanced that eel escaping upstream will randomly also trace an unfavourably positioned bypass during further attempts of downstream migrations.
- Downstream fishways which are a combination of a flat screen and a bypass channel running alongside the top edge of the screen have proven successful for many species. Laboratory experiments have shown that eel will passively drift into the bypass channel if the approach velocity is sufficiently high (chapter 5.6.3.4).
- The “Bodengalerie®” (bottom gallery) as an optional bypass has not been proven in practice so far. It consists of a shelter with stilled currents placed on the river bottom in a transverse position in front of a screen, while the opening of the gallery is facing the intake structure (ADAM et al., 2002). The intention of this arrangement is that after eel have collided with the screen and escape against the current, they will gather in the gallery and from there passively be led into a bypass.

5.6.3 Arrangement of generally effective mechanical barriers and bypasses

Whilst all facilities described in chapter 5.6.1 and 5.6.2 are designed to match the behaviour of individual species, other installation types have been developed where the downstream fishway or the forwarding of fish is not based on their active swimming behaviour but their drift through high sweeping velocities. These developments also were primarily made for the Pacific area in the USA. However, isolated similar constructions are also in use in Europe.

5.6.3.1 Eicher-Screen

The Eicher-Screen has been developed for hydropower plants with pressure conduit (TAFT, 1986). It consists of a Wedge-Wire-Screen with a very low bar spacing, d < 2.0 mm (figure 5.102, figure 5.103) installed inside the pressure pipe at a flat angle of approximately 20°. The velocity within the pressure pipe is approximately 1.5 m/s. The normal velocity however, is only 0.5 m/s conditioned by the flat inclination of the screen. The sweeping velocity of 1.4 m/s on the other hand is remarkably higher and drifts fish and flotsam over the smooth surface of the screen. At the tailwater end of the screen a small bypass conduit is connected to the pressure pipe by taking advantage of the flow by which fish and flotsam will be diverted (figure 5.104). The screen can be cleaned with the back-current by tipping the screen over a centrically arranged axis. Records on this system quote an efficiency of 98 % for Pacific smolts and a mortality rate below 10 % at screen and bypass conduit (TAFT, 1986). There are no results available for other fish species. The Eicher-Screen is so far used in isolated cases only in the propagation area of Pacific species of salmon, and solely at locations where the pressure loss generating at a screen can be neglected because of a high head (figure 5.105).

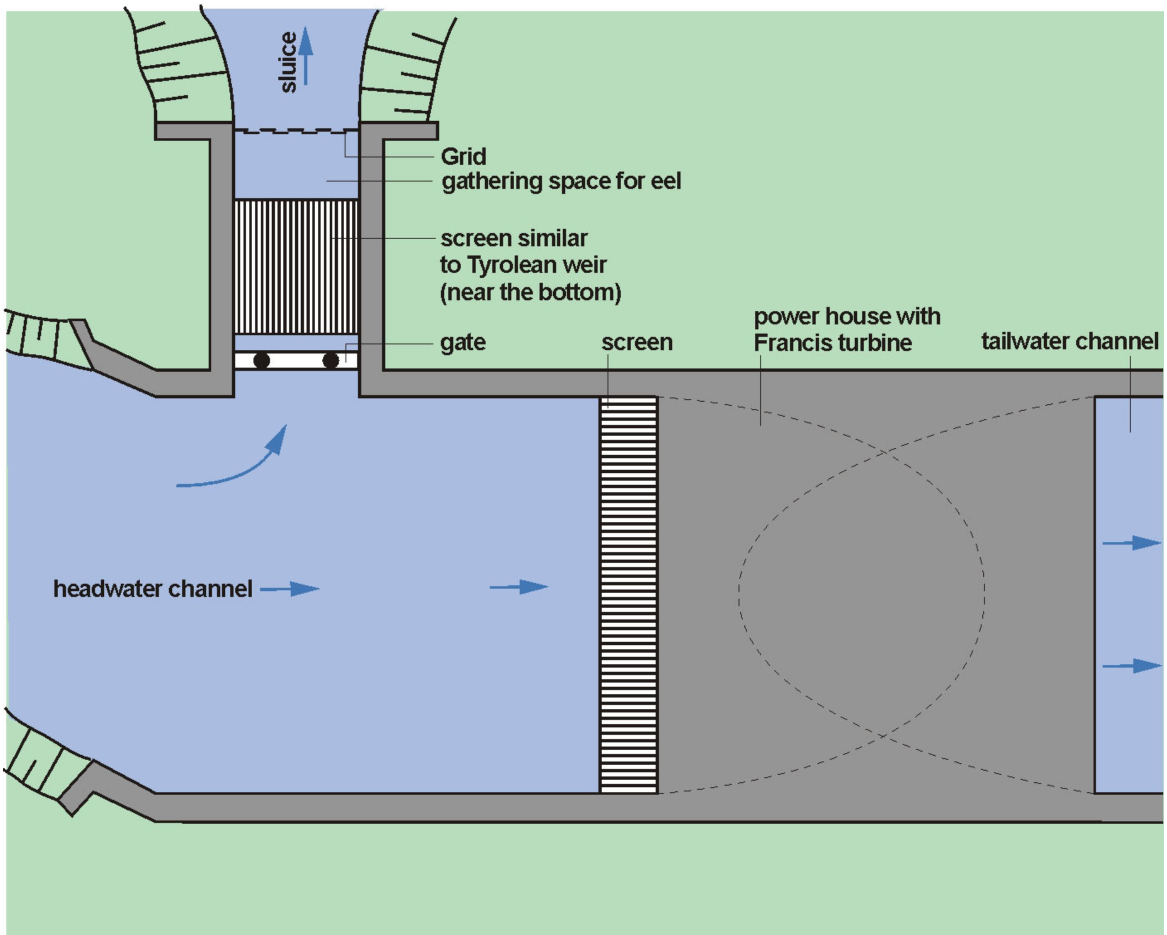


Figure 5.98: Position of the eel-catch at the location Dorlar on the Lahn river (Hessen, Germany)

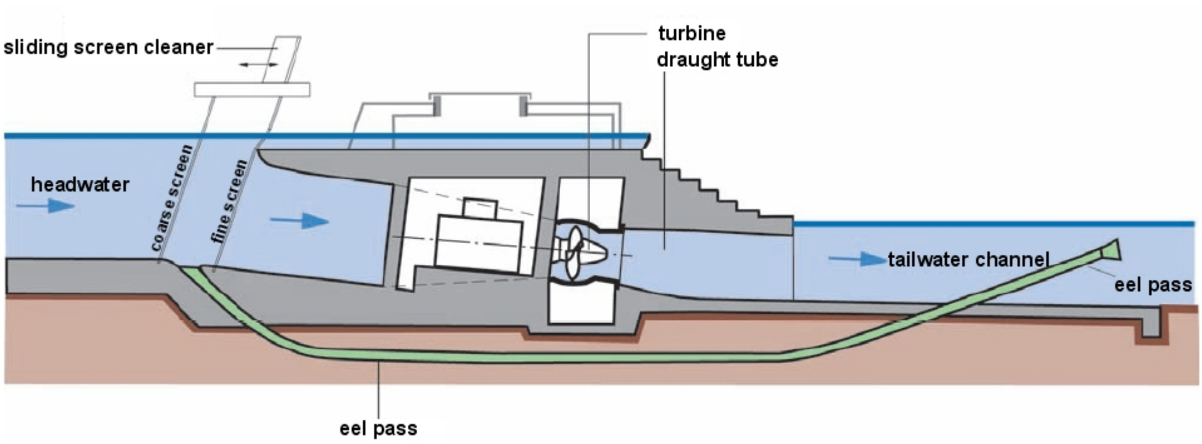
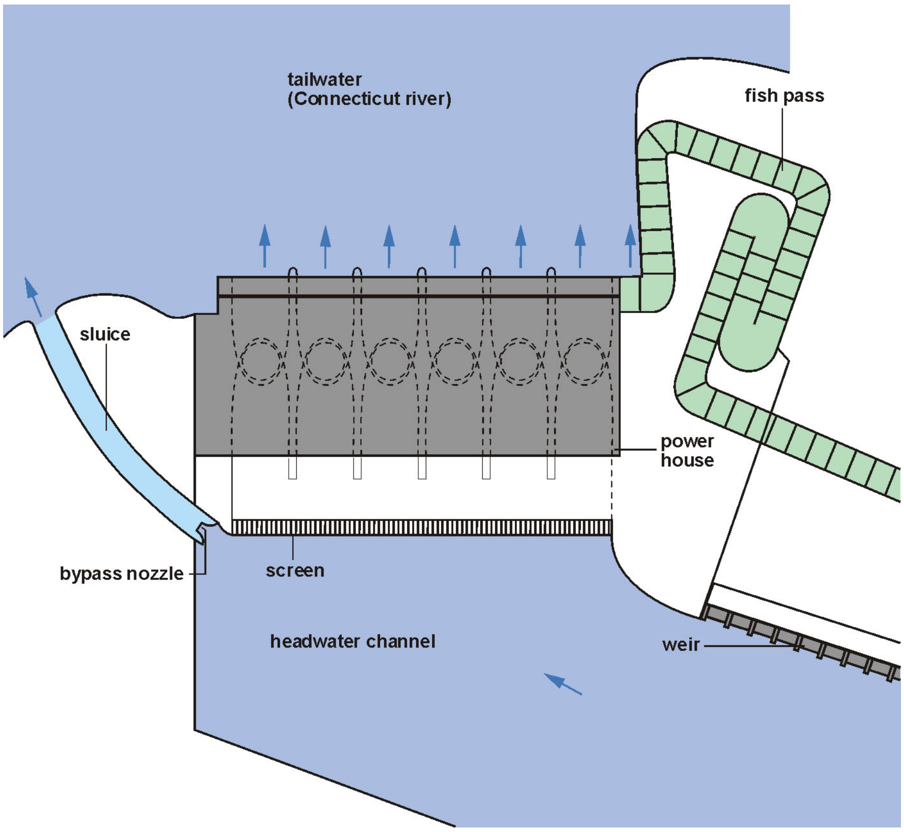


Figure 5.99: Eel bypass at the hydropower plant Hamm-Uentrop on the Lippe river (North Rhine Westphalia, Germany)

a)



b)

Figure 5.100: Hydropower plant Cabot Station on the Connecticut river (Massachusetts, USA):The flushing gate that serves as a bypass is arranged on the left beside the screen
a): plan of building and site
b): overview

Figure 5.101:
Detail of figure 5.100:Screen and flushing gate. The gate was immersed and illuminated in order to create a surface-near bypass opening (HARO, 2000)

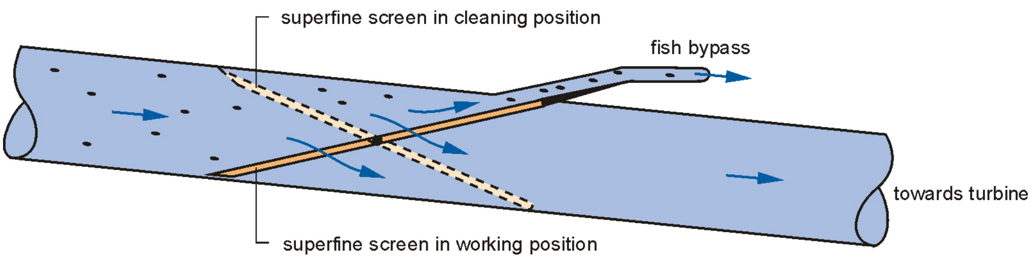


Figure 5.102: Schematic diagram of the Eicher-Screen

Figure 5.103:
Model of the Eicher-Screen for the Elwha Dam (figure 5.105); laboratory experiment by ALDEN RESEARCH LABORATORY INCORPORATION

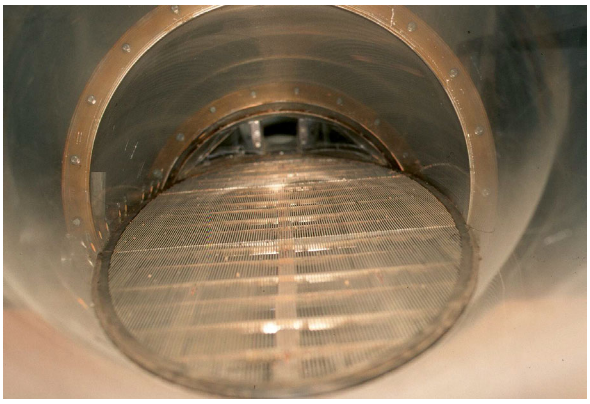


Figure 5.104:
Detail of figure 5.103: View of the Wedge-Wire-Screen inside the pressure pipe and the bypass conduit adjoining in flow direction

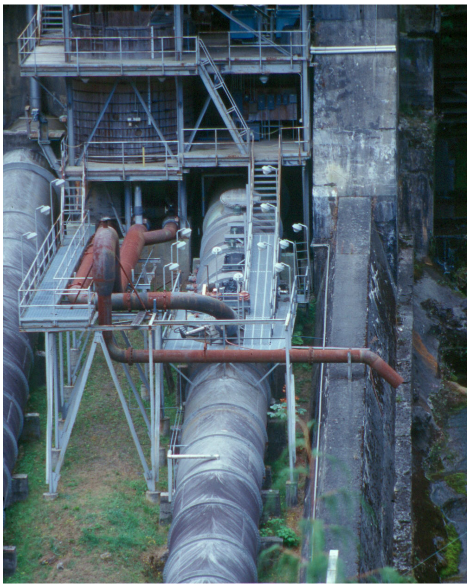


Figure 5.105:
Eicher-Screen at the Elwha Dam (Washington, USA): The Eicher-Screen has been experimentally installed in the pressure pipe that runs to the turbine. The bypass conduit leads to a tank where diverted fish will be checked

5.6.3.2 Modular-Inclined-Screen

The Modular-Inclined-Screen (MIS) can be seen as an advanced development of the Eicher-Screen. The rotatable Wedge-Wire-Screen in this case is installed in an intake structure with rectangular cross-section, of which the upper cover lies below the water level in order to produce a pressure flow in the area of the screen (figure 5.106). A coarse screen with a maximum clear bar spacing of 200 mm must always be connected in front of such installations. The MIS as well operates with high approach velocities of up to V_A = 3.0 m/s, so that fish will be drifted over the very flat screen installed at an inclination between 10° and 20° in the direction of the bypass which is arranged near the surface at the tailwater end.

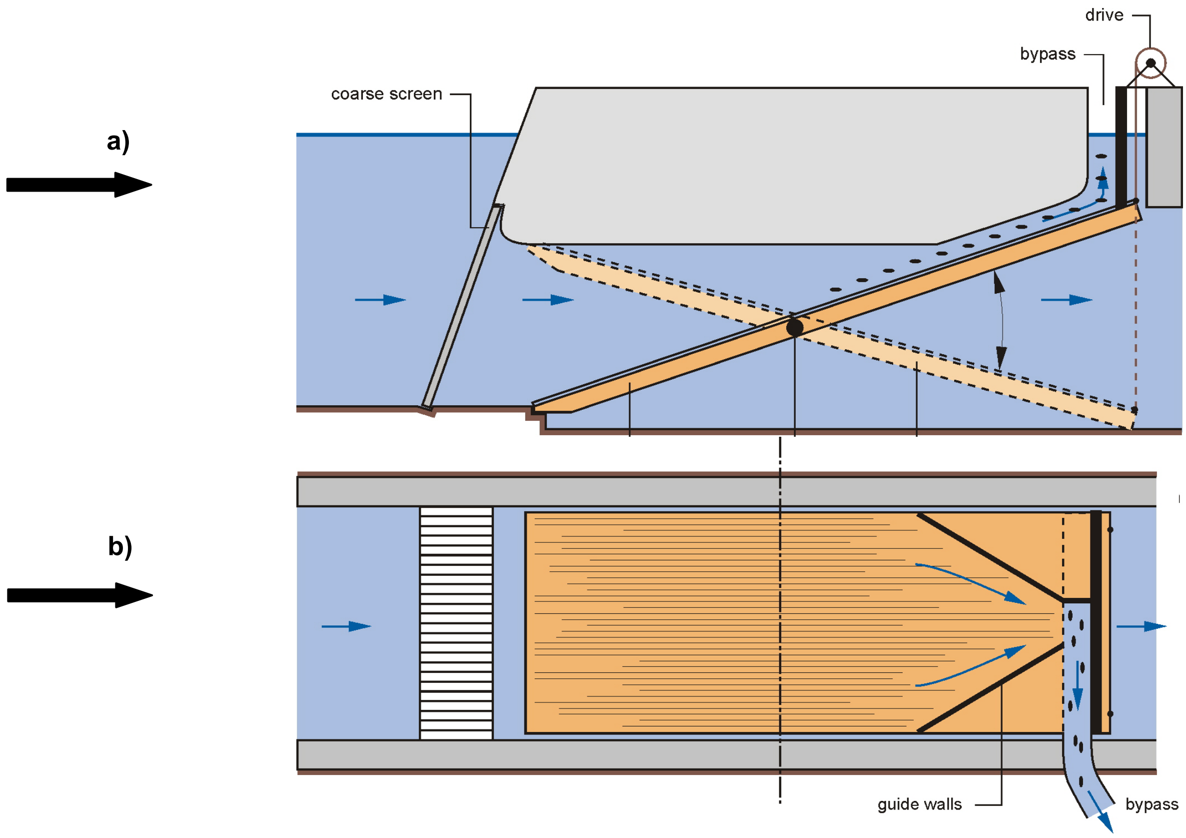


Figure 5.106:
Schematic diagram of the Modular-Inclined-Screen

a): cross-section **b): top view**

The MIS was developed by the ELECTRIC POWER RESEARCH INSTITUTE (EPRI) and examined under laboratory conditions but also in a pilot plant on the Hudson river for its effectiveness for potamodromous species and Pacific and Atlantic salmon smolts. Fish of a length of up to 10 cm only had been used in the laboratory (AMARAL et al., 1994). In this case, the survival rate of diverted fish at a clean screen amounted to 95 to 100 % for most tested species even if the approach velocity was 3.0 m/s. Unfortunately, so far there is no knowledge about the effectiveness of the MIS for larger and specifically European fish species available.

For the purpose of cleaning, the MIS is to be turned into the backwash position. The head loss at the screen depends on the hydraulic values of the construction and the actual status of clogging. The survival rate of diverted fish will be reduced in case of a greater head loss caused by clogging through leaves etc., as on the one hand the smooth surface will be covered and on the other side, the static pressure force will be increased. Hence, since concrete experiences are lacking, it is presently not possible to estimate the suitability of the MIS for European water bodies.

The costs for an MIS are estimated as very high: TAFT et al. (1997) state specific investment costs between 60,000 and 153,000 Euro for each m^3/s discharge. If the hydropower plant Wahnhausen on the Fulda river (Hesse, Germany) with a design flow of 60 m^3/s should be retrofitted, the roughly estimated costs would amount to 80,000 Euro per m^3/s (ARBEITSGEMEINSCHAFT GEWAESSER-SANIERUNG, 1998).

5.6.3.3 Flat screen with bypass channel

For decades flat screens have mainly been installed at small hydroelectric power plants. There are for example some historic screens (figure 5.107) in the river system of the Fulda river (Hesse, Germany), which successfully prevent the penetration of fish into the power plant or damage through being pressed against the screen because of their inclination of $\alpha < 45°$ and a clear bar spacing of the screen of $d < 20$ mm, although such construction has primarily been chosen for technical reasons (SCHWEVERS et al., 2001).

If such flat screens are overflowed and equipped with a bypass channel that runs parallel to the top edge of the screen, they can be used as a fish protection facility and also as a downstream fishway. Under such conditions they operate like the Eicher Screen (chapter 5.6.3.1) and Modular-Inclined-Screen (chapter 5.6.3.2). However, they cannot be cleaned through backwashing the tipped screen, but need conventional screen cleaning machines.

A precondition for the operatability of flat inclined screens is the installation of an impassable barrier with $P \leq 1$. The employment of such construction in the Allier river near Langeac (France) has proven less effective, as the majority of downstream migrating salmon smolts passed the 35 mm-screen instead of entering the bypass channel (figure 5.108). The use of an impassable barrier for eel is also an indispensable precondition for its operatability as this species of fish would otherwise squeeze actively between the screen bars (figure 5.26).

Within the framework of laboratory examinations (ADAM et al., 1999) it could be confirmed that impassable flat screens with $P < 1$ at an inclination of $\alpha < 45°$ can effectively be used as a fish protection facility. Whilst salmon smolts and potamodromous species however have avoided a collision, eel have not performed a avoidance reaction and thus collided with the screen. At least they were not pressed against the screen, but drifted with the sweeping velocity alongside the screen surface in the direction of the bypass. At approach velocities of $V_A < V_{sustained}$ they often turned by 180° and escaped upstream. If the approach velocity exceeded the capability of fish, they were passively drifted into the bypass channel.

Figure 5.107:
Flat screen of the Klostermuehle (mill) in the Solz river (Hesse, Germany) with an inclination of α < 45° and a clear width of 20 mm

Such flat screen with a traversing bypass channel was installed at the Floecks-muehle (mill) in the Nette river (Rhineland-Palatinate, Germany) in 2002. The screen of the power plant with a design flow of 1.7 m^3/s was replaced by a Wedge-Wire-Screen installed at an angle of α = 24° and a clear width of d = 5 mm (figure 5.109).

In January 2003, 98 eel of a length between 0.50 to 0.85 m were inserted in the headwater channel of the installation (ADAM & SCHWEVERS, 2003). 18 specimens or 18 % of the total migrated within 48 hours and it was possible to observe some directly at the screen, where the same reactions were performed as in the model channel:

- A portion of the eel performed a 180°-turn and escaped into the headwater (figure 5.11).
- Other specimens drifted with the transportation component of the approach flow alongside the screen or moved actively in wriggling motions on the screen surface, passed the top edge of the screen and then reached the bypass channel (figure 5.110).

The downstream migration was interrupted on the 3rd day of the examination because the temperatures had dropped below 4 °C, so that during the course of 14 days only one further individual eel could be recorded. All specimens that migrated downstream were caught in a container at the end of the bypass channel and no visible external injuries could be defined.

These experiments prove that it is possible to guide even bottom-orientated eel by means of a flat screen to a bypass located at the surface of the water body. The efficacy will be supported by approach velocities of $V_A > V_{sustained}$, because downstream migrating fish will inevitably be drifted. A precondition for the prevention of injuries in this connection is a smooth as possible screen surface like that of the Wedge-Wire-Screen.

The installation of such downstream fishways involves higher structural requirements in comparison to conventional screens. Screen losses are relatively low because of the flat inclination of the screen of 24°. However, the cleaning requirements are remarkably higher, which is not to be referred to the construction principle but to the small clear width.

Figure 5.108:
Flat screen with a traversing bypass channel at a hydropower plant in the Allier river near Langeac (France), which has proven less effective because of a too large clear width

Figure 5.109:
A Wedge-Wire-Screen installed at an angle of α = 24° with a clear width of d = 5 mm and a traversing bypass channel at the Floecks-muehle (mill) in the Nette river (Rhineland Palatinate, Germany)

5.6.3.4 Overflow weir with screen

For special applications where only a part of the discharge will be released and a certain head loss tolerated, for example at installations where water is discharged for irrigation purposes, the use of a Wedge-Wire-Screen seems suitable, which will be integrated in a curved way in the surface of an overflow weir (BUELL, 1996). This construction type is similar to the Tyrolean Weir (figure 6.8) known from the Alpine region, which is designed for the withdrawal of water from rivers carrying heavy bed loads. The essential difference to the Tyrolean Weir is that the course of the curve of the screen surface is hydraulically designed in such a way that not only the self-cleaning of the screen is possible at any time, but moreover a harmless diversion of fish. In this case, the discharge must not completely be released through the screen, as the fish will remain in the discharge portion which has not been released. The pressure conditions on the back of the weir or on the screen surface can be adjusted by varying the profile opposite the crest profile of a free, aired nappe (figure 5.111, figure 5.112).

The water will be withdrawn through a channel which is arranged inside the weir body below the screen surface diagonally to the current of the water body. This channel can be equipped with a flow restrictor, so that the withdrawal volume or the discharge taken from the water body can be adjusted.

Figure 5.110:
Eel which are passing the top edge of the flat screen at the Floecksmuehle (mill) in the Nette river (Rhineland-Palatinate) and then reach the traversing bypass channel

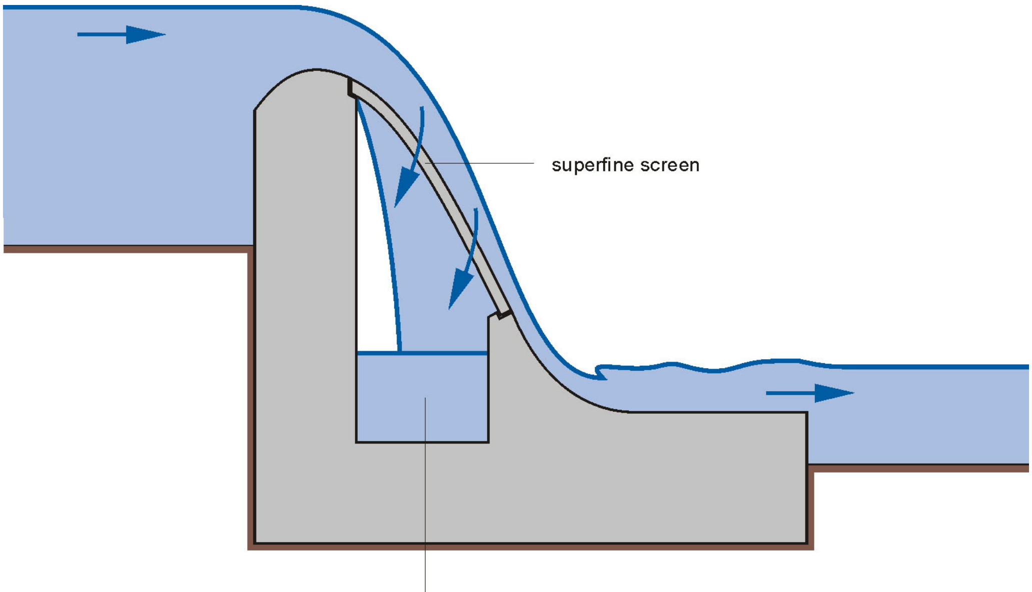


Figure 5.111: Schematic diagram of an overflow weir with integrated screen

Figure 5.112:
Overflow weir with integrated Wedge-Wire-Screen at an intake for an irrigation channel (Oregon, USA)

- At the hydropower plant in Buende-Kirchlengern on the Else river (North Rhine Westphalia, Germany), built in 1992, 4 pipes of a diameter of 200 mm each were installed in the area of the base plate in front of the 20 mm-screen. These pipes run into a collection pipe of a diameter of 250 mm which is led through below the turbine. This eel bypass runs into the tailwater after approx. 70 m. The pipes are admitted with approx. 0.2 m^3/s at a design flow of the power plant of 5.5 m^3/s. The fish population of the Else river is dominated by roach and gudgeon, followed by eel. During examinations of downstream movements between May and December 1997 a total of 249 fish was registered which had used the eelway for downstream migration. With 149 specimens the eel was the dominating species, followed by 44 gudgeon. The evidence of all 16 species that populate the river could at least be detected in the bypass as individual specimen (BARTMANN & SPAEH, 1998).
- At the hydropower plant in the Emmer Dam (North Rhine Westphalia), built in 1997, a so-called eel slide with bypass conduit was installed: In front of the 20 mm-screen there is an approximately 1.0 m wide and 0.1 m high feeding hopper at the bottom of the turbine channel which reduces towards the tailwater in a bypass pipe of 200 mm diameter. The bypass will be admitted with approximately 0.2 m^3/s when the increased discharge is 5.5 m^3/s. The flow velocity in the bypass pipe is approximately 2.0 m/s, and thus distinctly higher than the flow in the turbine channel. The eel population in the water body is rated "*very high*". During effectiveness inspections from mid August to Mid November, 1997, a total of 1,235 fish were registered, of which were 1,155 roach and 27 eel (BARTMANN & SPAEH, 1998).
- At the power plant Dringenauer Muehle on the Emmer river (Lower Saxony, Germany), built in 1991, with a design flow of 8.3 m^3/s, there is a 0.5 m wide and 0.15 m deep channel with six access openings in front of the shutter weir and runs over the entire width of the turbine inflow into a 250 mm-PVC-pipe. The pipe is led through under the power plant and ends in the tailwater. Examinations which were carried out in 1992 have shown that the highest damage rates among downstream migrating eel were caused by the 20 mm-screen or the screen cleaning machine (RATHCKE, 1994). In consequence thereof, a so-called escape pipe was installed in addition to the existing eel bypass which should offer a downstream migration possibility into the sluice to eel swimming in front of the screen. The diameter of the escape pipe is 300 mm. It opens in the wall of the turbine inflow 1.0 m in front of the screen and 1.0 m below water level, at approximately 1.5 m above ground. The maximum admission is 400 l/s. In autumn 1996 a total of 961 fish of 18 different species was recorded over 39 days when the maximum downstream migration was suggested. 724 specimens of the fish counted were roach and 102 eel, of which 64 were found in the escape pipe, 21 in the eel bypass, 10 in the fish pass and 7 among the screenings (RATHCKE, 1997).
- The catches of eel at the weir Dorlar on the Lahn river can be taken for comparison, although this corridor does not serve for the downstream migration of eel but for fishing. Two mills are operated at this location where the mean discharge is 22.5 m^3/s. The increased discharge of the mill on the right hand bank is 5.0 m^3/s. Here, a sluice is installed approximately 2.0 m in front of the screen, and an eel-catch is positioned behind (figure 5.98). When opening the sluice, a bottom-near gap is created which is admitted with approximately 0.2 m^3/s. In 1999 examinations were carried out over 204 days and produced a catch of 1,386 eel in the eel-catch.
- The hydropower-plant Hamm-Uentrop (North Rhine Westphalia, Germany) with a design flow of 21.0 m^3/s was equipped with an eel bypass (figure 5.99). For this purpose, 5 slots were inserted in the base plate of the inlet channel between the coarse screen with a clear spacing of 80 mm and

the fine screen with a clear spacing of 20 mm. The stainless steel pipes DN 100 were arranged in a fan shape and about 1.50 m below the concrete plate of the generator they run into an especially made joining structure of stainless steel. By using stainless steel, sharp edges and surface roughness were avoided to a large extent which could cause damage to fish during their bypass passage. A cast iron pipe DN 250 is connected to the joining structure and led into the tailwater of the power plant. The discharge of the system is approximately 100 l/s. In autumn 1999 an examination was carried out on eel which migrated downstream through the eel-pipe. 1,456 fish were counted in the eel-pipe over 77 days, of which 1,348 were eel. The examinations were repeated over 64 days in autumn 2000. At this time 348 fish had used this downstream fishway, of which 246 were eel (SPAEH, 2001b).

5.7 Fish transportation systems

If the continuity of rivers is not guaranteed then sometimes compensatory measures are taken, which means that fish willing to migrate either upstream or downstream will be caught at obstacles and then transported to a point where a harmless continuation of their migration is possible. Transportation possibilities which aim at the protection of downstream migrating fish can especially be found in rivers which are multiply impounded. In order to justify the costs for catching and transporting fish, such measures generally focus on the protection of target species of great importance to the fishing industry or those which are at high risk

In North America such measures concentrate on catching downstream migrating salmonide smolts of Pacific species and also Atlantic salmon. These activities are called “Trap and Truck”.

Example Columbia river

The example of a “trap and truck-system” most renowned exists at the Columbia river (Washington State and Oregon, USA). Despite comprehensive efforts on safeguarding the downstream migration of fish, a continuous reduction of the population in the entire river system was to be noticed and was caused by an increased storage level regulation (RAYMOND, 1979). Therefore, attempts were made to reduce this loss in population by means of a targeted trap and truck-system, which has recently been completed with a fish-friendly turbine management during main downstream migration periods. A preparatory test to catch fish at the Ice Harbour Dam could prove that large quantities of fish can be trapped within a short time and no damage worth mentioning occurred (PARK & FARR, 1972). Since then juvenile salmonids are being caught at the top weir of the Columbia river, the Little Goose Dam, and then released below the bottom weir, the Bonneville Dam. These fish are hereby saved the passage of a total of 8 weirs with hydropower utilization. The means of transportation originally used was a tanker. However, as it was feared that such transportation method could have a negative impact on the orientation of fish during their later upstream migration, as fish in a tanker would not be able to develop a downstream running smell gradient, the smolts were therefore transported by boat. During the transportation by boat, the water will continuously be exchanged with river water, so that the chemical gradient can be perceived by fish. Tests with fish which had been marked resulted in a return rate of transported fish that was 15 times greater than of those species which had migrated downstream independently (EBEL, 1980).

Example Garonne river

A “trap and truck-system” is also in operation for salmon at the Garonne river (France) since 1999 (figure 5.113). The salmon had become extinct in this river system, as the spawning areas in the upper reaches were no longer reachable because of numerous impassable weirs. 15 of these migration obstacles are concentrated over 60 km in the middle reaches of the river, whilst the lower reach of 230 km of the river is only interrupted by two weirs, the Le Bazacle near Toulouse and Golfech near Agen. Plans exist to restore the upstream and downstream continuity of the river system until 2045. In order to re-establish a salmon population in this river system within a short period, which also was needed for verifying the efficiency of fish protection facilities, upstream fish passes and downstream fishways which gradually had to be erected, a transportation system was installed consisting of the following components:

- Juvenile salmon are inserted into suitable sections of the upper reach of the Garonne river and its tributaries.
- The top two hydropower plants of the weirs in the middle reach, Pointis and Camon, are equipped with a bypass (figure 5.114) and a trapping system connected behind (figure 5.115). In this case,

the bypass water is led to a Tyrolean weir (figure 5.116), where a receiving channel is located at the downstream end through which fish drifting with the water flow will enter a holding pool. The effectiveness of the trap system rates between 70 and 80 % each, so that by combination of these two installations more than 90 % of all downstream migrating smolts will be caught.

- The smolts will be transported by truck about 200 km upstream and released in the tailwater of the bottom weir in Golfech.
- Spawning fish that migrate upstream will be dealt with in reverse order. These will be caught after having passed the fish passes Golfech and Le Bazacle at the bottom weir in Carbonne, and then transported by truck to be released in the upper reach. The new construction of another trapping station meanwhile allows trapping upstream migrating salmon already at the bottom weir in Golfech.

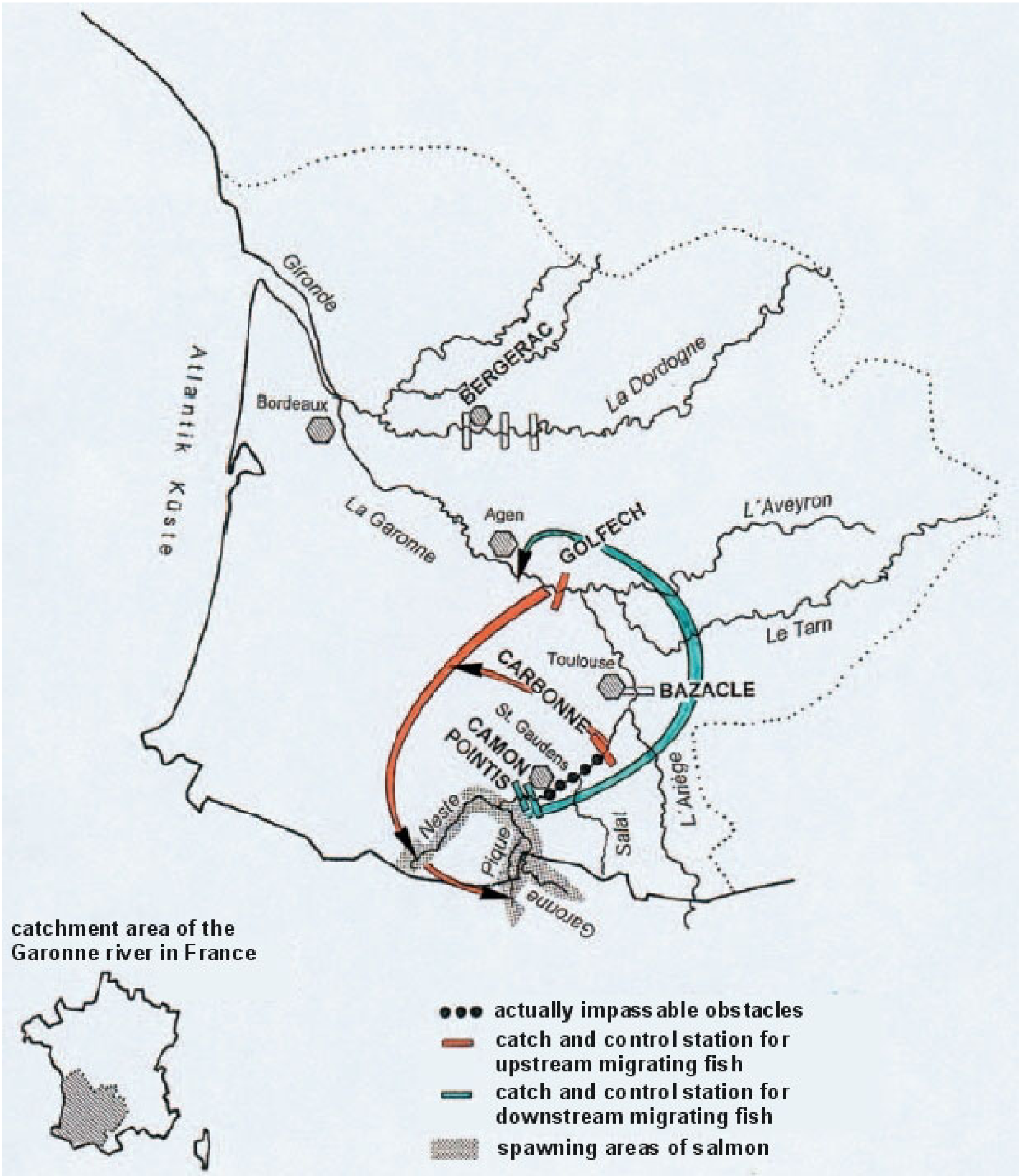


Figure 5.113: Trap & Truck in the Garonne river system (France). Spawning and maturing biotopes of salmon are indicated in grids. Downstream migrating smolts will be caught at the weirs Pointis and Camon, then transported downstream and released in the tailwater of the weir Golfech (blue arrow). Upstream migrating spawning specimens will be caught either at the weir Golfech or Carbonne and transported in reverse direction into the upper reaches (red arrow), where they will be released (changed according to MIGADO, 2003)

Figure 5.114:
Bypass at the side of the screen of the hydropower plant Camon (Garonne / France)

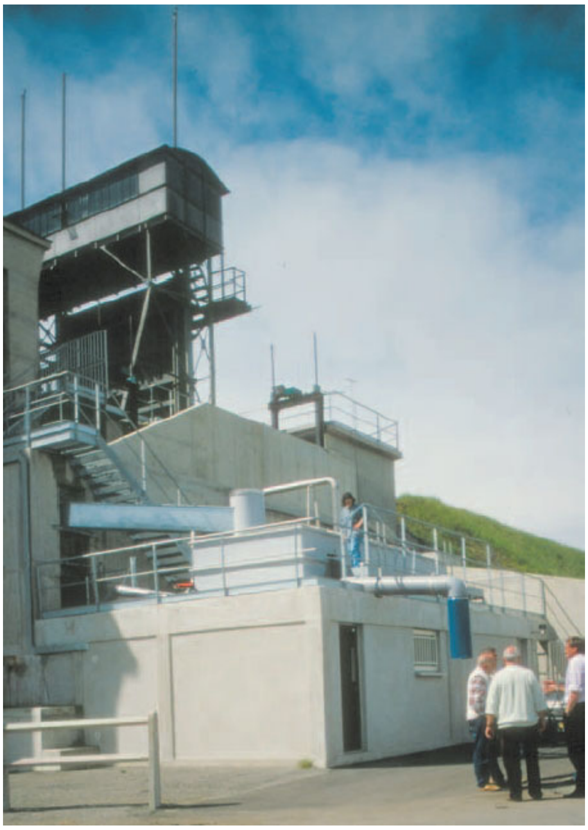


Figure 5.115:
Total view of the trapping system for downstream mi-grating smolts at the weir Pointis (Garonne / France)

Figure 5.116: Detail of figure 5.115: The bypass water is led to a Tyrolean weir, where a by-pass channel is installed at the downstream end, which receives fish and guides them into a holding pool.

By means of this method, 10,000 to 14,000 downstream migrating fish are caught per annum, of which 83 % are salmon smolts, which will be transported downstream. The number of spawning specimens in the Garonne river could be increased from about 100 to more than 500 specimens since this system was taken in operation (MIGADO, 2003).

Figure 5.117:
By means of this truck smolts will be transported 200 km down-stream to Golfech (Garonne / France) and released into the tailwater of the bottom weir

Example Moselle river

Since there are no downstream fishways provided at the hydropower plants on the Moselle river, there is a regular occurrence of damage to eel caused by turbines, which volume was no longer tolerable from economical and ecological views. The AALSCHUTZINITIATIVE RHEINLANDPFALZ / RWE POWER AG, therefore has mandated professional fishermen to catch silver eel during the autumn migration period from September to November in front of 10 hydropower plants in North Rhine Westphalia (Germany) designed for a discharge of 400 m^3/s: The catch of eel will be kept in a fish-friendly way and once a week transported by a fish transportation vehicle to the Rhine river near Linz where they will be released. The results of this fish transportation system have been compiled in table 5.24.

Table 5.24: Amount of silver eel caught annually in fyke nets in front of the 10 Moselle power plants in North Rhine Westphalia (Germany)

year	catch [kg]
1997	1,500
1998	1,932
1999	3,418
2000	4,600
2001	6,000
2002	4,735

5.8 Fish orientated installation management

5.8.1 Technical possibilities

The term *installation management with the aim to prevent fish damage* is to be understood as an operation mode of hydropower plants, intake structures and weirs, which on the one hand is influenced by the discharge and on the other hand by the migratory activities of target species (chapter 2, figure 2.10). Such adjusted operation of hydraulic installations is mainly applied to protect diadromous species, as their downstream migration period is very tight. Since eel and salmon for example, always migrate with rising discharges, these biological phenomena can be harmonized and optimized by technical correlations.

Examinations of BERG (1985) and HOLZNER (1999) at hydropower plants with Kaplan turbines have led to the conclusion that there is a direct correlation between the aperture angle of the runner blades or the wicket gate and the mortality rate of eel. This fact offers a possibility to reduce the damage rate for eel at a high turbine flow-through and large aperture angles. Additionally, nature observations have proven that the main migratory activities of eel take place during night hours.

Basically, any intake structure or hydropower plant can be operated according to the rules of a fish-friendly installation management. The following strategies are generally feasible for this purpose:

- reduction of flow rate in order to reduce the approach velocity in front of a screen
- optimization of the aperture angle of blades to facilitate a harmless fish passage
- putting some machines out of operation temporarily and opening the weir deliberately to create migration corridors which are free from danger
- putting the entire installation out of operation temporarily

When neglecting the desired achievement of a technically optimal efficiency, at discharges below the design flow it is generally feasible to adjust the turbines of a hydropower plant in such a way that a maximum possible opening will be created between the guide vanes and the runner blades, where applicable.

As such a setting implies that a greater water volume will pass through a machine, and the distribution of water to the other turbines will have changed, especially at installations which comprise several machines it must be examined whether one of the only partially admitted machines can be abandoned. The corresponding discharge which cannot be utilized for the generation of energy can then be used as a migration corridor in the sense of a bypass or supplied to the weir. However, despite the changed settings of guide vanes and runner blades and the consequently altered turbine flow-through it must further be guaranteed that the standard target impoundment tolerances will be kept. The existing wicket gates of power plant and weir must normally be re-aligned for this purpose.

Large hydropower plants are basically designed for a maximum flow period of 80 to 120 days. This means that within this time frame the design flow of the hydropower plant will be obtained or even exceeded. During this period it is not possible to influence the discharge by changing the settings of the guide blade or runner blade in order to optimize the passage for fish, since the turbines are already adjusted to the maximum discharge. Any excess portion of the design flow in these cases will be guided over the weir. If the flow rates are greater it may be required to switch off hydropower plants in dependence of their head, so that the entire water volume will flow over the weir.

Besides this method of a fish-friendly installation management which is favourable for the generation of energy, it may also be possible to purposively drain water over a weir or bypass system. A precondition for such discharge however, is the adjustability of the water flow in order to guarantee that the standard target impoundment will be kept, which is especially essential for navigable rivers. Furthermore, however, the generation of positive surge and waves of the negative surge should be avoided for ecological reasons also in rivers which are not navigable.

The extreme form of a fish-orientated installation management is the temporary stoppage of the entire water intake or hydropower plant and diversion of the entire water flow over the weir.

As all these measures partially involve a considerable loss of energy, the application period should be kept as short as possible. The key question in the area of a fish-friendly installation management, however, does not lie in the handling of the installation technique or discharge regulation, but in the definition of the beginning and the end of migratory activities of the target species. The willingness of the installation operator to reduce or even disclaim the generation of energy can only be possible where the periods and timing of the main migratory activities of the target species has been defined correctly and precisely and so facilitates a calculation of the energy loss. This is the only way to assess the economical impact of fish-orientated measures.

The advantage of this installation management in comparison to any other procedure concerned with fish protection and downstream fishways lies in low investments and operating costs as well as its quick realization. The costs involved with the energy loss however, may be considerably high. An appropriate analysis of the economical side will have to see into investments, operating costs and costs for energy losses by considering the efficiency of such measures in comparison with the costs for other procedures.

5.8.2 Early warning systems

General statements that eel migrate downstream during night hours of the autumn months are not suitable as a basis for a fish-orientated installation management, since the period described comprises several months. In order to define the migration periods of target species more accurately, it is necessary to develop reliable early warning systems or methods that allow the recognition of downstream migrations of fish.

5.8.2.1 Abiotic early warning systems

Abiotic early warning systems on the one hand are based on the mathematic correlation between meteorological / hydrological parameters, and on the other hand on information about the migratory activities of the target species concerned. For Pacific migratory salmonids such models have been developed and tested in the Columbia river (USA), which are based on a correlation between increased discharges in spring time and the downstream migration of smolts. The forecast accuracy achieved by this approach was between 39 % and 90 %. An appropriate correlation exists also for smolts of the Atlantic salmon (SCHWEVERS, 1999).

Although during such examinations only one parameter was correlated to the downstream migration event, it is quite normal that a combination of several factors can influence the downstream migration happening (chapter 2.4), which very much complicates the development of abiotic early warning systems. As a rule, the temperature of water and air, the conducting capacity, the turbidity of water, flow velocity, flow-through, content of oxygen, the moon phase and lightness are to be recorded. The provision of such information causes great difficulties, as a synchronous measuring system is essential for an analysis of the data recorded. However, the assessment of single effects is very difficult, since the facts may be restricted to a certain space and play a secondary role. In this connection, it should be mentioned how difficult it is to measure the oxygen content in wide rivers: selective measurements do not allow statements on the distribution of oxygen in the water body.

It is to be hoped that the accuracy of the early warning system can be enhanced, for example by means of Fuzzy-Logic-Models. The result of research work carried out in this respect is that an advanced recognition of the main migratory activities of eel is almost impossible (OBERWAHREN-BROCK, 1998), as rising discharges will not automatically release greater migratory activities, even if the phase of the moon is most favourable at that time. Analyses of catches made by professional fishermen on the Moselle river (Rhineland-Palatinate, Germany) did not lead to a specific correlation between discharge, moon phase and catch, not even under very similar preconditions. Therefore, for the time being it seems questionable that a reliable prognostication of the downstream migration of eel can be made on the basis of abiotic parameters.

5.8.2.2 Technical early warning systems

Technical early warning systems serve for the immediate recognition of fish migration by using detectors, of which the range of application seems to be limited so far:

- Underwater cameras for visual monitoring:Their application possibility is substantially influenced by the turbidity of water and the conditions of light.
- Echo sounding systems or hydrophones by which changes of the density are recorded:The identification of different species and the differentiation between fish, flotsam and bed loads still creates a problem. Additionally, when recognizing fish near the bottom and in the upper approximately 4 m of the water body, they may appear blurred as a result from the duration of the pulses transmitted and the sound velocity. These facts limit the range of the devices (MATTUKAT, 1999; SCHMIDT et al., 2004).

Telemetric markings are normally unsuitable for the recording of migratory activities of target species, as they only refer to the behaviour of single specimens. Furthermore, it is difficult and personnel-intensive to trace marked specimens (BEHRMANN-GODEL, 2000).

5.8.2.3 Biological early warning systems

Biological early warning systems are based on the assumption that specimens which are kept in a holding pool will show the same behavioural patterns as independent members of the same species (LOWE, 1952; BOETIUS, 1967). The early warning system MIGROMAT® (figure 5.118) therefore, is founded on the fact that eel kept in a holding pool will perform a pre-migratory restlessness prior to the actual migration happening. In order to monitor the activity of fish, they will be marked with micro-transponders and their position inside the two long-size-pools of the MIGROMAT® automatically recorded by the antennas (chapter 6.2.1.6). As the holding pool is admitted with water from the corresponding water body via pumps, the flow in which the fish are kept remains constant. Since 1997, several MIGROMAT®-systems have been installed for exploratory operations at the location Dorlar on the Lahn river (Hesse, Germany) as well as at the hydropower plants Linne and Lith on the Maas river (The Netherlands) and the hydropower plant Wahnhausen on the Fulda river (Hesse, Germany) in order to verify the general capability of this early warning system (ADAM, 2000, 2004). For this purpose, each of the locations has been chosen to facilitate by means of accompanying monitor inspections an alignment with information about migrations actually taking place in the water body. The methods concerned are listed in table 5.25.

Figure 5.118:
MIGROMAT® on the bank of the Maas river in Alphen (The Netherlands)

By means of this method it was confirmed at all four locations that eel being kept in holding pools have very reliably performed increased activities always at the time when downstream migration happenings of eel took place in the water body. Figure 5.119 gives an example of such correlation. Figure 5.120 shows results of the reliability of forecasts. A trial operation over the years 1999 to 2002 has proven that 50 % of the cases have shown accordance between the rise of activity and the evidence of an actual outdoor downstream migration happening of eel. Alarm messages without proof of a downstream migration however, occur almost just as often. They are partly to be referred to natural activity variations of eel, but partly also to data gaps in monitoring. On the other hand, downstream migration happenings in the water body which were not registered by the MIGROMAT®-system were rare exceptions. A quantification of downstream migrating eel in the Maas river has shown that 66 % of eel at the location Linne and 73 % at the location Alphen have migrated at days which had been prognosticated by the MIGROMATs® (BRUIJS et al., 2003).

Considering these positive results of the trial phase, the hydropower plant Wahnhausen on the Fulda river (Hesse, Germany) since 2003 is partly run in an eel-orientated operating mode on the basis of downstream migration periods prognosticated by a MIGROMAT®.

- The activity of eel kept in a holding pool is recorded continuously and assessed via different algorithms. In the case that certain threshold values are exceeded, this will automatically emit an alarm sent by Email to the control centre of the power plant operator.
- In consequence thereof the power plant will be throttled down to a maximum approach velocity of 0.5 m/s, so that damage to downstream migrating eel through being pressed against the screen will be prevented.
- The remaining water will be discharged via the turbine intake to the neighbouring weir field, in order to offer a migration corridor to eel.

During the downstream migration season 2003/04 the MIGROMAT® has released a total of 21 alarm messages. The assessment algorithms were very sensitively adjusted so that all migration waves could reliably be recorded. Two main migration waves took place during this period, one in the night of 14 December, 2003 and another between 14 and 17 January, 2004. The consequence of this sensitive adjustment was, however, that the power plant was operated in an eel-orientated mode over 12 nights, although the synchronously running monitoring had not recorded any downstream migration of eel. The objective for a further development of the MIGROMAT® therefore is that eel-orientated operating modes must be restricted to a realistically required extent by not impairing the protective effect of the procedure (ADAM, 2004).

Table 5.25: Methods employed for verifying the reliability of the MIGROMAT® (ADAM, 2004)

year	location	river	monitoring method	extent / quality of data
1999/2000 2000 2001/2002	Amends-Muehle (mill) Dorlar	Lahn	stationary fishing of eel	permanent until 24 December each year; gaps of data in case of illness of operator
2001	hydropower plant Linne	Maas	catches of professional fishermen on the Maas	irregular fishing activity and recording, emptying of fyke nets and fish traps by rotation over several days
2002/2003			marking of silver eel with NEDAP-transponder to trace their downstream migration in the Maas river and in the North Sea	permanent monitoring, gaps of data because of technical failures of antennae system
			control of turbine outlet by means of fish traps	episodic examination in 2002
2001	hydropower plant Alphen	Maas	professional fishermen	irregular fishing activity and -recording, emptying of fyke nets and fish traps by rotation over several days
2002/2003			NEDAP-transponder	permanent monitoring, gaps of data because of technical failures of the antennae system
2002/2003	hydropower plant Wahn-hausen	Fulda	stationary fishing of eel	regular emptying by operator, technically conditioned gaps of data, caused especially by high discharges
2003/2004			control of screenings	permanent

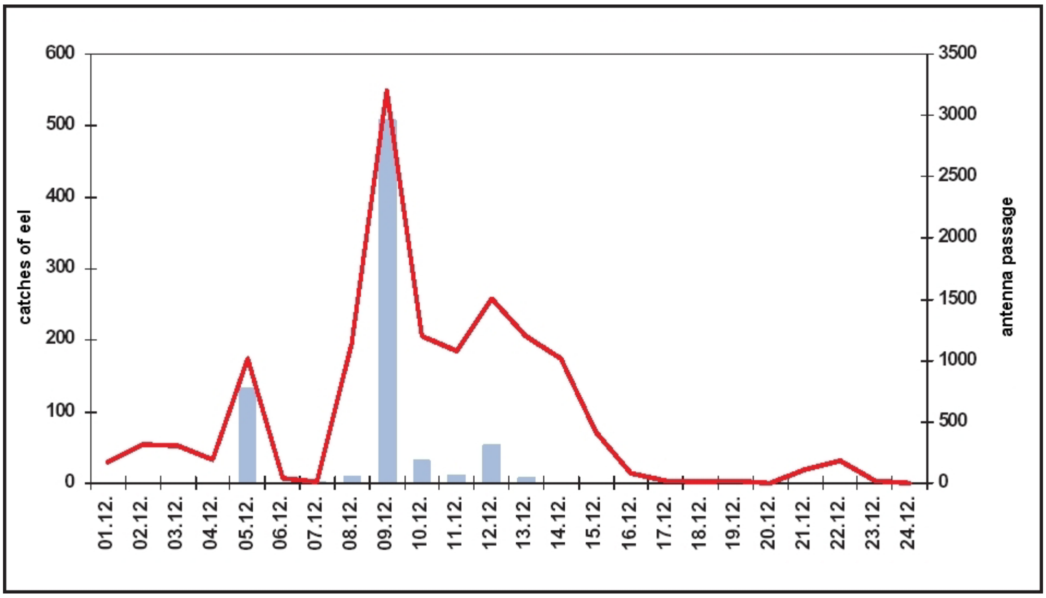


Figure 5.119: Correlation between the activity of eel in the MIGROMAT® and the migration happening in the river recorded by means of a catch of eel during the two main downstream migration waves on 05 and 09 December, 1999 at Dorlar on the Lahn river(line = activity of eel kept in holding pool, columns = evidence through catch of eel)

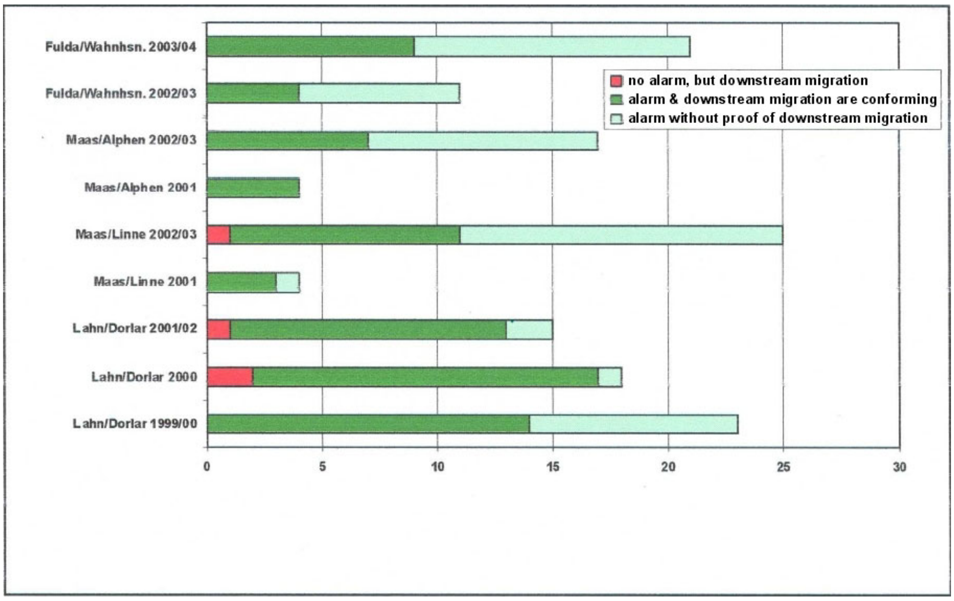


Figure 5.120: Reliability of MIGROMAT® so far achieved

5.9 Fish-friendly turbines

The problem of fish being damaged through turbines has often and in detail been examined (chapter 4.3). Next to mathematic procedures which are based on technical parameters and used for prognosticating the extent of damage or survival rates of fish (RABEN, 1957a, 1957b; TRAVADE & LARINIER, 1992), outdoor examinations at many different types of hydropower plants and turbines prove that fish become damaged during their passage of turbines (MONTÈN, 1985: TRAVADE et al., 1989; HOLZNER, 1999). The damage rates vary in dependence on the construction of the turbine. Consequently, it is possible to reduce damage to downstream migrating fish by choosing the appropriate turbine type for new constructions of hydropower plants. Specifically in the range of small hydroelectric power plants it is feasible to employ water wheels or Archimedean screws instead of turbines. Their efficiency is not substantially lower than that of a Kaplan turbine for example, but the damage rate may be remarkably less.

The above mentioned examinations of fish damage caused by turbines also show that damage in low-pressure installations is primarily caused by the impingement of fish on the entering edge of the runner and the shear velocities created in gaps. Before this background, research and development of constructions of fish-friendly turbines are an important approach where ichthyo-biologists, manufacturers of turbines and operators cooperate.

However, there is little room for constructive changes of turbines with the objective of reducing the mortality rate of fish, as the modern types of runners achieve a maximum efficiency and any change would result in a loss of energy. Despite this fact, there are chances for modifications depending on the cause of fish damage, whereby the choice of using an improved construction type for fish protection is subject to the specific conditions of the location concerned.

Essential for the development of fish-friendly turbines is that knowledge is available as precise as possible about the impacts machines have on fish during their passage, also about the flow conditions of the flow-through of the power plant and in the turbine.

Interpretations of theoretical contemplations, scientific basic research and hydraulic studies lead to the conclusion that the following design, hydraulic and operational requirements must be fulfilled in order to reduce the risk of injuries for fish in turbine passage (CADA et al., 1997; FRANKE et al., 1997; ERZINGER, 1999):

- Decreasing the number of runner blades and thus front edges of blades, in order to reduce the likeliness of a contact.
- Enlarging the distances between the blades and other structures in order to create zones which are as wide as possible.
- Blunting the front edge of blades, in order to reduce injuries which might be caused by sharp edges.
- Decreasing the rotating speed of the runner by reducing the rotary frequency of the turbine, in order to diminish the collision speed and thus the rate of injuries.

- Developing turbines where fish in their passage will be directed away from the periphery of the runner and towards the turbine shaft, as a contact with the blade near the shaft imposes a lower risk of injury than a contact with the blade point because of the low running speed.
- Minimizing the clearances between blade and runner hub as well as between fixed and movable parts.
- Smoothing surfaces of hydraulic contours, e.g. tie-bar, guide vanes and draught tube, in order to avoid grazing and cuts.
- Optimizing the operation of the turbine, in order to select the optimum settings that provide best survival chances for fish.
- Employment of blade designs which are hydraulically more favourable for the prevention of cavitation, so that damage through implosion can be avoided.

5.9.1 Fish-friendly optimization of conventional turbine types

Based on these considerations the “Advanced Hydropower Turbine Systems Program” was mandated by the American US DEPARTMENT OF ENERGY in the 1990s with the aim to develop fish-friendly turbines. The efforts put into a fish-friendly optimization of turbines according to CADA (1998) and SCHILLING et al. (2000) focussed on the following:

- Restricted lowering of pressure inside the turbine.
- Avoidance of cavitation effects.
- Minimizing shearing effects and turbulent flows.
- Reduction and minimization of clearances.

Within the frame of this large-scale project the American-German group VOITH HYDRO and SIEMENS modified the construction principle of the conventional Kaplan turbine. The primary concern was to eliminate or minimize any gap in the area of hub, blade and runner casing by optimizing the geometry of the turbine (figure 5.121). This type of turbine in America is called “Minimal Gap Runner” (MG-Runner), and in Germany at present “fish-friendly turbine”. Examinations of the efficiency of the MG-Runner are available from the Bonneville Dam at the Columbia river (Oregon, USA) (FISHER et al., 2000), according to which less damage to fish occurs if this type of turbine runs about 1 % below full load, i.e. underneath the operating point of best efficiency. However, this operating mode incurs energetic losses.

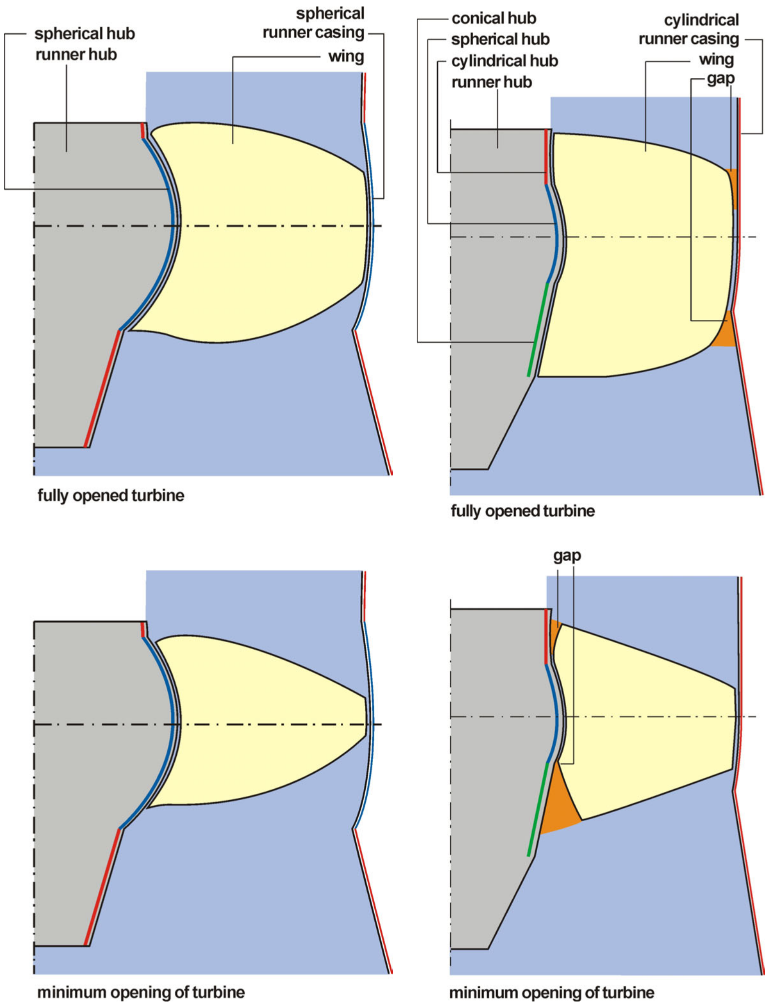


Figure 5.121:
Comparison between a conventional runner on the left hand side and an MG-Runner on the right hand side: The gaps will be minimized by aligning the geometry of the turbine, e.g. a ball-shaped hub and an expanded profile ring

5.9.2 Development of new fish-friendly turbines

The development of the spiral runner by the working group of ALDEN RESEARCH LABORATORY INCORPORATION and the NORTHERN RESEARCH AND ENGINEERING CORPORATION (COOK et al., 1997) was also initiated by the American large-scale project. This entirely new type of turbine consists of a runner with only two blades which are several times longer than wide and spiralled inside (figure 5.122). The substantially greater axial extension of the blades guarantees a soft reduction of the pressure inside the turbine, lower shearing effects and reduced turbulent flows in both vane channels. Mechanical injuries can be avoided to a large extent because of the very narrow gap between runners and casing.

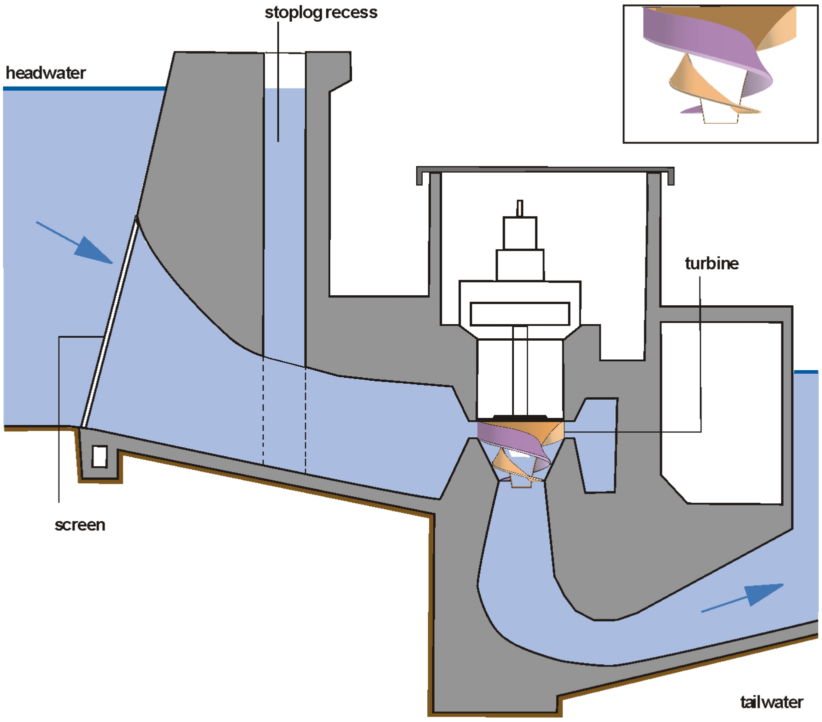


Figure 5.122:
Fish-friendly spiral-shaped turbine by NREC (changed according to HECKER et al., 1997)

The spiral-shaped turbine, of which presently only one prototype exists, according to first model calculations achieves an efficiency of 90 % at a mortality rate below 1.5 % (HECKER et al., 1997). Hence, it has a lower efficiency than Kaplan turbines, which obtain values between 92 and 94 %. In future it shall be possible to install the spiral-shaped turbine also in existing power plants and not require the exchange of generators etc. In this respect, however, it is to be observed that the spiral-shaped turbine can only be operated at full load. The possibility exists, however, that hydropower plants which consist of several turbines can be equipped with at least one spiral-shaped turbine: Fluctuating discharges can be compensated by the conventional turbines, whilst the survival rates of downstream migrating fish could be improved through a deliberate guidance of the specimens into the spiral shaped turbine.

5.9.3 Other development trends

In addition to research and development of turbine types which are acceptable under technical and biological viewpoints, science and industry carry out examinations of the hydraulics of a power plant. Of main interest is hereby a fish-friendly shaping of hydraulic contours, in particular in the turbine intake and in the suction tube.

5.10 Fish-friendly arrangement of intake structures

Based on the knowledge that the distribution of fish in rivers, lakes and reservoirs is inhomogenous, fish protection procedures have been developed in the former USSR and in Russia, which according to

PAVLOV (1989) follow the “ecological principle”, and the physical and behaviour principle, which means they are seen in relation to mechanical barriers and behavioural barriers.

The efficiency of these procedures relies on the condition that water extractions, primarily those for industrial and irrigation purposes, must be controlled and preferably extracted from zones with a low fish population. Fish larvae, fry and young fish are the main objective of these procedures as their swimming capacity is low, and they therefore would not be able to escape the drift in water intakes even at low approach velocities.

Such intake structures should generally not be positioned where fish concentrate in lakes or rivers and in locations of their migration paths. The highest density of larvae and fry will be found in spawning areas. Intake structures should therefore always be installed outside these areas. They are also unfavourably positioned in estuaries and where rivers enter lakes or reservoirs, as fish tend to drift from their spawning and feeding habitats into these areas where they will concentrate.

PAVLOV (1989) describes the following possibilities by which damage to fish larvae, fry and young fish can be minimized:

- Many species find their preferred spawning substrates in the littoral zone of rivers, reservoirs and lakes, where it is relatively warm and nutritious and therefore attract large numbers of fish. Intake structures in the littoral zone thus often cause considerable damage to fish populations. It should therefore be avoided to locate intake structures in littoral zones, disregarding whether rivers, natural or artificial lakes are concerned. The relocation of an intake structure in the Volgogradskaya reservoir (Russia) from the littoral zone into the superfluous water body at a depth of 6 m achieved a reduction of damage to fish fry by the factor 200.
- Fish fry in rivers concentrate alongside the undercut bank: it is possible that 50 to 70 % of drifting specimens are contained in only a quarter of the entire water body, and the highest concentration of fish will be at the end of the undercut bank. The consequence of such distribution pattern is that the highest rate of damage through water extraction is to be expected at the downstream end of the undercut bank. The lowest risk of damage will be at the bank on the opposite side of the intake structure. However, deviations from this rule are possible, for example where two narrow river bends follow one another. Hence, it would be sensible to examine the population of young fish prior to establishing the most suitable position for an intake structure.
- The vertical distribution of fish in a water body can also be utilized for fish protection by positioning the intake purposively into a layer of minimum fish concentration. Since fry of most species stay near the water surface, it would generally be advisable to position the intake near the bottom of the water body. However, there are species of which fry populate the zone in the bottom range of the water body. In this connection, PAVLOV (1989) states the Kuban river (Russia) as an example where the star-sturgeon is the target species of priority. In this case it has proven advantageous to position the intake not less than 2 m above the bottom of the water body in the non-utilized flow zone. In the case of polytropic still water bodies a positioning of the intake in the abyssal zone is to be recommended, as this is where during the summer half-year oxygen deficits or conditions of no oxygen content will prevail, so if at all, the population of fish in this area will be very thin.
- In reservoirs it is often feasible to extract water for drinking water use from different depths. Therefore it should be possible to withdraw water from depths where fish populations are the lowest; this may have to be varied depending on the season.
- Another possibility of minimizing fish loss is the regulation of water extraction during the course of the day. This facilitates the chance to react to vertical migrations performed by fish larvae in still water bodies periodically over a day (PAVLOV et al., 2002). Generally, it is to be recommended to extract water mainly in daytime and to reduce or stop any withdrawal over night, because the orientation possibilities of fry are limited in darkness (chapter 2.6.4), which therefore may involve substantially greater fish losses at night in comparison to daytime. According to details given by PAVLOV (1989), this strategy is employed successfully in the Khakovskoye-reservoir (Ukraine) where water is withdrawn for irrigation purposes. If the extraction of water is necessary at night, storage basins may be a suitable solution. These will be filled during daytime when the fish population is less and will be available for water extraction at night.
- High seasonal fluctuations of populations of young fish occur among anadromous species in particular: These species will only be seen downstream of their maturing biotope during the

relatively short migration period. These specimens can be effectively protected if the extraction of water will be restricted over the period of highest fish concentration. This strategy for example is adopted by some locations in the southern Ukraine, where the water extraction is stopped completely for 5 to 8 days in spring time.

- Finally, there is the possibility to employ storage basins for seasonal limitations of water extraction. PAVLOV (1989) reports about the integration of two intermediate basins in the Volga-Chogray-irrigation channel, which is designed for a flow-through of 2 km^2 of water per annum. Theses basins are filled with water during the cold season and then gradually emptied, so that water extraction from the Volga river can be restricted over the mass migration period of young acipenserids (*Acipenseridae*) during the summer.

Such ecological methods of fish protection hold a considerable potential, which so far also in Russia has only been exploited to a minor extent (PAVLOV, 1989). However, the practical realization requires purposive examinations of the downstream migration of fish and the rhythmic of fish damage per day and year, as the application of ecological procedures can only be effective if the distribution of fish in the water body concerned is exactly known with respect to space and time.

6 Effectiveness inspections

The term *effectiveness inspections* used in this chapter covers all techniques and procedures that can be used to assess the mortality and damage of migratory fish caused by hydraulic installations and the verification of the effectiveness and efficiency of fish protection facilities and downstream fishways.

Whereas the impact of obstacles on upstream migrating fish can be evaluated comparatively accurately through for example operational inspections of fish passes (DVWK, 1996; ADAM & SCHWEVERS, 2001), hydraulic installations not only interrupt downstream passageways, they also imply the risk of direct harm to fish during their downstream passage. Subsequently, any negative effects on migrating fish are much more complex and lead to consequences for the fish-ecology and fishery, which can only be assessed and quantified at great expenditure. This is one of the major reasons why only isolated relevant examinations have been carried out in Europe over the previous decades.

The impact of water intake structures and hydropower plants on migrating fish is more or less severe depending on various factors such as the hydrology of the water body, the construction type and its design capacity as well as the operation mode of the installation. In order to evaluate whether actions have to be taken with respect to a fish protection facility and/or downstream fishway, it is necessary to differentiate and quantify as precisely as possible the aspects “migration potential in a water body” and “mortality and damage caused by installations”. Dependent on the circumstances it is possible that an expert examination will lead to the conclusion that the downstream fish passage is sufficiently ensured without special installations, and fish protection facilities and/or downstream fishways will not be needed if the operation could be adjusted to a fish-friendly mode.

Different mathematic procedures, e.g. by RABEN (1957a, 1957b, 1957c), MONTÉN (1985) and LARINIER & DARTIGUELONGUE (1989), have been developed (chapter 4.2) to estimate the mortality rates caused by installations. However, it has been proven that the different formulae lead to results which only rarely meet realistic rates of damage. According to the present level of knowledge, practical examinations are therefore necessary, especially when as a first step the effect of fish protection facilities and downstream fishways or alternative procedures need to be understood, before with a second step they can be optimized. Studies on models but also behavioural observations in model channels under laboratory conditions could provide answers to these questions.

Effectiveness inspections of fish protection facilities and downstream fishways or alternative methods such as early warning systems and fish collection systems, as well as the proof of damage to fish caused by such installations (VOGEL et al., 1990; TRAVADE & LARINIER, 1992), always requires an immediate and time consuming inspection of the installation. For this purpose, the migrating fish should where possible be recorded in the total discharge of the relevant location. This means that the downstream fish passage must not only be checked for example via an existing bypass, but at the same time also via all potentially available migration corridors like turbine draft tubes, weir outlets, sluices, fish passes, and if applicable, navigation locks. This is the only way to gather well founded statements on the effectiveness of the fish protection facility and downstream fishway that are to be assessed. If for example examinations are limited to the inspections of partial flows due to technical constraints, it will be very difficult to interpret the results and thus their reliability.

The procedures employed to assess the mortality of fish and the function of fish protection facilities and downstream fishways described hereafter help to establish the following statements:

- Quantifying the rate of damage and mortality of fish in [%] caused by turbines and other structural parts.
- Recording damaged or killed fish according to species [specimens] or weight [kg] to calculate the loss for the fishing industry.
- Identification of preferred migration corridors.
- Checking the effectiveness of downstream fishways with respect to their attraction and safe passage of the available migration corridors.
- Checking the efficiency of fish protection facilities in respect of the rate of migrating fish being kept away from hazardous areas of the construction.
- Assessing the efficiency of fish-friendly constructions and techniques such as new turbine runners and modified operation modes to reduce the scope of damage.
- Determination of the efficiency of combined measures to protect and ensure the downstream migration of fish.
- Determination of the reliability of early warning systems that forecast migrations within the water body.

First of all, those aspects are to be determined for a particular location, which have to be examined in respect of fish migration and fish protection. Such examinations should be carried out and assessed by professionally qualified and ichthyo-biologically experienced personnel. They will also be responsible for the choice of suitable fishery methods, of which the most common ones are described hereafter.

6.1 Laboratory examinations

It is possible to obtain important knowledge about basic behavioural patterns of fish in the area of hydraulic installations by means of laboratory examinations. Although such behavioural observations, for example in a conditioned model channel, cannot be a substitute for findings established in outdoor examinations, they are still used as a basis for the development of operative fish protection facilities and downstream fishways and allow a first estimation of the effectiveness of such installations.

Fish belong to the species of vertebrate animals and are therefore subject to the regulations of the protection of animals act (Germany: BTierschG, 1986): this means that also within the frame of laboratory examinations, they must not be exposed to pain or avoidable suffering or damage. Furthermore, when dealing with living animals, it is always to be considered that the conditions under which they are kept and live, as well as the motivation of the individual, have a significant impact on the proposition of the test results. The implementation and especially the interpretation of laboratory examinations should therefore be restricted to personnel who are experienced in ichthyo-biology and who are professionally qualified.

Behavioural observations on fish are carried out in generously dimensioned, hydraulic model channels with side walls which are partially or completely made of glass, so that a direct observation of the animals is possible. It is also feasible to simulate almost realistic flow conditions. The sense of behavioural observations is to confront fish with protection, guiding and downstream constructions and to find out how fish react to such installations and how reliable their performance is (figure 6.1, figure 6.2). By means of this method it was possible recently to obtain wide knowledge about species-specific swimming behaviour and the orientation of downstream migrating fish in the flow as well as information about their reaction patterns to sources of interferences, screen constructions and bypass systems (ADAM & SCHWEVERS, 1998b; ADAM et al., 1999; AMARAL, 2000; HADDERINGH et al., 1999; GOEHL, 2001).

Figure 6.1:
Model channel at the Institut fuer Wasserbau und Wasser-wirtschaft of the University Darmstadt (Germany), where some of the laboratory exami-nations have been carried out mentioned in chapter 2 and 5

Figure 6.2:
Installation of components needed for behavioural obser-vations on fish

Laboratory examinations already have contributed to a better understanding of the mechanisms of downstream migrations of fish, but behavioural patterns observed under the artificial conditions of a model channel cannot be transferred to outdoor conditions unquestioned. For example, it is not possible to extrapolate the correct scale of biological facts by applying physical model conditions. It would therefore not be right to draw conclusions from the preferred swimming depths in the bounded water body of a model channel to appropriate migration corridors in river systems. Also, spatial arrangements, admission conditions etc. cannot be transferred to the conditions of real locations without prior verification. The findings obtained from behavioural observations must always be interpreted in the species-specific context and in dependence of the age and the development stage of fish. Behavioural observations in model channels are consequently primarily suitable for learning to understand general reaction patterns, which under outdoor conditions must not necessarily be any different.

6.2 Outdoor examinations

Provided there is no specific target species defined for a certain location, outdoor examinations must ensure that downstream migrations have been recorded at all representative operating conditions of hydraulic installations and that it is possible to evaluate statistics established on the findings. An interruption of the examination must be accepted especially at times of floods, when the exposure of the fishing device or its safe recovery will no longer be possible. Furthermore, attention is to be paid that the migratory behaviour of fish will not be influenced by the examination itself. The application of suitable proof or fishing methods must ensure that all one-summer and older specimens and particularly all downstream migrating fish of diadromous species will reliably be recorded. For this purpose it may be necessary to combine different methods.

Should target species be defined which are primarily to be protected in a water body or location, the outdoor examinations should always concentrate on the main migration periods of these specific species (chapter 5.1).

Depending on the location it is possible to use any of various fishing and proving methods in order to record fish which are moving in different migration corridors or the damage caused by hydraulic installations. Fishing devices covered with netting material like fyke nets, fish traps or anchored stow nets for eel belong to the traditional fishing methods. Since handling such mobile fishing devices is not just difficult in dependence of the discharge conditions, it is also a dangerous undertaking for the personnel in charge. The installation of stationary fishing devices therefore represents a suitable method especially where the downstream migration of the fish fauna will have to be documented over a longer period. A conclusion about the downstream migration potential in a water body or mortality and damage rates can also be taken from the amount of flotsam accumulating on the screen. By marking specimens and re-catching these it is tried to learn about the acceptance and continuity of migration corridors which are available for the downstream migration of fish.

6.2.1 Methods

6.2.1.1 Fyke-nets and fish traps

In order to catch fish from a water body, fishing bags made of netting are used in general, which are called fyke-nets, bow-nets or fish traps. Decisive for the shape and dimension of such fishing devices are the local conditions, e.g. the condition of the river bed, the discharge to be controlled, the water depth and flow velocities. The employment of fine-meshed netting in water bodies with great amounts of flotsam generally involves high technical expenditure, as the fishing device needs to be taken from the water for cleaning purposes at closer intervals. If wide-meshed nets are used the risk of clogging of the fishing device will be less, but the possibility of furnishing evidence of early development stages, small fish and species of stretched or eel-shaped bodies will be restricted.

A fyke-net is made of a more or less long, tapering tube of netting which is kept open through the flow and consequently can only be used in flowing water (figure 6.3). The fishing effect of the fyke-net is based on the fact that fish drift into the device with the current. The real fishing device, which is always located at the end of the netting tube can consist of a fishing bag or alternatively of a fishing box or fishing boat. The fish which concentrate in the netting tube will be received by the fishing device. If a fyke-net is to be employed, the flow velocity in the migration corridor to be controlled should not be below 0.8 m/s, allowing for the bulky netting bag to spread out in the flow and to ensure that fish cannot escape which have already been caught. The fishing bag is often additionally equipped with a fyke-net flute.

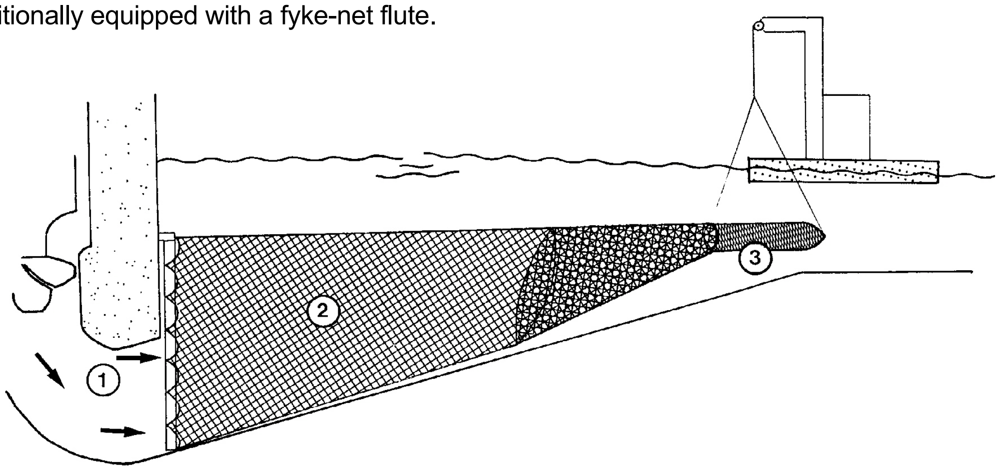


Figure 6.3:
A fyke-net (2) made of varying mesh widths is installed at the turbine outlet (1). The width of the mesh becomes smaller over the distance from the opening of the fyke-net to the fishing bag (3). The fishing bag will be hoisted by lifting devices positioned on a pontoon

Length and width of a fyke-net depend on the dimension of the cross-section to be controlled and the discharge (figure 6.4). The opening of the fyke-net is normally fixed to a steel-frame which by means of lifting devices will be pushed into the emergency closure bays of the turbine outlet. In order to meet the high pressure of the water in the fyke-net on the one hand, and to facilitate fishing of small fish on the other hand, the mesh-size of the netting should be as small as possible, or should reduce between the opening of the fyke-net and the fishing bag (table 6.1). Additionally, a further reduction of the mesh-width in the area of the fishing bag may be sensible, whereby knotless netting should be used as a rule in order to avoid injuries to fish caused by frictions at the fishing bag.

The use of bow-nets is recommended, if bypasses, sluices or the outlet of fish passes with discharges below 1.0 m^3/s are to be examined for downstream migrating fish. These bow-nets in comparison to fyke-nets will be kept open by means of rings or other stiffeners, as for traditional fishing they are mainly employed in stagnant waters. Fish will hereby be caught when actively swimming into the bow-net. In order to prevent any fish from escaping, they are equipped with flutes on the inside. Depending on the local conditions, especially on the conditions of the river bottom, it is possible to use inverted bow-nets made of knotless netting (figure 6.5) or boxes produced of perforated aluminium plates. In the latter case, care must be taken that the interior will be designed so that injuries to fish kept inside will be avoided.

Figure 6.4:
Fyke-net used for downstream migration examina-tions at the power plant Dettelbach on the Main river (Bavaria, Germany)

Table 6.1: Fyke-net dimensions of various examinations

location / river	turbine discharge [m^3/s]	opening [m^2]	stretched mesh [mm]	length [m]	author
France					
Mauzac / Dordogne	60	9.2 - 77.0	22 / 14	15 - 16	TRAVADE et al., 1987
Tuilière / Dordogne	52.4				
Poutès / Allier	14				
Germany					
Neckarzimmern / Neckar	40 - 80	105.0	80 / 60 / 40	76	BERG, 1985
Letzter Heller / Werra	15 - 18	not indicated	40 / 30 / 20	25	BERG, 1988
Dettelbach / Main	65	56.0	100 / 80 / 60 / 50 / 40 / 30 / 25 / 18 / 12	40	HOLZNER, 1999
Jaegersdorf / Saale	14.7	25.1	56 / 50 / 40 / 30 / 25 / 20 / 16 / 12	25	SCHMALZ, 2002b
The Netherlands					
Linne / Maas	30 - 100	50.0	28 / 20	35	HADDERINGH & BAKKER, 1998

The maximum mesh width or diameter of the hole should not exceed 10 mm to ensure the recording of eel and one-summer fish. When exposing bow-nets or fyke-nets it must be observed that the entire discharge to be examined for downstream migrating fish will be fed into the fishing facility and upstream migrating fish will be refused.

Any fish caught with fyke-nets or bow-nets must not be exposed to too great flow velocities and / or turbulences in order to prevent injuries. The netting tube of a fyke-net or inverted bow-net must be long enough to allow for the fishing bag to be positioned outside the main flow. Box-type traps should have stilled current zones, for example on the bottom of the trap. Should several migration corridors exist at one location, this may require the relevant number of fishing devices.

The making of bow-nets and fyke-nets in particular requires special skills because of the high stress on the material, the loads occurring and also in respect of handling the fishing devices. Such skills are possessed by professional fishermen and companies which are specializing in fishing devices. The frequency at which such fishing facilities must be recovered, emptied and cleaned is subject to the occurrence of flotsam and downstream migration activity. Working with bow-nets and fyke-nets requires intensive management by trained personnel. Suitable protection and safety precautions must be taken in the working area in order to make the work safe for operators and for a smooth work process on site.

Figure 6.5:
Inverted bow-net for the control of bypasses

6.2.1.2 Anchored stow-net for eel

Fishing boats which are equipped with booms that can be swivelled sideways over the ship's sides and on which fyke-nets are exposed to the flow are so-called anchored stow-nets for eel (HAUNS & HAUNS, 1996). Anchored stow-nets for eel in some cases were positioned in the tailwater of hydropower plants (figure 6.6, figure 6.7), in order to catch eel in particular which had drifted with the turbine water (JÖRGENSEN et al., 1999). It is to be considered however, that the efficiency of this fishing method will be reduced the greater the distance between boat and turbine outlet. Additionally, there is a possibility that fish from the tailwater of the hydropower plant which have never passed the hydropower plant will also enter the nets. Catches made with anchored stow-nets may be a basis for a rough calculation of the quantity of downstream migrating and damaged fish, but if more detailed information is needed, this requires the employment of methods which are more precise.

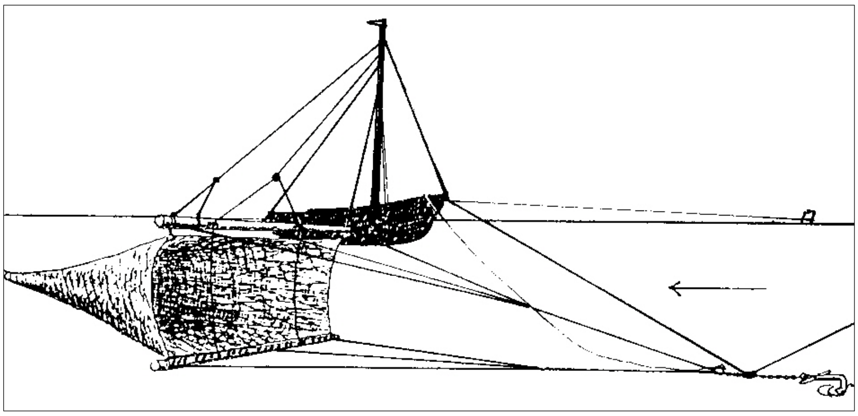


Figure 6.6:
Anchored stow-net for eel
(taken from:
HAUNS & HAUNS, 1996)

Figure 6.7:
Anchored stow-net for eel in the tailwater of the hydro-power plant Lith on the Maas river (The Netherlands)

6.2.1.3 Tyrolean weir

Tyrolean weirs are stationary hydraulic installations where a screen is installed inclined in flow direction at a maximum angle of 25°, similar to bed load retention dams in the Alpine region (figure 6.8). The principle of catching fish is that the water which needs to be separated from fish will flow through the screen surface, whilst fish and flotsam will be retained and guided to a flushing channel over the slope of the screen (figure 6.9), for which purpose the bars must be installed in flow direction. A fishing facility is located at the end of the channel, which preferably should be a fish chamber of solid build from which fish can be taken for examination. The bar spacing is always dependent on the target species and target sizes:

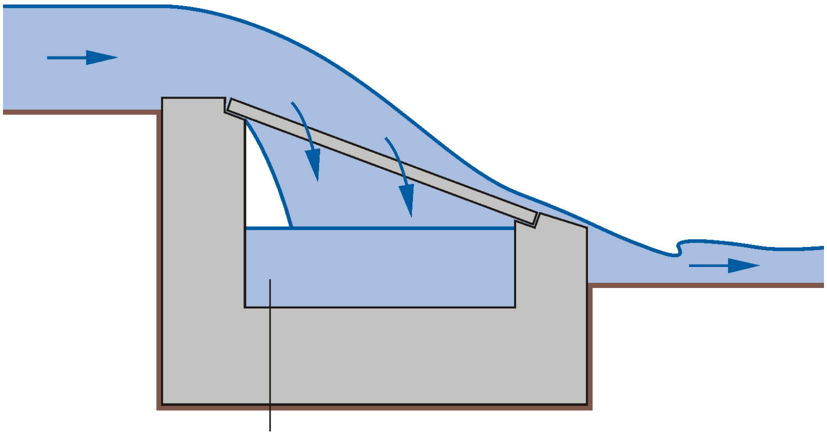


Figure 6.8: Schematic diagram of a Tyro-lean Weir

- A bar spacing of < 20 mm is required if evidence of yellow eel and masculine silver eel has to be provided.
- Flat steel screens with a maximum bar spacing of 5 mm are employed in France and Scandinavia for checking the efficiency of bypasses for salmon.
- In the USA, Tyrolean weirs are equipped with Wedge-Wire-Screens (figure 6.10). Such control stations have a bar spacing of only 1 mm (figure 6.11). They are used for giving evidence of the existence of the Atlantic salmon smolts, which can be of a length of up to 15.0 cm, but also smolts of species of the Pacific salmon, which will only be 3.0 to 4.0 cm long. A significant advantage of this type of screen is the very smooth surface which can almost exclude injuries to sensitive young fish.

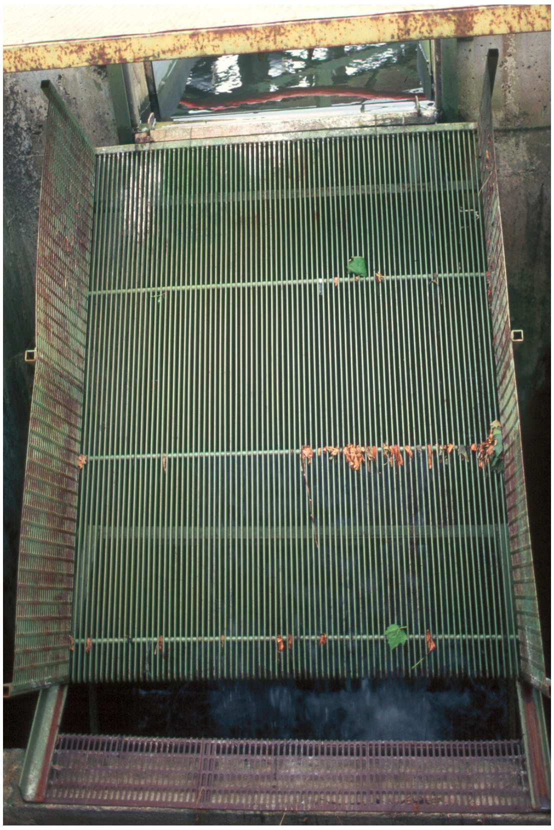


Figure 6.9:
Tyrolean Weir for checking down-tream migrating fish in the bypass of the power plant Halsou on the Nive river (France); the intake is shown at the top and the flushing channel at the bottom of the picture

Figure 6.10:
Very flat inclined Wedge-Wire-Screen at the bypass outlet at the Holyoke-Dam on the Connecticut river (Massachusetts, USA)

Figure 6.11:
Detail of figure 6.10:The very small bar spacing of 1 mm of the flat inclined Wedge-Wire-Screen and the very smooth surface minimize the risk of injuries for fish

6.2.1.4 Control of trash and flotsam

Important particulars about the composition and quantity of the organisms transported with the water and also about their downstream migration period in the water body concerned (RAUCK, 1980; WEIBEL, 1991; WEIBEL et al., 1999) can be obtained when examining flotsam occurring at screens of intake structures. Furthermore, such controls provide information about fish loss owed to the screen, which for example may be caused by too high approach velocities building up in front of screens with small bar spacing.

6.2.1.5 Catch-marking-repeated catch

The catch-marking-repeated catch method implies that fish will be marked externally, for example by means of colours or plastic tags (figure 6.12, figure 6.13) and then released into the headwater of a hydraulic installation. Provided the marked fish can be re-caught in the tailwater with suitable fishing devices or through intensive search by means of electro-fishing, this allows gaining knowledge about the traceability of migration corridors and their continuity. If the number of random samples of marked specimens is sufficient to permit a statistical cover of the results, it will be feasible to estimate the survival rate of fish on the basis of the repeated catch quota applicable to the specific location.

The fish which have to be marked should preferably be taken from the water body where the control point is located. If the target species chosen for the effectiveness inspection are anadromous salmonids, especially salmon, then it is also possible to use salmon smolts from fish hatcheries.

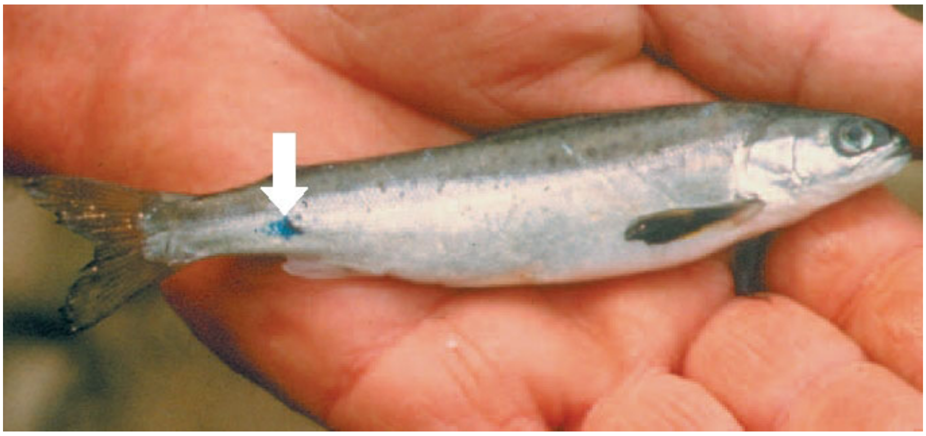


Figure 6.12:
Salmon smolt marked with alcyan-blue

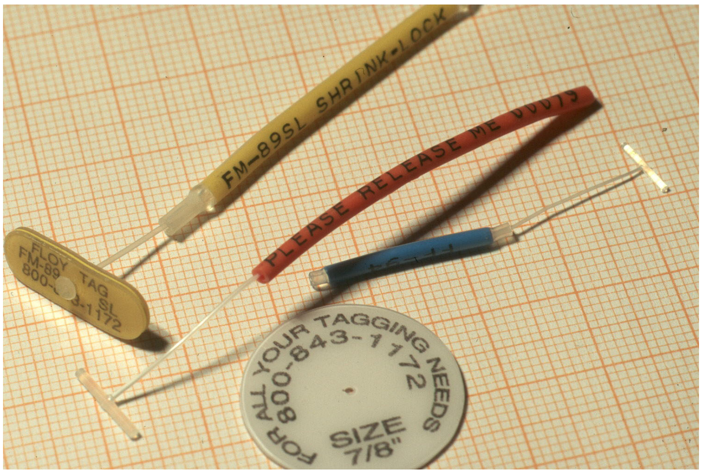


Figure 6.13:
Selection of plastic tags, so-called "anchor-tags", which are attached to the fish by means of a plastic thread in the musculature, preferably in the area of the fin on the back

"HI-Z Turb'n Tags" have specifically been developed in the USA for examining downstream migrations of fish and the survival rate at hydropower plants (HEISEY et al., 1993). With this kind of marking, from a capsule that is externally fixed to the fish, gas will escape after some time or, caused by pressure fluctuations during a turbine passage fill a balloon by which the fish will be pulled up to the surface of the water (figure 6.14). This method relieves the traceability of fish in the tailwater of the installation and allows that when searching for fish it will be possible to catch living and injured but also killed specimens.

In Germany for example, independent of the marking method selected, a permission to carry out animal experiments has to be granted according to § 8, para. 1 of the animal protection act (BTierschG, dated 25 May, 1998), which can be applied for at veterinary authorities of governmental institutions. The marking itself must be carried out by trained personnel only, i.e. veterinary surgeons or biologists. In this context it is also to be observed that a deliberately induced passage of fish through hazardous areas of an installation is ethically and morally questionable and generally requires permission in line with the animal protection act.

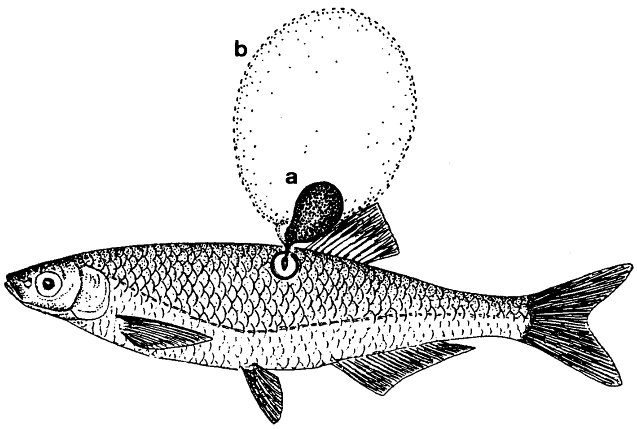


Figure 6.14:
A HI-Z Turb'n Tag attached to a fish in

a) a compressed and

b) filled condition

6.2.1.6 Telemetry and transponder technology

In order to trace the migratory behaviour of fish over great distances in outdoor conditions, modern marking and locating technologies are increasingly in use in Europe.

For telemetry, battery operated radio transmitters are surgically implanted in fish. Specimens who have been marked this way and returned into their original water body can thus continuously be located by means of the individual signals emitted by the transmitters which are received by antennae, and their migration can thus be kept under control (LARINIER & TRAVADE, 1999; BEHRMANN-GODEL, 2000). Technically advanced transmitters are additionally equipped with temperature and pressure sensors, which supply further information about how the activity is dependent on temperature and migration depth. Since the price for transmitters and reception units is very high, and tracing fish by telemetry involves a lot of time, it is in many cases possible to mark a few specimens only. However, this monitoring method provides a precise idea about the individual migration paths and behavioural pattern of the sample taken at random.

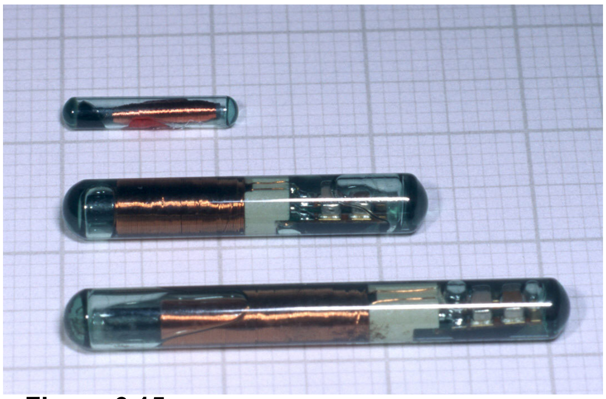


Figure 6.15:
Passive transponder of different sizes (top: TROVAN®, centre and bottom: Texas Instruments TIRIS®)

Transponders consist mainly of a ferrite coil encased with glass that is inductively activated and then emit an identification signal. Depending on the size of fish they will be injected or implanted and subsequently facilitate an individual and permanent marking.

So-called "passive integrated transponder" (PIT-Tags) have no own energy source and therefore last infinitely. As the length of these tags is between 12 and 30 mm and the diameter between 2 and 4 mm (figure 6.15) they can easily be injected into fish. Their effective radius however is relatively narrow and depending on the design limited to between 0.3 and 5.0 m. In the USA, PIT-Tags are employed on a large scale basis for routine monitoring of downstream migrating fish. The corresponding antennae are preferably installed in bypass systems (PRENTICE et al., 1990). In Germany, PIT-Tags so far outdoors have been used exclusively for effectiveness inspections of fish passes (ADAM & SCHWEVERS, 1997b).

Figure 6.16:
Active transponder (NEDAP TRAIL System®) for examining the downstream migration of eel in the Maas river (The Netherlands)

The effective radius of passive transponder, however, is insufficient for large migration corridors where active transponders like the NEDAP TRAIL System® are required. These are equipped with a battery to intensify the induced signal (SUN, 1998). Active transponders are of such a size (approx. 80 * 20 mm) that they need to be implanted in the abdominal cavity of the fish (figure 6.16). Nonetheless, their effective radius is not wide enough to reliably control water bodies of a width of up to 2.0 km and a depth of up to 30.0 m. This is achieved by antenna strands which are laid on the bottom of the water body. Migrations of salmon and sea trout are monitored by means of this technology in the Dutch section of the Rhine system and in the lower Rhine in North Rhine Westphalia since 1998 (VAATE & BEUKELAAR, 1999). The same technology is used in the Maas river since 2001 in order to record downstream migration periods and migration corridors of silver eel (BRUIJS et al., 2003).

6.2.1.7 Echo depth sounding

Whilst the aforementioned marking techniques allow keeping track of the behaviour of individual specimen, the method of echo depth sounding is a means of observing fish concentrations or migrations of shoals. In future, therefore, if horizontal transducers would be further developed, echo depth sounding could be used in the intake area of hydropower plants in the sense of early warning systems for taking record of downstream migrating fish. However, the hydraulic conditions that prevail in this area and ascending gas bubbles as well as flotsam make a certain and especially an automatic identification of downstream migrating fish more difficult.

6.2.2 Evaluation

6.2.2.1 Assessment of mortality and damage rates

The implementation of outdoor examinations is required for the assessment of mortality and damage rates at hydraulic installations. The number and weight of fish will hereby be recorded species-specific. Additionally, it will be differentiated between:

- killed and fatally injured fish,
- sub-lethally injured fish,
- unharmed fish.

In order to facilitate a sure identification of damage it is necessary to keep all fish caught alive in an intermediate basin where they have to be observed. On the one hand it may be possible that injuries which seemed less grave at first sight prove lethal, whilst on the other hand inner injuries which were not directly identifiable after the catch has been recovered become noticeable through peculiarities in posture, behaviour and motion. The period of keeping fish intermediately in a holding pool normally covers 24 to 96 hours. Generally, a group of fish that has not been in contact with the specific hydraulic installation must be kept under the same conditions in order to verify losses occurring during longer observations of fish in a holding pool.

The portion of killed fish is called mortality (M). The mortality rate is calculated in [%] from the number of killed fish (t) in relation to the total of all registered fish (n) according to the following formula:

$$M = \frac{t}{n} \cdot 100$$

The damage rate (S) additionally covers living but injured fish (v):

$$\mathrm{S} = \frac{\mathrm{t} + \mathrm{v}}{\mathrm{n}} \cdot 100$$

These formulae, however give a full account of the mortality or damage rate at a location if only one single migration corridor is available.

Should there be several (i) migration corridors at one location, then (M) and (S) must be calculated separately for all downstream fishways on the basis of the above mentioned formulae. The total damage rate of the location (S_{total}) is calculated as follows:

$$S_{total} = \frac{\sum (t_i + v_i)}{\sum n_i} \cdot 100$$

Consequently, for locations where the majority of downstream migrating specimens use migration corridors with a low risk of damage, the total damage rate will be significantly less than the damage rate for passages of the most hazardous downstream fishway.

Mortality and damage rates are not constant, installation-specific parameters. Moreover, they are directly dependent on the actual operating state of the hydraulic installation as well as the species and sizes of fish under observation. Therefore, documents on control examinations must always identify the operating state prevailing at the time of the examinations and to which species and sizes of fish the values of mortality or damage apply.

A realistic average value of the total mortality or damage rate can only be assessed if the installation was operated in a representative state during the examinations. Generally, it is appropriate to differentiate the values assessed at these operating states by fish species and fish sizes, however, it is necessary that migratory stages of diadromous species are identified separately.

The mortality resulting from fish being pressed against screens of hydropower plants and intake structures can be assessed by taking samples from trash and flotsam that has accumulated on screens (WEIBEL, 1991). At intake structures, often there are several filters arranged in tandem, so that samples of trash and flotsam must be taken individually for each filter. Depending on the bar spacing or mesh width of such filters it is to be considered that small organisms will always pass the barrier.

6.2.2.2 Quantification of fish loss

For the ecological assessment of fish loss, in particular that of diadromous species, which additionally may possibly be needed for the establishment of compensation payments to the fishing industry, it is necessary to evaluate the absolute number [piece] and weight [kg] of fish killed or damaged by the hydraulic installation. This too has to be done species-specific.

From experience it is almost impossible in this respect to extrapolate the damage that was assessed over just a few examination days to the total extent of the damage as the migration happening of the different species is very irregularly distributed over a year. Precise details can be obtained only for actually examined periods. The result of extrapolations therefore, will be the more accurate the longer the period over which effectiveness inspections have been carried out. Details which HOLZNER (1999) has gained within the frame of a two year long scientific examination of the damage of downstream migrating fish at the hydropower plant Dettelbach on the Main river (Germany) are based on the results of 111 examination days.

The migration of diadromous species concentrates on relatively few days or nights of a year, which for salmonids like salmon and sea trout can be quite well prognosticated by means of meteorological and hydrological parameters.

The most reliable quantification of the extent of damage for these species can therefore be obtained if the control examination will in fact be carried out on days when the downstream migration can be expected.

6.2.2.3 Effectiveness of fish protection facilities

The objective of fish protection facilities is to prevent fish from entering hazardous installation areas. The effectiveness of such installations is rated by the extent to which they really obstruct the passage of fish. The hydropower plant or intake structure will be operated intermittently for this purpose, preferably in intervals of 8 or 24 hours, with and without a fish protection installation. At the same time, the number of fish that has passed the protection installation will be species- and size-specifically assessed (RAUCK, 1980). The efficacy ($E_{protection}$) of the fish protection installation in [%] will result from a comparison of fish passages taking place with and without a protection facility according to the following formula:

$$E_{protection} = 1 - \frac{n_m}{n_o} \cdot 100$$

with:

n_m=number of fish passing the installation despite a protection facility

n_o=number of fish passing the installation without a protection facility

6.2.2.4 Effectiveness of downstream fishways

The effectiveness of downstream fishways is rated by the portion of downstream migrating fish that has in actual fact used the specific migration corridor. A precondition for a reliable estimation therefore, is the quantification of the total number of fish in all migration corridors of the corresponding location and the assessment of fish that have passed the downstream fishway. The effectiveness (E_{Ab}) is calculated in [%] from the number of fish that has passed the bypass (p) in relation to the total number of fish having migrated downstream (n) on the basis of the following formula:

$$E_{Ab} = \frac{p}{n} \cdot 100$$

The effectiveness of a downstream fishway can differ entirely in relation to the different behavioural and reaction patterns of the various downstream migrating species, and therefore must generally be assessed species-specific. Additionally, the efficacy of fish protection installations is always subject to the specific operating state and must therefore appropriately be documented.

Smolts of salmonids migrate downstream at a rate of 100 % within a period of maximally two months in spring time. Accordingly, the extensive inspections of all downstream migration corridors of a location can be dispensed with for salmon and sea trout if a sufficient number of specimens has been marked and released into the headwater. The passage of fish in the downstream migration facility will be controlled solely, and it can be assumed that any of those fish that have not been marked will have migrated via other corridors. Losses on account of predation can hereby generally be neglected. The effectiveness in this case too is to be calculated on the basis of the above mentioned formula, where (n) stands for the entirety of all marked fish.

If the effectiveness of a downstream migration facility is insufficient, telemetric examinations have proven successful for a causal analysis. LARINIER & TRAVADE (1999) were able to specify hydraulic conditions which are crucial for the traceability by differentiating the behavioural patterns of salmon smolts in the headwater of hydropower plants on the basis of space and time. Based on these findings, it was possible to improve the effectiveness of bypasses decisively.

6.2.3 Assessment of effectiveness inspections

At this point it must be said that, although it is possible to assess damage rates and the efficiency of fish protection technologies and downstream fishways by means of effectiveness inspections, no generally applicable measures in the sense of limit values have so far been elaborated which would permit a final assessment of the respective results. The extent of actions deriving from the results of an effectiveness inspection therefore must be clarified with the responsible authorities of a specific location.

7 Frame conditions for planning and permission

7.1 The requirements of the EU-Water Framework Directive

The EU-Water Framework Directive (EU-WFD, 2000) today is the decisive legislation for water management and for an ecologically oriented approach to water bodies. The central idea is to classify the condition of water bodies by the status of the following biological quality criteria:

- fish
- macrozoobenthos
- aquatic fauna

In flowing water bodies which comply with the “good ecological status” according to the EU-WFW, the community of fish species shall deviate only slightly in composition and abundance from the type-specific community, due to human activities that affect physical/chemical and hydromorphological elements. Only in individual cases will the age structure of the fish fauna impose greater impairments and impact on reproduction and development of single species.

The demand of the EU-WFD for water bodies which have changed significantly and cannot reach the “good ecological status” is that at least the ecological potential must be developed the best possible. In this respect, river continuity is a vital precondition for the realization of the “good ecological status”, as well as for the development of the ecological potential, and is therefore explicitly demanded by the EU-WFD.

Thus, the definition of the target species for fish protection and downstream fish migration can be directly derived from the criteria of the EU-WFD for all water bodies, because especially those species are to be protected, whose population would be endangered without functioning fish protection facilities and downstream fishways at hydropower plants and intake structures.

The diadromous species represent without doubt the primary target group, as their reproduction is dependent on the migration between marine and freshwater habitats:

- Juveniles of anadromous species must be able to migrate unharmed from inland biotopes, where they grow up, to the sea, where they are to become sexually mature.
- The catadromous eel in the development phase of the sexually mature silver eel is dependent on a free downstream passage of river systems to participate in the reproduction in marine spawning areas.

Potamodromous species like barbel, burbot and huchen also migrate over great distances in inland water bodies. However, potamodromous species are not imperatively dependent on a completely free passage of entire river systems. Potamodromous species therefore are to be considered as target groups only where their population is at risk because of lacking fish protection.

The protection measures required for each of the target groups at the individual location must always take the appropriate river basin district and applied river basin management into consideration. The chances and limits of the technologies available and also the time required for their realization must be accounted for. The following aspects in respect of fish protection and an ensured downstream passage need to be clarified:

- For which target species must migration be ensured?
- Which qualitative and quantitative protection measures are required at a location?

7.2 Planning principles

The following data are to be established for existing and new installations prior to planning fish protection facilities and downstream fishways:

- Hydrological values, e.g. annual duration curve and significant values.
- Ichthyo-biological zoning of the water bodies.
- Actual and potential natural fish fauna.

- Design flow or extraction discharge of the hydraulic structure, if possible annual and daily hydrograph curve.
- Design of the migration obstacle, especially of a weir, intake structure, hydropower plant etc. on the basis of a site plan. Verification of technical and other conditions, flow conditions, bottom structures and stream profiles in the head- and tailwater.
- Kind of water utilization and degree of the expected damage of fish, especially of the target species (machine specific on the basis of existing examinations, and if required implementation of new examinations).
- Estimation of existing downstream migration corridors, e.g. via the weir, time distribution and expected effectiveness.

7.3 Determination of requirements for fish protection facilities and downstream fishways

In a first step, the requirements are to be defined which derive from the EU-WFD and are to be applied to the entire construction and any new part:

- Determination of target species under consideration of the river basin (chapter 2).
- Analysis of the existing facilities with respect to the damage and / or mortality rate as well as migration possibilities for the target species.
- Decision whether measures are required for fish protection facilities and downstream fishways.
- Coordination of the installation profile with the participants, so that the objectives of the EU-WFD can be achieved within periods to be determined.
- Clarification and agreement on possibly required additional examinations or effectiveness inspections (chapter 6).

7.4 Analysis of possible measures

Upon clarification and agreement of the tasks involved, the technologies are to be examined which are feasible for a fish protection facility and/or downstream fishway at an impounding and/or hydraulic structure. For this purpose one of the following or a combination of several measures are to be evaluated:

- Modification of the structure with the aim to prevent or reduce damage to fish.
- Technical modifications to turbine or pump, e.g. concerning the geometry, number of blades, speed, etc. (chapter 2, chapter 4, chapter 5.9).
- Technical modifications applied to impounding structures, e.g. with respect to water depths and structural elements in the stilling basin, the opening, etc. (chapter 4).
- Technical improvements of the intake screen, e.g. reduction of the approach velocity by means of face enlargement, reducing bar spacings etc. (chapter 5.1, chapter 5.2).
- Modification of the operation mode (chapter 5.8).
- Adjusting the operation mode of the structure to the migration periods of target species, e.g. by reducing discharge or approach velocity for a limited time (chapter 5.1, chapter 5.2, chapter 5.8.2).
- Optimizing the operation mode, e.g. at hydropower locations with several turbines, all or a defined number of turbines can operate in an area with least possible damage to fish, while other machines are stopped (chapter 5.8).
- Application of behavioural barriers (chapter 5.3): According to the knowledge available, fish protection and attraction of bypasses by means of the different behavioural barriers is currently restricted. The effect of behavioural barriers is species-specific, a deliberate influencing of the entire fish fauna at one location is generally impossible. Behavioural barriers basically require a low approach velocity. If it is reduced to 0.3 m/s, this will account for the weakest species under

unfavourable conditions, e.g. low water temperatures or strong turbidity. Especially at hydropower plants the approach velocity is often higher and moreover unsteady, so that at least locally the critical values will be significantly exceeded. Steady flow velocities can often only be generated in intake channels.

- Application of mechanical barriers (chapter 5.2): The maximum velocities for smolts and migrating silver eels are meanwhile known, and must not be exceeded under the aspect of fish protection. Various mechanical barriers exist with sufficiently small spacings, through which fish cannot pass physically. Presently, their application seems technically possible in Central European water bodies at a discharge of approx. 10 m^3/s. A further development of mechanical barriers and the required screen cleaning machines can only be carried out on the basis of operating experiences at pilot plants.
- Construction of bypasses (chapter 5.5, chapter 5.6, chapter 5.7): Design criteria for the layout and construction of bypasses in small and medium-scale water bodies can be specified for species which migrate near the surface. Solutions for large-scale water bodies must be found stepwise on the basis of these experiences. Several approaches are being developed for fish migrating near the bottom.
- Fish can alternatively be moved downstream by means of transportation systems, especially down rivers with several obstacles (chapter 5.8), and it is possible to protect migrating eels by means of early warning systems (chapter 5.9).

7.5 Summary and prospects

The present volume of the ATV-DVWK-Topics contains a systematic compilation of the actual knowledge of the biology of the downstream migration of fish, the requirements for fish protection facilities and downstream fishways and the technical solutions available.

Based on international investigations, this publication is a comprehensive summary of the subject matter. Solution approaches are demonstrated that can be used in practice and thus constitute a significant step forward. However, this work also shows that the problems concerning fish protection and fish migration are strongly dependent on the individual conditions prevailing at a location and the target species to be considered in the respective water body or river reach. On the basis of the actual knowledge level, generally applicable technologies and procedures cannot be recommended. Hence, this publication contains elaborated and proven solutions which may be suitable for many, but not for every area. Concerning the decision on the feasibility of a fish protection facility and downstream fishway as well as on possible further planning procedures, the scientific / technical deficits must also be accounted for.

Eventually, economical consequences and the perspective for a realization of a free downstream passage of a migration obstacle in respect of time and applicable permission regulations have to be weighed in the light of the EU-Water Framework Directive.

The knowledge compiled in this publication emphasizes the necessity of problem-oriented scientific research, especially with respect to the behaviour of migrating fish and the possibilities of damage protection as well as the provision of a passage in flow direction. Subsequently there is the immediate essential demand that uniform methods and assessment standards are employed for effectiveness inspections of installations. In such a way investment failures can be avoided and the knowledge gained may contribute to further development works.

The present volume of the ATV-DVWK -Topics refers to the available knowledge on fish protection technologies and downstream fishways and can be used for the realization of the objectives of the EU-WFD, as both, the “good ecological status” and the best possible “development of the ecological potential” are only achievable if water bodies are passable for the fish fauna. And this requires upstream as well as downstream continuity.

8 Legal principles

The fishery laws of the Federal States of Germany partly open the possibility to commit the constructor and operator of intake structures or hydropower plants (generally called “power plant” in the corresponding wordings of the law) to build suitable facilities which will prevent fish from entering installations.

According to § 101 of the Prussian Fishery Law dated 11 May, 1916 it was possible to oblige the owner of turbines to prevent fish from entering installations by providing suitable facilities. Similar demands were directed to constructors of hydropower plants through the fishery law of Bavaria of 15 August, 1908. The Grand Ducal fishery law of Hesse (Germany) dated 27 April, 1881, recommended grids as a means for the protection of fish.

Since at that time already the difficulty was known to retrofit existing installations with protective facilities, exceptions were permitted for installations which were in operation at the time the law came into force (§ 76 BayFischG, 1908; § 54 GrHeFischG, 1881). These special laws are still applicable. The commentary on the fishery law of Lower Saxony (TESMER & MESSAL, 2000) says that requirements that have been claimed after this law has been enacted can only be ordered if the costs will be assumed and compensation paid. This interpretation is guided by the Prussian Fishery Law of 1916.

The issue of retrofitting installations is not mentioned in most of the fishery laws of the other Federal States of Germany. This problem is incorporated in amendments of the fishery laws by the addendum “or operates”.

With the exception of Hamburg all Federal States of Germany have established regulations in their fishery laws which permit instructions to the constructors of new hydropower plants and other intake structures to provide installations suitable for preventing fish from entering the structure. However, this regulation is only valid in some Federal States of Germany if such facilities are consistent with the actual intention or economically reasonable.

In cases where it is not possible to create protective facilities, the constructor will be obliged to reasonably contribute to the fish stock; this for example applies to North Rhine Westphalia, Bavaria and Brandenburg. The retrofitting of existing installations with facilities that will protect fish is demanded in only a few Federal States of Germany.

Those fishery laws which have recently been amended furthermore contain regulations for unavoidable damages, i.e. damage to fish that occurs despite protective facilities. Compensation payments are to be made in such cases as a rule.

There is no mention of the design of a protection facility in the fishery laws. In this respect, the operator generally has freedom of choice, provided the protection facility prevents fish from entering the turbine. Some Federal States of Germany, however, recommend or even demand with their regulations contained in the respective fishery law that the design of screens must account for a bar spacing of a maximum of 20 mm in order to meet the requirements for an effective protection facility. Brandenburg is the only Federal State that demands a maximum clear width of 18 mm. Concerning the use of fish-friendly turbines the fishery laws would have to be amended like those in Brandenburg.

Independent of the fishery laws of the Federal States of Germany, the animal protection act of 25 May, 1998, stipulates that no actions shall be allowed by which invertebrates will be caught, deflected or deterred and will cause pain or suffering to animals. In this connection, the installation of a 20 mm-screen at large-scale water withdrawals with high flow velocities in the area of the screen surface creates problems in view of the animal protection act and the actual passage of a turbine.

Next to the fishery laws of the Federal States and the national legislation, increasingly there are European legal standards to be complied with, like for example the directive “Fauna-Flora-Habitat” dated 21 May, 1992, also called FFH-directive. Its general objective is to sustain the European nature heritage, and next to the protection of species contains the development of a European network of protected areas, called “Natura 2000”. In Annex II there is a list of native fish species of Germany, which need to be protected:

Lampetra planeri (brook lamprey)
Lampetra fluviatilis (river lamprey)
Petromyzon marinus (sea lamprey)
Eudontomyzon spp. (Danube lamprey)
Acipenser sturio (sturgeon)
Alosa spp. (allis shad and twaite shad)
Hucho hucho (huchen)
Salmo salar (salmon)
Chalcalburnus chalcoides (Danube bleak)
Coregonus oxyrhynchus, anadromous populations in specific regions of the North Sea (houting)
Aspius aspius (asp)
Gobio albipinnatus (white-finned gudgeon)
Gobio uranoscopus (Danube gudgeon)
Leuciscus souffia (vairone or stroemling)
Rhodeus sericeus amarus (bitterling)
Rutilus frisii meidingeri (Black Sea roach)
Rutilus pigo (Danube roach)
Cobitis taenia (loach)
Misgurnus fossilis (weatherfish)
Gymnocephalus schraetzer (Danube ruffe)
Zingel streber (streber)
Cottus gobio (bullhead)

A network of special protected areas must be identified according to clause 3/1 of the FFH-directive for many potamodromous and all anadromous species, with the exception of the smelt, that are indigenous to Germany, in order to guarantee the continuance, or where required the restoration of a favourable preservation state of natural biospheres and habitats of these species in their natural propagation area. Clause 10 finally puts emphasis on the cross linkage of rivers, for example, as linear landscape elements and on their importance for migration, the geographical propagation and the genetic exchange of wild species.

The European Water Framework Directive (EU-WFD) was put into force by the European Commission on 22 December, 2000. The primary objective of the common water policy demanded by the EU-WFD is to bring the water bodies into a good ecological status within the forthcoming 15 years. The directive had to be transferred by the member states of the EU into national legislation by the end of 2003. The water resources act was amended on 18 June, 2003 to meet this demand. Also the water acts of the Federal States of Germany were harmonized accordingly. One of the key points of the EU-WFD refers to the biological evaluation of river systems, which is a consideration beyond the previous purely chemical consideration. The continuity of river systems can be interrupted by obstacles to the extent that the composition of species and quantities of a symbiosis will change. Some suitable measures are unavoidable since the interference may only have a minor impact on the composition of species and quantities required for the good ecological status aimed at. For example, water bodies used for navigation and / or generation of energy can be classed by the member states as “artificial” or “heavily modified water bodies”. Feasible measures must be taken to reduce the negative impact on the status of the water body.

The nature conservation act of the Federal Republic of Germany demands in § 2, clause 1 that the ecological capacity is to be sustained and improved, and that impairments must be avoided or compensated. With reference to nature conservation, the required freedom is provided by the framework act of the Federal Republic of Germany for the legislation of the federal states. Issues concerning fishery however, are generally not determined by nature conservation acts.

9 Literature

ADAM, B. & U. SCHWEVERS (1997a): Aspekte des Schwimmverhaltens rheophiler Fischarten. - Österr. Fischerei 50, 256 - 260.

ADAM, B. & U. SCHWEVERS (1997b): Zur Funktionskontrolle von Fischwegen - Einsatz automatischer Kontrollstationen unter Anwendung der Transponder-Technologie. - DVWK-Schriften 119, Bonn (Wirtschafts- und Verlagsgesellschaft Gas und Wasser mbH), 100 S.

ADAM, B. & U. SCHWEVERS (1997c): Das Verhalten von Fischen in Fischaufstiegsanlagen. - Österr. Ficherei 50, 82 - 87.

ADAM, B. & U. SCHWEVERS (1998a): Fischaufstiegsanlagen als Wanderhilfen für aquatische Wirbellose. - Natur und Landschaft 73, 251 - 255.

ADAM, B. & U. SCHWEVERS (1998b): Zur Auffindbarkeit von Fischaufstiegsanlagen - Verhaltensbeobachtungen an Fischen in einem Modellgerinne. - Wasser & Boden 50/4, 55 - 58.

ADAM, B. & U. SCHWEVERS (2001): Planungshilfen für den Bau funktionsfähiger Fischaufstiegsanlagen. - Bibliothek Natur & Wissenschaft, Band 17, 64 S.

ADAM, B. & U. SCHWEVERS (2003): Untersuchung der Aalabwanderung über einen Feinstrechen mit Bypaßrinne. - Kirtorf-Wahlen (Institut für angewand- te Ökologie), imAuftrag der Floecksmühle Energietechnik GmbH, 21 S.

ADAM, B. (1996): Zur Berücksichtigung von Wirbellosen beim Bau von Fischaufstiegsanlagen. - Österr. Fischerei 49, 186 - 190.

ADAM, B. (1999): Aalabwanderung - Ergebnisse von Versuchen in Modellgerinnen. -Arbeiten des Deutschen Fischereiverbandes 70, 37 - 68.

ADAM, B. (2000): MIGROMAT® - ein Frühwarnsystem zur Erkennung der Aalabwanderung. - Wasser & Boden 52/4, 16 - 19.

ADAM, B. (2004): MIGROMAT ® - Frühwarnsystem für die Aalabwanderung. - Tagungsband 16. SVK-Fischereitagung, 02. - 03. März 2004, Fulda, 1 - 18.

ADAM, B., O. ENGLER & U. SCHWEVERS (2001): Verhaltensbeobachtungen von Fischen an Rechen und Bypässen. - Im Rahmen des von der Deutschen Bundesstiftung Umwelt geförderten Projekts "Entwicklung und Erprobung eines Feinstrechens für Wasserkraftanlagen" (Az: 16321). - Kirtorf- Wahlen (Institut für angewandte Ökologie), im Auftrag des Ingenieurbüros Floecksmühle, 49 S.

ADAM, B., U. SCHWEVERS & U. DUMONT (1999): Beiträge zum Schutz abwandernder Fische - Verhaltensbeobachtungen in einem Modellgerinne. - Solingen (Verlag Natur & Wissenschaft), Bibliothek Natur und Wissenschaft 16, 63 S.

ADAM, B., U. SCHWEVERS & U. DUMONT (2002): Rechen- und Bypassanordnungen zum Schutz abwanderndnderAale. - Wasserwirtschaft 92/4+5, 43 - 46.

ADLMANNSEDER, J. (1986): Kleinspannungs-Fischscheuch- und Leitanlagen. - Österr. Fischerei 39, 246 - 255.

ALLEN, K. R. (1944): Studies on the biology of the early stages of the salmon (Salmo salar). 4. The smolt migration in the Thurso River in 1939. - J. Anim. Ecol. 13, 63 - 85.

AMARAL, S. V. (2000): Evaluation of an angled barrack and a louver array for guiding silver American eels to a bypass. - 1st International Catadromous Eel Symposium, 20. - 24. August 2000, St. Louis, Missouri, Pre-Prints, 28-1 - 28-8.

AMARAL, S. V., F. C. WINCHELL, D. T. MICHAUD, L. D. EVERHART & C. W. SULLIVAN (1998): Evaluation of behavioral fish protection technologies. -AFS meeting August 1998.

AMARAL, S. V., F. C. WINCHELL, T. C. COOK & E. P. TAFT (1994): Biological Evaluation of a modular inclined screen for protecting fish at water intakes. - Paolo Alto (EPRI Project RP2694-01).

ANDERSON, J. J. (1988): Diverting migrating fish past turbines. - Northwest environmental Journal 4, 109 - 128.

ANDERSON, N. H. & D. M. LEHMKUHL (1968): Catastrophic drift of insects in a Woodland stream. - Ecology 49, 198 - 206.

ANONYMUS (1899): Turbinen und Fische. - Allg. Fi- scherei- Z. NF 24: 283. ARBEITSGEMEINSCHAFT GEWÄSSERSANIERUNG (1998): Wiederherstellung der Durchwanderbarkeit der Staustufe

Wahnhausen in der Fulda. - Aachen und Kirtorf-Wahlen (Ingenieurbüro Floecksmühle & Institut für angewandte Ökologie), im Auftrag des Regierungspräsidiums Kassel, 2 Bände, zus. 382 S.

ASCE (American Society of Civil Engineers) (1995): Guidelines for design of intakes for hydroelectric plants. - New York.

ASE (Arbeitskreis Schulinformation Energie) (1997): Wasserkraft / Lehrerinformationen. - Heidelberg (Energie-Verlag).

BAARS, M., E. MATHES, H. STEIN & U. STEINHÖR- STER (2001): Die Äsche. - Hohenwarsleben (Westarp Wissenschaften), Neue Brehm Bücherei 640, 128 S.

BACKIEL, T. (1966): On the dynamics of an intensively exploited fish population. - Verh. internat. Verein. Limnol. 16, 1237 - 1244.

BAINBRIDGE, R. (1958): The speed of swimming of fish as related to size and to the frequency and amplitude of the tail beat. - J. exp. Biol. 35, 109 - 133.

BAINBRIDGE, R. (1960): Speed and stamina in three fish. - J. exp. Biol. 37, 129 - 153.

BARDY, D., M. LINDSTROM & D. FECHNER (1991): Design of extended length submerged traveling screen and submerged bar screen fish guidance equipment. - Waterpower '91, 345 - 354.

BARTMANN, L. & H. SPÄH (1998): Erfahrungen mit Aalbypässen an Wasserkraftanlagen Westfalens (Wesereinzugsgebiet). - Arbeiten Dt. Fischereiverband 70 (Durchgängigkeit von Fließgewässern für stromabwärts wandernde Fische), 93 - 117.

BARUS, V., J. GAJDUSEK, D. S. PAVLOV & V. K. NEZDOLIJ (1984): Downstream fish migration from two Czechoslovakian reservoirs in winter conditions. - Folia Zoologica 33: 167 - 181 BATES, D. W. & R. VINSONHALER (1957): Use of louvers for guiding fish. - Trans. Am. Fish. Soc. 86, 38 - 57.

BATES,D.W.&R.VINSONHALER(1957): Use of louvers for guiding fish. - Trans. Am. Fish. Soc. 86, 38 - 57.

BATES, D. W. & S. G. JEWETT(1961): Louver efficiency in deflecting downstream migrating steelhead. - Trans. Am. Fish. Soc. 90, 336 - 337.

BAUCH, G. (1953): Die einheimischen Süßwasserfische. - Radebeul (Neumann Verlag), 187 S.

BEALL, E. & C. MARTY (1983): Dévalaison et survie d'alevins de saumon atlantique, Salmo salar en milieu semi-naturel controlé. - Bull. Fr. Pêche Piscic. 290, 135 - 148.

BEAMISH, F. W. H. & I. C. POTTER (1975):The biology of the anadromous sea lamprey (Petromyzon marinus) in New Brunswick. - J. Zool. 177, 57 - 72.

BEAMISH, F. W. H. (1978): Swimming capacity. - In: Hoar, W. S. & D. J. Randall (Hrsg.): Fish physiology Vol. - VII. New York (Academic Press).

BEHRMANN-GODEL, J. (2000): Telemetrische Untersuchungen der herbstlichen Wanderung von Blank-aalen (Anguilla anguilla L.) in der Staustufe Trier. - AbschlußberichtfürdieAalschutzinitiative Rheinland-Pfalz / RWE Energie AG - Konstanz (Limnologisches Institut der Universität, AG Fischökologie), 29 S.

BELL, M. C. & A. C. DELACY (1972): A compendium on the survival of fish passing through spillways and conduits. - Fish. Engeneering Research Pro- gram, Corps of Engeneers, North Pacific Division, Portland, Oregon, 121 S.

BENTLEY, W. W. & H. L. RAYMOND (1968): Collection of juvenile salmonids from turbine intake gatewells of major dams in the Columbia River system. - Trans. Am. Fish. Soc. 97, 124 - 126.

BEN-YAMI, M. (1976): Fishing with light. - Surrey/ GB (Fishing News Books), 121 S.

BERG, R. (1985): Turbinenbedingte Schäden an Fischen. Bericht über Versuche am Laufkraftwasser- werk Neckarzimmern. - Langenargen (Institut für Seenforschung und Fischereiwesen), 25 S.

BERG, R. (1987): Fischschäden durch Turbinen. -Arb. Dt. Fischereiverb. 44: 41 - 47

BERG, R. (1988): Gutachterliche Stellungnahme zu Fischschäden durch den Betrieb der Wasserkraft-anlage "Am letzten Heller". - Langenargen (Institut für Seenforschung und Fischereiwesen), 34 S.

BERG, R. (1988): Gutachterliche Stellungnahme zu Fischschäden durch den Betrieb der Wasserkraft-anlage „Am letzten Heller". - Langenargen (Institut für Seenforschung und Fischereiwesen), 34 S.

BERG, R. (1993): Untersuchung einer Fischscheucheinrichtung am Kraftwerk Neckarzimmern. - Lan-genargen (Fischereiforschungsstelle des Landes Baden-Württemberg), 20 S.

BERG, R. (1994): Untersuchungen mit Fischscheucheinrichtungen am Kraftwerk Guttenbach (Neckar). - Langenargen (Fischereiforschungsstelle des Landes Baden-Württemberg), 25 S.

BERNOTH,E.M.(1990): Schädigung von Fischen durch Turbinenanlagen. - Dt.Tierärztl.Wschr.97,161-163.

BLAXTER, J. H. S. & W. DICKSON (1959): Observations on the swimming speed of fish. - J. Cons. perm. int. Explor. Mer 24, 472 - 479.

BLESS, R. (1990): Die Bedeutung von gewässerbaulichen Hindernissen im Raum-Zeit-System der Groppe (Cottus gobio L.). - Natur und Landschaft 65, 581 - 585.

BLESS, R., A. LELEK & A. WATERSTRAAT (1998): Rote Liste der in Binnengewässern lebenden Rundmäuler und Fische (Cyclostomata & Pisces). - Schriftenreihe für Landschaftspflege und Natur- schutz 55, 53 - 59.

BOETIUS, J. (1967): Experimental indication of lunar activity in European silver-eels, Anguilla anguilla (L.). - Medd. Dan. Fisk.- og Havunders. 6, 1 - 6.

BOLLRICH, G. & G. PREISSER (1992): Technische Hydromechanik, Band 1. - Berlin, 456 S.

BOMASSI, P. & F. TRAVADE (1987): Projet de réimplantation du saumon dans la partie supérieure de l'Allier:expériencessurlapossibilitédedévalaisondes saumoneaux au barrage hydroélectrique de Poutès. - In:Thibault, M. & R. Billard (Hrsg.): La restauration des rivières à saumons, Paris (INRA), 183 - 194.

BONE, Q. & N. B. MARSHALL (1985): Biologie der Fische. - Stuttgart (Gustav Fischer Verlag), 236 S.

BORN, O. (1995): Untersuchungen zur Wirksamkeit von FischaufstiegshilfenamunterfränkischenMain-Diss., TU München, Institut für Tierwissenschaften, 235 S.

BORNE, M. von dem (1882): Die Fischereiverhältnisse des Deutschen Reiches, Oesterreich-Ungarns, der Schweiz und Luxemburgs. - Berlin (Moeser-Verlag), 306 S.

BOWMAKER, J. K. (1990): Visual pigments of fishes. - In: DOUGLAS, R. & M. B.A. DJAMGOZ (Hrsg.): The visual system of fish. - London (Chapman and Hall), 81 - 107.

BRÄUTIGAM, R. (1961): Über Versuche zur Intensivierung des Blankaalfanges durch die Kombination von Lichtsperren und Großreusen und ihre grundsätzlichen Bedingungen. - Fischerei-Forschung 4/1, 19 - 25.

BRÄUTIGAM, R. (1962): Intensivierung des Blankaalfanges mit Hilfe von Lichtsperrketten und Bedingungen der gewerblichen Anwendung. - Fischereiforschung 5, 8 - 15.

BRETT, J. R. & D. MACKINNON (1953): Preliminary experiments using lights and bubbles to deflect migrating young spring salmon. - J. Fish. Res. Bd. Canada 10, 548 - 559.

BRITTAIN, J. E. & T. J. EIKELAND (1988): Invertebrate drift - a review. - Hydrobiologia 166, 77 - 93.

BROWN, R. E. (1997): Utilization of strobe lighting as a cost effective deterrent for fish turbine mortality. - "Fish Passage Workshop", May 1997, Milwaukee, Wisconsin, USA.

BRUIJS, M. C. M., H. V. WINTER, U. SCHWEVERS, U. DUMONT et al. (2003): Management of silver eel: Human impact on downstream migrating eel in the river Meuse. - Kema-Report 50180283-KPS/ MEC 03-6183, Abschlußbericht des EU-Forschungsprojektes Q5RS-2000-31141, 105 S.

BRUSCHEK, E. (1965): Elektrische Fischsperren. - Österr. Fischerei 18, 162 - 165.

BUELL, J. W. (1996): Biological performance evaluation for an overflow weir profile bar fish screen for East Fork irrigation district. - Portland/ Oregon (Buell & Associates, Inc.), 21 S.

BUTSCHEK, V., & J. HOFBAUER (1977): Versuche über die Schädigung von Aalen durch Kaplanturbinen. - Berichte Fischereiverb. Unterfranken 9, 173 - 180CADA, G.F. (1998): Better Science Supports Fish- Friendly Turbine Designs. - Hydro Review 11, 58.

CADA, G. F., C. C. COUTANT & R. R. WHITNEY (1997): Development of biological criteria for the design of advanced hydropower turbines. - Idaho Falls (U.S. Department for Energy, Idaho Operation Office), 85 S.

CHENOWETH, D. L. (1999): Bonneville lock and dam: Meeting the challenges of a new century. - Hydro Review 8/1999 special report, 2 - 6.

CHRISTEN (1996): Literaturrecherche über Mortalität von Fischen in Kaplan-Turbinen. - Im Auftrag der Badenwerk AG, Karlsruhe, 29 S.

CHRISTIE, A. E. (1990): A synopsis of Ontario hydro advances to protect and guide fish. - Proc. internat. Symp. on Fishways in Gifu, Japan, 37 - 44.

CLAY, H. C. (1995): Design of fishways and other fish facilities. - Boca Raton (CRC Press), 2. Auflage, 248 S.

COLLINS, G. B. (1976): Effects of dams on Pacific salmon and stealhead trout. - Marine Fish. Rev. 38/11, 39 - 46.

COOK, T. C., G. E. HECKER, H. B. FAULKNER & W. JANSEN (1997): Developmentofamorefishtolerant turbine runner. - Idaho Falls (Alden Research Laboratory Report 13-97/M 63 F), 172 S.

CRAMER, F. K., & R. C. OLIGHER (1964): Passing fish through hydraulic turbines. - Trans. Am. Fish. Soc. 93: 243 - 259.

DARTIGUELONGUE, J., & M. LARINIER (1987): Évaluation des dommages subis par les juvéniles lors de leur passage à travers les turbines des micro- centrales de St-Pee-sur-Nivelle et Lailhacar (Py- rénées atlantiques). - In: Thibault, M., & R. Billard (Hrsg.): La restauration des rivières a saumons, Paris (INRA), 175 - 182.

DEELDER, C. L. (1984): Synopsis of biological data on the Eel Anguilla anguilla (Linneaeus 1758). - FAO Fish. Synopsis 80 (Rev. 1), 1 - 73.

DENIL, G. (1937): La méchanique du poisson de rivière. - Ann. Trav. publ. Belg. 38, 255-284.

DIN 1184, Teil 1 (1993): Schöpfwerke/Pumpwerke; Planung, Bau und Betrieb. - Berlin (Beuth-Verlag).

DIN 19661, Teil 1 (1998): Wasserbauwerke:Kreuzungs- bauwerke, Durchleitungs- und Mündungs- bauwerke. - Berlin (Beuth Verlag).

DIN 19700, Teil 13 (1986): Stauanlagen, Staustufen - Berlin (Beuth Verlag).

DIN 4047, Teil 5 (1989): Landwirtschaftlicher Wasser- bau, Begriffe, Ausbau und Unterhaltung von Gewässern - Berlin (Beuth Verlag).

DIN 4048, Teil 1 (1987): Wasserbau, Begriffe Stau- anlagen - Berlin (Beuth Verlag).

DRIMMELEN, D. E. van (1951): Vangst van schieraal met behulp van licht. - Visserij Nieuws 3, 137 - 140.

DUCHARME, L. J. A. (1972): An application of louver deflectors for guidingAtlantic salmon (Salmo salar) smolts from power turbines. - J. Fish. Res. Bd. Canada 29, 1397 - 1404.

DUMONT, U. (2000): Bericht zum Verhalten eines Wedge-wire-screen an einer kleinen Wasserkraft- anlage. Aachen (Ingenieurbüro Floecksmühle).

DUMONT, U. et al. (2002): Studie zur Ermittlung und gewässerökologischen Bewertung von Stauanlagen in den Gewässern von NRW und zur Ausweisung von gewässerökologisch angepassten energetischen Nutzungsmöglichkeiten.-ImAuftragdesMinisteriums für Umwelt, Naturschutz, Verbrau-cherschutz und Landwirtschaft des Landes NRW. - Aachen, (in Bearbeitung).

DVWK (Deutscher Verband für Wasserwirtschaft und Kulturbau e.V.) (1996): Fischaufstiegsanlagen - Bemessung, Gestaltung, Funktionskontrolle. - Bonn (Wirtschafts- und Verlagsgesellschaft Gas und Wasser mbH), Merkblätter zur Wasserwirtschaft Heft 232, 120 S.

EBEL, G. (2001): Untersuchungen zur Funktionsfähigkeit der Fischabstiegsanlage am Wasserkraft- anlagenstandort „Mahlmühle Weißenfels" (Saale). - Halle (Büro für Gewässerökologie und Fischerei- biologie), Studie im Rahmen des Planfeststellungsverfahrens zur Reaktivierung der Wasserkraft- nutzung, 66 S.

EBEL, W. J. (1980): Transportation of chinook salmon, Oncorhynchus tshawytscha, and steelhead, Salmo gairdneri, smolt in the Columbia River and effects on adult returns. - US National Marine Fisheries Service, Fish. Bull. 78, 491 - 505.

EDWARDS, S. J., J. DEMBECK, T. E. PEASE, M. J. SKELLY & D. RENGERT (1988): Effectiveness of angled-screen intake system. - J. Hydr. Eng. 114, 626 - 639.

EG-WRRL (2000): Richtlinie 2000/60/EG des Euro- päischen Parlaments und des Rates vom 23. Ok- tober 2000 zur Schaffung eines Ordnungsrahmens für Maßnahmen der Gemeinschaft im Bereich der Wasserpolitik. - Amtsblatt der Europäischen Gemeinschaften L 327 vom 22. 12. 2000, 1 - 72.

EHRENBAUM, E. (1894): Beiträge zur Naturgeschichte einiger Elbfische (Osmerus eperlanus L., Clupea finta Cuv., Acerina cernua L., Acipenser sturio L.). - Wiss. Meeresunters. NF. 1, 37 - 82.

EICHER, G. J. (1985): Fish passage: protection of downstream migrants. - Hydro Review 1985, 95 - 99.

EICHER, J. (1970): Fish passage. - Am. Fish. Soc. Spec. Publ. 7, 163 - 171.

ELLIOTT, J. M. (1971): Upstream movements of benthic invertebrates in a Lake District stream. - J. Anim. Ecol. 40, 235 - 252.

EnBW ING (2000): InterneFirmenunterlagen-(unveröff.).

ENGEL,A. P. & E. WEBER (2003): Lochblechrechen - neue Anwendungen einer alten Technik. - Wasser- wirtschaft 93/6, 42 - 44.

ERZINGER, S. (1999): Technischer Bericht Sulzer Hydro Nr. Z/H-600/99-016, 11 - 13. - Ravensburg (Sulzer Hydro).

FÄNGSTAM, H. (1993): Individual downstream swimming speed during the natural smolting period among young of Baltic salmon (Salmo salar). - Can. J. Zool. 71, 1782 - 1786.

FÄNGSTAM, H., I. BERGLUND, M. SJÖBERG & H. LUNDQVIST (1993): Effects of size and early se- xual maturity on downstream migration during smolt- ing in Baltic salmon (Salmo salar). - J. Fish Biol. 43, 517 - 529.

FAWLEY aquatic research laboratories Ltd, Report to the National Rivers Authority, No. FIR 087/94.

FAY, R. R. (1988): Hearing in vertebrates, a: Psychophysics databook. - Winnetka, Illinois, USA (Hill- Fay Associates).

FIELDS, P. E. & G. L. FINGER (1956): The effectiveness of constant and intermittently flashing light barriers in guiding young sliver salmon. - Technical Report No. 22, College of Fisheries, Univ. of Washington.

FISH GUIDANCE SYSTEMS Ltd & HYDRO ENERGY DEVELOPEMENTS Ltd (1996): Testing of an acoustic smolt deflection system, Blantyre Hydroelectric Power Scheme. ETSU H/01/00046/ REP.

FISHER,R.,D.MATHUR,P. G.HEISEY,R.WITTINGER, R. PETERS, B. RINEHART, S. BROWN & J. R. SKALSKI (2000): Initial test results of the new Kaplan Minimum Gap Runner design on improving. - Turbine Fish Passage Survival for the Bonneville First Powerhouse. - Rehabilitation Project, VOITH HYDRO, 12 S.

FLETCHER, R. I. (1990): Flow dynamics and fish recovery experiments: water intake systems. - Trans. Am. Fish. Soc. 119, 393 - 415.

FONTAINE, Y. (1994): L'argenture de l'anguille: métamorphose, anticipation, adaptation. - Bull. Fr. Pêche Piscic. 335, 171 - 185.

FRANKE et al. (1997): Development of environmentally advanced hydropower turbine system design concepts. - Idaho (National Engineering and Environmental Laboratory), INEEL/EXT-97-00639.

FREDRICH, F. & H. H. ARZBACH (2002): Wanderungen und Uferstrukturnutzung der Quappe, Lota lota in der Elbe, Deutschland. - Z. Fischk. Suppl. 1, 159 - 178.

FREDRICH, F. (1999): Wanderungen und Habitatwahl potamodromer Fische in der Elbe. - Statusseminar Elbe-Ökologie 2. - 5. November Berlin, Tagungsband, 50 - 53.

GEITNER, V. & U. DREWES (1990): Entwicklung eines neuartigen Pfahlfischpasses. - Wasser & Boden 42, 604 - 607.

GENNERICH, J. (1954): Elektrische Fischsperre an der Mosel. - Mitt. BfG 56, 9 - 12.

GERHARDT, P. (1893): UeberAalleitern undAalpässe. - Z. Fischerei 1, 194 - 199.

GESSEL, M. H., J. G. WILLIAMS, D. A. BREGE & R. F. KRCMA (1991): Juvenile salmonid guidance at the Bonneville Dam second powerhouse, Columbia River, 1983 - 1989. - North Am. J. Fish. Manage- ment 11, 400 - 412.

GIESECKE, J. & E. MOSONYI (2003): Wasserkraftanlagen: Planung, Bau und Betrieb. - Berlin (Sprin- ger-Verlag), 3. Auflage, 813 S.

GLOSS, S. P., & J. R. WAHL (1983): Mortality of juvenile salmonids passing through Ossberger crossflow turbines at small-scale hydroelectric sites. - Trans. Am. Fish. Soc. 112, 194 - 200.

GÖHL, C. (2001): Hydraulischer Modellversuch zur Entwicklung einer Fischabstiegsanlage fürAale an der Staustufe Dettelbach. - Tagungsband Symposium ARGEAlpine Wasserkraft am 18./19. Oktober 2001 in Chur, Schweiz, 87 - 99.

GÖRLACH, J. & F. KRÜGER (1996): Grundlagenermittlungen zur Überprüfung, Umgestaltung und zum Neubau von Fischaufstiegsanlagen in Fließgewässern 1. Ordnung im Land Brandenburg. – Müncheberg (ZALF), im Auftrag des LUA Brandenburg, 86 S.

GOSSET, C. & F. TRAVADE (1999): Étude de dispositifs d'aide à la migration de dévalaison des salmonidae: barrières comportementales. - Cybium 23/1 suppl. 45 - 66.

GRAY, J. (1953): The locomotion of fishes. - In: Marshall, S. M. & A. P. Orr (Hrsg.): Essays in marine biology, Edinburgh (Oliver & Boyd), 1 - 16.

GRIVAT, J. (1983): Conception and application of electric screens to fish. - Bulletin de l´Association Suisse des Électriciens 74, 1294 - 1297.

HADDERINGH, R. H. & H. D. BAKKER (1998): Fishmortality due to passage though hydroelectric power stations on the Meuse and Vecht rivers. - In: JUNGWIRTH , M. SCHMUTZ & S. WEISS (Hrsg.): Fish migration and fish bypasses. - Oxford (Fishing News Books), 315 - 328.

HADDERINGH, R. H. & H. JANSEN (1990): Electric fish screen experiments under laboratory and field conditions. - In: Cowx, I. G. (Hrsg.): Developments in electric fishing, Cambridge (Fishing News Books), 266 - 280.

HADDERINGH, R. H. (1978): Mortality of young fish in the cooling water system of Bergum power station. - Proc. International Association of Theoretical and Applied Limnology 20 (Kopenhagen, 7. - 14. 8. 1977), 1822 - 1836.

HADDERINGH, R. H. (1982): Experimental reduction of fish impingement by artificial illumination at Bergum power station. - Int. Revue ges. Hydrobiol. 67, 887 - 900.

HADDERINGH, R. H. (1993): Das Wegführen von Aalen von Wassereinlässen von Kraftwerken mit- tels Licht. - Vortrag 7. SVK Fischereiseminar, Januar 1993, Bad Godesberg.

HADDERINGH, R. H., & A. G. SMYTHE (1997): Deflecting eels from power stations with light. - Paper presented at the "Fish passage workshop", May 6 - 8, 1997, Milwaukee, USA, 7 S.

HADDERINGH, R. H., G. H. M. VAN AERSSEN, R. F.

DE BEIJDER & L. J. VAN DER VELDE (1999): Reaction of silver eels to artificial light sources and water currents: an experimental defection study. - Regulated Rivers: Research and Management 15, 365 - 371.

HADDERINGH, R. H., J. W. VAN DER STOEP & J. W. P. M. HABRAKEN (1992): Deflecting eels from water inlets of power stations with light. - Irish Fisheries Investigations Series A (Freshwater) 36, 80 - 89.

HADDERINGH, R. H., KOOPS, F. B. J. & VAN DER STOEP, J. W. (1988): Research on fish protection at Dutch thermal and hydropower stations. - Kema Scientific & Technical Reports 6/2, 57 - 68.

HAEFNER, J. W. & M. D. BOWEN (2002): Physicalbased model of fish movement in fish extraction facilities. - Ecological Modelling 152, 227 - 245.

HALSBAND, E. & I. HALSBAND (1975): Einführung in die Elektrofischerei. - Schriften Bundesforschungs-anstalt für Fischerei 7, 2. Auflage.

HALSBAND, E. & I. HALSBAND (1989): Wasserkraftwerke werden erst durch elektromechanische Fischumleitungen für die Fische umweltfreundlich. - Fischwirt 39/1, 3 - 4.

HALSBAND, E. (1989): Nur durch elektrischen Impulsstrom ist das Scheuchen und Leiten von Fischen wirksam möglich. - Fischwirt 39/10, 1 - 4.

HANSON, B. N. (1999): Effectiveness of two surface bypass facilities on the Connecticut River to pass emigrating Atlantic salmon smolts. - In: Odeh, M. (Hrsg.): Innovations in fish passage technology, Bethesda/Md. (American Fisheries Society), 43 - 59.

HANSON, C. H., J. R. WHITE & H. W. LI (1977): Entrapment and impingement of fishes by power plant cooling-water intakes: an overview. - Marine Fish. Rev. 77/10, 7 - 17.

HARDEN JONES, F. R. (1968): Fish Migration. - London (Edward Arnold), 325 S.

HARO, A. (2000): Downstream Movement and Passage of Silver Eel Phase American Eel in the Connecticut Mainstream. Vortragsmanuskript. - Turners Falls /Ma, USA (S.O. Conte Anadromous Fish Research Center).

HARO,A., D. DEGAN, J. HORNE, B. KULIK & J. BOUBEE (1999): An investigation of the feasibility of employing hydroacoustic monitoring as a means to detectthepresenceandmovementoflarge,adulteels (Genus Anguilla). - S. O. Conte Anadromous Fish Research Center Internal Report No. 99-01, 39 S.

HATTOP, W. (1964): Erfahrungen mit Elektro-Fischabweisern. - Dt. Fischerei-Z. 11, 321 - 328.

HAUNS, A. & R. HAUNS (1996): Die Aalschokker-Fischerei auf der badischen Seite des Rheins - Der Aal und sein Geheimnis. - Rastatt (Selbstverlag), 164 S.

HAWKINS, A. D. (1986): Underwater sound and fish behavior. - In: Pitcher, J. T. (Hrsg.): The behavior of teleost fishes. - London (Chapman & Hall).

HAYMES, G. T., P. H. PATRICK & L. J. ONISTO (1984): Attraction of fish to mercury vapour light and its application in a generating station forebay. - Int. Revue ges. Hydrobiol. 69, 867 - 876.

HECKER, G. E., T. C. COOK & W. JANSEN (1997): A new fishfriendly turbine runner. - Proceedings of the international conference on Hydropower, Waterpower ´97, 383 - 391.

HEISEY, P. G., D. MATHUR & L. D'ALLESANDRO (1993):A new technique for assessing fish passage survival at hydro power stations. - Can. Tec. Rep. Fish. Aquat. Sci. 1905, 32 - 38.

HEMSEN, J. (1960): Fische und Turbinen. - Österr. Fischerei 13, 113 - 122.

HOEK, P. P. E. (1901): Bericht über Beobachtungen und Untersuchungen der Lebensweise des Lach- ses im Gebiete der oberen Mosel in der Zeit vom August bis November 1900. - Fischerei-Zeitung (Neudamm) 4, 625 - 630.

HÖFER, R. & U. RIEDMÜLLER (1996): Fischschäden bei Salmoniden durch Turbinen von Wasserkraft-anlagen.- Kirchzarten (Büro für Nutzung und Ökologie der Binnengewässer), im Auftrag des Re-gierungspräsidiums Freiburg, 85 S.

HOLCIK, J. (Hrsg.) (1986): The Freshwater Fishes of Europe, Bd. 1,I: Petromyzontiformes. - Wiesbaden (Aula-Verlag), 313 S.

HÖLKE, H. (1964): Aalfang mit Hilfe von elektrischem Licht in der Fluss-Fischerei. - Dt. Fischerei-Zeitung 11, 82 - 88.

HOLZNER, M. (1999): Untersuchungen zur Vermeidung von Fischschäden im Kraftwerksbereich, dar- gestellt am Kraftwerk Dettelbach am Main / Unter- franken. - SchrR. Landesfischereiverband Bayern 1, 224 S.

HOLZNER, M. (2000): Untersuchungen über die Schädigung von Fischen bei der Passage des Main-kraftwerks Dettelbach. - Dissertation TU München, Insitut für Tierwissenschaften, 251 S.

HUET, M. (1949): Aperçu des relations entre la pente et les populations piscicoles des eaux courantes. - Schweiz. Z. Hydrol. 11, 322 - 351.

ILLIES, J. (1961): Versuch einer allgemeinen biozönotischen Gliederung der Fließgewässer. - Internat. Revue ges. Hydrobiol. 46, 205 - 213.

INGENDAHL, D. (1993): Untersuchung des Wanderverhaltens des atlantischen Lachses Salmo salar und der Bachforelle Salmo trutta fario, insbesondere an hydroelektrischen Einrichtungen. - Diplomarbeit, Univ. Köln, 132 S.

JENS, G. (1953): ÜberdenlunarenRhythmusder Blankaalwanderung. - Arch. Fischereiwiss. 4, 94 - 110.

JENS, G. (1987): Plädoyer für den 20-mm-Turbinenrechen. - Das Wassertriebwerk 36, 145 - 147.

JENS, G. (1992): Stellungnahme zum Entwurf eines "Beobachtungs- und Warnplans zum Erkennen des

kritischen Zeitpunkts der Auslösung des Aalzugs in der Fulda" vom 2. Juni 1992. - Boppard, 9 S.

JENS, G. et al. (1997): Fischwanderhilfen: Notwendigkeit, Gestaltung, Rechtsgrundlagen. - SchrR. Ver-band Dt. Fischereiverwaltungsbeamter und Fischereiwissenschaftler 11, 113 S.

JOHNSON, D. E., P. E. FIELDS, P. S. KAREKAR & G. L FINGER. (1958): Conditions under which light attracts and repels pre-migratory salmon in clear and turbid, still and running water. - Technical Re- port No. 42, College of Fisheries, Univ. of Washington.

JOLIMAITRE, J. F. (1992): Franchissement par l'alose feinte de l'aménagement de la chute de Vallabrègues: étude du franchissement de l'écluse de nagivation. Avant-projet de passe à poissons sur le seuil de Beaucaire. - Conseil Supérieur de la Pêche, 42 S.

JONSSON, B. & J. RUUD-HANSEN (1985): Water temperature as the primary influence on timing of seaward migrations ofAtlantic salmon (Salmo salar) smolts. - Can. J. Fish. Aquat. Sci. 42, 593 - 595.

JONSSON, N. (1991): Influence of water flow, water temperature and light on fish migration in rivers. - Nordic J. Freshw. Res. 66, 20 - 35.

JÖRGENSEN, L., L. KROLL & K. OBERWAHREN- BROCK (1999): Die Aalabwanderung an der Stau-stufe Fankel/Mosel: Auswertung des Fischereiversuchs vom 04. 09. 1993 bis 12. 12. 1993. - In: Aalschutzinitiative Rheinland-Pfalz / RWE-Energie AG (Hrsg.): Projektfortschrittsbericht 1, 57 - 78.

KARP, C. A., L. HESS & C. LISTON (1995): Reevaluation of louver efficiencies for juvenile chinook salmon and striped bass at the Tracy fish collection facility, Tracy, California, 1993. - Tracy Fish Collection Facility Studies 3, 29 S.

KAUSCH, H. (1972): Stoffwechsel und Ernährung der Fische. - In: Handbuch der Tierernährung, Bd. 2, Hamburg (Paul Parey Verlag), 690 - 738.

KEMA (1990): Afleiden van vis met licht bij de centrale Bergum. -Arnhem/NL, Rapport Nr. 98265-MOB 90- 3382.

KEMA (1993): Reactie van licht op vis (laboratorium- experimenten), deel 2: paling (Salmo trutta trutta L.). - Arnhem/NL (KEMA), Rapport Nr. 63635-KES/ WBR 93-3109.

KEMA (1994): Reactie van zeeforel (Salmo trutta trutta L.) op zeer lage lichtniveaus tijdens laboratoriumexperimenten. -Arnhem/NL (KEMA), Rapport Nr. 63863-KES/WBR 94-3120.

KEMA(1998): Tegengaan van visinzuiging met strobos- coop lampen. Praktijkexperimenten bij de centrale Diemen. - Arnhem/NL (KEMA), Rapport Nr. KPG/ CET 98-5060.

KINZELBACH, R. (1987): Das ehemalige Vorkommen des Störs, Acipenser sturio (Linneaeus, 1758), im Einzugsgebiet des Rheins (Chondrostei: Acipen- seridae). - Z. angew. Zool. 74, 167 - 200.

KLAUSEWITZ, W. (1975): Die Bioindikatorfunktion einer alten Fischsammlung aus dem Main. -Aus Hessischen Museen 1, 55 - 58.

KLEEMANN, J. (2003): Gutachten zur Wirkungsgradbestimmung an einer Wasserkraftschnecke. - Kaiserslautern (Technische Universität Kaiserslautern, Lehrstuhl für Strömungs- und Verdrängungsmaschinen), 14 S.

KLEINSCHMIDTASSOCIATES(1997): Karapiro hydroelectric station downstream eel passage scoping study. - Hamilton (New Zealand), 35 S.

KLINGE, M. (1994): Fish migration via the shipping lock at the Hagestein barrage: results of an indicative study. - Water Science & Technology 29/3, 357 - 361.

KNUDSEN, F. R., C. B. SCHRECK, S. M. KNAPP, P. S. ENGER & O. SAND (1997): Infrasound produces flight and avoidance responses in Pacific juvenile salmonids. - J. Fish Biol. 51, 824 - 829.

KNUDSEN, F. R., P. S. ENGER & O. SAND (1992): Awareness reactions and avoidance responses to sound in juvenile Atlantic salmon, Salmo salar L. - J. Fish Biol. 40, 523 - 534.

KNUDSEN, R. F., P. S. ENGER & O. SAND (1994):Acoi-dance responses to low frequency sound in downstram migratingAtlantic salmon smolt, Salmo salar. - J. Fish Biol. 45, 227 - 233.

KOCH, W. (1932): Fischmarkierungsversuche am badischen Rhein und Neckar. - Badische Fischereizeitung 9, 145 - 156 und 164 - 176.

KOOPS, H. (1960): Die Bedeutung der Staustufe Geesthacht für die Quappenfischerei der Elbe. - Kurze Mitt. Inst. Fischereibiologie Univ. Hamburg 10, 43 - 56.

KOOPS, H. (1962): Die Wanderung des Aals, Anguilla anguilla L., in Abhängigkeit vom Sommerhochwasser. - Kurze Mitt. Inst. Fischereibiologie Univ. Hamburg 12, 19 - 26.

KOTHÉ, P. (1959): Erprobung einer elektrischen Fischpasshinweisung. - Dt. gewässerkundl. Mitt. 3, 112.

KUHLMANN, H. (1997): Zur Bestandssituation des Europäischen Aales. - Arbeiten Dt. Fischereiverband 69, 47 - 61.

KYNARD, B. & J. O'LEARY (1990): Behavioral guidance of adult American shad using underwater AC electrical and acoustical fields. - Proc. internat. Symp. on Fishways in Gifu, Japan, 131 - 135.

LANDESFISCHEREIVERBAND BAYERN E.V. (HRSG.) (2000): Bedeutung und Wiederherstellung der Fließgewässervernetzung. - Schriftenreihe des Landesfischereiverbandes Bayern 2, 72 S.

LARINIER, M & F. TRAVADE (1999): The development and evaluation of downstream bypasses for juvenile salmonids at small hydroelectric plants in France.-- In: Odeh, M. (Hrsg.): Innovations in fish passage technology. - Bethesda/Md. (American Fisheries Society), 25 - 42.

LARINIER, M. & F. TRAVADE (2002): Downstreammigration: problems and facilities. - Bull. Fr. Pêche Piscic. 364 suppl. 181 - 205.

LARINIER, M. & J. DARTIGUELONGUE (1989): La circulation des poissons migrateurs et transit à tra- vers les turbines des installations hydroélectriques. - Bull. Fr. Pêche Piscic. 312/313, 90 S.

LARINIER, M. & S. BOYER-BERNARD (1991a): La dévalaison des smolts de saumon Atlantique au barrage de Poutès sur l'Allier (43): utilisation de lampes a vapeur de mercure. - Bull. Fr. Pêche Piscic. 323, 129 - 148.

LARINIER, M. & S. BOYER-BERNARD (1991b): Dévalaison des smolts et efficacité d'un exutoire de dévalaison à l'usine hydroélectrique d'Halsou sur la Nive. - Bull. Fr. Pêche Piscic. 321, 72 - 92.

LARINIER, M. (1996): Passes à poissions. - Paris (CSP, Collection Mise au Point).

LARINIER, M. (2002): Biological factors to be taken into account in the design of fishways, the concept of obstruction to upstream migration. - Bull. Fr. Pêche Piscic. 364 suppl., 28 - 38.

LARINIER, M., F. TRAVADE, D. INGENDAHL, J. M. BACH & D. PUJO (1993): Experimentation d'un dispositif de dévalaison pour les juvéniles de sau- monAtlantique (année 1992) usine hydroélectrique de Soeix (Gave d'Aspe). - Électricité de France, Direction des Études et Recherches.

LELEK, A. & C. KÖHLER (1990): Restoration of fish communities of the river Rhine two jears after a heavy pollution wave. - Regulated Rivers: Research and Management 5, 57 - 66.

LEONHARDT, E. (1905): Der Lachs: Versuch einer Biologie unseres wertvollsten Salmoniden. - Neudamm, 60 S.

LESKE & STRUNCK (1993): Hydraulische Untersuchungen der Stepenitz. - Magdeburg (PROWA Planungsgesellschaft mbH), im Auftrag des LUA Brandenburg.

LIENING, H. J. (1996): Der Neubau der Wasserkraftanlage Karlstor in Heidelberg. - Wasserwirtschaft 86, 402 - 405.

LOEFFELMAN, P. H., D. A. KLINECT & J. H. VAN HASSEL (1991): Fish protection at water intakes using a new signal development process and sound system. - Waterpower '91, 355 - 365.

LOWE, R. H. (1952): The influence of light and other factors on the seaward migration of silver eel. - J. Anim. Ecol. 21, 275 - 309.

MAES,J.,B.PEETERS,F.OLLEVIER,A.PARMENTIER, E.THOELEN, H. FRANCOIS,A. W. HTURNPENNY, D.J.LAMBERT&J.R.NEDWELL(1999): Evaluation of the fish guidance system at the cooling water inlet of the nuclear power plant Doel 3 / 4. - Unpublished report to Electrabel, Doel. - Leuven/B (University of Leuven).

MANN, H. (1965): Ergebnisse der Aalmarkierungen in der Elbe im Jahr 1963. - Fischwirt 15, 1 - 7.

MANTEIFEL, B. P., I. I. GIRSA& D. S. PAVLOV (1978): On the rhythms of fish behaviour. - In: J. E.THORPE (Hrsg.):RhythmicActivityofFishes,London(Academic Press), 215 - 224.

MARTIN, P. D. & C. W. SULLIVAN (1992): Guiding American shad with strobe lights. - Hydro Review 11/7, 52 - 58.

MARZLUF, W. (1985): Fische elektronisch verscheuchen. - Elektrische Energie-Technik 39/4, 66 - 67.

MATHUR, D., P. G. HEISEY & D.A. ROBINSON (1994): Turbine-passage mortality of juvenile American shad at a low-head hydroelectric dam. - Trans. Am. Fish. Soc. 123, 108 - 111.

MATOUSEK, J. A., T. E. PEASE, J. G. HOLSAPPLE & R. C. ROBERTS (1988): Biological evaluation of angledscreen test facility. - J. Hydr. Eng. 114, 641 - 649.

MATTHEWS, G. M., G.A. SWAN & J. R. SMITH (1977): Improved byass and collection system for protection of juvenile salmon and steelhead trout at Lower Granite Dam. - Marine Fish. Rev. 77/7, 10 - 14.

MATTUKAT, F. (1999): Hydroakustische Untersuchungen zur Aalabwanderung und Überprüfung von Standort und Fängigkeit des in der Mosel ausgebrachten Hamens. - Berlin (Institut für Gewässerökologie und Binnenfischerei).

McCAULEY, D. J., L. MONTUORI, J. E. NAVARRO & A. R. BLYSTRA (1996): Using strobe lights, air bubble curtains for cost effective fish diversion. - Hydro Review 15, 42 - 51.

McKEOWN, B. (1984): Fish Migration. - London (Croom Helm Ltd.), 224 S.

MEYER-WAARDEN, P. F. (1957): Überdenelektrischen Scheucheffekt und seine Verwendung in Fischerei und Wasserbau. - Arch. Fischereiwiss. 7, 192 - 209.

MIGADO (Association Migrateurs Garonne Dordogne) (2003): Visite technique bassin Garonne Dordogne. - Le Passage (MIGADO), Exkurionsführer, 28 S.

MOHR, E. (1952): Der Stör. - Leipzig (Neue Brehm- Bücherei -Akademische Verlagsgesellschaft Geest & Portig), 66 S.

MONTÉN, E. (1985): Fish and Turbines - Fish injuries during passage through power station turbines. - Stockholm (Vattenfall), 111 S.

MOSONYI, E. (1966): Wasserkraftwerke. - Düsseldorf (VDI-Verlag) 2 Bände, zus. 2391 S.

MUIR, J. F. (1959): Passage of young fish through turbines. - J. Power Division, Proc. Am. Soc. Civil Eng. 85 PO, 23 - 46.

MÜLLER,K.&E.BERG(1982):Springmigrationofsome anadromous freshwater fish species in the northern Bothnian Sea. - Hydrobiologia 96, 161 - 168.

MÜLLER, K. (1987a): The migration behaviour and orientation of the coastal population of the Burbot (Lota lota L.) in the Gulf of Bothnia. - Fauna norrlandica 1, 1 - 15.

MÜLLER, K. (1987b): Der Wanderhecht. - Österr. Fischerei 40, 196 - 200.

MÜLLER, R. & H. J. MENG (1990): The fate of the fish populations in the river Rhine after the Schweizerhalle accident. - Limnologie aktuell 1 (Biologie des Rheins), 405 - 421.

MUNLV (Ministerium für Umwelt, Naturschutz, Landwirtschaft und Verbraucherberatung) (2001): Wanderfischprogramm Nordrhein-Westfalen. - Düsseldorf, 110 S.

NAUDASCHER, E. (1992): Hydraulik der Gerinne und Gerinnebauwerke. - Wien (Springer-Verlag), 352 S.

NEITZEL,D.A.,T.J.CLUNE&C.S.ABERNETHY(1990): Evaluation of rotary drum screens used to protect juvenile salmonids in the Yakima river basin, Washington, USA. - Proc. internat. Symp. on Fishways in Gifu, Japan, 523 - 529.

NEMETH, R. S. & J. J.ANDERSON (1992): Response of juvenile coho and chinook salmon to strobe and mercury vapor lights. - North Am. J. Fish. Management 12, 684 - 692.

OBERWAHRENBROCK, K. (1999): Grundlagen und Anforderungen an ein Frühwarnsystem zur Vorhersage von Aalabwanderungszeiträumen. - In: Aalschutzinitiative Rheinland-Pfalz / RWE-EnergieAG (Hrsg.): Projektfortschrittsbericht 1, 19 - 33.

ODEH, M. & C. ORVIS (1998): Downstream fish passage design considerations and developments on hydroelectric projects in the north-east USA. - In: Jungwirth, M. et al. (Hrsg.): Fish migration and fish bypasses. - Oxford (Fishing News Books), 67 - 280.

ODEH, M. (Hrsg.) (1999): Innovations in Fish Passage Technology. - Bethesda/Md, USA (American Fisheries Society).

ODGAARD,A. J., M. P. CHERIAN & R.A. ELDER (1988): Fish division in hydropower intake. - J. Hydr. Eng. 114, 505 - 519.

PARK, D. L., & E. FARR (1972): Collection of juvenile salmon and steelhead trout passing orifices in gatewells of turbine intakes at Ice Harbour dam. - Trans. Am. Fish. Soc. 101, 381 - 384.

PATRICK, P. H., R. W. SHEENAN & B. SIM (1982): Effectiveness of a strobe light eel exclusion scheme. - Hydrobiologia 94, 269 - 277.

PAVLOV, D. S. (1969): Entrapment of fingerlings in pumping installations as related to features of their behaviour and orientation in the stream of water. - Problems of Ichthyology 9, 237 - 243.

PAVLOV, D. S. (1989): Structures assisting the migrations of non-salmonidfish:USSR.-FAO FisheriesTechnical Paper 308, 1 - 97.

PAVLOV, D. S. (1994): The downstream migration of young fishes in rivers: mechanisms and distribution. - Folia Zoologica 43, 193 - 208.

PAVLOV, D. S.,A. I. LUPANDIN & V. V. KOSTIN (2002): Downstream migration of fish through dams of hydroelectric power plants. - Oak Ridge / Tennessee (Oak Ridge National Laboratory), 249 S.

PECHLANER, R. (1986): Driftfallen und Hindernisse für die Auswärtsbewegung von wirbellosen Tieren in rhithralen Fließgewässern. - Wasser undAbwasser 30, 431 - 463.

PELZ, G. R. & A. KÄSTLE (1989): Ortsbewegungen der Barbe Barbus barbus (L.) - radiotelemetrische Standortbestimmungen in der Nidda (Frankfurt/ Main). - Fischökologie 1/2, 15 - 28.

PRENTICE, E. F., T.A. FLAGG, C. S. MCCUTCHEON & D. F. BRASTOW (1990): PIT-tag monitoring systems for hydroelectric dams and fish hatcheries. - Am. Fish. Soc. Symp. 7, 323 - 334.

PRESS, H. & SCHRÖDER, R. (1966): Hydromechanik im Wasserbau. Verlag von Wilhelm Ernst & Sohn, Berlin, München.

PROTASOV, V. R. (1970): Vision and near orientation of fish. - Jerusalem (Israel program for scientific translations), 175 S.

PUGH, J. R., G. L. MONAN & J. R. SMITH (1971): Effect of water velocity on the fish guiding efficiency of an electrical guiding system. - Fishery Bulletin 68, 307 - 324.

RABEN, K. von (1955): Kaplanturbinen und Fische. - Wasserwirtschaft 45: 196 - 200.

RABEN, K. von (1957a): Zur Beurteilung der Schädlichkeit der Turbinen für Fische. - Wasserwirtschaft 47, 60 - 63.

RABEN, K. von (1957b): Zur Frage der Beschädigung von Fischen durch Turbinen. - Wasserwirtschaft 47: 97 - 100.

RABEN, K. von (1957c): Über Turbinen und ihre schädliche Wirkung auf Fische. - Z. Fischerei NF. 6, 171 - 182.

RASMUSSEN,G.,K.AARESTRUP&N.JEPSEN(1996): Mortality of sea trout and Atlantic salmon smolts during seaward migration through rivers and lakes inDenmark.ICESC.M.AnaCatfishcommittee, theme cession on anadromous and catadromous fish restoration programs: A time for evaluation, 14 S.

RATHCKE, P. C. (1994): Untersuchung über die Schädigung von Fischen durch Turbine und Rechen im Wasserkraftwerk Dringenauer Mühle (Bad Pyrmont). - Arbeiten des Deutschen Fischereiverbandes 65, 37 - 65.

RATHCKE, P. C. (1997): Effektivitätsüberprüfung einer neu installiertenAalableitung im Kraftwerk "Dringenauer Mühle" (Bad Pyrmont). - Wedel (Fischereiwissenschaftlicher Untersuchungsdienst P. C. Rathcke), im Auftrag des Niedersächsischen Landesamtes für Ökologie, 23 S.

RAUCK, G. (1980): Mengen und Arten vernichteter Fische und Krebstiere an den Rechen des Einlaufbauwerkes im Kernkraftwerk Brunsbüttel. - Veröff. Inst. Küsten- und Binnenfischerei 71, 21 S.

RAYMOND, H. L. (1979): Effects of dams of impoundments on migrations of juvenile Chinook salmon and steelhead from the Snake River, 1966 - 1975. - Trans. Am. Fish. Soc. 108, 505 - 529.

RISSLER, P. (1998): Talsperrenpraxis - München (R. Oldenbourg Verlag).

RUETTIMANN, M. (1980): Autoekologische Untersuchung der Eintagsfliegenlarve Ecdyonurus venosus (Fabr.) (Ephemeroptera) unter besonderer Berücksichtigung der Aufwanderung. - Dissertation, ETH Zürich, 66 S.

RUGGLES, C. P. (1990): A critical review of fish exclusion systems for turbine intakes with particular reference to a site on the Connecticut River, USA. - Proc. internat. Symp. on Fishways in Gifu, Japan, 151 - 156.

SAND, O., P. S. ENGER, H. E. KARLSEN, F. KNUDSEN & T. KVENSTUEEN (2000): Avoidance responses to infrasound in downstream migrating European silver eels, Anguilla anguilla. Environmental Biology of Fishes 57, 327 - 336.

SCHEFFEL, H. J., R. KNUST & M. SCHIRMER (1995): Der Nordseeschnäpel Coregonus oxyrhynchus: Bald wieder befischbare Populationen in niedersächsischen Gewässern? - Fischer & Teichwirt 46, 19 - 21, 38 - 39.

SCHEURING, L. (1929): Die Wanderungen der Fische I. - Ergebn. Biol. 5, 405 - 691.

SCHEURING, L. (1930): Die Wanderungen der Fische II. - Ergebn. Biol. 6, 4 - 326.

SCHIEMENZ, F. (1960): Unterschied der Wanderungen der Fische, insbesondere der Aale verschiedenen Reifegrades, im unkanalisierten Strom und im kanalisierten Strom. - Z. Fischerei NF. 9, 133 - 154.

SCHIEMENZ, F. (1962): Wanderweite und Wanderdruck bei den Fischen und die Auswirkungen auf den Fischbestand in Flussstrecken mit Wehren. - Österr. Fischerei 15, 22 - 26.

SCHILLING, R, H. STEIN & H. STROBL (2000): Fischfreundliche Turbinen; Numerische Simulation des Fischdurchganges durch Wasserturbinen. - Tagungsunterlagen zur Informations- und Presseveranstaltung "Fischschäden an Wasserkraftwerken" am 13. 10. 2000 in Obernach. - München (BayerischesStaatsministeriumfürErnährung,Landwirtschaft und Forsten).

SCHMALZ, W. (2002a): Untersuchung der Möglichkeiten der Anwendung und Effektivität verschiede- ner akustischer Scheucheinrichtungen zum Schutz der Fischfauna vor Turbinenschäden. - Schleusingen (Labor für hydraulisches Versuchswesen, Gewässerschutz und Ökologie der Bauhaus-Universität Weimar, Institut für Wasserwesen), 77 S.

SCHMALZ, W. (2002b): Modifizierung, Erprobung und Untersuchung einer neuarteigen Fangtechnik zur Erforschung des Fischabstiegs im Bereich von Wasserkraftanlagen. - Schleusingen (Labor für hydraulisches Versuchswesen, Gewässerschutz und Ökologie der Bauhaus-Universität Weimar, Institut für Wasserwesen), 45 S.

SCHMASSMANN, W. (1924): Über den Aufstieg der Fische durch die Fischpässe an den Stauwehren. - Schweiz. Fischerei-Zeitung 32, 222 - 229.

SCHMIDT, M., M. KÜHLMANN, H. GASSNER & E. I. MEYER (2004): Hydroakustische Untersuchungen zum Fischbestand der Hennetalsperre. - SchrR. Landesfischereiverband Westfalen und Lippe e.V. 3, 48 S.

SCHNEIDER, J. (1998): ZeitlicheundräumlicheEinischungjuveniler Lachse (Salmo salar (Linnaeus, 1758)) allochthoner Herkunft in ausgewählten Habitaten. - Dissertation, Univ. Frankfurt, 218 S.

SCHRÖDER, R. (1994): Technische Hydraulik - Kompendium für den Wasserbau. Springer-Verlag, Berlin.

SCHWEVERS, U. &ADAM, B. (1996): Wehrkataster der Lahn-Wiesbaden (Hess.Ministerium des Inneren und für Landwirtschaft, Forsten und Naturschutz), 48 S.

SCHWEVERS, U. & B. ADAM (1999): FischaufstiegsuntersuchungenamhessischenMain.-Tagungsband 2. Mainsymposium 1999. - Würzburg (Arbeitsgemeinschaft Main e.V.), 6 - 32.

SCHWEVERS, U. & C. GUMPINGER (1998): Der Fischaufstieg durch die Schiffsschleuse an der Staustufe Lahnstein. - Verh. Ges. Ichthyol. 1, 203 - 210.

SCHWEVERS, U. (1998): Die Biologie der Fischabwanderung. - Solingen(VerlagNatur&Wissenschaft), Bibliothek Natur und Wissenschaft 11, 84 S.

SCHWEVERS, U. (1999): Zum Abwanderungsverhalten von Junglachsen - Erfahrungen aus dem Programm "Lachs 2000" im Rheinsystem. - Arbeiten des Deutschen Fischerei-Verbandes 70, 119 - 141.

SCHWEVERS, U. (1999a): Analyse des Fischwanderweges Main: der hessische Unterlauf. - In: IKSR (Hrsg.): 2. Internationales Rhein-Symposium „Lachs 2000" - Tagungsband, 163 - 178.

SCHWEVERS, U. (2004): Anordnung, lichte Weite und Anströmung von Fischschutz- und Fischabstiegsanlagen. - Tagungsband Symposium „Lebensraum Fluß - Hochwasserschutz, Wasserkraft, Ökologie", 16. - 19., Juni 2004, Wallgau.

SCHWEVERS,U.,B.ADAM&O.ENGLER(2001):Wehrkataster für das Fuldasystem. - Kirtorf- Wahlen (Institut für angewandte Ökologie), im Auftrag des Regierungspräsidiums Kassel, 4 Bände, zus. 1930 S.

SIEBOLD, C. T. E. von (1863): Die Süßwasserfische von Mitteleuropa. - Leipzig (Wilh. Engelmann).

SILIGATO,S.,B.KAPPUS&H.RAHMANN(2000): Querverbauungen in der Jagst und deren Einfluss auf dieLängsdurchgängigkeitfürdieFischfauna.-Jahresheft Ges. Naturkunde Württemberg 156, 279 - 295.

SKINNER, J. E. (1974): A functional evaluation of a large louver screen installation and fish facilities research on California water diversion projects. - In: Jensen, L. D. (Hrsg.): Proc. 2nd entrainment and intake screening workshop, 225 - 249.

SÖRENSEN, I. (1951): A investigation of some factors affecting the upstream migration of the eel. - Rep. Inst. Freshwater Res. Drottningholm 32, 126 - 172.

SPÄH, H. (1999): Fischaufstiegskontrollen am Fisch- aufstieg Lünen-Beckinghausen. - Im Auftrag des Lippeverbandes, Bielefeld.

SPÄH, H. (2001a): Fischereibiologisches Gutachten zur Fischverträglichkeit der patentgeschützten Wasserkraftschnecke der RITZ-ATRO Pumpwerks- bau GmbH. - Bielefeld, im Auftrag der RITZ-ATRO Pumpwerksbau GmbH, 16 S.

SPÄH, H. (2001b): Funktionskontrolle am Aalbypass Wasserkraftanlage Hamm-Uentropp. - Im Auftrag der RWE Power AG, Bielefeld.

STAAS, S. & I. STEINMANN (2002): Untersuchung zur Smoltabwanderung und Quantifizierung der jährlichen Lachs-Smoltproduktion im Siegsystem 2002. - Nörvenich (Limnoplan), Beitrag zum Wanderfischprogramm NRW, im Auftrag des Landesfischereiverbandes Westfalen und Lippe e.V., 30 S.

STAHLBERG, S. & P. PECKMANN (1986): Bestimmung der kritischen Strömungsgeschwindigkeit für einheimische Kleinfischarten. - Wasserwirtschaft 76(7/8), 340 - 342.

STATE OF CALIFORNIA, DEPARTMENT OF FISH AND GAME (1997): Fish screening criteria. - Sacramento/Ca, 5 S.

STEINMANN, P. (1937): Die Wanderungen unserer sogenannten Standfische im Fluss und Strom. - Revue Suisse de Zoologie 44, 405 - 409.

STEINMANN, P., W. KOCH & L. SCHEURING (1937): Die Wanderungen unserer Süßwasserfische, dargestellt auf Grund von Markierungsversuchen. - Z. Fischerei 35, 369 - 467.

STOKESBURY, K. D. E., & M. J. DADSWELL (1991): Mortality of juvenile clupeids during passage through a tidal, low-head hydroelectric turbine at Annapolis Royal, Nova Scotia, North America. - J. Fish. Management 11: 149 - 154.

STRAHKOV, V.A. (1975): Experience in the application of electrical screening for concentrating and fishing of migrating species. - Izvestia GosNIORKh 96, 56 - 62.

STROBL, T. & C. GÖHL (2001): Modellversuch für eine Fischabstiegsanlage für Aale. - Mitgliederrundbrief ATV-DVWK Landesverband Bayern 2/2001, 26 - 29.

STROHMEIER, P. (1998): Analyse der biologischen Durchgängigkeit des oberfränkischen Mains und seiner wichtigsten Nebenflüsse -Bayreuth (Bezirksfischereiverband Oberfranken e. V.), 195 S.

SUN, K. (1998): Technical aspects of the NEDAPTRAIL ® SYSTEM . - In: VAATE, A. bij de, A. BREUKE-LAAR & A. van der KOLK (Hrsg.): Proceedings workshop sea trout migration in the river Rhine. - 23. / 24. Oktober 1998, Maastricht, 41 - 54.

TAFT, E. P. (1986):Assessment of downstream migrant fish protection technologies for hydroelectric application. - EPRI research project 2694-1. - Boston (Stone & Webster Engineering Corporation).

TAFT, E. P., G. E. HECKER, C. COOK & C. W. SULLIVAN (1997): Protecting fish with the Modular Inclined Screen. - Proc. international clean water conference, Baltimore/Md.

TAFT, E., G. GARNETT & S. AMARAL (1999): Fish protection at cooling water intakes. - Status Report, EPRI TR-114013, Palo Alto/Ca.

TAYLOR, R. E., & B. KYNARD (1985): Mortality of juvenileAmerican shad and blueback herring passed through a low-head Kaplan turbine. - Trans. Am. Fish. Soc. 114, 430 - 435.

TESCH, F. W. (1983): Der Aal: Biologie und Fischerei. - Hamburg (Verlag Paul Parey) 2, Auflage, 340 S.

TESCH, F. W. (1994): Verfolgung von Blankaalen in Weser und Elbe. - Fischökologie 7, 47 - 59.

TESCH, F. W., H. WESTERBERG & L. KARLSSON (1990): Tracking studies on migrating silver eels in the central Baltic. - Int.Revueges.Hydrobiol.75,866.

TESMER, G. & E. MESSAL (1996): Das niedersächsische Fischereigesetz, Kommentar. - Wiesbaden (Kommunal- und Schulverlag).

TIMM, G. (1987): Moderner Wasserkraftwerksbau mit Fischscheuchanlagen in Hameln. - Das Wassertriebwerk 36, 41 - 50.

TRAVADE, F. & M. LARINIER (1992): La migration de dévalaison: problèmes et dispositifs. - Bull. Fr. Pêche Piscic. 326/327, 165 - 176.

TRAVADE, F., J. DARTIGUELONGUE & M. LARINIER (1987): Dévalaison et franchissement des turbines

et ouvrages énergétiques: l'expérience EDF. - La Houille Blanche 1/2, 124 - 133.

TRAVADE, F., P. BOMASSI, J. M. BACH, C. BRUGEL, P. STEINBACH, J.F.LUQUET & G.PUSTELNIK (1989): Use of radiotracking in France for recent studies concerning the EDF fishway program. - Hydroécol. appl. 1/2, 33 - 51.

TURNPENNY, A. W. H., G. STRUTHERS & K. P. HANSON (1998): A UK guide to intake fish-screeningregulations, policy and best practice. - London (Crown copyright), 127 S.

TURNPENNY, A. W. H., J. M. FLEMING, K. P. THATCHER & R. WOOD (1995): Trialsofanacoustic fish deterrent system at Hartlepool power station. - FAWLEY aquatic research laboratories Ltd. client research report to nuclear electric plc, No. FRC 163/95.

TURNPENNY,A. W. H., S. R. BLAY, K. JEFFRYS. & K. LAWTON (1998): Trials of a "SPA" acoustic barrier to reduce fish entrainment at Farmoor raw water intake, River Thames, Summer 1998. FawleyAquatic Research Laboratories Ltd. Client Research Report the Environment Agency and Thames Water plc, No. FCR 299/98.

VAATE, A. bij de & A. W. BREUKELAAR (1999): Sea trout (Salmo trutta) migration in the Rhine delta, The Netherlands. - In: IKSR (Hrsg.): 2. Internationales Rhein-Symposium „Lachs 2000" - Tagungsband, 80 - 84.

VAW(VersuchsanstaltfürWasserbau,HydrologieundGlaziologie der eidgenössischen technischen Hochschule, Zürich) (1999): Untersuchungen über den Einfluss der Geometrie und Anströmung von Einlaufrechen auf den Betrieb von Wasserkraftanlagen-BerichtNr.4109. Studie imAuftrag der Vereinigung Deutscher Elektrizitätswerke (VDEW) e.V. - Zürich, 198 S.

VDEW (1996): Die öffentliche Elektrizitätsversorgung 1995. - Frankfurt a.M. (Vereinigung Deutscher Elektrizitätswerke).

VDSF (Verband Deutscher Sportfischer e.V.) (2003): Dokumentation der Wiedereinbürgerungsprojekte des atlantischen Lachses (Salmo salar L.) in Deutschland. - Offenbach (VDSF), 135 S..

VOGEL, D. A., K. R. MARINE & J. G. SMITH (1990): A summaryofevaluationsofupstreamanddownstream anadromous salmonid passage at Red Bluff diversion dam on the Sacramento river, California, USA. - Proc. internat. Symp. on Fishways in Gifu, Japan, 275 - 281.

VOLLESTAD, L.A., B. JONSSON, N.A. HVIDSTEN,T. F. NAESJE, O. HARALDSTAD & J. RUUD-HANSEN (1986): Environmental factors regulating the seaward migration of European silver eels (Anguilla anguilla). - Can. J. Fish. Aquat. Sci. 43, 1909 - 1916.

VOLZ, J. & S. J. de GROOT (1992): Erster Nachweis des Störs (Acipenser sturio) im niederländischen Rhein seit 40 Jahren. - Fischökologie 6, 3 - 6

WBW (Wasserwirtschaftsverband Baden-Württemberg. e.V.) (1994): Leitfaden für den Bau von Kleinwasserkraftanlagen. - Stuttgart (Frankh-Kosmos Verlag), 2. Auflage.

WEIBEL, U. (1991): Neue Ergebnisse zur Fischfauna des nördlichen Oberrheins - ermittelt im Rechen- gut von Kraftwerken. - Fischökologie 5, 43 - 68.

WEIBEL, U. (1997): Untersuchung des Fischanfalles im Rechengut zweier thermischer Kraftwerke am Nördlichen Oberrhein. - Zwischenbericht im Rahmen des Projektes "Angewandte Ökologie" der Landesanstalt für Umweltschutz Baden-Württemberg. - Heidelberg (Institut für Umweltstudien), 141 S.

WEIBEL, U., J. WOLF & J. HIRT (1999): Die Fischfauna als Bioindikator zur Bewertung der gewässermorphologischen Veränderungen an den großen Flüssen Baden-Württembergs. - Kandel (IUS Wei- ser & Ness), gefördert vom Projekt „Angewandte Ökologie" der Landesanstalt für Umweltschutz Baden-Württemberg, 86 S.

WELTON, J.S., W. R. C. BEAUMONT, M. LADLE, B. E. DEAR & J. E. MASTERS (1996): Smolt trapping using acoustic techniques. Analysis of results of the 1995 smolt run. Institute of Freshwater Ecology, RL/T11064K5/3.

WINCHELL, F. C. & C. W. SULLIVAN (1991): Evaluation of an Eicher fish diversion screen at Elwha Dam. - In:Darling,D.D.(Hrsg.):Waterpower'90:Proc.internat. conf. on hydropower, Denver/Colorado, 93 - 102.

WINCHELL,F.C.,E.P.TAFT,S.V.AMARAL,D.MICHAUD, L. EVERHART & C. W. SULLIVAN (1997): Evaluati- on of behavioral devices for attracting/repelling fishes commonly entrained at Midwest Hydro Projects. - "Fish Passage Workshop", May 1997, Milwaukee, Wisconsin, USA.

WINCHELL, F. C., S. V. AMARAL & E. P. TAFT (1994): Research update on fish protection technologies for water intakes. - EPRI Research Project TR- 104122, Final Report.

WITTMACK, A. (1876): Beiträge zur Fischereistatistik des Deutschen Reiches. - Circulare Dt. Fischereiverband 12.

WONDRAK, P. (1989): Entschädigungsgrundlagen bei "Turbinenschäden". - Fischer & Teichwirt 40/5, 135 - 138.

WOOD,C.C.,N.B.HARGREAVES,D.T.RUTHERFORD & B. T. EMMETT (1993): Downstream and early marine migratory behaviour of Sockeye salmon (Oncorhynchus nerka) smolts entering Barkley Sound, Vancouver Island. - Can. J. Fish.Aquat. Sci. 50, 1329 - 1337.

WOOD, R., K. P. THATCHER, A. WOODCOCK & A. W. H. TURNPENNY (1994): Fish deterrent trials at the River Foss Pumping Station, York, 1993 - 1994.

ZANKE, U. (1997): Strömungsuntersuchungen zur Verbesserung der Situation für einen Fischabstieg an der Fuldastaustufe Wahnhausen. - Darmstadt (TU Darmstadt, Institut für Wasserbau und Wasserwirtschaft, Fachgebiet Wasserbau, Bericht 439/97), 61 S.

ZAUNER, G. (1997): Acipenseriden in Österreich. - Österr. Fischerei 50, 183 - 187.

10 List of used names of species

(in alphabetical order)

Allis Shad	
-European Allis Shad	*Alosa alosa*
-Twaite Shad or Thwail	*Alosa fallax*
-American Alewife or River Herring	*Alosa pseudoharengus, Alosa sapidissima*
Asp	*Aspius aspius*
Atlantic Salmon	*Salmo salar*
Barbel	*Barbus barbus*
Beluga	*Huso huso, Acipenser huso*
Bitterling	*Rhodeus sericeus amarus*
Bleak	*Alburnus alburnus*
Bream	*Abramis brama*
Bullhead	*Cottus gobio*
Burbot	*Lota lota*
Carp	*Cyprinus carpio*
Catfish	*Silurus glanis*
Chub	*Leuciscus cephalus*
Crabs	*Eriocheir sinensis*
Crucian	*Carassius auratus gibelio*
Crucian Carp	*Carassius carassius*
Dace	*Leuciscus leuciscus*
Danube Bream	*Abramis sapa*
Eel	
-European Eel	*Anguilla anguilla*
-American Eel	*Anguilla rostrata*
Flounder	*Pleuronectes flesus*
Goldfish	*Carassius auratus auratus*
Grayling	*Thymallus thymallus*
Grey Knight Goby	*Proterorhinus marmoratus*
Gudgeon	*Gobio gobio*
Houting or Whitefish	*Coregonus oxyrhynchus*
Huchen	*Hucho hucho*
Ide	*Leuciscus idus*
Lamprey	
-Brook Lamprey	*Lampetra planeri*
-River Lamprey	*Lampetra fluviatilis*
-Sea Lamprey	*Petromyzon marinus*
Loach	*Barbatula barbatula, Cobitis taenia*
Mackerel	*Scomber scombrus*
Minnow or Pink	*Phoxinus phoxinus*
Moderlieschen	*Leucaspius delineatus*
Nase	*Chondrostoma nasus*

Perch	
-Perch, European Perch	*Perca fluviatilis*
-American Perch, Yellow Perch	*Perca flavescens*
-Sea Bass	*Dicentrarchus labrax*
Pike	*Esox lucius*
Pumpkin-Seed or Sun-Perch	*Lepomis gibbosus*
Roach	*Rutilus rutilus*
Rud or Red-Eye	*Scardinius erythrophthalmus*
Ruffe	*Acerina cernua*
Salmon	
-Atlantic Salmon	*Salmo salar*
-Pacific Salmon	*Oncorhynchus sp.*
-Sockeye	*Oncorhynchus nerka*
-Pink Salmon	*Oncorhynchus gorbuscha*
-Coho Salmon	*Oncorhynchus kisutch*
-Chum Salmon	*Oncorhynchus keta*
-King Salmon or Chinook Salmon	*Oncorhynchus tschawytscha*
Schneider	*Alburnoides bipunctatus*
Smelt	
-European Smelt	*Osmerus experlanus*
-American Smelt	*Osmerus modax*
-Atlantic Smelt	*Acipenser sturio*
-Sterlet	*Acipenser ruthenus*
-Sturgeon or Star-Sturgeon	*Acipenser stellatus*
-Osetr-sturgeon / also Danube or Russian sturgeon	*Acipenser güldenstaedti*
Sprat	*Sprattus sprattus*
Stickleback, three-spined	*Gasterosteus aculeatus*
Stone Moroko	*Pseudorasbora parva*
Tench	*Tinca tinca*
Trout	
-Brown Trout	*Salmo trutta f. fario*
-Sea Trout	*Salmo trutta f. trutta*
-Lake or Salmon Trout	*Salmo trutta f. lacustris*
-Rainbow Trout	*Oncorhynchus mykiss*
Tuna	*Thunida spec*
Vimbra Abream or Zanthe	*Vimba vimba*
White Bream	*Blikka bjoerkna*
Zander	*Stizostedion lucioperca*
Zope	*Abramis ballerus*

11 Glossary

abundance: Number of specimens of a species in relation to a surface unit or unit of volume.
acipenserids: Species of fish belonging to the family of sturgeon, e.g. Atlantic sturgeon (*Acipenser sturio*) and beluga (*Huso huso*).
anadromous: Species which reproduce in freshwater and migrate back to the sea to grow mature, e.g. the salmon (*Salmo salar*).
anthropogenic: Changes caused by human beings.
arid: Regions with a dry climate.
biotope: Habitat of a symbiosis with typical ecological conditions, e.g. flowing water bodies or lakes.
candela [cd]: Base quantity of the strength of a light source. One candela is the luminous intensity by which a black projector radiates vertically onto a surface of 1/60 cm^2 at a temperature of 2045.5 °K (solidification temperature of platinum under normal pressure).
catadromous: Species which reproduce in the sea and migrate back to freshwater systems to grow mature, e.g. the eel (*Anguilla anguilla*).
cavitation: Steam bubbles build up in liquids under a heavy pressure drop and implode with rising pressure.
clupeids: Species which belong to the family of herring, e.g. allis shad (*Alosa alosa*) and twaite shad (*Alosa fallax*).
cyclostomata: The phylogenetically very old class of round-mouthed species, e.g. brook lamprey (*Lampetra planeri*), river lamprey (*Lampetra fluviatilis*) and sea lamprey (*Petromyzon marinus*). These species which in the closer sense do not belong to fish, have no paired fins and instead of an upper and a lower jaw have a sactorial mouth armed with sharp teeth.
cyprinids: Fish species from the family of carp fish, e.g. carp (*Cyprinus carpio*) and roach (*Rutilus rutilus*).
decapitated: The head has been removed.
diadromous: Species that during their life cycle migrate between marine and freshwater habitats.
discharging or diversion power plant: A discharging power plant or diversion power plant is a hydropower plant which is located at a bypass reach outside the parcel of a water body via which water is withdrawn from the diversion channel and fed into the hydropower plant.
eco-type: Portion of a population which by adjusting to specific ecological conditions has achieved a genetic and physiologic privileged position, but cannot be addressed as a separate species. For example, the eco-types brown trout (*Salmo trutta forma fario*), lake or salmon trout (*Salmo trutta forma lacustris*) and sea trout (*Salmo trutta forma trutta*) have developed from the species trout (*Salmo trutta*).
fuzzy-logic: Statistical procedure to analyze less precise or still insufficiently definable correlations, e.g. the rise of discharges and the downstream migration of eel.
gas bubble disease: Bubbles which develop under the skin, in blood vessels and in the eyes because the body of the fish becomes oversaturated with gas through a heavy fall of pressure.
glass eel: Young eel of a body length between 8 and 10 cm with no skin pigmentation so that they are therefore colourless.
habitat: Place where animal- or plant species live within a biotope.
hydro-acoustic organ: The gas-filled air bladder as hydro-static organ allows fish to adjust their specific gravity to the density of the surrounding water and hereby to reduce the effort needed for swimming. Furthermore, for some fish the air bladder as sound box transfers sound stimuli directly to the brain, e.g. for cyprinids via the Weberian ossicles or for clupeids via appendices of the air bladder. These species therefore have a good hearing capability.
industrial water: Water discharged from a water body, which condition can change chemically and / or physically through utilization.
interstitial: A system of gaps in the substrate.
Kelt: Spawned salmon that returns to the sea and migrates upstream again into inland waters for reproduction.
lumen [lm]: A measure for a light flux: a luminous flux that radiates from a point source of light of the luminous intensity 1 candela into the solid angle [W] = 1 steradian [sr].
lux [lx]: A measure for illumination: A light flux (lumen) that impinges on a receiving surface.
mariculture: Production of animals in the sea, e.g. breeding of salmon.

nematodes: Threadworms that often live parasitic, e.g. the air bladder worm of the eel, the *Anguillicola crassus*.
one-summer: A definition of the age of fish. A one-summer fish is about 1 year old.
original bed / diversion channel: The bed of a water body, from which water is withdrawn for the operation of a diversion power plant.
pelagic: Fish living in the free water body, e.g. grayling (*Thymallus thymallus*) and bream (*Abramis brama*).
percids: Fish species from the family of perch, e.g. freshwater perch (*Perca fluviatilis*) and zander (*Stizostedion lucioperca*).
phototactic: Movements of living creatures influenced by light. In case of a positive phototaxis the movement is directed towards the light source, in case of a negative phototaxis however, the movement is directed away from the light source.
physoclists: Fish species without a connecting passage between air bladder and front intestine. The filling state of the air bladder as hydrostatic organ is regulated by the blood circulation.
physostomic species: Fish species with a connecting passage between air bladder and front intestine. The air bladder as hydrostatic organ is filled by swallowing air, whilst gas is expelled through contraction of the intestine.
piscivorous: Fish-eating.
population: The total of specimens of a species within a specific space, which sexually have reproduced amongst each other over several generations and therefore are genetically related.
potamodromous: Species that migrate more or less expansively between the different reproduction, maturing and feeding habitats in freshwater, e.g. the barbel (*Barbus barbus*) and nase (*Chondrostoma nasus*).
predators: Species that feed themselves predaciously, e.g. predators like the pike (*Esox lucius*) and fish-eating birds like the cormorant (*Phalacrocorax carbo sinensis*).
process water: Water discharged from a water body, which will be returned after chemical or physical utilization or forwarded for further treatment.
rheo-active velocity (V_{rh}): This is the flow velocity at which fish react to the current and align their body axis parallel to the flow direction.
rheotactical: The reaction of fish to the flow. If the rheotaxis is positive, the fish align their body axis head-in-front and parallel to the approach velocity.
river power plant or run-off river power plant: Power house and weir in most cases are located directly side-by-side in the river and transversely to the streamline.
salmonids: Fish species from the family of salmon, e.g. Atlantic salmon (*Salmu salar*) and trout (*Salmo trutta*).
Sargasso-Sea: Part of the Atlantic Ocean, south of the Bermuda islands, where the spawning areas of the European (*Anguilla anguilla*) and the American eel (*Anguilla rostrata*) are situated.
silurids: Fish species from the family of *Silurus glanis*, for example the catfish.
silver eel: Eel that is ready to migrate downstream or is migrating downstream. The typical colour of its belly side is silvery.
smoltifying: The phase when stationary living young salmonids transform into the downstream migration stage (smolt).
smolts: Young salmonids which are ready to migrate downstream or which are migrating downstream. The typical colour of their body is silver.
sub-lethal: Injuries are not lethal.
surge tank or chamber: A structure where the pressure of the water is coordinated, distributed and regulated.
thyristor: Electronic component for switching alternating voltages.
yellow eel: Eel living in freshwater and being almost mature. The colour of its belly side is yellowish-golden.

Fish Protection Technologies and Downstream Fishways

The EU-Water Framework Directive defines the good ecological status by the composition of an aquatic symbiosis that is only insignificantly impaired. An important biological precondition herby is the continuity of river systems, especially for fish. Whilst the construction of operable fish passes according to the DVWK Merkblatt 232 “Fish Passes - Design, Dimensions and Monitoring”, published in 1996, can guarantee that migration obstacles can be safely passed by upstream migrating fish, however, the problem of obstructed or forestalled downstream migrations and damage to downstream migrating fish caused by hydraulic installations has only recently been taken up.

The present volume of the ATV-DVWK-Topics complements the above mentioned Merkblatt and introduces fish protection technologies and downstream fishways that are nationally (Germany) and internationally available to restore the downstream directed continuity of river systems. Since this task not only requires knowledge in the fields of hydraulic engineering and fishery-biology / ecology, there is interdisciplinary understanding of the problem needed for the conception of operable fish protection facilities and downstream fishways. For this reason, the publication starts with an introduction to biological and technical principles. A separate chapter deals with damage to fish that may occur when overcoming weirs, intake structures and hydropower plants. The central issues outlined are the different technologies which on the one hand will have to prevent fish from entering hazardous installation areas, and on the other hand guarantee the harmless downstream migration for fish. Special attention is paid to the correct arrangement and dimension of bypasses, so that such alternative migration corridors can safely be traced and passed. Furthermore, alternative procedures like a fish-friendly installation management, fish transportation systems and fish-friendly turbines are presented. The publication “Fish Protection Technologies and Downstream Fishways - Dimensioning, Design, Effectiveness Inspection” summarizes the actually available national (Germany) and international state of the art and understands itself as an instrument to meet the objectives of the EU-Water Framework Directive and the requirements for the protection of animals and species.

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