FISH PASSES

DESIGN, DIMENSIONS AND MONITORING

DVWK

Fish passes – Design, dimensions and monitoring

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This co-publication by FAO and DVWK (German Association For Water Resources and Land Improvement) is a translation of a book that was first published by DVWK in German in 1996. The FAO Fisheries Department has decided to produce the English edition to make available the valuable information contained in this technical document on a world-wide scale as no comparable work was so far available, especially as regards the close-to-nature types of fish passes.

This document was translated into English by Mr. D. d'Enno, Translator, United Kingdom, and Mr. G. Marmulla, Fishery Resources Officer, FAO, Rome. It was edited by G. Marmulla and Dr. R. Welcomme, FAO Consultant and former staff member of FAO's Fisheries Department.

The German edition "*Fischaufstiegsanlagen – Bemessung, Gestaltung, Funktionskontrolle*" was prepared by the Technical Committee on "Fishways" of the DVWK and published in the DVWK "Guidelines for Water Management" that are the professional result of voluntary technical-scientific co-operative work, available for anyone to use. The German edition was financially supported by the German Federal Inter-State Working Group on Water (LAWA).

The recommendations published in these Guidelines represent a standard for correct technical conduct and are therefore an important source of information for specialist work in normal conditions. However, these Guidelines cannot cover all special cases in which further, or restricting, measures are required. Use of these Guidelines does not absolve anyone from responsibility for their own actions. Everyone acts at his or her own risk.

Acknowledgments

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Abstract

Key words: fish pass; fishway; fish ladder; technical fish passes; close-to-nature types; hydraulic calculation; upstream migration; free passage; river rehabilitation; restoration; longitudinal connectivity; monitoring

Many fish species undertake more or less extended migrations as part of their basic behaviour. Amongst the best known examples in Europe are salmon (*Salmo salar*) and sturgeon (*Acipenser sturio*), which often swim several thousands of kilometres when returning from the sea to their spawning grounds in rivers. In addition to these long-distance migratory species other fish and invertebrates undertake more or less short-term or small-scale migrations from one part of the river to another at certain phases of their life cycles.

Fish passes are of increasing importance for the restoration of free passage for fish and other aquatic species in rivers as such devices are often the only way to make it possible for aquatic fauna to pass obstacles that block their up-river journey. The fish passes thus become key elements for the ecological improvement of running waters. Their efficient functioning is a prerequisite for the restoration of free passage in rivers. However, studies of existing devices have shown that many of them do not function correctly. Therefore, various stakeholders, e.g. engineers, biologists and administrators, have declared great interest in generally valid design criteria and instructions that correspond to the present state-of-the-art of experience and knowledge.

The present Guidelines first refer to the underlying ecological basics and discuss the general requirements that must be understood for sensible application of the complex interdisciplinary matters. These general considerations are followed by technical recommendations and advice for the design and evaluation of fish passes as well as by proposals for choosing their hydraulic dimensions correctly and testing the functioning. Fishways can be constructed in a technically utilitarian way or in a manner meant to emulate nature. Bypass channels and fish ramps are among the more natural solutions, while the more technical solutions include conventional pool-type passes, slot passes, fish lifts, hydraulic fish locks and eel ladders. All these types are dealt with in this book. Furthermore, particular emphasis is laid on the importance of comprehensive monitoring.

These Guidelines deal with mitigation of the upstream migration only as data on improvement of downstream passage was scarce at the time of the preparation of the first edition, published in German in 1996. Therefore, the complex theme of downstream migration is only touched on but not developed in depth.

Foreword by FAO

In many countries of the world inland capture fisheries, in their various facets, play an important role in securing food availability and income and in improving livelihoods either through food or recreational fisheries. Since years, the Food and Agriculture Organization of the United Nations (FAO) does not relent to promote the concept of sustainability in the use of resources and sustainable development continues to be a highly desirable goal in all fisheries and aquaculture activities. However, to achieve this objective in capture fisheries, especially, not only improved fisheries management but also sound ecosystem management is needed.

Freshwater is becoming a more and more precious resource and there is increased competition for its use by the various sectors, e.g. agriculture, fishery, hydropower production, navigation etc., of which fishery is generally not the most important one economically. The responsibility for the protection of the aquatic ecosystem usually lies outside the fishery and in many cases, the fishery has to be managed within the constraints imposed by the external sectors. Activities such as dam construction for water supply and power generation, channelization for navigation and flood control, land drainage and wetland reclamation for agricultural and urban use all have a profound impact on the aquatic ecosystem and thus on the natural fish populations. One of the worst effects of dams and weirs is the interruption of the longitudinal connectivity of the river which means that fish cannot migrate freely anymore. This does not only concern the long-distance migratory species but all fish that depend on longitudinal movements during a certain phase of their life cycle.

The Fisheries Department's Regular Programme and field-based activities are tailored to provide management advise on best practices and help implementing the Code of Conduct for Responsible Fisheries and the relevant Technical Guidelines. In the framework of the Department's Major Programme, the Inland Water Resources and Aquaculture Service (FIRI) implements, *inter alia*, an activity on prevention of habitat degradation and rehabilitation of inland fisheries, including considerations regarding fish migration and mitigation measures. As normative work under this activity, FIRI gathers, reviews, analyzes and disseminates information in relation to dams and weirs and their interactions with fish and fisheries and promotes the rehabilitation of the aquatic environment as an appropriate tool for the management of inland waters.

In the attempt of making aquatic resources more sustainable, FIRI pays special attention to improved fish passage and restoration of the free longitudinal connectivity as these are important issues on a worldwide scale that attract growing interest. This book "Fish passes – design, dimensions and monitoring" which has originally been published in German by Deutscher Verband für Wasserwirtschaft und Kulturbau e.V., DVWK (German Association For Water Resources and Land Improvement) is an extremely valuable contribution to the mitigation of obstructed fish passage. It first refers to the underlying ecological basics and discusses the general requirements, that must be understood for the sensible application of the complex interdisciplinary matters, before it gives technical recommendations and advice for the design of fish passes, the correct choice of their hydraulic dimensions and the evaluation of their effectiveness. Based on knowledge and experience from mainly Europe and North America, the book describes the various types of fish passes, with special emphasis on "close-to-nature" solutions. Monitoring is dealt with as a key element for success.

The FAO Fisheries Department decided to co-publish the English edition to make widely available the valuable information contained in this technical document. This is the more important as no comparable book existed so far in the Anglophone literature, especially as regards the close-to-nature types of fish passes. It is hoped that this book contributes largely to increase the awareness of the need for unobstructed fish passage and to multiply the number of well-designed and well-dimensioned fish passes around the globe to restore lost migration routes.

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Foreword to the English edition by DVWK

Great efforts have been undertaken in Germany in the past decades to bring the water quality of surface waters back to an acceptable state, defined as “slightly to moderately loaded” according to the German biological water quality classification. Improvements were mainly achieved through the construction of sewage treatment plants for purifying domestic and industrial sewage. Today efforts in water protection management are more and more directed towards the restoration of the natural ecosystem functions of the river channel, its banks and the former floodplains. Changes in channel morphology should therefore be reversed as far as possible, and obstructions that cannot be overcome by migratory fish be eliminated.

In 1986, the responsible Ministers of the five riparian countries of the river Rhine, the third largest river in Europe, and the relevant Directorate of the European Commission set a political agenda for the restoration of the Rhine and agreed to undertake actions to enable the return of salmon and other migratory fish to the Rhine and its tributaries by the year 2000. To achieve this objective, fish passes were, and still are, required in many places, but generally valid design criteria were lacking for the construction of fully functional fishways, particularly for solutions that look natural and blend well with the landscape. To satisfy this demand the German Association for Water Resources and Land Improvement, DVWK (Deutscher Verband für Wasserwirtschaft und Kulturbau e.V.), the professional, non-governmental and non-profit body representing German experts engaged in water and landscape management, prepared and published these Guidelines in 1996. In the meantime the salmon has already been detected again in the river Rhine and some of its tributaries. What a progress!

An interdisciplinary working group of biologists and engineers compiled research results and experiences from Germany and other countries that reflect the current state-of-the-art of technology in this field. With the publication of these Guidelines in English, the DVWK hopes to contribute to making the experience and guidance on restoring the longitudinal connectivity of flowing surface waters available to hydro-engineers and fishery specialists in other countries. With this book we hope to make a contribution to the transfer of knowledge across national boundaries, and will be pleased if it gives useful suggestions for the forward-looking management of waters in Europe and world-wide.

Bonn, October 2002
Dr. Eiko Lübbe,
Chairman of the DVWK’s Standing Committee
on International Cooperation.

Foreword[1]

Fish passes are of increasing importance for the restoration of free passage for fish and other aquatic species in rivers. Such devices are often the only way to make it possible for aquatic fauna to pass obstacles that block their up-river journey. They thus become key elements for the ecological improvement of running waters.

The efficient functioning of fish passes is a prerequisite for the restoration of free passage in rivers. Studies of existing devices have shown that many of them do not function correctly. Many specialists have therefore declared great interest in generally valid design criteria and instructions that correspond to the present state-of-the-art of experience and knowledge.

A specialized Technical Committee set up by the German Association for Water Resources and Land Improvement has determined the current state-of-the-art technology for construction and operation of fish passes, through interdisciplinary co-operation between biologists and engineers. Research results and reports from other countries have been taken into account.

The present Guidelines first refer to the underlying ecological basics and discuss the general requirements that must be understood for sensible application of the complex interdisciplinary matters. These general considerations are followed by technical recommendations and advice for the design and evaluation of fish passes as well as by proposals for choosing their hydraulic dimensions correctly and testing the functioning.

In preparing these Guidelines it became clear that some questions, particularly those related to the design and integration of fish passes at dams used for hydroelectric power production, could not be answered to complete satisfaction. The reasons are, firstly that there is little reliable data on the functioning of fishways and that the behaviour of fish in the vicinity of fish passes needs further study. Secondly, defining the dimensions of close-to-nature constructions by applying the present hydraulic calculation models can only provide rough approximations. There is thus still a considerable need for research that would fill such gaps in our knowledge. For the same reason, it is, unfortunately, not possible to respond immediately to the wish for recommending standards for fish guiding devices and downstream passage devices that many professionals concerned with the subject have expressed.

The Technical Committee was composed of the following representatives of consulting firms, engineering consultants, energy supply companies, universities and specialized administrations:

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[1] to the original German publication

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Herewith the Technical Committee wishes to thank the representatives of fishery associations, angling clubs, the Society of German Fishery Administrators and Fishery Scientists, the dam operating companies and experts from public authorities and administrative bodies who have supported the work of the Technical Committee through special contributions and advice. All those who sent in constructive suggestions at the reviewing stage are also thanked.

Bonn, November 1995 Werner Schaa

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1 Introduction

Many fish species undertake more or less extended migrations as part of their basic behaviour. Amongst the best known examples are salmon *(Salmo salar)* and sturgeon *(Acipenser sturio)*, which often swim several thousands of kilometres when returning from the sea to their spawning grounds in rivers. In addition to these long-distance migratory species other fish and invertebrates undertake more or less short-term or small-scale migrations from one part of the river to another at certain phases of their life cycles.

Weirs had already been installed during the Middle Ages in many streams and rivers in Europe to exploit their water power potential. These historical features still constitute an essential component of our cultural landscape. Rivers continue to be subject to further wide ranging and intensive anthropogenic uses as a result of industrialisation and increasing human populations.

Besides such purposes as flood control, navigation and production of drinking water, hydropower production plays an important role in the construction of new dams today, especially under the aspect of the increased promotion of the use of renewable energy. Hydro-electric energy is therefore vigorously promoted as a means of reducing CO_2 emission from fossil energy sources. The character and quality of river ecosystems are deeply affected when obstacles such as dams and weirs are placed across a river. The construction of dams and weirs results in the flooding of entire sections of rivers that are thus transformed into water storage impoundments and lose their riverine character. Moreover, these obstacles interrupt the longitudinal connectivity of a river so that unhindered passage for aquatic organisms is no longer ensured. This, together with other factors such as water pollution, leads to a decrease in the population size of some fish species (e.g. salmon, sturgeon, allis shad), sometimes to levels close to extinction.

The negative effects of man-made barriers such as dams and weirs on migratory fishes were known early on. For instance, in the thirteenth century the Count of Jülich delivered a writ for the Rur (tributary of the Maas in North Rhine-Westphalia) ordering that all weirs should be opened for salmon migrations (TICHELBÄCKER, 1986). Certainly such radical solutions are no longer practical today, but present-day obstacles can be made passable by the construction of fish passes. Although constructing fish passes does not eliminate the basic ecological damage caused by the dams, such as loss of river habitat or loss of longitudinal connectivity, this measure attenuates the negative ecological impact of these obstructions to a certain extent and thereby increases their ecological compatibility. For instance, the success of the programme begun in the mid 1980s to reintroduce salmon and sea trout in rivers of North Rhine-Westphalia should not be attributed exclusively to the improved water quality due to the construction of sewage treatment plants but also to the re-linking of potential spawning waters (the Sieg river system) to the main river (Rhine) by building fish passes at critical obstacles (STEINBERG & LUBIENIECKI, 1991). Moreover, this re-linking of aquatic ecosystems is an important contribution to efforts to facilitate the recolonization of rivers by endangered fish species and, more generally, to species and habitat conservation. Today, the restoration of the longitudinal connectivity of rivers is a declared sociopolitical goal. This can be achieved by either decommissioning (i.e. the demolition) barriers that are no longer required, by replacing them with bottom slopes or through construction of fish passes.

Fish passes are structures that facilitate the upstream or downstream migration of aquatic organisms over obstructions to migration such as dams and weirs. While the objective of re-linking waterbodies is by no means limited to benefiting fish but rather aims at suiting all aquatic organisms, such terms as “fish ladders”, “fishways”, “fish passes” and “fish stairs” will be used throughout these Guidelines in the absence of a more appropriate general term that would encompass other aquatic organisms as well as fish. This terminology is also to be seen against the historical background since in the past emphasis was laid on helping fish to ascend rivers. Today, the term “fishway” is used in a broader sense to refer not only to the fish fauna but to all aquatic organisms that perform migrations. It further broadens its meaning to also include downstream migration - an aspect which is becoming increasingly important.

Fish ladders can be constructed in a technically utilitarian way or in a manner meant to emulate nature. Bypass channels and fish ramps are among the more natural solutions, while the more technical solutions include conventional pool-type passes and slot passes. Apart from the conventional types, special forms such as eel ladders, fish lifts and hydraulic fish locks are also used. These Guidelines present the current state of knowledge on fish passes for *upstream* migration only and give advice on, and instructions for, their construction, operation and maintenance as well as on testing their functioning.

Currently there is also a need by management for information on the design and construction of behavioural barriers for fish (e.g. screens of air bubbles, light, electric current, etc. to prevent fish from being sucked into turbines or water abstraction points[#]) and devices to help fish descend (i.e. bypass systems to ensure downstream migration[#]). Since there is a considerable lack of information on these themes at present, the DVWK has initiated research in this area and launched an initiative to prepare other specific Guidelines in relation to these issues. Therefore, the theme of downstream migration will only be touched on in the present booklet but not developed in depth.

[#] explanation added by the editor

2 Ecological principles

2.1 Running water ecosystems

Running waters naturally interlink different eco-regions, and are of essential ecological significance. They are, therefore, rightly called the "vital lines of communication in nature". Hardly any other ecosystem exhibits such great structural diversity and, as a consequence, features such rich and diverse colonization by different species of plants and animals. But probably also no other ecosystem is used to the same extent for human activities or is as highly impacted by pollution or structural alterations.

The character of an unimpaired running water ecosystem is determined naturally by a complex and extraordinarily complicated structure involving numerous abiotic (non-living) and biotic (living) factors. Thus a change in only one of the parameters provokes a chain of very different effects on the living communities of running waters (biocoenoses). At present we have little knowledge of the mechanisms by which such effects are produced.

The combination of different geophysical, climatic and other abiotic factors has a decisive influence on the structure as well as on the quality of the different habitats within a river. The following therefore describes some of these fundamental parameters.

2.1.1 Geology and Climate

Different eco-regions, e.g. the lowlands near the coasts, the highlands and the alpine region, differ fundamentally in their geological and climatic properties, and therefore, not surprisingly, the character of the running waters of such regions differs correspondingly. The hydrological characteristics of rivers as well as the hydrochemical properties of the water itself are determined by such factors as altitude, precipitation and the composition of the outcropping rocks. The slope of the terrain is also an orographic factor and has a decisive effect on the character of other abiotic factors, e.g. water velocity and bottom substrate composition as well as on the processes of erosion and sedimentation.

2.1.2 Water velocity

Water velocity is the most important determining factor in running waters ecologically. The fauna of running waters live in constant danger of being swept away by the current, consequently, permanent colonization of running waters is only possible for such organisms that have either developed mechanisms to withstand the drift or are in a position to move against the current.

In adapting to the various flow characteristics in running waters, aquatic fauna have developed different biological strategies for avoiding the loss of territory from downstream drift:

Adaptation of body form

The body shapes of both fish and benthic (bottom-dwelling) invertebrates are optimally adapted to the flow regimes of their respective habitats. Fish in fast flowing upper reaches of streams have torpedo-shaped bodies and thus only offer low resistance to the current (e.g. brown trout, *Salmo trutta f. fario*, or minnow, *Phoxinus phoxinus)*, while high-backed fish such as bream, *Abramis brama,* and carp, *Cyprinus carpio*, colonize waters with more gentle currents (Figure 2.1).

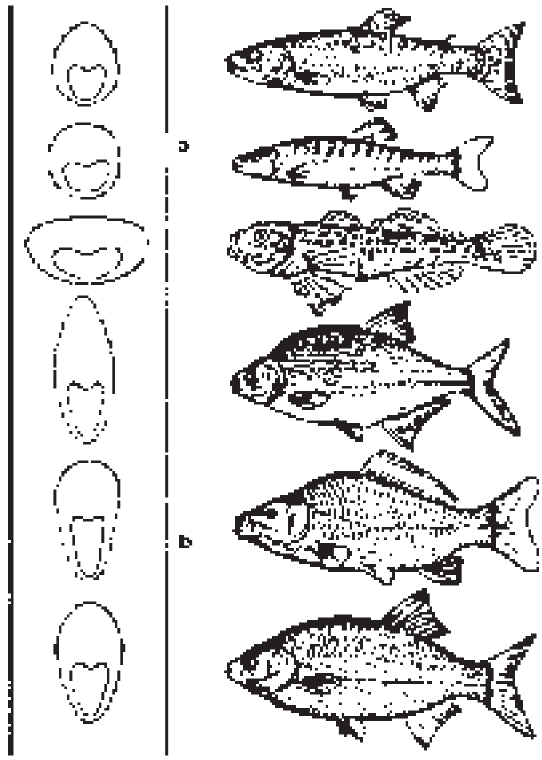


Fig. 2.1: Adaptations of body forms of fish to different flow velocities (from SCHUA, 1970)
(a) Species occurring in the fast flowing upper reaches of streams: brown trout, minnow, bullhead;
(b) Species occurring in slow flowing river regions: bream, carp, rudd.

Adaptation of behaviour

Many aquatic organisms use active behavioural adaptations to avoid being carried downstream. A clear example is mayflies of the genus *Baetis* that press their bodies onto the substrate when the current flows faster and thus only offer slight resistance (Figure 2.2).

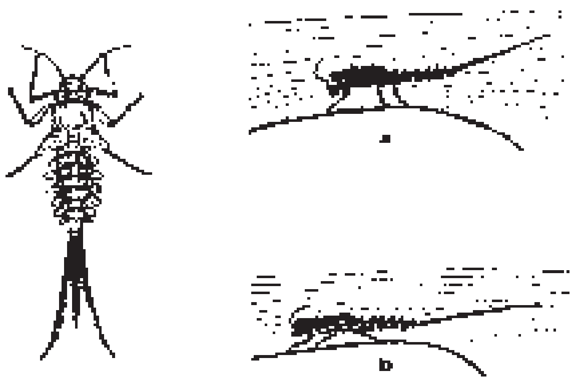


Fig. 2.2: Body posture of mayfly larvae of the genus Baetis (from SCHUA, 1970)
(a) in weak currents
(b) in strong currents

Attachment strategies

Many benthic invertebrates attach themselves to the substrate by means of suckers (leeches and blackfly larvae *Simulium spp.)*, by secretion of spun threads (midge larvae), or by means of hooks, claws or bristles on their limbs.

Organisms living in areas with gentle current

Areas of gentle current form behind and under larger stones; the bullhead *(Cottus gobio)*, for example, uses these areas as shelter. The bullhead seeks direct contact with the substrate and, as it grows, favours shelters of different sizes depending on its body size. Fish and numerous invertebrate organisms find shelter against high water velocity and predators in the rivers' interstitial space, i.e. in the gaps between the bottom substrate particles. Thus for example, yolk-sac larvae of the grayling *(Thymallus thymallus)*, protect themselves from predators by penetrating as deep as 30 cm into the interstices.

Compensatory migrations

Compensatory migrations are directional movements that serve to balance losses of position caused primarily by drifting. For example, young bullheads swim up to 2 km upstream after having been transported downstream with the current as young fry when their swimming ability was not yet well developed (BLESS, 1990). The imagoes of some insect species fly upstream to compensate for the loss of terrain that they had incurred as a result of larval drift (PECHLANER, 1986). Similar compensatory migrations are known with freshwater hoppers (Gammaridae) (HUGHES, 1970; MEIJERING, 1972).

Slope is the dominant factor that determines water velocity (and the current) of morphologically unimpaired rivers and hence the general structure of the river channel. Water velocity can also change considerably under the influence of local differences in channel width. These dynamic changes of the river structure are accompanied by the formation of different current patterns, which are at the basis of the multiform mosaic-like character of aquatic habitats. Variations in flow regime also alter the living conditions in running waters. There are for example areas where gentle currents prevail at normal water level but which are exposed to high current velocity during times of flood (Figure 2.3). During the flood aquatic organisms are swept downstream more easily and the fauna must balance the loss of terrain by compensatory movements after flooding abates.

2.1.3 Shear stress and substrate distribution

The energy of running water dynamically remodels the channel of natural watercourses by erosion and sedimentation. The shear stress of the water causes solids to be transported (bed load) and shifted on a large scale. This leads to the formation of different bottom and bank structures as well as differing current patterns:

- In meandering and braided rivers, steep cut banks form at the outer edge of a bend through removal of bottom and bank material by erosion, while flat bank deposits are formed at the inner edge by deposition of materials.
- Deposition of gravel, sand and silt locally reduces the water depth, thus forming shallows.
- Removal of solid materials causes greater water depths (deep pools, holes).
- Sections with gentle current alternate with rapid current sections (pool and riffle structures) over relatively short distances.
- Dynamic shifts in the course of the river channel form bays, blind side arms and backwaters.

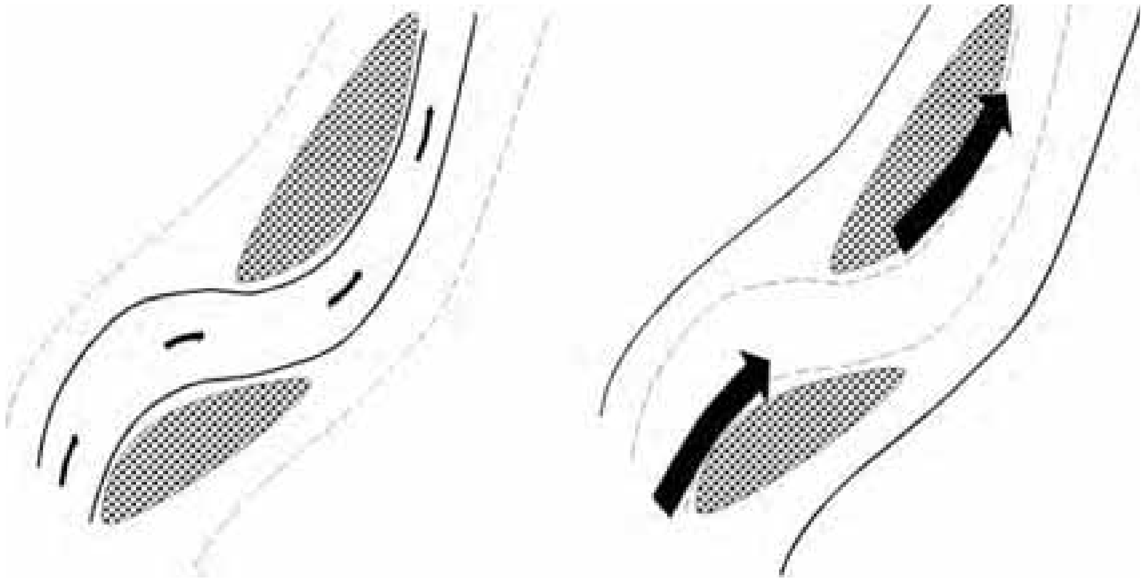


Fig.2.3: Changes in flow characteristics in a river at different discharge conditions
(a) at low water level: slow velocities; the water flows round obstacles
(b) at high water level: high velocities; the water flows over obstacles

Running waters transport solids depending on their grain size (Figure 2.4). At high water velocities and correspondingly high shear stress at the bottom, even large substrate particles are carried along by the current. When there is a decrease in the shear stress, the coarse substrates are the first to sediment out while finer fractions are carried on until even these are deposited in zones of reduced currents. Accordingly, in natural or nearly natural rivers the substrate shows a mosaic distribution corresponding to the different currents and is colonized by different living communities (biocoenoses), each with their own specific habitat requirements. Because the habitat requirements for many species can alter considerably during their life cycles, this differentiated substrate is an essential precondition for a rich variety of species to populate running waters:

- Many fish species, e.g. brown trout *(Salmo trutta f. fario)*, grayling *(Thymallus thymallus)*, barbel *(Barbus barbus)*, and riffle minnow *(Alburnoides bipunctatus)* require gravel beds composed of specific substrate particle sizes to spawn on.
- The larvae (ammocoetes) of brook, river and sea lampreys *(Lampetra planeri, Lampetra fluviatilis, Petromyzon marinus)* need, in addition, fine sedimentary deposits where they are burrowed and develop over many years while feeding by filtering organic material from waters flowing over them.
- The nase *(Chondrostoma nasus)* feeds by grazing on algae growing on stones; it therefore needs stones and boulders while feeding and a gravel substrate for spawning.

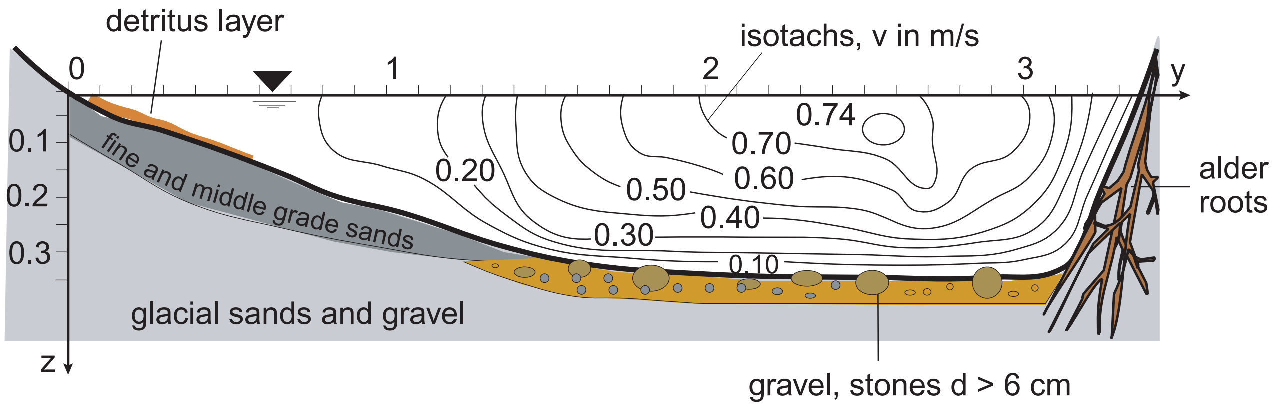


Fig. 2.4: Substrate distribution depending on flow velocity

2.1.4 Temperature

The temperature of running water is of special importance to the limnetic biocoenosis. Many species are adapted to a narrow temperature range for their metabolic functions and normal behaviour. Such species can only tolerate a limited degree of deviation from their temperature optimum. Even a slight warming of running waters through thermal pollution (input of water warmed up in ponds, cooling water from thermal power stations, etc.) or warming of impounded waters through intense solar radiation can limit their colonization by such temperature sensitive organisms. Conversely, the reproduction of fish is linked to a minimum temperature that differs for each species. While brown trout *(Salmo trutta f. fario)* spawns at temperatures below 5ºC, the reproduction of the nase *(Chondrostoma nasus)* is only triggered at 8ºC, and the reproduction of the minnow *(Phoxinus phoxinus)* starts at 11ºC. Species typical of the lower river reaches (potamon) such as carp *(Cyprinus carpio)* and tench *(Tinca tinca)* only spawn at temperatures well over 20ºC. Water temperatures and temperature variations also play a fundamental role in the migratory behaviour of fish (JONSSON, 1991). Thus the smolts of salmon and sea trout in the Norwegian river Imsa prefer to migrate downstream at temperatures over 10ºC, whereas most adult eels swim down the river at temperatures between 9º and 12ºC. Increasing water temperatures also trigger upstream migration of fish. However, too high a water temperature hinders upstream migration because, when the temperature exceeds a species specific limit, the metabolism of the fish may be taxed and the fish's physical strength may be limited.

2.1.5 Oxygen

Dissolved oxygen plays a significant role in the aquatic environment. Uptake of oxygen through the surface of the water under turbulent flow conditions in running waters (i.e. the physical intake of oxygen) is significant but oxygen is also produced by planktonic and epiphytic algae as well as higher aquatic plants, through the process of photosynthesis (biological oxygen supply). The solubility of oxygen is largely dependent on water temperature as much less oxygen dissolves in water at higher temperatures than at lower temperatures. Organic pollution, which is eliminated by oxygen-consuming microbial decomposition in the process of self-purification of rivers, can reduce oxygen levels in the water considerably. In extreme cases this can cause the death of aquatic organisms. Fish mortalities are frequently not due to toxic substances (cyanide, pesticides, etc.) but rather to a lack of oxygen arising from the oxygen-consuming breakdown of organic matter such as sewage or liquid manure. The oxygen content of the water, which in turn is closely linked to the water velocity and current, exerts a considerable influence on the colonization of running waters by aquatic organisms:

- Invertebrates that are adapted to high oxygen levels in the headwaters of streams, meet their total oxygen demand by diffusion over the body surface. Due to the rapid current, an intensive supply with oxygen-rich water is guaranteed to satisfy breathing needs, so that different stonefly larvae for example, have not developed any special organs (gills) for absorbing oxygen.
- Species such as, for example, mussels (bivalves), the larvae of mayflies *(Ephemeroptera)* and caddis flies *(Trichoptera)* that live in river stretches with more gentle currents have gills as breathing organs that facilitate the exchange of oxygen.
- Some benthic organisms such as, for example, midge larvae *(Chironomidae)* and tube worms *(Tubifex tubifex)* have haemoglobin in their body fluids as a special adaptation to habitats with chronic oxygen deficiency. Haemoglobin has a high capacity to bind oxygen, so that those organisms endowed with it are able to meet their oxygen demand even in a low-oxygen environment.
- Also some fish species have developed adaptations to different oxygen levels in the water. Species such as brown trout *(Salmo trutta f. fario)* and minnow *(Phoxinus phoxinus)* that live in the upper reaches of streams (rhithron), where the water remains cool even in summer, have at their disposal sufficient oxygen all year round if the waters are natural and unpolluted. Therefore, these species have comparatively low-performance gills and thus have to rely on a good oxygen supply from the water: brown trout cannot tolerate oxygen concentrations significantly below 9 mg/l for long periods.
- However, species of the lower reaches of slow-flowing rivers (potamon) are adapted to naturally occurring oxygen deficits. For instance, carp *(Cyprinus carpio)* can survive in oxygen concentrations of 2 to 3 mg/l. Some indigenous species from loach family *(Cobitidae)*, for example spined loach *(Cobitis taenia)*, weather-fish or bougfish *(Misgurnus fossilis)* and stoneloach *(Noemacheilus*

barbatulus) have the ability of intestinal breathing as an adaptation to habitats with chronic oxygen deficiency. When the oxygen content of the water is low, these species can swallow air from which oxygen is extracted in their intestines by a special breathing organ.

2.2 River continuum

The “River Continuum Concept” by VANNOTE *et al.* (1980) describes the ecological function of rivers as linear ecosystems and the effects of interruptions of their connectivity. This energy-flow model provides a theoretical basis for claiming the integrity of the linear connectivity of river systems and is based on the characteristic alteration of abiotic factors in the course of a river as described in section 2.1. Aquatic species show adaptations to the specific living conditions prevailing in any particular river reach and form characteristic biocoenoses that change in a natural succession along the watercourse as the abiotic factors vary. An idealised model, based on the fundamental relations between the gradients of the physical factors and the biological mechanisms that influence the composition of living communities in rivers, can be constructed according to the following assumptions:

- The discharge of the river increases constantly from source to mouth.
- The steepness of the slope usually decreases with increasing distance from the source.
- The velocity of the current is very high in the upper reaches and decreases steadily towards the estuary, where there is a regular tidal reversal of the direction of the current.
- The substrate is graded along the course of the river in a characteristic manner determined by the velocity of the current. While the substrate of the upper reaches mainly consists of boulders, pebbles and coarse gravel, fine gravel and sand dominate in the middle reaches, and the estuary area is characterized by fine sand, silt and clay substrate.
- The average annual temperature of well under 10ºC in the upper reaches of temperate streams is comparatively low but increases along the course of the river. Also the range of temperature variation continually increases along the course of the river. While the temperature near the source is usually quasi-constant throughout the year, it may vary between 0ºC in winter and 20ºC in summer in the lower reaches.
- In the upper reaches of a stream the oxygen content is characterized by saturation or supersaturation. Because of the strong turbulent flow, there is a permanent uptake of atmospheric oxygen. The oxygen content of the water in a river drops with the length of its course, not least because of the higher water temperature and slower flow velocity. In the lower reaches, aquatic plants, and especially phytoplankton, increasingly influence the oxygen content of the water.

Special cases, e.g. the effects of discontinuous slope development, a rapid increase in discharge because of inflowing larger tributaries, or the energy intake while flowing through lakes, are not considered in this generalized model.

The River Continuum Concept illustrates the fact that there is likewise the formation of a characteristic biological gradient, corresponding to the alteration of different abiotic factors in the course of a river. This gradient can also be understood in terms of the biological energy flow in the river and is the expression of a set pattern of input, transport, use and storage of organic matter in the river and its biocoenoses. The biological gradient is recognisable as certain species or types of organisms are replaced by others in a characteristic sequence along the river course. The biocoenoses of a particular reach of a river or even of the whole river system are thus typically interlinked in a set pattern, and follow, according to the River Continuum Theory, the common strategy of minimising energy losses within the whole system. Thus the biocoenoses of lower reaches take advantage of the incomplete energy transformation of organic material by the upstream biocoenoses, whereby mainly the organic material that is transported downstream is further broken down (Figure 2.5).

This theory is supported by the fact that invertebrates in different parts of the river (upper, middle and lower reaches) utilize different food elements and exhibit different nutrition strategies. The fundamental bioenergetic influences along the river continuum consist of both local influxes of allochthonous materials including organic matter and light as well as the drift of organic material from the upper reaches and from tributaries discharging into the middle and lower reaches:

- The upper reaches are strongly influenced by vegetation on the banks. On one hand this reduces autotrophic production in the river itself through shading, but on the other provides the river with a large amount of allochthonous dead organic matter, particularly in the form of fallen leaves.

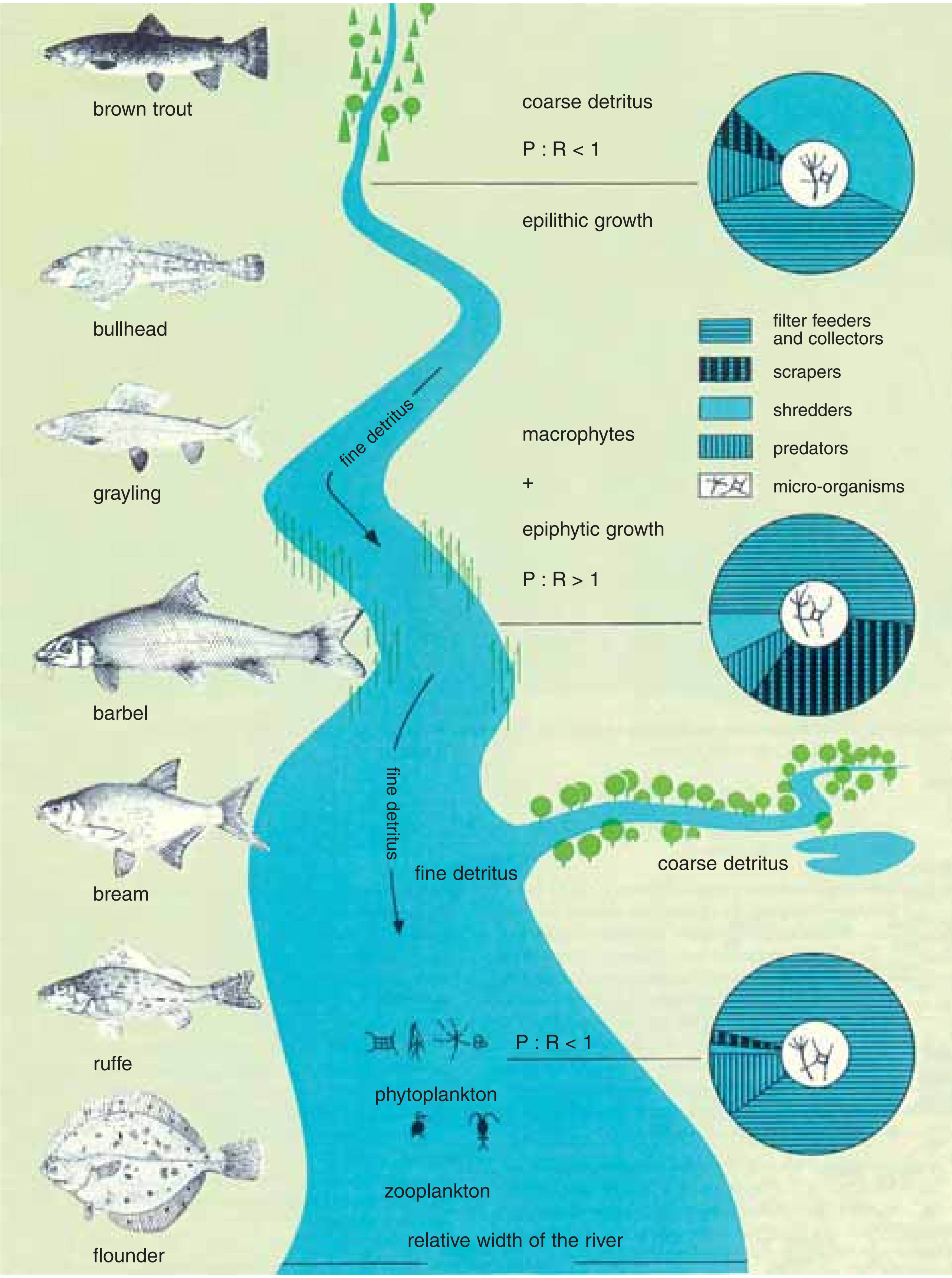


Figure. 2.5 River Continuum Concept: Alteration of structural and functional characteristics of running water biocoenoses as a function of the width of the river (From: Bavarian Regional Office for Water Management, 1987)
P = primary production; R = respiratory activity; P/R = ratio of primary production to respiratory activity

- The significance of the influx from the terrestrial zones decreases with increasing river width. At the same time both the autotrophic primary production in the water itself as well as the downstream transport of organic material from the upper reaches increase significantly.
- The physiological differences between biocoenoses of different river reaches are reflected in the ratio of the primary production (P) to the respiratory activity (R) of the biocoenosis (P/R). In the upper reaches respiratory activity dominates while in the middle reaches primary production is more important. In the lower reaches, however, the primary production is strongly reduced through increased water turbidity and greater water depth. At the same time, a large amount of fine organic material, which comes originally from fallen leaves in the upper reaches, is imported by the flow, so that here again respiratory activity predominates over primary production.

The different morphological and physiological strategies of aquatic organisms can be understood as an expression of their adaptation to the basic food elements that are present and the prevailing nutritional conditions in the different river stretches. The following feeder types can be distinguished:

- “Shredders”, that use coarse organic material (> 1 mm), such as fallen leaves, and that are reliant on the supporting activity of micro-organisms.
- “Collectors”, that filter small (50 mm – 1 mm) or very small (0.5 – 50 mm) particles from the flowing water or take them up from the substrate. Like the shredders, the collectors are also reliant on the microbial organisms and their metabolic products, which they ingest together with the food particles.
- “Scrapers”, that are specialized in grazing on the algal growth on the substrate.
- “Predators”, that feed on other functional types of feeders.

In accordance with the specific nutritional conditions (P/R < 1), both shredders and collectors together dominate the invertebrate biocoenoses of the upper reaches. Scrapers are mainly to be found in the middle reaches (P/R > 1). As the river width increases and as the food particle size decreases significantly, the collectors again gain importance in the biocoenoses of larger rivers. The proportion of predators only changes slightly in the course of the river, but the species composition differs. We thus have:

Upper reaches: *shredders and collectors*
Middle reaches: *scrapers*
Lower reaches: *collectors*

Fish communities also show a characteristic sequence along the course of the river. Cold-water fish communities of the upper reaches, which are composed of few species, are successively replaced by warm water communities with high species diversity. The species in the upper reaches mainly feed on invertebrates (are invertivores), while the fish communities of the middle reaches consist of both invertivores and piscivores (eating other fishes). Plankton-eating (planktivore) species are limited to the lower reaches of large rivers. We thus have:

Upper reaches: *invertivore fish*
Middle reaches: *invertivore and piscivore fish*
Lower reaches: *planktivore fish*

The basic prerequisite for the functioning of this model is that the animal communities can alter and adapt to local conditions without problems in accordance with the dynamics of the system. For example individual species should be free to search for suitable feeding grounds in accordance with their life cycle and the seasonal conditions. This requires unhindered upstream and downstream passage for organisms in the relevant river stretches. Disturbances of the biological energy influx, for example through lack of shrubs on the banks, or disturbancies of the energy and material flows due to damming, as well as disturbances in the formation of biocoenoses, that are typical of a certain ecosystem, undoubtedly have a negative influence on the colonization of the whole river system. Interruptions of the river continuum, and thus of the circulation of materials in the river, lead to changes in the energy balance.

2.3 Biological zoning of running waters

Knowledge of the interactions between abiotic and biotic factors in rivers, allows the demarcation of the habitats of typical biocoenoses from one another within the river continuum, thus permitting the division of the river into distinct individual zones. This zoning has quite practical implications; for example it provides an essential basis for an ecologically oriented fishery and allows the negative effects of human interventions in a river to be clearly demonstrated. For fishery purposes, the different river stretches are traditionally classified by main indicator fish species that are commercially significant and that characterise the fish composition of a particular section. Experience shows that fish communities in the upper reaches are mainly composed of brown trout *(Salmo trutta f. fario)* and grayling *(Thymallus thymallus)*, while the middle reaches are mainly populated by barbel *(Barbus barbus)* and the lower reaches by bream *(Abramis brama)*. In each section typical “associated fish species” can be related to these indicator species. This longitudinal succession of fish communities (i.e. zonation[#]), that follows a distinct pattern, was exemplarily documented by MÜLLER (1950) for the river Fulda and the same sequence of fish communities is present in the Rhine and Elbe systems with, however, some slight differences in the species composition (see Table 2.1):

- The **upper trout zone**[##] is populated by three fish species, i.e. apart from the indicator species brown trout *(Salmo trutta f. fario)*, only the brook lamprey *(Lampetra planeri)* and the bullhead *(Cottus gobio)* are found as “associated species”.
- In the **lower trout zone** (Figure 2.6) the loach *(Noemacheilus barbatulus)* and the minnow *(Phoxinus phoxinus)* occur in addition to the above-mentioned species.
- The **grayling zone** (Figure 2.7) is also populated by all the species of the trout zone but the grayling *(Thymallus thymallus)* dominates over brown trout. Furthermore, numerous other species, such as the chub *(Leuciscus cephalus)*, roach *(Rutilus rutilus)* and gudgeon *(Gobio gobio)* are also present.
- In the **barbel zone** (Figure 2.8) the species of the upper trout zone may still occur but not as breeding populations, while altogether *Cyprinidae*, such as barbel *(Barbus barbus)*, bleak *(Alburnus alburnus)*, whitebream *(Blicca bjoerkna)* and nase *(Chondrostoma nasus)*, and the predators pike *(Esox lucius)* and perch *(Perca fluviatilis)* dominate. The range of species in this zone is considerably larger than that of the grayling zone.
- The fish coenosis of the **bream zone** (Figure 2.9) lacks those “associated species” of the grayling and barbel zones that prefer fast currents such as the riffle minnow *(Alburnoides bipunctatus)* and minnow *(Phoxinus phoxinus)*. The barbel *(Barbus barbus)*, too, is also only found locally in stretches of stronger current. Instead, bream *(Abramis brama)* and other typical still water species such as tench *(Tinca tinca)*, carp *(Cyprinus carpio)* and rudd *(Scardinius erythrophthalmus)* dominate.
- The estuarine zone at the river mouth is called the **ruffe-flounder zone.** This zone is already subject to the influence of the tides. Both, limnetic species such as the ruffe *(Gymnocephalus cernua)* and the species of the bream zone, can be observed simultaneously with marine species such as the flounder *(Platichthys flesus)* and the herring *(Clupea harengus)*.

The biocoenoses of rivers are thus characterised both by indicator fish species and associated species. This zonation applies not only to fish but also to aquatic invertebrates. Thus, even if the indicator fish species are absent, as might be the case in severely polluted or heavily anthropologically modified waters, the fish zone can be identified correctly on the basis of the associated fish species and invertebrates. For

[#] remark by the editor
[##] remark by the editor: nomenclature of the zones according to Huet, 1949

Figure 2.6
Trout zone of the River Felda (Hesse)

Figure 2.7
Grayling zone of the River Ilz (Bavaria)

Figure 2.8
Barbel zone of the River Lahn (Hesse)

Figure 2.9
Bream zone of the River Oder (Brandenburg)

Table 2.1: Distribution of selected fish species in the major fish zones of the water systems of the Rhine, Weser and Elbe (modified after SCHWEVERS & ADAM, 1993)

	Upper trout zone	Lower trout zone	Grayling zone	Barbel zone	Bream zone	Ruffe-flounder zone
Brown trout *(Salmo trutta f. fario)*						
Bullhead *(Cottus gobio)*						
Brook lamprey *(Lampetra planeri)*						
Stone loach *(Noemach. barbatulus)*						
Minnow *(Phoxinus phoxinus)*						
Stickleback *(Gasterosteus aculeatus)*						
Grayling *(Thymallus thymallus)*						
Riffle minnow *(Alburnoides bipunct.)*						
Dace *(Leuciscus leuciscus)*						
Gudgeon *(Gobio gobio)*						
Chub *(Leuciscus cephalus)*						
Roach *(Rutilus rutilus)*						
Barbel *(Barbus barbus)*						
Nase *(Chondrostoma nasus)*						
Bleak *(Alburnus alburnus)*						
White bream *(Blicca bjoerkna)*						
Perch *fluviatilis)*						
Pike *(Esox lucius)*						
Bream *(Abramis brama)*						
Ruffe *(Gymnoceph. cernua)*						
Orfe *(Leuciscus idus)*						
Rudd *(Scardinius erythrophthalamus)*						
Carp *(Cyprinus carpio)*						
Tench *(Tinca tinca)*						
Anadromous species						
Sea trout *(Salmo trutta f. trutta)*						
Salmon *(Salmo salar)*						
River lamprey *(Lampetra fluviatilis)*						
Sea lamprey *(Petromyzon marinus)*						
Allis shad *(Alosa alosa)*						
Twaite shad *(Alosa fallax)*						
Sturgeon *(Acipenser sturio)*						
Catadromous species						
Eel *(Anguilla anguilla)*						
Flounder *(Platichthys flesus)*						

Main distribution area of reproductive populations

Secondary distribution area of reproductive populations

Table 2.2: River zoning (after ILLIES, 1961)

	upper reaches	upper trout zone	epi-rhithron
brook	middle reaches	lower trout zone	meta-rhithron
	lower reaches	grayling zone	hypo-rhithron
	upper reaches	barbel zone	epi-potamon
river	middle reaches	bream zone	meta-potamon
	lower reaches	ruffe-flounder zone	hypo-potamon

example the barbel zone, which is characterized by a high proportion of isopods (slaters), diptera larvae (flies) and hirudinids (leeches), by a low population density of sand-hoppers (amphipods) and caddis flies (trichoptera) and by the absence of certain plecoptera species (stoneflies), can be reliably distinguished from the grayling zone (ILLIES, 1958).

In order to emphasize this fact, ILLIES (1961) introduced a generally accepted international nomenclature for running waters to replace the zonation based on indicator fish species. He first divided running waters into two major categories, brooks (rhithron) and rivers (potamon), which are each further subdivided into three. For the waters of Central Europe, ILLIES' nomenclature is synonymous with the classification by indicator fish zones (TABLE 2.2).

ILLIES (1961) showed that sequences of biocoenoses comparable to that of the river Fulda, which is typical for Central European waters, also exist in the Amazon basin as well as in Peruvian and South African waters. But not surprisingly, the component species are different. However, the indigenous indicator and associated fish species of those waters have developed similar strategies to survive within the currents to those that have evolved in the homologous species of the Central European rivers. They also exhibit the same feeding habits as do the European fish and therefore occupy comparable ecological niches. Therefore, the River Continuum model, and thus the biological zoning of rivers, may in principle be regarded as having world-wide validity.

HUET (1949) showed through systematic studies of physico-chemical parameters and fish distribution in numerous rivers, mainly in France but also in Belgium, Luxembourg and Germany, that the formation of river zones is primarily determined by the current. HUET used both slope and, as an approximation of discharge, the width of rivers as a measure of current. The relationship between these two parameters and river zonation are shown in TABLE 2.3. In this table HUET's original data are complemented by differentiating between epi- and meta-rhithron based on experience from the Weser and the Rhine systems. Figure 2.10 provides a simple means for classification of river zones based on slope and river width. This classification is valid for the moderate climates in Central Europe, and thus also for all the river systems in Germany (HUET, 1949).

2.4 Potentially natural species composition

In considering the whole spectrum of European freshwater fish species, it is clear that at present certain fish species do not find suitable habitat conditions in many rivers. Thus 51 of the total 70 indigenous fish species that could theoretically be

Table 2.3: Slope classification of the river zones (modified after HUET, 1949)

	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				

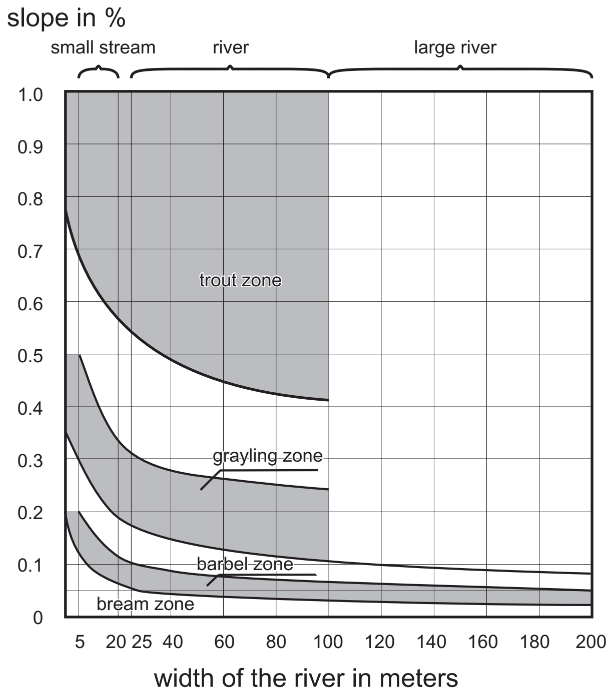


Fig. 2.10 Graphical representation of the relations between slope, river width and river zoning for determination of indicator fish zones (modified from HUET, 1959). The typical core zones are shown in grey; the zones lying between the grey fields are transitional zones. However, these transitions take place gradually in rivers.

present in Germany appear on the Red List of Extinct or Endangered Species for the Federal Republic of Germany (BLESS *et al*, 1994). Because of the continuing improvements in water quality and the extensive efforts in ecological upgrading of aquatic biotopes, the number of fish species that are able to recolonize lost terrain is increasing.

For some years now, there have been an increasing number of reports of the return of migratory fish species to various river systems from which they had been absent for decades. The assumption that the positive development of stocks of even severely endangered species progresses steadily is justified by the fact that populations of sea trout *(Salmo trutta f. trutta)*, flounder *(Platichthys flesus)* and river lamprey *(Lampetra fluviatilis)* have been shown to be steadily increasing. Furthermore spawning sea lampreys *(Petromyzon marinus)* have been reported from the Sieg river and sturgeons *(Acipenser sturio)* have been caught in the Dutch estuary of the Rhine (VOLZ & DE GROOT, 1992). Thus, the hope that once barren waters can be recolonized, even with "ecologically demanding" fish species, appears to be realistic.

Both the fauna actually present and those species that could potentially recolonize a certain river sector within a reasonable time have to be taken into account to ensure that sufficient consideration is given to ecological interests in planning water management and hydraulic engineering measures. The concept of a "potential natural fish species composition" of a certain ichthocoenosis can be used, to facilitate such planning. Here all species should be included that were originally indigenous in a certain river sector and that find there at present, or will be able to find there in the foreseeable future, a suitable habitat. The re-creation of suitable habitats can be achieved through improvements in water quality, structural rehabilitation of the river and the restoration of the longitudinal connectivity of a river system.

Different aspects should be considered in determining the potentially natural fish species composition. Since the accurate determination of the potentially natural fish fauna is an essential precondition for correct ecological evaluation of a river, it should generally be performed by fishery experts according to the following criteria:

- **River zoning:** The first requirement for determining the potentially natural fish species composition is the exact identification of the river zone (cf. chapter 2.3). A first approximation of the potentially natural species spectrum can be derived by assigning both indicator and associated fish species to the selected zone.
- **Biogeographical aspects:** The specific species composition of the fish communities in the catchment basin, which depends on both the typically regional characteristics and the specific properties of the river, has to be taken into consideration in determining the species of the potential natural fish fauna of any river. For instance, the nase *(Chondrostoma nasus)* is found in the Central European river systems (from the Loire to the Vistula), but is completely absent from both the Weser and Elbe systems as well as from the rivers in Schleswig-Holstein. On the other hand, the distribution of the huchen *(Hucho hucho)* (Figure 2.15) and several species of percidae, such as the little chop *(Aspro streber)* and the striped ruffe *(Acerina schraetzer)*, are exclusive to the Danube system.
- **Topographical particularities:** Aquatic biocoenoses reflect special topographic conditions, which must be considered in determining the potential natural fish fauna. For example, no indicator fish zones can be defined for rivers that flow through lakes, or take their origin from lakes, as under these conditions

mixed biocoenoses occur that are characterised by stagnant water fish species in the still water areas of the river and by riverine species in the areas at the lake outlets.

- **Quality of the habitats:** Additions or absences from the potential natural species spectrum may be caused by massive human interventions and anthropogenic changes in the river morphology. For example, many rivers of the barbel zone, e.g. the Moselle and the Main, are impounded for almost their entire course with cascades of dams. Similarly, if there is also no possibility of lateral migration into the tributaries of the barbel and grayling zone, the habitats of current-dwelling species are damaged to such a degree that recolonization by these species appears unrealistic for the foreseeable future. On the other hand, still-water species such as carp, which were not indigenous, usually find suitable spawning conditions in dammed rivers and colonize these waters with permanent and reproductive populations.
- **Historical evidence:** Indications of the potential natural fish fauna are usually obtained from historical sources (v. SIEBOLD, 1863; WITTMACK, 1876; LEUTHNER, 1877; v. d. BORNE, 1883 and others), or from analyses of historical catch reports. Typical examples of the latter are the one carried out for the reconstruction of the former area of distribution of sturgeon in the Rhine system by KINZELBACH (1987), or the investigations of KLAUSEWITZ (1974a, 1974b, 1975) of the original fish fauna of the Main by scrutinizing old fish collections. Some caution is needed in interpreting such historical records as the species mentioned are usually those most exploited by fisheries, while such small fish as bitterling *(Rhodeus sericeus amarus)*, bougfish *(Misgurnus fossilis)* and white asp *(Leucaspius delineatus)*, although ecologically important, are rarely mentioned. Furthermore, the lack of a standard German nomenclature across the different regions of the country involving the same name being used for different species causes considerable difficulties in the interpretation of historical sources. For example the German words “Schneider” [cutter] and “Weißfisch” [white fish] have each been used to designate different fish species in different regions.

2.5 Migration behaviour of aquatic organisms

Fish rely on migrations to satisfy their requirements with regard to the structure of the biotope during their different life stages. Migrations are undertaken both by fish and by the less mobile benthic invertebrates (Figure 2.11). Migrations may be either longitudinal in the main channel, or lateral between the main channel and side waters. Where rivers repeatedly form lakes along their course, as for example in the North German lowlands, there is a need for the interlinking of these different ecosystems to allow the organisms to migrate so as to satisfy their migration and habitat requirements. Longitudinal connectivity of rivers thus has an extremely important role to play with regard to reproductive exchange as well as to the spreading of populations and the recolonization of depopulated stretches of river.

Compensatory upstream migration

Terrain losses caused by drifting can be actively balanced by upstream movements.

Moving between different habitats

Some fish undertake intra-annual migrations between their feeding and resting habitats, or inhabit in the course of their life cycle different parts of a river that offer specific conditions that satisfy the requirements of their different development phases. This becomes particularly clear when looking at the life cycle of the bullhead *(Cottus gobio*; Figure 2.12) (BLESS, 1982). The bullhead, being active at night, rests under cover during the day. It therefore seeks hollows in the substrate that correspond exactly to its size. While the adult fish have a preference for river reaches with rapid current and correspondingly coarse substrate,

Fig. 2.11: Larvae of the caddis fly *Anabolia nervosa* in a fish pass in the Dölln river (Brandenburg)

Figure 2.12:
Bullhead *(Cottus gobio)*

Figure 2.13:
Nase *(Chondrostoma nasus)*

Figure 2.14:
Salmon *(Salmo salar)*

young fish, during their growing phase, find their optimal habitat in areas with gentle currents and fine grained substrates. Such differing substrate conditions do not often exist very close to each other, particularly in waters that have been influenced by anthropogenic activities, so that moving between habitats at different stages during the life cycle may involve migrations over long distances. A range of activity of up to 300 km has been proven for nase *(Chondrostoma nasus)* (Figure 2.13) and barbel *(Barbus barbus)* (STEINMANN, 1937).

At the end of summer different fish species move into winter habitats. These are usually located in the lower reaches of rivers and thus in deeper stretches with more gentle currents. There fish move down to the bottom of the river where they stay for hibernation while reducing their metabolism.

Spawning migration:

Spawning migrations are a special type of migration between different parts of a species' range. They are undertaken by most indigenous fish species within the river system in which they live. Known examples are the barbel *(Barbus barbus)* and brown trout *(Salmo trutta f. fario)*. If spawning migrations are blocked by impassable obstructions, the fish may spawn in parts of the river where conditions are less suitable (emergency spawning). This results in lower recruitment or complete failure of reproduction with subsequent extirpation of the species from the habitat.

Diadromous migration behaviour:

The life cycle of diadromous migratory fish species includes obligatory movement between marine and freshwater ecosystems. The necessity of unhindered passage through the river system can be well demonstrated on the basis of the biological requirements of such diadromous migratory fish. Interruption of the migratory routes inevitably leads to extinction of the populations. With regard to the direction of migration, two groups of migrants can be distinguished:

- Catadromous species, such as the eel *(Anguilla anguilla)*, migrate downstream as adults to reproduce in the open sea. With eels, reproduction takes place exclusively in the Sargasso Sea, and the willow-leaf-shaped larvae (leptocephali) drift passively with the sea currents into coastal regions. After metamorphosis, the as yet unpigmented young fish ("glass eels") migrate upstream, where they develop until they are sexually mature (Figure 2.16).
- Anadromous species, such as salmon *(Salmo salar)* (Figure 2.14), sea trout *(Salmo trutta f. trutta)*, sturgeon *(Acipenser sturio)*, allis shad *(Alosa alosa)*, sea lamprey *(Petromyzon marinus)* and the river lamprey *(Lampetra fluviatilis)* migrate from the sea into rivers when they are sexually mature in order to spawn in the upper river reaches. In turn, the young fish migrate back to the sea after a certain time where they then grow until they are sexually mature (Figure 2.17).

Population exchanges:

The balancing of differing population densities in neighbouring river stretches takes place through upstream or downstream migrations and leads to genetic exchange between populations.

Downstream migrations:

Downstream migrations fulfil yet another essential biological function in addition to that of spawning migrations of eels or the downstream migration of salmon and sea trout smolts. For example when ecological catastrophes happen, such as severe floods or discharges of pollutants, benthic invertebrates in particular can drift downstream (i.e. a so-called "catastrophic drift"). In all cases irrespective of whether migrations are actively undertaken (i.e. escape) or passively endured, the aquatic organisms thus depend on adequate free longitudinal connectivity.

Propagation:

The mobility of aquatic organisms plays a critical role in the recolonization of whole waterbodies and water courses, or of portions of them that are chronically barren or which were depopulated in a single catastrophic event. Thus only a short time after the Sandoz accident recolonization of the barren stretches of the Rhine occurred (MÜLLER & MENG, 1990), so that only two years after the accident the fish populations had recovered and no longer showed signs of damage (LELEK & KÖHLER, 1990). This rapid regeneration is particularly attributed to immigration from the tributaries into the river Rhine.

Large freshwater mussels of the family najadae are peculiar in the way they propagate as they spread through their larval stage (glochidium larvae). These larvae parasitize the gill epithelia or the fins of indigenous fish, and can thus be transported by their hosts over long distances in the water system before they fall onto the sediment and develop into sexually mature mussels.

2.6 Hazards to aquatic fauna caused by dams and weirs

The indigenous fish fauna of Germany is subjected to many threats that have resulted in a severe reduction in the stocks of many species. The principal sources of danger of hazards for indigenous fish are the following human interventions in aquatic biotopes:

- Water pollution through domestic and industrial sewage discharges, as well as run-off from agriculture (fertilisers, pesticides, erosion), and atmospheric emissions (SO_2, acid rain, etc.).
- Changes in channel morphology that lead to ecological degradation or destruction of habitats.
- Disruption of longitudinal connectivity caused by impassable obstacles.
- Effects of fishing activities on fish stocks.

BLESS *et al.* (1994) found that, due to these hazards, of the 70 indigenous German freshwater fish species:

4	species	were extinct or missing;
9	species	were threatened with extinction;
21	species	were severely endangered;
17	species	were endangered.

Of the fish species that are extinct, missing or threatened with extinction, 82% are migratory species, or species with a high oxygen demand requiring clean gravel for spawning and that can only live in biotopes with rapid currents (BLESS *et al.*, 1994). Thus, one of the most critical threats to these species is the damming of rivers. The extinction of these populations can be blamed on the interruption of free passage caused by obstacles as well as the formation of artificially impounded waters behind dams and weirs. These obstacles undoubtedly alter the hydraulic and morphological properties of the river to a degree which depends on the size and extent of the reservoir. Further threats to aquatic biocoenoses (LWA, 1992) are:

- The increased cross-sections of the impoundments behind dams and weirs significantly reduce flow velocity and the variability of the current.
- Increased sedimentation of fine sediments in the impoundment that covers the coarse substrate so that the original mosaic of differing grain sizes is altered.
- Many aquatic organisms lose their hyporheic interstitial habitat as a result of the failure to rearrange sediments by the current.
- Flow-through through the interstices of the substrate, and thus the availability of oxygen, is reduced. Sedimenting organic matter is increasingly broken down anaerobically so that sapropel (i.e. putrefying sludge) builds up, particularly in eutrophic waters.
- The water temperature increases due to the reduced flow velocity and the longer retention time of the water in the impoundment.
- Oxygen deficiency can occur in the impoundment because the water's capacity to bind oxygen decreases as it warms up and because the intake of atmospheric oxygen at the air/water interface is reduced due to the reduced turbulence.

Figure 2.15:
Huchen *(Hucho hucho)*

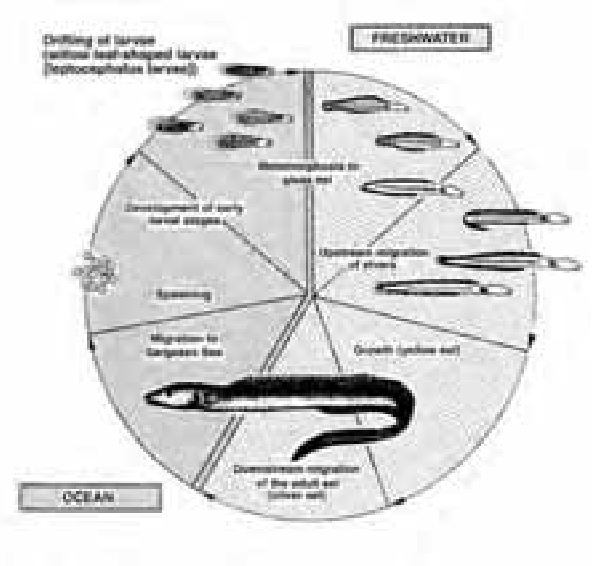


Fig. 2.16: Life cycle of catadromous migratory fish: example of the eel *(Anguilla anguilla)*

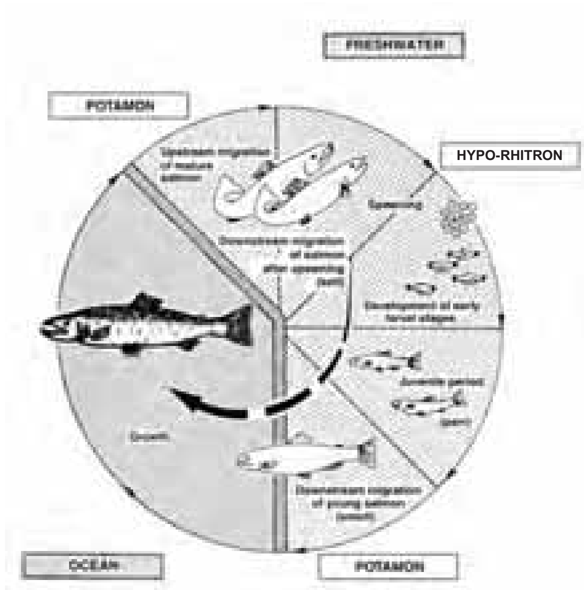


Fig. 2.17: Life cycle of anadromous migratory fish: example of the salmon *(Salmo salar)*

- Reduced current in the impoundment coupled with increased nutrient inflow into the waters favour the growth of aquatic plants often resulting in algal blooms or excessive weed growth. The photosynthetic production from an excessive biomass of plants can lead to a considerable increase in pH, and thus bears the risk of fish mortality particularly under strong solar radiation. Furthermore, the massive decay of aquatic plants in autumn can lead to fish mortality through oxygen deficiency or depletion.
- Light penetration to the river bottom is considerably reduced at greater water depths; thus growth of periphytic algae is impaired.
- Energy flow, as described in the river continuum concept, is interrupted by increased sedimentation of organic matter. This results in disturbances in the metabolic processes in rivers.

These alterations to the habitats in rivers caused by damming and impoundment have lasting negative influences on the biocoenoses:

- Especially the current-dwelling (rheophilic) species and organisms with high oxygen demand lose their habitat, particularly in larger impoundments.
- Species that need clean gravel for spawning do not find appropriate spawning grounds, and organisms living in the interstices, as well as bottom-living fish, lose their shelter.
- Species that feed on periphytic algae, such as the grazers among invertebrates or the nase *(Chondrostoma nasus)* among fishes, lose their feeding grounds.
- The food supply for fish is reduced because of an altered and/or reduced range of invertebrates.
- The loss of important parts of the habitat leads to disturbance of the age structure of the fish populations thus endangering species.
- The biocoenosis is reduced to those adaptable species that have no problem to tolerate the altered abiotic conditions.

Channel reaches below dams (i.e. the original natural main channel#) that fall dry due to the abstraction of water by bypass power stations constitute a further problem for aquatic organisms. As at bypass power stations the water is usually re-injected into the channel only at some distance further downstream, only little water remains in the original natural channel or the channel might even dry out completely over prolonged periods. In comparison to intact river sections, these dried-out reaches are extremely impaired with the following threats for the biocoenoses:

- A severely reduced flow regime minimizes the variability of the current, so that only the bottom of the river channel is wetted and pools of stagnating water are formed (so-called trap effect). Riverine species can no longer find an adequate habitat.

remark by the editor

- The water in the impacted river reach (i.e. in the original natural main channel[#]) is severely warmed in summer, so that there is a danger of the reach drying-out completely with a consequent dehydration of the aquatic organisms.
- Furthermore, the formation of ground ice (anchor ice) in winter can kill organisms.
- Other physical-chemical parameters also alter due to the absence of the current, which is the normal determinant in rivers. This causes further changes such as, for example, algal bloom and increased oxygen consumption.
- When the maximum turbine flow-through capacity of the hydroelectric power station is exceeded, i.e. when more water is in the river than can pass through the turbines, the rapidly increased discharge into the original natural main channel that was then almost dry can lead to increased drifting of aquatic fauna.

Establishing minimum flow requirements for the impaired channel stretch downstream of a dam attempts to counter these problems (DVWK, 1995). There are different approaches and regionally different processes for the setting of minimum flows which, however, are not further dealt with in these Guidelines.

[#] remark by the editor

3 General requirements for fish passes

Longitudinal connectivity in rivers is critical ecologically to satisfy the diverse migratory needs of aquatic species (Chapter 2.5). It is, therefore, an essential requirement for all waters to which migratory species are native. When restoring longitudinal and lateral connectivity to a river system it is ecologically sound practice to link the main channel with backwaters and secondary biotopes such as waterbodies that were created after the extraction of solids (e.g. flooded quarries, gravel pits, peat workings etc.). Longitudinal connectivity must be conserved or restored regardless of the size of river, the extent of structural modification of the channel, the present water quality or the interests of current users. Numerous examples show that the degree of pollution and the use that is made of a waterbody can change within a very short time, and that anthropogenic interests can be forced into the background. Thus, the restoration of longitudinal connectivity becomes important even for river reaches whose present ecological condition allows only limited colonization by aquatic organisms. On this basis the elaboration of concepts that support the interlinking of river systems makes a real contribution towards sounder river management. However, even individual mitigation measures can fit effectively into the overall, ecologically oriented concept of the restoration of longitudinal connectivity (SCHWEVERS & ADAM, 1991).

Free longitudinal passage through rivers is mainly impeded, or made impossible, by sudden artificial

Figure 3.1:
Even if not very high, sudden drops like the one shown present impassable obstacles to migration for small fish. Lauge stream at Gardelegen (Saxony-Anhalt)

Figure 3.2:
Culverts with detached jets scouring the adjacent stream bottom are an impassable obstacle to migration for aquatic organisms. Pritzhagener Mill in the Stöbber (Brandenburg)

drops (Figure 3.1), weirs or dams that cannot be passed by aquatic organisms. Apart from such structures, culverts (Figure 3.2) or stretches of river that have been intensively modified by concrete-lined channels, paved river bottoms or prefabricated concrete half-shell elements can also act as obstructions to migration. Before planning a fish pass, the first step must be to question the need to maintain the existing cross-river obstruction, since the construction of a fish pass is always only the "second best solution" for restoring unhindered passage through a river. In smaller rivers, particularly, there are numerous weirs and dams, such as mill and melioration weirs, whose original purpose has been abandoned but which still stop migration of aquatic organisms. The removal of such obstacles should be given preference over the insertion of a fish pass when attempting restoration of longitudinal connectivity. Exceptions to this principle may occur where conflicts arise with other ecological requirements, such as the preservation of a valued wetland by the higher level of the impounded waters, or with regional socio-cultural needs.

The following basic considerations pertain to fundamental features, such as the optimal location and design criteria of fishways in a river, which are independent of the particular type of fish pass. The general criteria that fish passes should meet include the biological requirements and the behaviour of migrating aquatic organisms and thus constitute important aspects in planning fishways. However, it has to be pointed out that present-day knowledge of the biological mechanisms that trigger or influence migrations of such organisms is still sketchy and there is a great need for further research to serve as a basis for criteria for fish pass construction.

General standards for fish passes include different individual aspects that must be taken into account in planning for the construction of a new dam, in assessing an existing fish pass or in planning for the fitting of fishways to an existing dam. These requirements should take priority over economic considerations. Depending on local circumstances, it might well be necessary to build several fish passes at one dam to ensure satisfactory passage of all species. Statements that are generally valid are given preference here over specific solutions for individual cases, since each dam has its own peculiarities that derive from its configuration and integration into the river.

3.1 Optimal position for a fish pass

While in rivers, that have not been dammed, the whole width of the channel is available for the migration of aquatic organisms, fish passes at weirs and dams usually confine migrating organisms to a small part of the cross section of the channel. Fish passes are usually only relatively small structures and therefore have the characteristics of the eye of a needle, particularly in rivers and large rivers (Figure 3.3). In practice, the possible dimensions of any fishway are usually severely limited by engineering, hydraulic and economic constraints, particularly in larger rivers. Thus the position of a fishway at the dam is of critical importance.

Fish and aquatic invertebrates usually migrate upstream in, or along, the main current (Figure 3.4 and Figure 3.5). For the entrance of a fishway to be detected by the majority of upstream migrating organisms, it must be positioned at the bank of the river where the current is highest. This has the added advantage that, with a position near the

Figure 3.3
Aerial view of the Neef dam in the Moselle River (Rhineland-Palatinate) to show the size of the fish pass (see white arrow) in comparison to the total size of the dam.

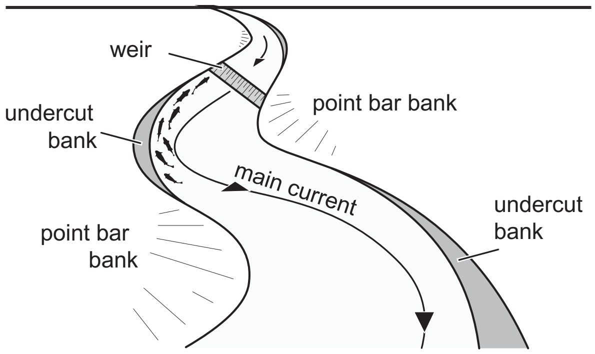


Fig. 3.4: Diagram showing the flow pattern in a river with undercut banks and point bar banks. Fish swimming in or along the main current will arrive at the weir along the side of the undercut bank. Consequently, a fish pass should be positioned as closely as possible to the point where the fish meet the obstacle (modified after JENS, 1982).

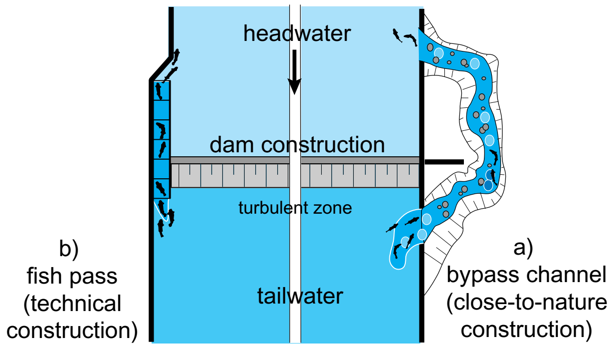


Fig. 3.5: a) Optimum position of a bypass channel and
b) optimum position of a technical fish pass:

Fish migrating upstream are guided by the main current and swim up to the zone of highest turbulence in the tailwater directly below the dam or the turbine outlet. In the vicinity of the bank, fish seek a way to continue to move upstream. Most importantly, it must be ensured that fish can pass the bottom sill of the stilling basin (modified after LARINIER, 1992d).

bank, the fish pass can be more easily linked to the bottom or bank substrate.

The most suitable position for a fish pass at hydroelectric power stations is also usually on the same side of the river as the powerhouse. The water outlet of (i.e. the entrance[#] to) the fish pass should be placed as close as possible to the dam

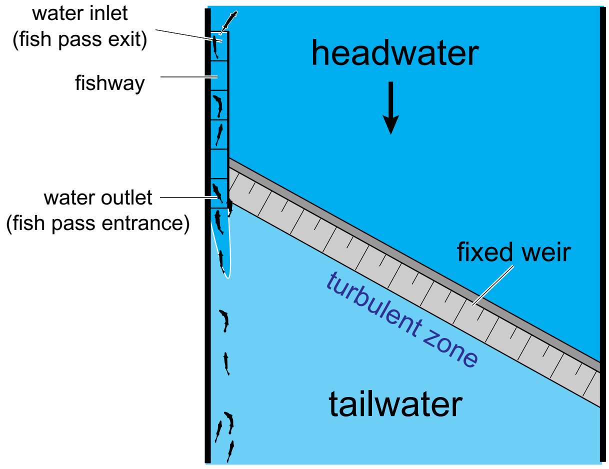


Fig. 3.6: Fish moving upstream gather in the narrow angle between the weir and the bank. This is the most suitable location for the construction of a fish pass (after LARINIER, 1992d).

or turbine outlet. Placing the outflow of the fish pass (and thus its entrance) in the immediate vicinity of the dam or weir minimizes the formation of a dead zone between the obstruction and the fish pass entrance. This is important, as fish swimming upstream can easily miss the entrance and remain trapped in the dead zone. A fish pass that extends far into the tailwaters below the dam considerably limits the possibility that fish find the entrance, a design fault that has been responsible for the failure of many fish passes.

Where dams or weirs are placed diagonally across the river and overflow along their entire crest, upstream migrating fish usually concentrate at the upstream, narrow angle between weir and bank (Figure 3.6). Therefore, the fish pass should clearly be sited in this area.

As regards bypass hydroelectric power stations, there are two options for positioning the fish pass to ensure longitudinal connectivity. Firstly the fish pass can be built at the power station, providing a link between the tailwater channel and the headwater channel. Secondly it can be constructed at the weir, acting as a link between the original natural main channel and the headwater of the impoundment. Usually a fish pass is constructed at only one of these locations. Since the fish generally follow the strongest current, they tend to swim up the tailwater channel to the turbine outlet rather than entering the old main channel through which the discharge is usually lower. Construction of a

[#] remark by the editor

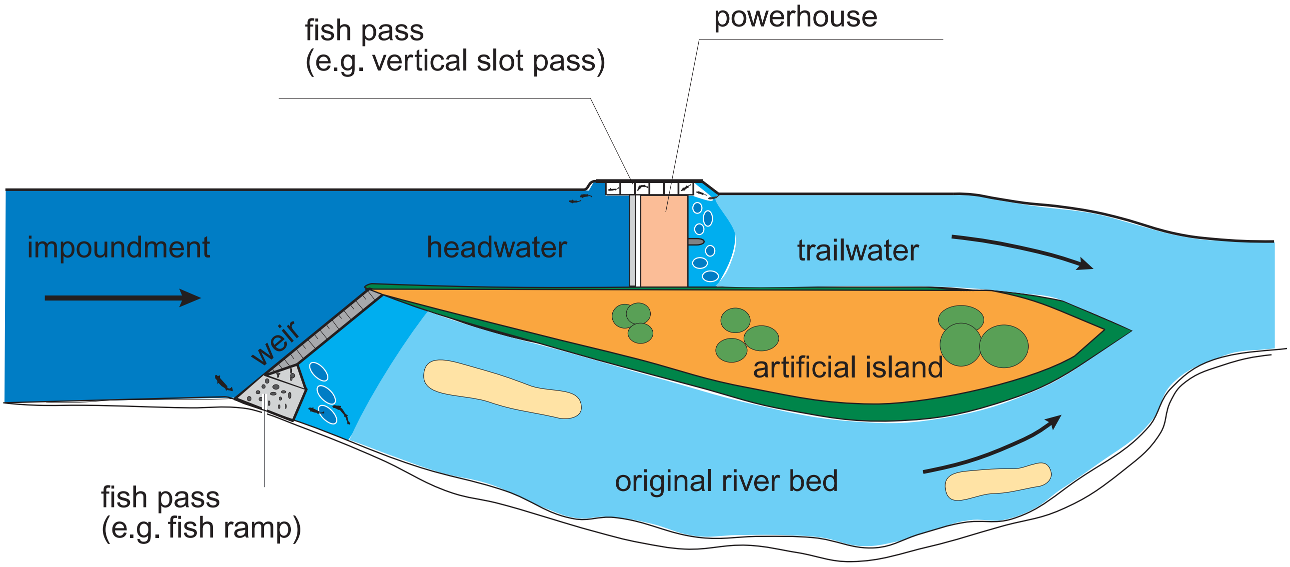


Figure 3.7: Ensuring longitudinal connectivity at a bypass hydroelectric power station through construction of two fish passes, i.e. one directly at the hydropower plant and the other at the weir.

fish pass from the tailwater channel to the headwater channel is therefore needed in such cases. However, when the turbine capacity of the power plant is exceeded, excess water is spilling over the dam into the old main channel, so it is also advisable to install a fish pass at the barrage. The water from this second fish pass can also be used to provide minimum environmental flows in the old channel so that running water conditions are maintained there, provided that the discharge is sufficiently high. From an ecological point of view, it is therefore highly advisable in such cases to construct two fish passes, one at the hydropower plant and one at the barrage (Figure 3.7).

3.2 Fish pass entrance and attraction flow

The perception of the current by aquatic organisms plays a decisive role in their orientation in rivers. Fish that migrate upstream as adults usually swim against the main current (positive rheotaxis). However, they do not necessarily migrate within the maximum flow but, depending on their swimming abilities, they may swim along its edge. If migration is blocked by an obstruction, the fish seek onward passage by trying to escape laterally at one of the dam's sides. In so doing they continue to react with positive rheotaxis and, in perceiving the current coming out of a fishway, are guided into the fish pass.

The properties of the tailrace below a dam (water velocity and degree of turbulence) influence the attracting current that forms at the entrance to the fish pass. The attraction exercised by the current is also influenced by the velocity and angle of the emergent flow, as well as by the ratio of river discharge to discharge by the fish pass. The attracting current must be perceptible, particularly in those areas of the tailrace that are favoured by the target species or to which the fish are forced to swim due to the tailwater characteristics. The velocity at which the attracting current exits the fish pass should be within the range of 0.8 to 2.0 m s^{-1} (SNiP, 1987).

Particularly where the tailwater level fluctuates, a special bypass can be used to channel additional flow directly from the headwater to the entrance of the pass in order to boost the intensity of the attracting current. Using a bypass avoids that the flow characteristics in the pass are negatively influenced by an increased flow within the pass that is, in fact, only needed at the fish pass entrance. The bypass can be in the form of a pressure pipe, but it is usually better to have an open channel. Under no circumstances should the velocity of this additional water, that comes out of the bypass, hinder fish to swimming into the pass. Except for special cases flow velocity should not exceed 2 m s^{-1}. The addition of an antechamber at the fish pass entrance is described by the Russian Standard Work on fish passes (SNiP, 1987). Such chambers, that receive water from both the fish pass and the bypass, are now part of many installations in France and the USA. Flows from the discharge of the fishway and that of the bypass mix in this antechamber to form the attraction current that ejects into the river (Figure 3.8). In this case, the

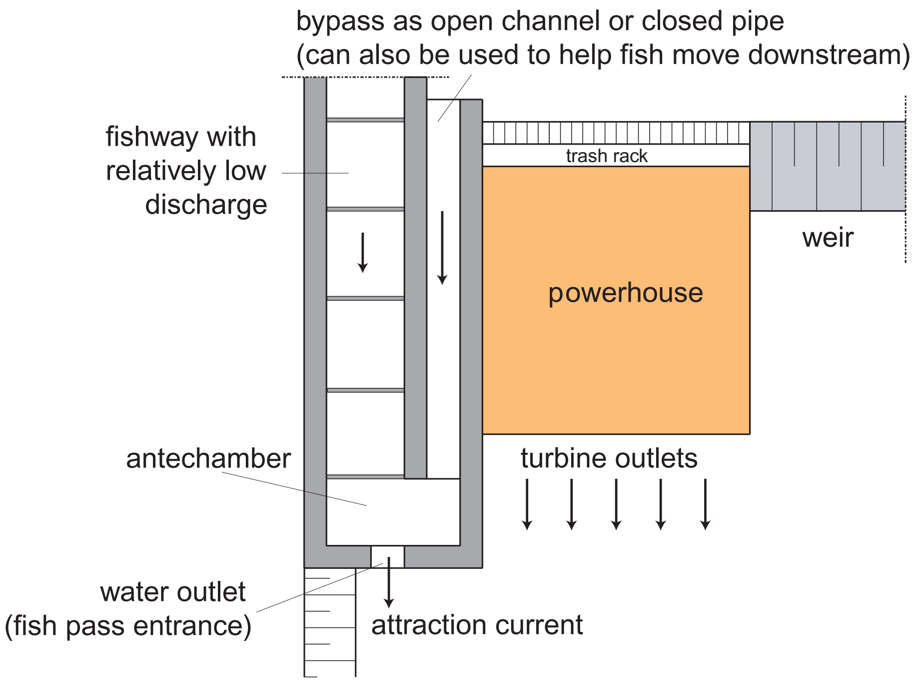


Figure 3.8:
Additional discharge is sent through a bypass into an antechamber downstream of the first pool of the fish pass to increase the attraction current at the fish entrance

velocity at the water outlet (i.e. the fish pass entrance#) must not exceed 2 m s^{-1} even at low water.

There is an unproved assumption that either the increased influx of atmospheric oxygen into the water or the splashing sounds from the water in the fish pass exert a "luring effect" that can be used in optimising fish pass design. Unfortunately this has not yet been substantiated. Technical devices for guiding fish in a certain direction, such as behavioural barriers or mechanical guiding devices, are not dealt with in these Guidelines, since no reliable data on the efficiency of such devices is yet available. Laboratory experiments on the effects of lateral inflows into rivers as well as observations on the behaviour of fish at fish passes that function well provide the basis for the following remarks. Theoretical approaches using calculations to determine the propagation characteristics of the attracting current are provided by the Russian Standard Work (SNiP 1987) and by KRAATZ (1989).

The entrance of the fish pass must be positioned where fish concentrate while moving upstream. The characteristics of the tailwater currents and the structural details of the hydropower station determine the area of concentration. In many cases this is directly below the weir or dam, at the foot of the barrage or at the turbine outlets. Therefore, any current to attract fish must be directed from the entrance to the pass towards the area of concentration in such a way that fish, in following

remark by the editor

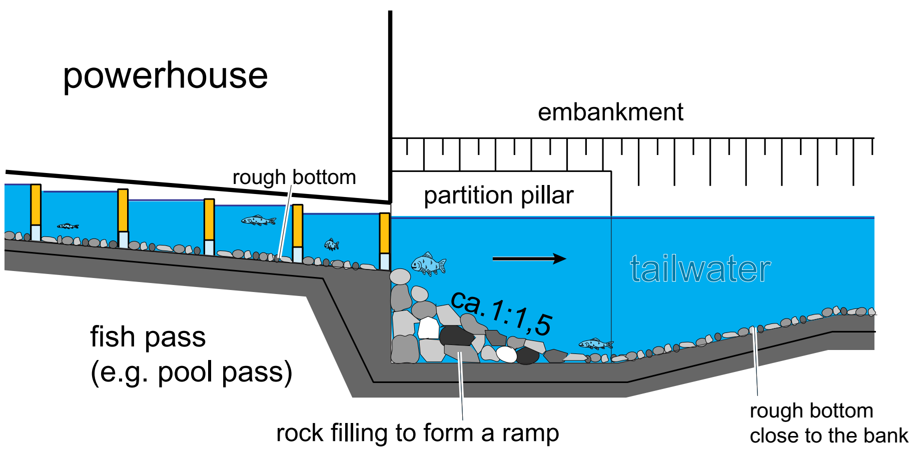


Figure 3.9:
Underwater rockfill ramp connecting the fish pass entrance with the river bottom

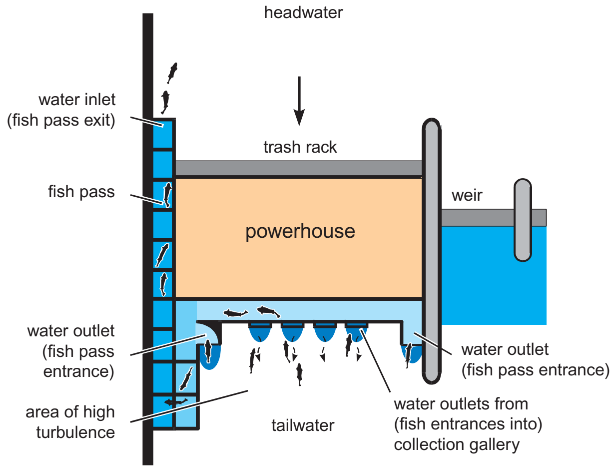


Fig. 3.10: Diagram of an American hydroelectric power station with a collection gallery (after LARINIER, 1992d)

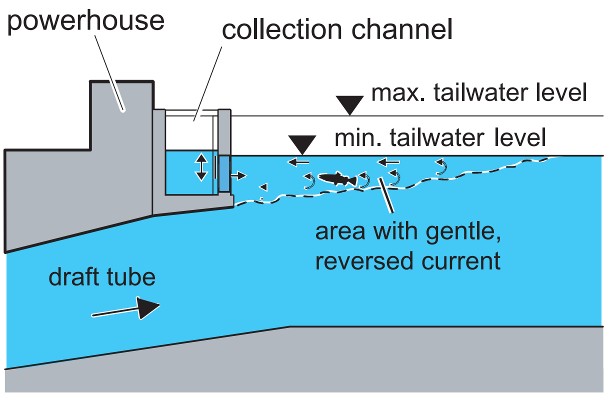


Fig. 3.11: Cross-section through a collection gallery (after LARINIER, 1992d)

the current, will be drawn to the entrance of the pass and thus enter the fishway.

If possible, the entrance of the fish pass should be at the bank, parallel to the main direction of flow, so that fish can swim in without altering direction. If the entrance to the fish pass is located too far downstream of the obstruction the fish will have difficulty finding it.

The further downstream of the dam that the attracting current flows into the river, the more important it is that this current is clearly perceptible to fish moving upstream. An adequate attracting current can be obtained by increasing the water velocity at the entrance to the fishway or by passing a high discharge through the pass itself or by putting additional attraction water through a bypass. Model experiments showed that an attracting current that leaves the fish pass entrance at a maximum angle of 45° is most effective for the fish, provided that enough water is available to allow a high discharge through the fishway at a sufficiently swift velocity. A wider angle projects the jet further towards mid-river but is accompanied by the risk that the attracting current does not anymore follow the bank and that fish swimming near the bank only notice this attracting current when they are right by the entrance.

A critical problem is how to construct the fish pass entrance so that fish can swim into the fishway even at low water levels. Entry into the fishpass can be eased, even for bottom-living fish species and macrozoobenthos, by linking the fish pass to the natural river bottom. This can be done with a ramp with a maximum slope of 1:2 (Figure 3.9). Some existing fish passes have their entrances oriented towards the weir and thus at an angle of 180° relative to the river current. In such cases the entrance is unsuitable in that it can not establish an attracting current to enable the fish to find the entrance to the fishway.

A collection gallery has been incorporated into the design of American hydroelectric power stations to serve as a special type of fish pass entrance (CLAY, 1961). This type of construction is inspired by the fact that many fish swim upstream through the turbulent zone at the outlet of the power station's turbines and thus arrive directly at the obstacle. A gallery located over the turbine outlets stretches over the whole width of the obstacle at exactly this point. This gallery has various outlets, one next to each other, through which the attracting current is discharged. Fish entering the gallery are led through it into the actual fish pass, which also has its own direct entrance (Figures 3.10 and 3.11). This type of construction is, however, not suitable for bottom-living fish.

Since diurnal fish avoid swimming into dark channels the fish pass should be in daylight and thus not covered over. If this is not possible the fishway should be lit artificially in such a way that the lighting is as close as possible to natural light.

3.3 Fish pass exit and exit conditions

Where the fish pass is installed at a hydroelectric power station, its water inlet (exit into the headwater#) must be located far enough from the weir or turbine intake so that fish coming out of the pass are not swept into the turbine by the current. A minimum distance of 5 m should be maintained between the fish pass exit and the turbine intake or the trash rack. If the current velocity of the headwater is greater than 0.5 m s^{-1}, the exit area of

remark by the editor

the fish pass has to be prolonged into the headwater by a partition wall.

In general, if the headwater level of the impoundment is constant, the design of the water inlet does not present a problem. However, special provisions have to be made at dams where the headwater level varies. Here the fish pass either has to be of such a type that it's functioning is only slightly affected by varying headwater levels, or relevant structural adaptations of its water inlet area must be incorporated. A vertical slot exit has proved appropriate for technical fish passes if the variations in headwater level are at maximum between 0.5 to 1.0 m. Where variations in level exceed one metre, several exits must be constructed at different levels for the fishway to remain functional (Figure 3.12).

With certain types of fish pass, mechanical regulation of the flow-through discharge may be necessary for the pass to continue to function. Simple aperture controls at the exit (i.e. the water intake) may be suitable. When the impoundment shows greater variations in level, more complex structures with control systems or barrier devices may be necessary. Unfortunately such devices are liable to malfunction or, alternatively, the staff may operate the control systems improperly causing a lessening in the efficiency of the fish pass.

Strong turbulence and current velocities over 2.0 m s^{-1} must be avoided at the exit area of the fish pass so that fish leave the pass for the headwaters more easily. Furthermore, linking the exit of the fishway with the natural bottom or bank substrate by means of a ramp facilitates the movement of migrant benthic organisms from the fish pass into the headwater.

The water intake of the fishway should be protected from debris by a floating beam.

Structural provisions should be made so that a control device (e.g. a trap) can be installed at the exit of the fishway to monitor its effectiveness. These could be footings for a fish trap and an adjacent lifting device for instance. It should also be possible to shut down the flow through the fishpass, e.g. for control and maintenance work.

3.4 Discharge and current conditions in the fish pass

The discharge required to ensure optimum hydraulic conditions for fish within the pass is generally less than that needed to form an attracting current. However, the total discharge available should be put through the fish pass to allow unhindered passage of migrants, especially during periods of low water. This is particularly advisable for dams that are not used for hydropower generation. If more water is available to supply the fishway than is needed for the hydraulically-sound functioning of the existing or planned fish pass, alternative designs should be envisaged, e.g. the construction of a rocky ramp that should be as wide as possible. In some cases a structural adaptation of the fishway's exit area may be necessary to limit the discharge through the fish pass, e.g. during floods, in the interest of efficient functioning.

Using supplementary water to increase flows that does not originate from the river on which the fish pass is situated, such as discharge from water diversions or sewage treatment plants, should be avoided. The mixing of waters of different physical-chemical properties disturbs the sensitive olfactory

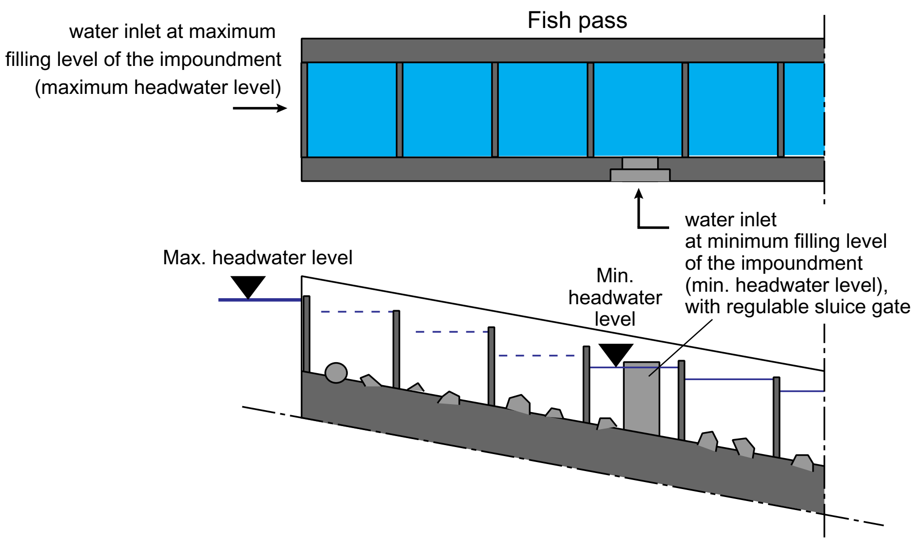


Figure 3.12: At the side of the impoundment, several water inlets (fish exits[#]) at different levels guarantee that fish can leave the fish pass even at varying (lower) headwater levels.

[#] Remark by the editor

orientation capability of the fish and thus reduces their urge to continue migration.

The turbulence of the flow through the fishway should be as low as possible so that all aquatic organisms can migrate through the pass independently of their swimming ability. LARINIER (1992b) recommends that the volumetric energy dissipation in each pool of a pool pass should not exceed 150 to 200 W per cubic meter of pool volume.

In general, current velocity in fishways should not exceed 2.0 m s^{-1} at any narrow point such as in orifices or slots and this limit to velocity should be assured by the appropriate design of the pass. The average current velocity in the fishway must be significantly lower than this value, however. The pass should incorporate structures that form sufficient resting zones to allow weak swimming fish to rest during their upstream migration. Furthermore, the current velocity near the bottom is reduced if the bottom of the fish pass is rough. As a rule, there should be laminar flow through the fish pass as plunging (turbulent) flow can only be accepted under specific local conditions, such as over boulder sills.

3.5 Lengths, slopes, resting pools

Instructions for the correct dimensions of fishways include information on such features as slope, width, length and water depth as well as the dimensions of orifices and resting pools. These instructions depend mainly on the particular type of fish pass to be built as well as on the available discharge. Type-specific instructions are to be found in the relevant sections of these Guidelines that deal with the different types of fish passes. All instructions given in these Guidelines are minimum requirements.

The body length of the biggest fish species that occurs or could be expected to occur (in accordance with the concept of the potential natural fish fauna) is an important consideration in determining the dimensions of fish passes. The fact that fish can grow throughout their whole lives must be taken into account when gathering information on the potential fish sizes. The body lengths shown in Table 3.1 are average sizes. Maximum sizes, such as that of the sturgeon that can grow to 6.0 m in length, are not provided.

The average body length of the largest fish species expected in the river as well as the permissible difference in water level must be considered in defining the dimensions of a fish pass, (cf. Chapters 4 and 5). Since a difference in water level of only Δh = 0.2 m entails a maximum current velocity of 2.0 m s^{-1} for instance at orifices and crosswalls, it is recommended that the water level difference between pools in a fishway be also kept below 0.2 m (Figure 5.4). Such a maximum difference in water level leads to a current velocity in the layer just above the rough bottom that allows even fish that have a weak swimming performance to pass. Waterfalls and drops where aerated jets would form must be avoided.

For more technical constructions the maximum permissible slope ranges from 1:5 to 1:10, depending on the construction principle chosen, while close-to-nature constructions should show maximum slopes less than 1:15 corresponding to the natural form of rapids (cf. Chapter 4). It is, however, acceptable for the slope of a natural-looking fish pass to not correspond to the natural slope of the river at this very location.

The swimming ability of the fish species of the potential natural fish fauna and all its life stages has to be considered in setting the length of a fishway. However, data on the swimming velocity of fish is

Table 3.1: Average body lengths of adults of some larger fish species

	Fish species	Body length [m]
Sturgeon	*Acipenser sturio*	3.0
European catfish	*Silurus glanis*	2.0
Pike	*Esox lucius*	1.2
Salmon	*Salmo salar*	1.2
Huchen	*Hucho hucho*	1.2
Sea lamprey	*Petromyzon marinus*	0.8
Sea trout	*Salmo trutta f. trutta*	0.8
Allis shad	*Alosa alosa*	0.8
Barbel	*Barbus barbus*	0.8
Lake trout	*Salmo trutta f. lacustris*	0.8
Bream	*Abramis brama*	0.7
Orfe	*Leuciscus idus*	0.7
Carp	*Cyprinus carpio*	0.7
Chub	*Leuciscus cephalus*	0.6
Grayling	*Thymallus thymallus*	0.5
Twaite shad	*Alosa fallax*	0.4
River lamprey	*Lampetra fluviatilis*	0.4
Brown trout	*Salmo trutta fario*	0.4

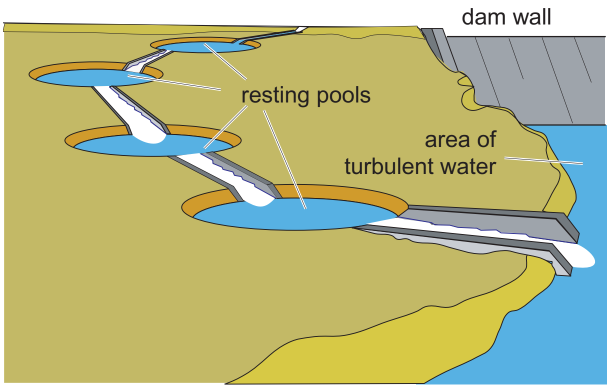


Fig. 3.13: Technical fish pass with resting pools, bypassing the obstacle in a bent design (modified from TENT, 1987)

not listed here since the values determined in different investigations differ markedly from one another or is even contradictory (JENS, 1982; STAHLBERG & PECKMANN, 1986; PAVLOV, 1989; GEITNER & DREWES, 1990). In any case, the requirements of the weakest species, or of the weakest life stages, must be considered when defining the dimensions of a pass.

Resting zones or resting pools should be provided in fishways. Here fish can interrupt their ascent and recover from the effort. In some types of pass, such as slot or pool passes, resting zones are inherent to the design. In others, such as rock ramps, they can easily be created. Resting pools where turbulence is minimal should be inserted at intermediate locations (Figure 3.13) into types of fishways that have normally no provision for resting zones due to their design. The dimensions of a resting pool should be set so that the volumetric power dissipation must not exceed 50 W m^{-3} of pool volume. Valid data on the maximum permissible length of fish passes are not generally available. However, for types of pass without rest zones and of a length that is excessive for fish to negotiate in a single effort, it is recommended that resting pools are placed at intervals of such lengths as defined by the difference in level of not more than 2.0 m between pools. Denil passes must be broken up by resting pools at least after every 10-m-stretch of linear distance for salmonids, and at least after every 6 to 8 m for cyprinids.

Fig. 3.14: Coarse bottom substrate in a slot pass; Lower Puhlstrom weir in the Unterspreewald (Brandenburg)

3.6 Design of the bottom

The bottom of a fish pass should be covered along its whole length with a layer at least 0.2 m thick of a coarse substrate (Figure 3.14). Ideally the substrate should be typical for the river. From the hydraulic engineering point of view, a coarse substrate is necessary for the creation of an erosion-resistant bottom. However, the bottom material used for this should be as close to natural as possible and should form a mosaic of interstices with a variety of differently sized and shaped gaps due to the varied grain size. Small fish, young fish, and particularly benthic invertebrates can retreat into such gaps where the current is low and can then ascend almost completely protected from the current. The creation of a rough bottom usually presents few problems in close-to-nature types of fishways.

The rough bottom must be continuous up to and including the exit area of the fish pass, as well as at the slots and orifices. In some more technical types of construction, such as Denil passes, the creation of a rough bottom is not possible. This means that benthic invertebrates cannot pass through them and thus these constructions do not fulfil one of the essential ecological requirements for fish passes.

3.7 Operating times

The migrations of our indigenous fishes take place at different times of the year. While many cyprinid species (Cyprinidae) migrate mainly in spring and summer, the spawning migrations of salmonid species (Salmonidae) occur mainly in autumn and winter. The migratory movements of benthic invertebrates probably occur during the entire vegetative period. The time of the day at which aquatic organisms move in rivers also differs for the different groups. Thus, numerous benthic invertebrates are mainly active at twilight and at night, while the time of maximum activity of the different fish species varies considerably and can in fact even alter during the year (MÜLLER, 1968). Because of this variability in the timing of migrations fish passes must operate throughout the year. Limited operation can be tolerated only during extreme low- and high water periods (i.e. for the 30 lowest days and the 30 highest days in one year), since at such times fish usually show a decrease in migratory activity.

Continuous 24-hour operation must be guaranteed since, once they have entered the fishpass, invertebrates that are little mobile would be unable to escape even a short drying out of the pass and inevitably die if the pass is only operating periodically.

3.8 Maintenance

The need for regular maintenance must be considered from the start of planning a fish pass as poor maintenance is the chief cause of functional failure in fishways. Obstruction of the exit of the pass (i.e. the water inlet) and of the orifices, damage to the fish pass structure or defective flow control devices are not rare but can be overcome through regular maintenance. There must be unhindered and safe access to the pass so that maintenance can be assured. Close-to-nature types of construction such as rock ramps are easier to maintain than highly technical structures because obstruction with debris of the water inlet area or the boulder bars is rarely total and does not immediately halt operations. Highly technical structures therefore require more frequent maintenance. A maintenance schedule can be drawn up or adjusted on the basis of operational experience of the type and frequency of malfunction of the fish pass in question. Maintenance must always be carried out after floods, however.

3.9 Measures to avoid disturbances and to protect the fish pass

The competent authorities should establish zones closed to fishing above and below fishways in order to protect migrating fish from any disturbance. Such regulations can be made on the basis of the fisheries law of the administrative entity in which the fish pass is installed. Leisure activities such as swimming and boating should also be kept away from the immediate neighbourhood of fish passes. Only in exceptional and well-justified cases, fish passes can be built close to boating lanes, boat slips or shipping locks. Furthermore, access to fish passes should be limited to maintenance workers, control personnel or scientists to carry out scientific studies.

When viewing windows are built in fishways, as in monitoring stations for observing migrations, one-way glass should be used and the observation chamber darkened.

The functioning of the fish pass must not be impacted negatively if the barrage or any nearby stretches of water are altered, for example by deepening the channel, raising the elevation of the dam, or by the construction of a hydropower station.

3.10 Integration into the landscape

Every effort should be made to integrate the fish pass into the landscape as harmoniously as possible, although the correct functioning of the fishway must take priority over landscaping. Under this aspect, particularly close-to-nature types of construction link functional and landscaping considerations in the best possible way and may also play an important role as substitute biotopes for rheophilic organisms.

Natural building materials or construction materials that are typical of the local conditions should be used in the construction of fishways in a consequent manner. The wood used should not be chemically treated. Vegetation should be allowed to proliferate naturally as far as possible to create possible cover for migratory fish and shade the fishway, although it might be necessary to initially plant suitably adapted local plants and shrubs to get the vegetation started.

4 Close-to-nature types of fish passes

The “close-to-nature style” of construction of sills and fish passes, such as rock ramps, imitates as closely as possible natural river rapids or brooks with steep gradients (Fig. 4.2). Also the construction material chosen corresponds to what is usually present in rivers under natural conditions.

The constructions described below are usually site-specific and thus cannot be applied generally. However, they meet biological requirements more satisfactorily than the technical constructions described in Chapter 5 with regard to the connectivity of rivers. Furthermore, the close-to-nature design enables new running-water biotopes to be created in a watercourse, while blending pleasantly into the landscape.

For the purpose of these Guidelines the following constructions are defined as “close-to-nature types” of fish passes (Fig. 4.1):

- Bottom ramps and slopes,
- Bypass channels and
- Fish ramps.

There are similarities in the design of the various types of close-to-nature constructions and hybrid forms exist. For example, bottom slopes, fish ramps and bypass channels can be constructed in cascades, using boulder sills or single boulders to increase the roughness of the bottom substrate. Hydraulic calculations related to the hydraulics of close-to-nature constructions will be dealt with in summary form in section 4.4.

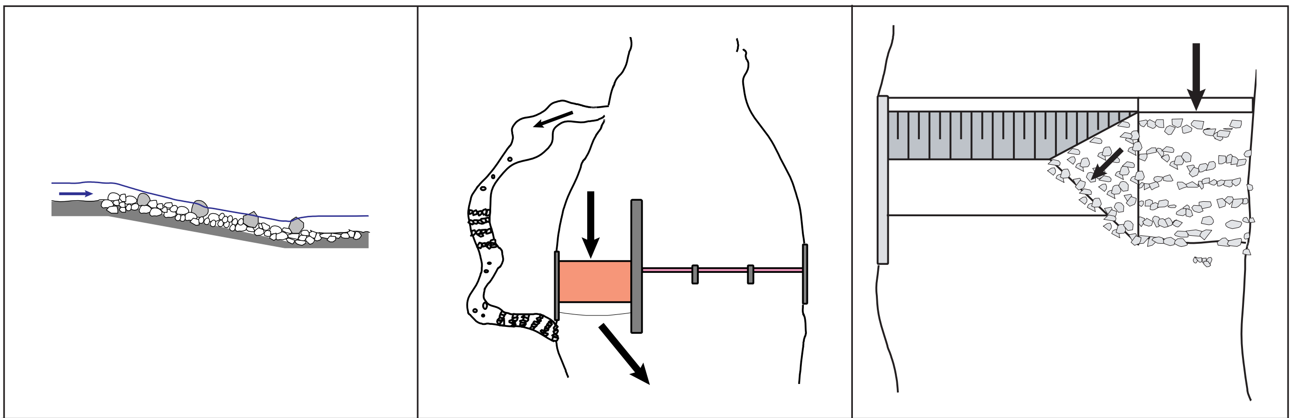
4.1 Bottom ramps and slopes

4.1.1 Principle

A bottom ramp or slope is a mechanism to disperse the hydraulic head (i.e. the difference in water level between the impoundment and the water surface downstream[#]) over a certain distance by keeping the hydraulic gradient of the slope as gentle as possible.

Bottom ramps and slopes were originally developed with the aim of stabilising river bottoms. They are included here, together with fish passes, especially because gently inclined, low-gradient rocky ramps or slopes exhibiting a rich mosaic of structural diversity represent the most advantageous method

[#] text in brackets added by the editor



a) **Bottom ramp and slope:**	b) **Bypass channel:**	c) **Fish ramp:**
A sill having a rough surface and extending over the entire river width with as shallow a slope as possible, to overcome a level difference of the river bottom. This category also includes stabilizing structures (e.g. stabilizing weirs), if the body of the weir has a shallow slope similar to the slope of a ramp or slide and is of loose construction.	A fish pass with features similar to those of a natural stream, bypassing a dam. As the dam is preserved unchanged, its functions are not negatively affected. The whole impounded section of the river can thus be bypassed.	A construction that is integrated into the weir and covers only a part of the river width, with as gentle a slope as possible to ensure that fish can ascend. Independently of their slope, they are all called ramps; in general the incorporation of perturbation boulders or boulder sills is required to reduce flow velocity.

Figure 4.1: The three types of natural-looking fish passes

Figure 4.2:
A river stretch with close-to-nature features, e.g. rich in varied slopes, provides a pattern for the design of natural-looking bottom sills.

Uneven slopes, often divided up into cascades, are characteristic of such river stretches. Low drops over boulder sills are followed by pools in which fish find shelter and can survive periods of low-water. Aschach (Bavaria).

for the restoration of a river continuum as they best imitate the conditions of a river stretch naturally rich in structural diversity and gradient (Fig. 4.2).

The conventional construction of sills must usually be modified to allow fish passage, in order to respond to the demand for longitudinal connectivity in rivers. Smooth concrete bottom ramps and steep hydraulic drops are unsuitable as they do not allow the upstream migration of fish and will therefore not be dealt with in these Guidelines.

According to DIN[#] 4047, Part 5, the distinction between a bottom ramp and a bottom slope is based solely on the gradient of the slope: Artificial structures that have gradients of 1:3 to 1:10 are defined as being “ramps” while those exhibiting gentler slopes of 1:20 to 1:30 are called “bottom slopes”. Constructions that have gradients of 1:15 or less are therefore generally included amongst bottom slopes in these Guidelines.

Bottom ramps and slopes are especially useful as substitutes for vertical or very steeply inclined drops in the river. They are also being used, to an increasing extent, as substitutes for regulable weirs if a flow control system is no longer required, in which case they operate as protection structure or sills that maintain the headwater level. From a general ecological point of view, this method has the important advantage that natural flow conditions will even be restored in the impoundment upstream of the weir due to silting-up of the area in the medium to long term.

4.1.2 Design and dimensions

4.1.2.1 Construction styles

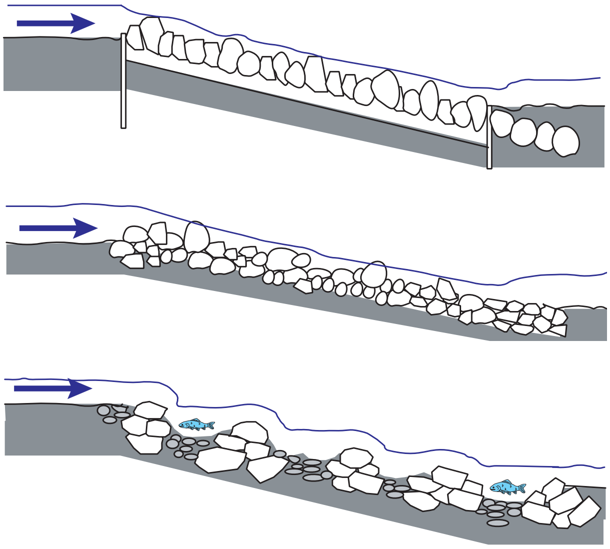
Bottom ramp and slope constructions (Fig. 4.3) can be classified as follows:

- Set or embedded-boulder constructions (conventional ramps in dressed and ordered construction mode)
- Rockfill constructions (loose rock construction)
- Dispersed or cascaded constructions (embedded rocky sills construction)

Conventional boulder ramps with slopes of 1:8 to 1:10 and with correspondingly high flow velocities should be adopted only where there is very heavy hydraulic stress. From an ecological point of view, loose rockfill constructions, and in particular rocky sill constructions, are to be preferred.

Embedded-boulder constructions (Fig. 4.3, a) are generally limited to ramps with gradients of approximately 1:10. The ramp is constructed by setting on edge individual boulders that are 0.6 to 1.2 m in size and are often attached to one another. The structure generally stands on a base layer (base course) which, depending on the outcropping stratum, consists of a layer (course) of crushed stones or a multistage gravel base layer (course). The base layer is dimensioned in accordance with conventional rules. The extreme upstream and downstream boulders of such a ramp are usually kept in place by sheet-pile walls, rows of piles or securing steel elements (rammed-in railway rails, steel girders or the like).

[#] DIN (Deutsche Industrie-Norm[en]): German Industrial Standards (remark by the Editor)



a) Embedded-boulder construction (dressed construction):
Single layer structure on a base layer (base course); boulders set evenly and often clamped to one another; uniform roughness; rigid structure; resists to high discharges; downstream river bottom must be stabilized.

b) Rockfill construction (loose construction):
Loose multilayer rockfill; downstream river bottom must be stabilized; a base layer (base course) is necessary if the natural bottom substrate is sandy; resilient structure; divers roughness; low costs.

c) Dispersed/cascaded construction (boulder bar construction):
Slopes broken by boulder bars forming basins; basins can be left to their own dynamics to form pools; great structural variety; low costs.

Figure 4.3: Construction of bottom ramps and slopes (altered from GEBLER, 1991)

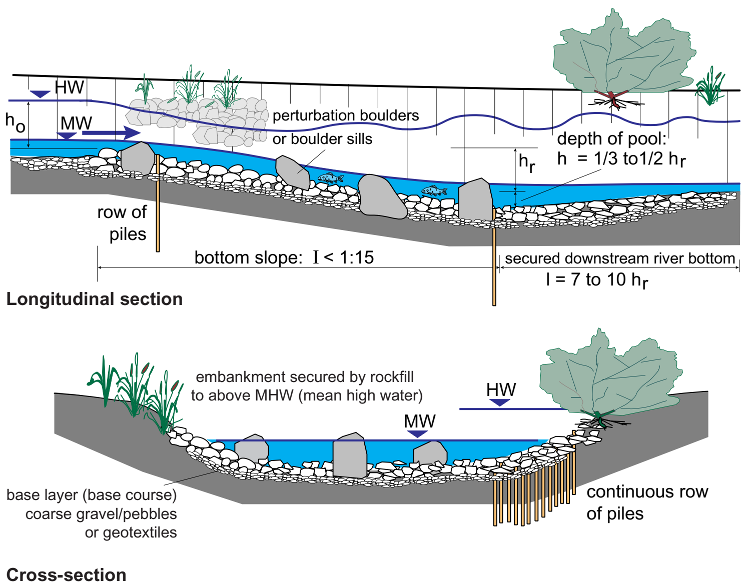


Figure 4.4:
Bottom slope as rockfill construction (modified from GEBLER, 1990)

The area of stabilized bottom downstream of the downward securing element is kept quite short, being only 3 to 5 m in length. However further bottom-securing elements are required downstream where there is a danger of pool formation through erosion. These usually take the form of rockfills. Construction usually requires dry excavation. The structure thus formed is relatively rigid but can withstand very heavy hydraulic stress due to the bonding effect of the boulders.

From an ecological point of view, **rockfill constructions** (Fig. 4.4) are to be rated more satisfactory than embedded-boulder constructions. Their main body consists of a multi-layered rockfill where the thickness of the layers is at least twice the maximum diameter of the biggest stones used.

Incorporating individual large boulders can increase roughness. A cascaded design using rock sills is also possible, whose main purposes are to keep an appropriate water level on the ramp under low-water conditions and to enhance structural diversity. The rock filling can also be secured by rows of wooden piles or elements consisting of sectional steel reinforcing bars. A naturally erosion-resistant river bottom requires no further stabilisation at the transition to the tail water. In this case the rockfill is extended with a constant slope to below the level of the tail water river bottom and the secured zone downstream is kept short, i.e. only approximately 3 to 5 m. A continuous transition with a trough-shaped pool, as shown in Fig. 4.4, should be created in rivers in low-lying areas with substrates that are not resistant to erosion or are sandy or silty, and the adjacent downstream bottom-securing part should be prolonged accordingly.

The embankments along the ramp and the immediate downstream bottom zone must also be secured with rockfill that reaches above the mean high-water line. Planting the embankments with appropriate vegetation enhances their resistance to erosion and keeps the main flow axis in the centre of the river during floods.

Works to build loose rockfill ramps can generally be carried out without diverting the river. However, the greater overall length of the ramp as compared to boulder constructions offsets any savings in costs.

All elements of the river fauna can negotiate rockfill ramps.

Embedded rocky sills constructions (stepped pools or dispersed/cascaded ramps) (Fig. 4.5) mainly consist of a number of boulder bars composed of large field boulders or river boulders having diameters of d_s = 0.6 to 1.2 m. To enhance stability the boulder bars can be arranged in an arch (in top view) so that the boulders lean against one another keeping themselves in place. With an erosion-resistant, stony or coarse-gravel bottom, as is the case in mountain streams, the boulder bars are embedded as deeply as 2.5 m (cf. also Fig. 4.3.c) and are secured by rows of piles or steel elements. In another variant a base layer is built up from rockfill and the boulder bars are bonded into the river bottom. In these cases, the boulder bars need not be so deeply embedded. The result is a construction comparable with that shown in Fig. 4 .4. The transition to a rockfill construction with additional boulder sills is smooth.

Boulder bars form basins that are filled with gravel and large cobble material and can be left to natural dynamics. Even sandy substrates typical of rivers in lowland areas normally remain in the basins. Although the substrate may be removed at high discharges, it quickly re-accumulates when flow velocities are again reduced.

The distances between bars, and the arrangement of the boulders, should be chosen in such a way as to ensure that differences in water level of Δh = 0.2 m are not exceeded.

It has to be emphasised that the structural diversity of the embedded rocky sills constructions is sometimes so high that the slopes can hardly be recognized as artificial structures. The planning and construction of such ramps calls for greater experience than do the other types of close-to-nature passes.

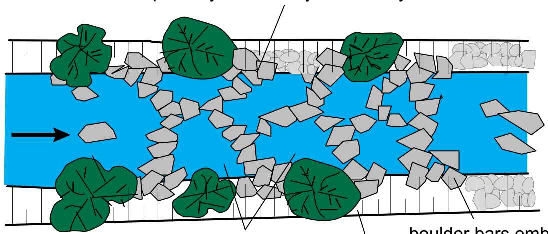


Fig. 4.5: Bottom step in boulder bar construction (plan view)

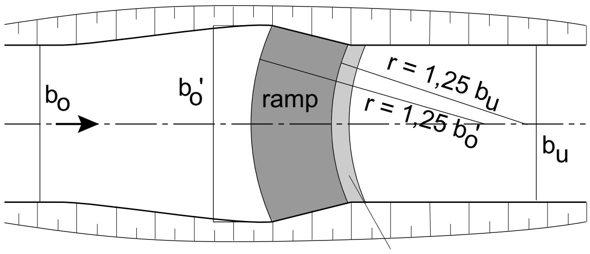


Fig. 4.6: Plan view of a curved bottom ramp (after SCHAUBERGER, 1975)

River fauna can negotiate bottom slopes carried out as boulder bar constructions in both directions without limitation.

4.1.2.2 Plan view

Bottom ramps are constructed with a spatial curvature as shown in Fig. 4.6 in large rivers with bottom widths of b_{bot} >15 m. The crest profile has a pitch of 0.3 to 0.6 m in cross-section. Ramps in smaller rivers do not generally include any spatial curvature and a rectilinear crest is constructed instead. The adjacent downstream zone of stabilized bottom protects the construction against retrogressive erosion. A low water channel should be incorporated to protect the ramp from drying out or from having too shallow a water depth during low discharges.

4.1.2.3 Longitudinal section

As a rule, bottom ramps using boulder construction are designed with slopes of 1:8 to 1:10 (dressed construction). Sills carried out as rockfill and bar constructions are designed with flatter slopes of 1:15 to 1:30.

The flow velocities that occur when boulder ramps have slopes of 1:10 must certainly be regarded as excessive for many fish and benthic species. This situation can be improved by adopting a profile that rises towards the riverbanks, producing zones of calmer flow in the marginal areas.

Even at low discharges the mean depth of water should not be less than h = 0.30 to 0.40 m. Big boulders and fairly deep basins forming resting pools make it easier for fish to ascend and give a very varied and also optically attractive flow pattern. Bar-type bottom constructions fulfil these criteria best.

The maximum permissible flow velocity in fish passes is v_{max} = 2.0 m/s.

4.1.3 Remodelling of drops

Steep drops that are impassable by aquatic fauna can often be converted to a bottom slope with relatively little effort. In the case of small drops (Fig. 4.7), all that is needed is a heap of field rocks or river stones at a shallow inclination into which larger boulders or boulder bars can be embedded. Such slopes should be about 1:20. The edge of the drop should either be bevelled or covered with stones to ensure continuity with the bottom substrate.

4.1.4 Conversion of regulable weirs into dispersed or cascaded ramps

If water management requirements allow, the conversion of weirs into a dispersed or cascaded ramp should be preferred to the construction of a separate fish pass.

A dispersed or cascaded ramp allows the water level to be maintained upstream and avoids any

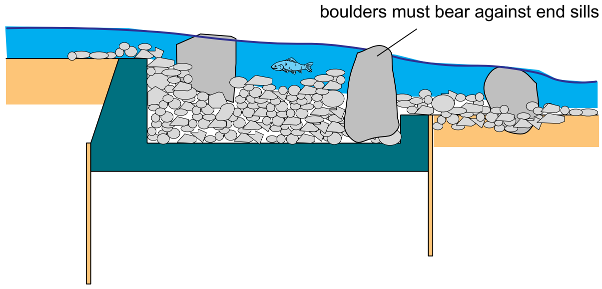


Fig. 4.7: Conversion of an artificial drop into a rough bottom slope.

undesired lowering of the ground water levels in the riverine low lands. However, the water levels can no longer be regulated. Nor is it any longer possible to increase the discharge cross-section by lowering the weir during flooding; as a consequence, water levels can rise when there are heavy flows. Widening the ramp crest can improve the performance of the sills. The substitution of a weir by a dispersed or cascaded ramp is particularly suitable if the intensity of agricultural utilization of the low lands has been reduced, or if other uses such as hydropower generation or navigation have been abandoned.

One advantage of this method is that the impounded area above the sill is allowed to silt up and free-flowing conditions can be re-established in the medium to long term. In any case, investigations should always be made to determine whether the ground water levels need to be maintained or whether local conditions would allow for lowering of the head, thereby rehabilitating more of the former impoundment.

As far as possible, the ramp structure should take the form of a simple rockfill; the top layer can also incorporate large boulders or boulder bars (Fig. 4.8). The gaps between rocks can be

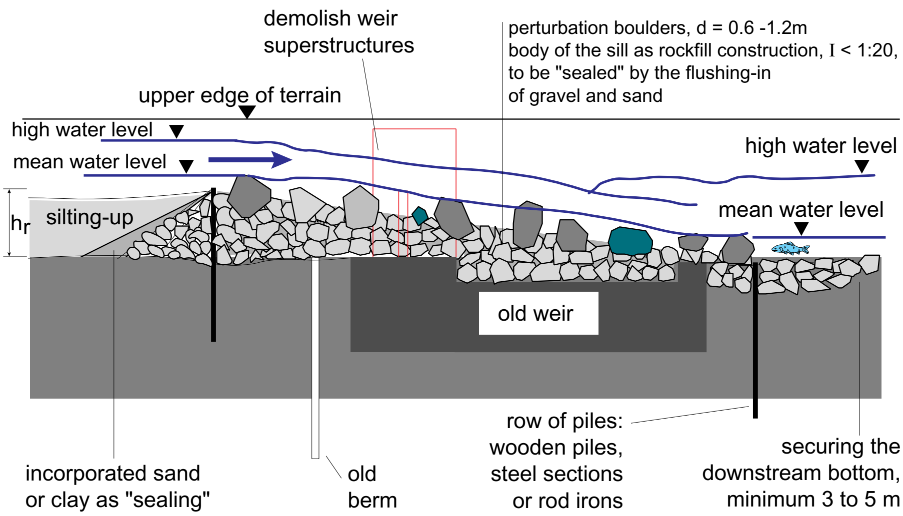


Figure 4.8
Conversion of a regulable weir into a protection sill

substantially filled by washing in gravel and sand (alternatively these can be incorporated continuously during construction), thus reducing water losses at low discharges and preventing the ramp from drying-out. An initial pouring of sandy/clayey material has also proved effective as a sealant. Both the sill crest and the connection to the riverbed downstream can be secured by rows of piles.

The superstructures (flow regulation elements) of regulatable weirs must be demolished and the substructure (stilling basin) covered over.

4.1.5 Overall assessment

From the ecological point of view, the construction of rough bottom ramps with a low inclination angle is the best way to restore fish passage in rivers where the obstacle cannot be completely removed. Loose constructions (rock fills) and bar constructions are to be preferred to more conventional boulder ramps. The use of concrete should be minimal consistent with stable constructions.

Rockfill or bar-type bottom sills can also be used to modify both drops in rivers and regulatable weirs.

Maintenance is relatively low and can be limited to the occasional removal of floating debris and waste, as well as periodic checks for possible damage, in particular after flooding.

The entire aquatic fauna can freely pass these constructions in both upstream and downstream directions.

4.1.6 Examples

GROSSWEIL BOTTOM RAMP

Details of the river		**Details of the bottom ramp**	
River:	Loisach, Bavaria	Construction:	Boulders
Discharge:	MNQ = 8.68 m^3/s	Width:	b = 72 m
	MQ = 23.1 m^3/s	Difference of head:	h = 2.7 m
	HQ_{100} = 400 m^3/s	Slope:	1 : 10, marginal zones 1 : 15
Responsible:	WWA Weilheim	Year of construction:	1973/74

Constructional design:

The construction is in the form of a rough boulder ramp (weight of boulders 3-5 t) in dressed and ordered mode with an upstream and downstream sheet-pile wall. The adjacent downstream zone of stabilized bottom is short. Since experience was slight at the time of construction as to whether or not fish could ascend such ramps, a 4 m wide fish pass, constructed from boulders of different heights to form pools, was incorporated in the right-hand third alongside the boat slide.

The ramp becomes very shallow towards the left bank, which leads to highly differentiated flow patterns with lower water depth and lower flow velocities in this marginal zone. This allows even fish that are weak swimmers to ascend. In contrast, it is difficult for fish to find the actual fish pass due to the highly turbulent flow conditions at the fish pass entrance where there is almost no attraction current. The shallow marginal zones are therefore substantially more effective and completely adequate to sustain fish passage. Based on the positive experience collected here, the Water Management Authority (WWA) of Weilheim has constructed other bottom ramps without separate fish passes in their area with excellent results.

The fishery lessees of this river could observe a positive development of the fish stock.

Figure 4.9: Grossweil/Loisach bottom ramp (view from downstream) The considerably reduced flow velocities and the differentiated flow pattern in the shallower marginal zone ensure that even weaker swimmers amongst the fish species, as well as benthic fauna, can negotiate the ramp, so that other mitigation facilities (i.e. a separate fish pass) are not needed.

BISCHOFSWERDER PROTECTION SILL

Details of the river		**Details of the protection sill**	
River:	Dölln Stream, Brandenburg	Construction:	Rockfill sill
Discharge:	MNQ = 0.44 m^3/s	Width:	b = 4.0 to 6.0 m
	MQ = 0.9 m^3/s	Slope:	I = 1 : 20
	HQ_{25} = 5.1 m^3/s	Length	l = 20 m
Height of sill	h = 1.0 m	Depth of water	h = 0.3 to 0.6 m at MQ
Responsible:	LUA Brandenburg	Max. flow velocity	v_{max} = 1.3 to 2.2 m/s
		Year of construction:	1992

Description of construction:

This protection sill replaced a plank dam (culture dam) and was constructed as a rockfill ramp. The body of the ramp consists of river stones (d = 25 cm) and was "sealed" by clayey-sand that was poured-in at the start of construction. Large boulders (d = 50 to 100 cm) reduce the flow velocity and give the fish shelter as they ascend.

Monitoring of the upstream migration has confirmed that the ramp can be negotiated. A dense ichthyocoenosis, rich in species, has developed due to immigration from the River Havel in those sections of the Dölln stream situated above the ramp that previously had an impoverished aquatic fauna.

Figure 4.10:
Plank dam before modification - an impassable obstacle for the aquatic fauna

Figure 4.11:
Bischofswerder protection sill after modification

MAXLMÜHLE BOTTOM SILL

Details of the river		Details of the bottom ramp	
River:	Mangfall, Bavaria	Construction:	Bar construction
Discharge:	MNQ = 1.16 m^3/s	Width:	b = approx. 15 m
	MQ = 4.83 m^3/s	Height of step	h = 1.7 m
	HQ_{100} = 270 m^3/s	Slope:	I = 1 : 26
Responsible:	Free State of Bavaria/ WWA Rosenheim	Year of construction:	1989

Description of construction:

A number of constructions with steep drops that could not be negotiated by the aquatic fauna were replaced by bottom ramps of the close-to-nature design in the restored part of the Mangfall River at Maxlmühle (near the Weyarn motorway bridge).

The ramp shown below is of the bar construction type; the body of the ramp consists of individual, transverse bars embedded to a depth of 2.5 to 3 m. The transverse bars are curved and offset, so that they lean against one another. The resulting basins are filled with indigenous bottom material and left to their natural dynamics (pool formation, silting-up). Bottom ramps designed in this way blend very well into the river landscape and can hardly be recognized as artificial constructions. They are passable by the entire aquatic fauna.

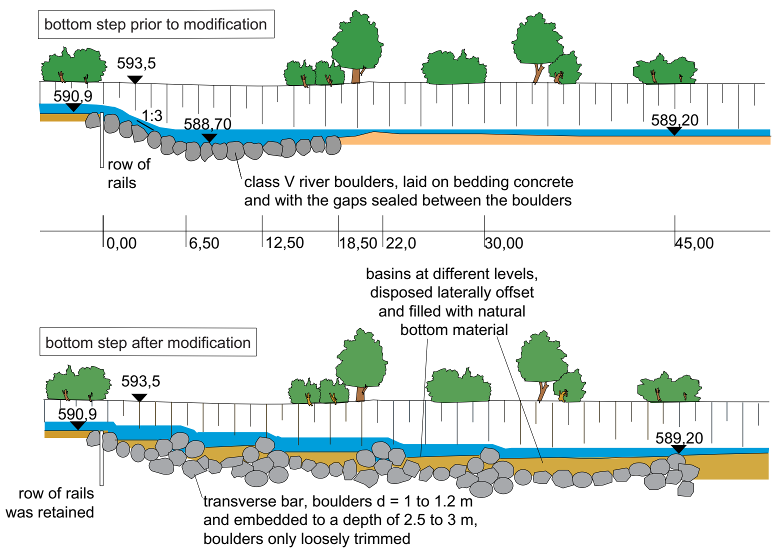


Figure 4.12:
Longitudinal section of a bottom step in the Mangfall River, boulder bar construction (diagrammatic).

Figure 4.13:
Bottom step in the Mangfall River
The bar construction used in this case creates an extraordinary structural variety. In order to restore migrations, the transformation of a drop in the river bottom over the entire width of the river must always be regarded as the best possible solution, being preferable to any separate fish ladder.

MÜHLENHAGEN BOTTOM SILL

Details of the river		Details of the bottom ramp	
River:	Goldbach near Mühlenhagen	Construction:	Rockfill construction
	Mecklenburg/West Pomerania	Width:	b = 3.4 m
Discharge:	MQ = 0.38 m^3/s	Slope:	I = 1 : 20
	HHQ = 2.8 m^3/s	Length	l = 38 m
Height:	h_{tot} = 1.70 m	Year of construction:	1992
		Responsible:	Altentreptow District

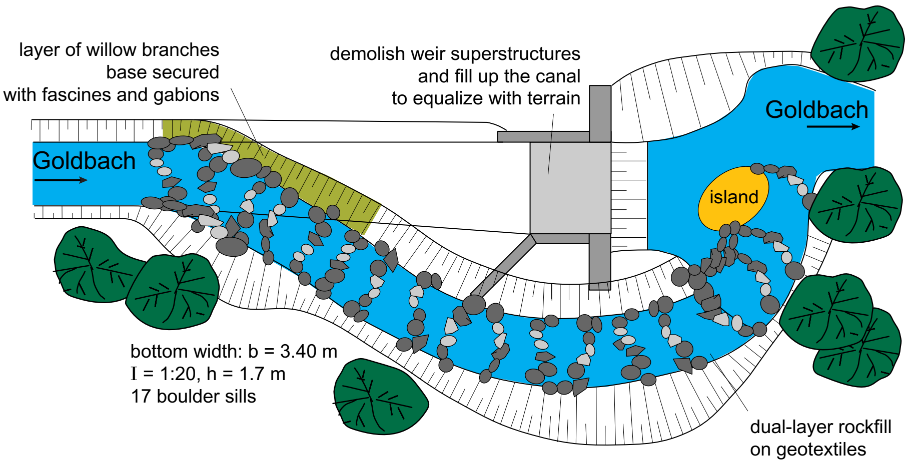


Figure 4.14: Plan view showing the position of the Mühlenhagen/Goldbach bottom ramp

Figure 4.15: Mühlenhagen/Goldbach bottom ramp

No right of use exists any longer at the abandoned mill weir. The bypassed millpond is silted up but represents an aquatic biotope that is worth protection. Simply demolishing the weir installation would have led to considerable bottom erosion and the lowering of the water table in the headwater area. The weir was therefore replaced by a rough bottom slope with a shallow gradient, in order to maintain the actual headwater level to which nature got accustomed over the last centuries.

The ramp has a total height of 1.7 m and a slope of 1:20. Boulder bars form cascaded basins to keep flow velocities within permissible limits. The water depths in the pools are 30 to 40 cm. The channel cross-section was secured by a layer of stones on a geotextile base. Field boulders of 40 to 50 cm in diameter were used to create the bars.

4.2 Bypass channels

4.2.1 Principle

The term 'bypass channel' is used for fish passes that bypass an obstacle and that are in the form of a natural-looking channel that mimics a natural river. The channel can be of considerable length. Bypass channels are particularly suitable for the retrofitting of already existing dams where migration is to be restored by inserting a fish pass, since it generally requires no structural alterations of the dam itself.

As a rule, only a proportion of the discharge is diverted through the bypass channel. However, in the case of abandoned culture weirs, protection sills or dam installations on smaller rivers, the total discharge up to a predetermined value (usually mean water level), can be sent through the bypass channel; the dam itself remains functional, but then serves exclusively to pass floods.

The main disadvantage of a bypass channel is the relatively large surface area required for the construction. Whether or not such type of fish pass can be used, therefore depends much on the particular local conditions. On the other hand, the extended length of such a channel offers an ideal opportunity for a close-to-nature construction that blends pleasantly into the landscape.

Constructing a bypass channel does not only mean providing a passage for migratory fish but also means creating the prerequisite for rheophilic (current-loving) species to use the channel as habitat. This aspect deserves even closer attention in the restoration of those impounded rivers where conditions for living and reproduction of stenotypic, rheophilic river species are particularly adversely affected.

Moreover, bypass channels maintain or restore the river continuum as they provide flow conditions similar to those of an undisturbed river and thus allow migrants to by-pass the entire impounded area, sometimes up to the limit of the backwater, without incurring any sudden changes in the abiotic characteristics.

4.2.2 Design and dimensions

The principles of "close-to-nature" river restoration should be applied in the design of a bypass channel, (DVWK 1984, LANGE & LECHER, 1993 *et al*). However, because of the steeper slopes it is often essential that the bottom and the banks be stabilised and that measures are taken to reduce flow velocities.

A natural brook rich in steep slopes, such as that shown in Fig. 4.2, can be taken as a model for designing a bypass channel.

From this model, the following design criteria for bypass channels can be derived, where the dimensions given are minimal suitable requirements:

Slope:

I = 1:100 to max. 1:20,
in accordance with the nature of the river;

bottom width:

$b_{bot} > 0.80$ m;

mean depth of water:

$h > 0.2$ m;

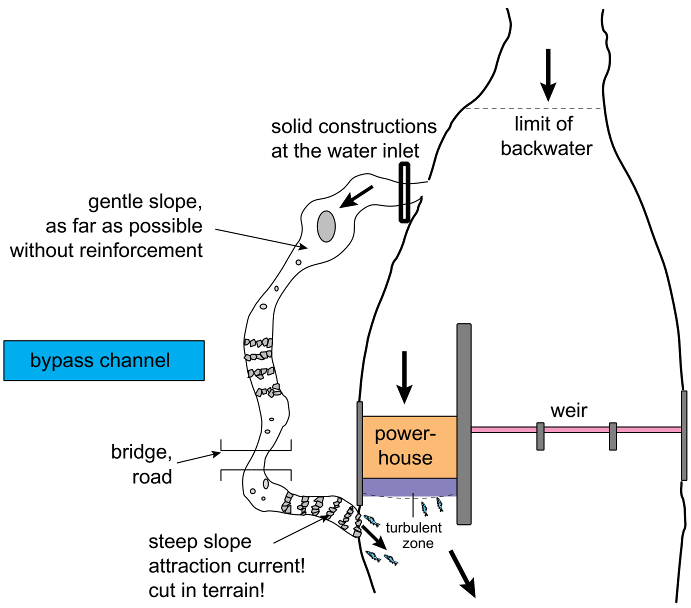


Figure 4.16:
Bypass channel.
Bypass around a dam:
example of common design

mean flow velocity:

v_m = 0.4 to 0.6 m/s

(predominant water depth and mean flow velocity depending on the size and nature of the river);

maximum flow velocity:

v_{max} = 1.6 to 2.0 m/s, locally limited;

bottom:

rough, continuous, connectivity with the interstitial spaces; if possible use should be made of the natural, locally available substrate, without further sealing or additional securing of the bottom;

shape:

sinuous or straight, possibly meandering, with pools and rapids;

cross-section

variable, preferably banks protected using biological engineering methods, big boulders, boulder sills to break the slope;

width-related discharge:

$q > 0.1\ m^3/s \cdot m$

4.2.2.1 Plan view

The shape adopted should be selected in accordance with local spatial circumstances, and the geological and slope characteristics. The channel can be straight or sinuous or even bent. The positioning of the entrance to the bypass below the dam is ruled by the same principles as those that apply to more technical passes. The bypass channel must sometimes be turned back on itself by 180° to ensure that the entrance from the tailwater is placed directly beneath the weir or the turbine house. Due to the considerable length of some bypass channels, the outlet into the headwater must often be placed quite far upstream.

A special form of bypass channel is the so-called pond pass that consists of a succession of pond-shaped widened sections, which are connected to one another via drops in the artificial river (boulder sills) or via short steep channels (JENS, 1982, JÄGER, 1994).

Bypass channels can also be combined with other constructions. For example, technical fish passes (pool, Denil or vertical slot passes, cf. Chapter 5) may be used to overcome locally difficult sections in the channel or to make the connection to the tailwater.

4.2.2.2 Longitudinal section

The slope of the bypass channel should be as gentle as possible. A guide value for the upper limit of the slope is I_{bot} = 1:20. A steep slope can be broken up by incorporating rock sills. Areas of calmer flow, pools or pond-like widenings enable fish to ascend more easily, particularly when they follow longer sections with steep slopes, and also serve as refuges.

If sufficient space is available for the bypass channel, only a few sections with a steeper slope should be incorporated (Figure 4.16). A section with steeper slope is useful at the connection to the tailwater in order to produce a satisfactory attraction current. The other sections can then be constructed following the natural slope of the rivers

Figure 4.17:
Bypass channels make it possible to follow a design close to nature and to blend in well with the locality. In this example, the contour was chosen as a function of the existing tree cover.
Lapnow Mill (Brandenburg).

in that particular region and require no extensive reinforcements.

The critical water depth must be based on the potential natural fish fauna and its swimming performance (depending on the fish zone) but should not be less than h = 0.2 m.

4.2.2.3 Channel cross-section

The width of the cross-sections, the water depth and the current should be as diverse as possible. However, the bottom width should not be less than 0.80 m. Narrowing and widening the channel contributes towards a natural-looking design. Reinforcement of the cross-section will normally be needed and is essential in stretches of particularly steep slope. Guidelines for methods for river restoration that give characteristics close to natural features should be used in deciding the type of reinforcement to be adopted. Generally it is sufficient to secure the bottom with coarse gravel or with river stones placed on a gravel or geotextile underlay. The interstitial spaces thus created also offer satisfactory possibilities for colonisation by, and migration of, benthic invertebrate fauna. Furthermore, the coarse stones hold back the finer particles of sediment so that the natural bottom substrate can accumulate in the interstices.

It is preferable to use combined construction methods to secure the base of the slope and the banks, for example by using living plants in combination with rocks, fascines (bundles of sticks) and the like. Fig. 4.18 shows some examples of consolidation with fascine sheeting, set blocks, layers of willow branches, copse planting or plantings using willow sticks and combinations thereof.

If the indigenous bottom substrate is sufficiently resistant to erosion and if there is no risk to adjacent properties, the bypass channel can be left to its own natural dynamics and the bottom doesn't need to be artificially secured.

Slight shading of the channel by plantations of trees or bushes has a favourable effect on fish migration (since fish can hide and can find shelter), while at the same time they blend pleasantly into the landscape and contribute towards bank stabilization.

4.2.2.4 Big boulders and boulder sills

With slopes of between 1:20 to 1:30, it is generally not possible to maintain the permissible mean flow velocity of 0.4 to 0.6 m/s in the bypass channel without additional controlling structures. Large boulders are the natural and visually most attractive material for such additions.

The following methods can be used:

- The incorporation of big boulders in an offset, irregular arrangement that leads to increased roughness. During medium and low discharge, the water flows around or only slightly over such boulders. The boulders also increase the water depth and reduce flow velocity. Ascending fish find refuges in the flow shadow of the boulders. Local alternations in the flow regime may occur in the narrowed cross-section (Fig 4.19). Guide values for the setting of the boulders are:

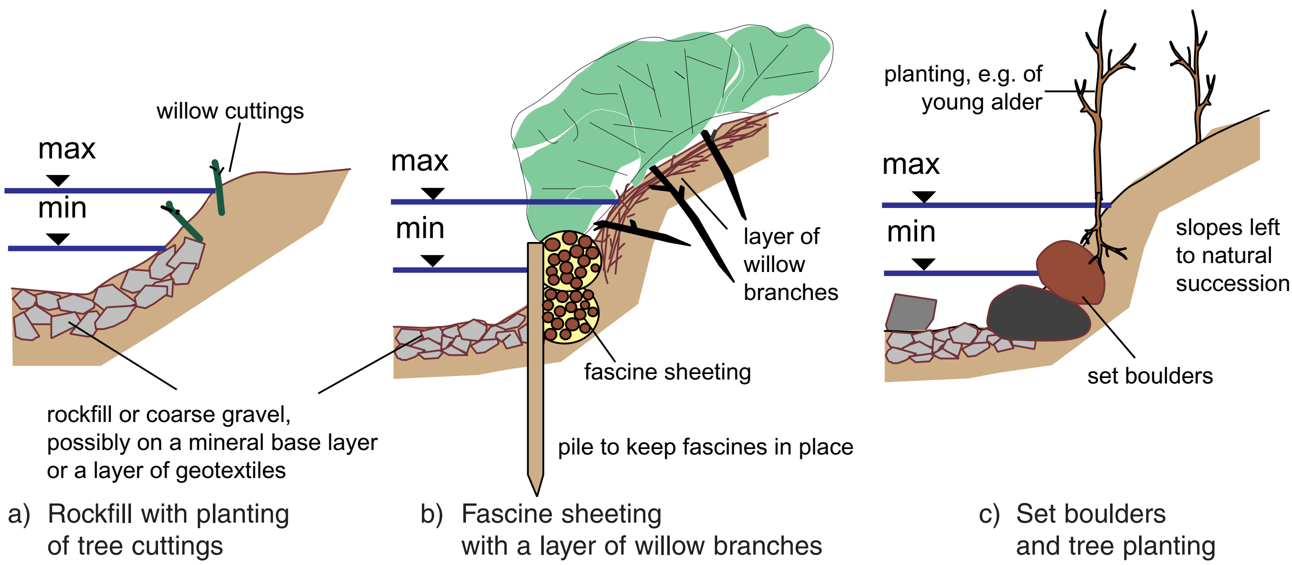


Figure 4.18: Examples for securing bottom and banks of bypass channels

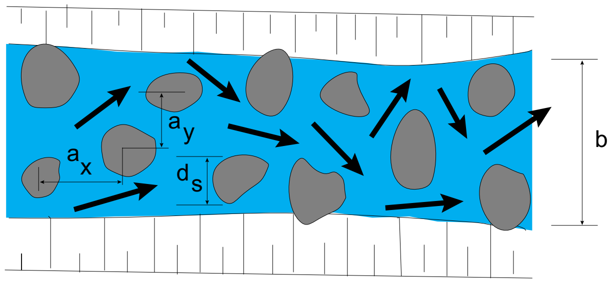


Fig 4.19: A bypass channel in which perturbation boulders have been placed

$$ax = ay = 2 \text{ to } 3\ ds$$

(for the definition of a_x, a_y and d_s see Fig. 4.19)

The clear distance between these big boulders should be at least 0.3 to 0.4 m.

They should be embedded into the bottom by up to one third or one half of their depth. The boulders must be big enough to prevent any unauthorised displacement, for example, by children at play.

- The incorporation of transverse bars can narrow the flow cross-section to such an extent that a pool is formed between the bars where water is held back. The transverse bars are formed from large boulders embedded into the reinforced bottom at varying depths. This method is in principle illustrated in Fig 4.20, the boulders here being staggered in the bars. As a rule, large rectangular-sided rocks (square stones) are required, set on edge.
- The incorporation of submersible boulder sills (cascades). These sills, which are totally or only partially submerged, are formed from large boulders embedded in the bottom. As water is slowed down by the damming effect, pools are formed, in which a water depth of between h = 0.3 and 0.6 m should be aimed at (depending on the nature of the stream). The distance between the bars (clear pool length) should not be less than 1.5 m in rhithronic reaches, where, because of the bottom slope, the individual bars are stepped in relation to one another, forming a cascade (stepped pool pass). The height of drop at each sill must not exceed Δh_{max} = 0.20 m. In potamonic reaches smaller drops of Δh = 0.10 to 0.15 m should be adopted to allow *inter alia* for inaccuracies in construction, minor clogging with debris, etc. The distance between the bars must be such that no detached free overflow jet is produced and the sill always remains in the backwash of the next sill downstream. In addition, individual large boulders can also be incorporated in the pools (Fig. 4.20). The spacing between the sills and the water depths must be sufficient to form resting zones in the basins. It is therefore recommended that the volumetric power dissipation should be limited to E = 150 W/m^3 in the potamon and to E = 200 W/m^3 in the rhithron (for energy conversions in the basins see also section 4.4).

  This construction pattern allows even fine sediment to be retained in the basins, thus creating substrate conditions closely resembling natural conditions.

4.2.2.5 Design of the water inlet and outlet areas of the bypass channel

Particularly where the headwater levels fluctuate or where there is a risk of the banks flooding, solid

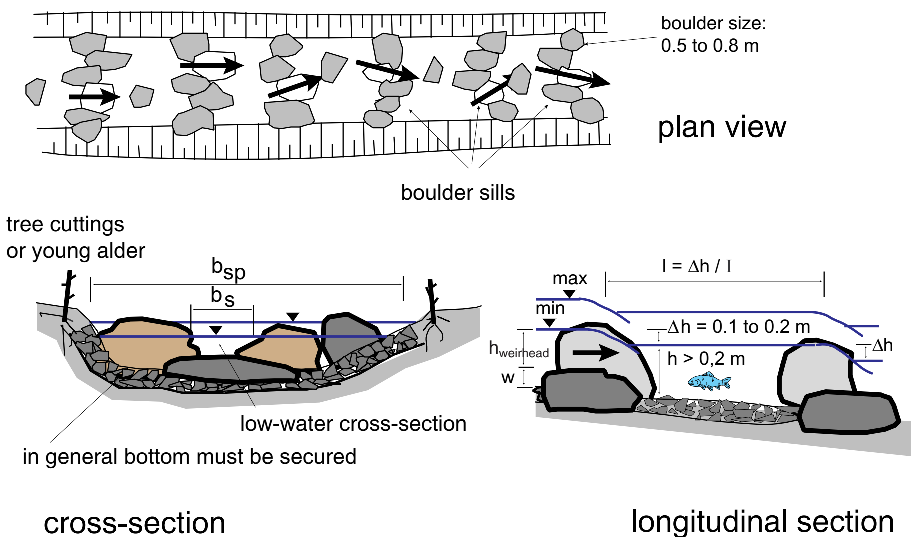


Fig 4.20:
Boulder sills for breaking the slope in a bypass channel

Figure 4.21:
Control device at the water inlet of a bypass channel in a retention dam (shortly before completion). The construction limits the inflow and can be closed when floods occur or for maintenance work on the channel. It is essential that the opening extends right down to the bottom and does not interrupt the continuity of the bottom substrate.
Lech dam at Kinsau (Bavaria).

constructions and flow control mechanisms are required at the water inlet of the bypass channel (i.e. fish pass outlet#). The flow through the channel can be limited and the channel can even be blocked off for maintenance working this way. Such a mechanism can be created satisfactorily by simple supporting concrete or quarry-stone walls equipped with a suitably dimensioned control device. The height of the opening must ensure that the fish pass does not run dry even at low-water – something that must be avoided in a bypass channel because it would not only stop fish ascending but also have adverse effects on the benthic fauna present in the channel. The fish pass outlet should also be designed in such a way as to allow for the use of a fish trap during monitoring operations.

The design of the water outlet (entrance to the fish pass#) must ensure that there is an adequate attraction current in all operational situations. In order to achieve this the connection to the tailwater should be as steep as possible, so that the flow velocities create an adequate guiding effect. Where tailwater levels fluctuate, the discharge cross-section can be narrowed by a solid construction that opens through a slot (cf. section 5.2 on slot passes), thus increasing the flow velocity at the water outlet.

The bottom of the fish pass should be connected directly to the river bottom, if ever possible.

Adequate reinforcements are needed round the water outlet (fish pass entrance#) to counteract the increased stress on the riverbanks and bottom that usually occurs below dams. The first part of the bypass channel (i.e. the part just following the entrance to the pass#) may have to take the form of a technical fish pass, particularly when connecting to a massively consolidated tailwater channel of a hydroelectric power station or when there are widely fluctuating tailwater levels.

4.2.2.6 Crossings

The length of bypass channels means that some form of crossing is usually needed for traffic or other purposes. Such crossings should be designed to ensure that no new obstacles to migration are created and a bridge is usually the best solution. A (dry) berm under the bridge facilitates the migration of other animals (amphibia, otters, etc.).

Crossings must be designed in such a way that the cross-section of the bypass channel is not narrowed. A rough, continuous bottom is also indispensable under the bridge or in the tunnel to ensure that small fish and benthic fauna can pass through. If it is impossible to use the natural bottom substrate, a 0.20 to 0.30 m thick layer of coarse gravel or pebbles will suffice. The length of the crossing should not exceed 10 times the width of the opening.

4.2.3 Overall assessment

The most important advantages of bypass channels are as follows:

- They blend pleasantly into the landscape.
- They can be negotiated by small fish and benthic invertebrates.

remark by the editor

- They create new habitats, particularly as a secondary biotope for rheophilic species.
- They have a reduced tendency to clogging and are therefore more reliable to operate, with reduced maintenance efforts.
- They by-pass an obstacle usually in a long bend and are therefore particularly suitable for retrofitting to existing dams, that have no fish pass, as normally no constructional alterations to the dam are required.
- They make it possible for migratory species to avoid the entire impounded area, from the foot of the dam to the limit of the backwater.

These advantages are counterbalanced by the following disadvantages:

- The large surface area required.
- The great length of the channel.
- The sensitivity to fluctuations in the headwater level, which may possibly make necessary an additional construction at the water inlet (fish pass exit).
- Connection to the tailwater is often only possible by including a technical fish pass.
- Deep cuts into the surrounding terrain may be needed.

4.2.4 Examples

VARREL BÄKE STREAM BYPASS CHANNEL

Details of the river		Details of bypass channel	
River:	Varrel Bäke Stream, Lower Saxony	Length:	l = 130 m
		Width:	b_{bot} = 2.50 m
Function:	Mill dam	Slope:	I = 1 : 45
Discharge:	MNQ = 0.35 m^3/s	Discharge:	Q = 0.25 to 0.50 m^3/s
	MQ = 0.96 m^3/s	Depth of water:	h = 0.30 to 0.80 m
	MHQ = 8.14 m^3/s	Flow velocity:	v_{max} = 1.3 to 1.4 m/s
Height of fall:	h_{tot} = 2.9 m	Distance between rock sills:	3.35 m
		Year of construction:	1992
		Responsible:	Ochtumverband

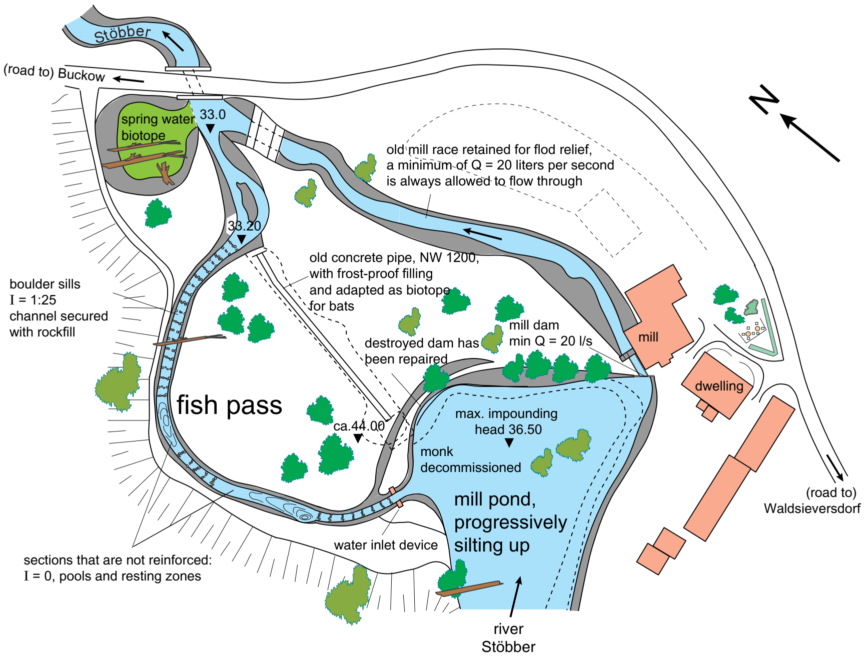
Figure 4.22:
Bypass channel in the Varrel Bäke stream near the Varrel Estate (Lower Saxony)

Although the abandoned mill dam is no longer used for hydropower generation, it had to be preserved for reasons of bottom stabilisation and the maintenance of the ground water levels. Water for feeding the fishponds is diverted at a location upstream of the mill dam. With discharges up to MNQ (mean low water level), the portion of discharge not required for feeding the fish ponds is sent through the fish pass.

Although the slope is relatively gentle, structural elements had to be incorporated to increase the water depth and reduce flow velocity. The crossbars consist of boulders set on edge and embedded in bottom sills. Due to their height, the boulders remain fully effective to positively influence the hydraulics, even with fairly high discharges. The banks are secured to above the mean water level with a rockfill covered by a carpet of vegetation.

SEIFERT'S MILL BYPASS CHANNEL			
Details of the river		**Details of bypass channel**	
River:	Stöbber, Brandenburg	Length:	l = 120 m
Discharge:	MNQ = 0.15 m^3/s	Width:	b_{bot} = 2.4 m
	MQ = 0.37 m^3/s	Slope:	I = 1 : 25
	MHQ = 0.88 m^3/s	Water depth:	h = 0.20 to 0.50 m
Function:	Mill dam	Flow velocity:	v_{max} = 1.8 m/s
Height of fall:	h_{tot} = 3.30 m	Year of construction:	1993

Figure 4.23:
Sketch of position of Seifert's Mill Dam



Although the former mill dam is no longer used to generate power, the millpond had to be preserved as a retention basin and for the reason of protecting the wetland biotope that had developed. A bypass channel of 120 m in length, through which the total discharge is sent up to a MHQ (mean high-water discharge), has been constructed next to the mill dam. The total difference in height of 3.30 m meant that the bed of the channel had to be secured in parts, with boulder sills incorporated. Other stretches exhibit zero gradient and have no reinforcements, so that natural dynamics were able to develop pools, steep banks and silting.

Figure 4.24:
Bypass channel at Seifert's Mill

The alternation of reinforced stretches with boulder sills and unreinforced stretches produces a highly variable flow regime. The areas with zero gradient can be left to their natural dynamics. The foreground of the photograph shows a cutting of the sloping bank, but this does not endanger the installation.

KINSAU BYPASS CHANNEL

Details of the river		Details of bypass channel	
River:	Lech, Bavaria	Length:	l = approx. 800 m
Discharge:	MQ = 85 m^3/s	Discharge:	Q = 0.8 m^3/s
	HQ_{100} = 1400 m^3/s	Width:	variable, b_{bot} = 2.5 - 4.0 m
Utilisation:	Hydroelectric power production	Slope:	variable, on average
Height of fall:	h_{tot} = 6.5 m		I = 1 : 100 max. about 1 : 30
Responsible:	BAWAG	Year of construction:	1992

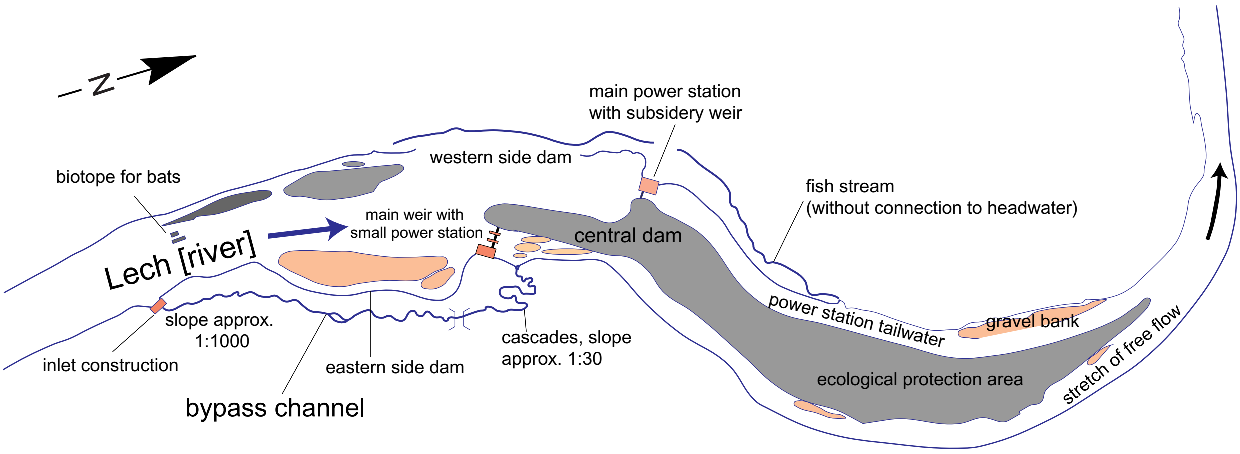


Figure 4.25: Sketch of position

Figure 4.26:
Below the main weir the bypass channel is connected to the old river bed, which for operational reasons is given a minimum discharge of 20 m^3/sec. The photograph shows the upstream section of the bypass channel of the Lech dam at Kinsau. This zone was constructed with a gentle slope so that an undulating design could be achieved without reinforcement of the channel cross-section. The maximum difference in height is overcome in the lower section, which is constructed in cascade form and has a slope of I = 1:20 to 1:30. The discharge is controlled by an inlet construction that also protects the bypass channel against floods.

The situation at this weir would be significantly improved by a second fish ladder at the main power station.

4.3 Fish ramps

A weir can only be converted to a bottom ramp or slide over its whole width (cf. section 4.1) if the water levels do not need to be controlled and adequate discharge is available. This is often not the case because of the water requirements for hydroelectric power generation, flood protection, agriculture or fish farms. In these cases, a rough ramp of reduced width (a so-called fish ramp) can be integrated into at least a portion of the weir installation to ensure that the aquatic fauna can migrate (Fig. 4.27). Fish ramps are also suitable for retrofitting to existing weirs that don't have a fish pass.

The model for designing a fish ramp is again derived from Nature. The primary objective of fish ramp design is to mimic the structural variety of natural river rapids or streams with more or less steep slopes, similar to that shown in Fig. 4.2.

4.3.1 Principle

A fish ramp is normally integrated directly in the weir construction, and concentrates, as far as possible, the total discharge available at low and mean water level (Fig. 4.27). At by-pass power stations, for example, the necessary residual discharge can be sent through the fish ramp and water only spills over the weir crest during floods.

Big boulders or boulder sills are arranged to form cascades on the fish ramp to ensure the water depths and flow velocities required to allow upstream migration of fish.

The width of the ramp is mainly defined by the discharge at times of upstream fish migration. The efficiency of ramps for facilitating upstream migration might be reduced when discharges are heavy, as in the case of flooding. The need for structural stability is an essential element in calculating the size of a fish ramp that must withstand floods.

4.3.2 Design and dimensions

4.3.2.1 Plan view

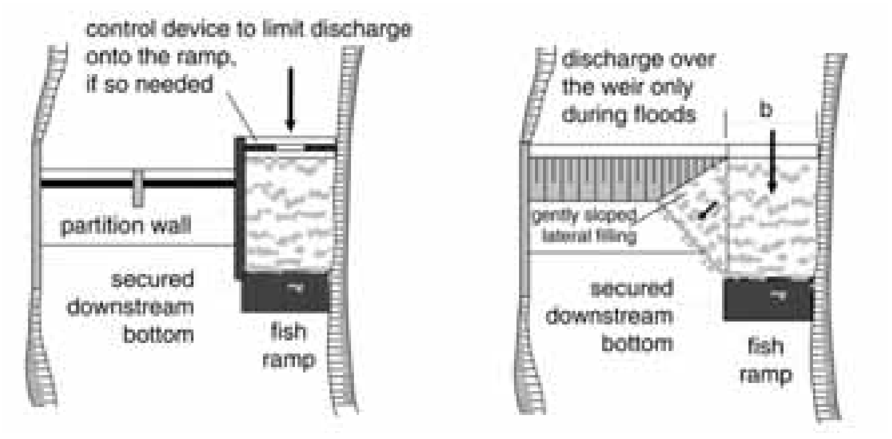
As a rule, fish ramps are set by riverbanks and the bank that receives the greater portion of the current is the most favourable. The upper, acute angle should be selected for the construction of the fish ramp at submerged weirs standing obliquely in the river. An existing empty evacuation channel or abandoned sluiceway can often be used for the construction of a fish ramp.

Fish ramps installed at fixed weirs with very steep slopes, at obstacles with vertical drops or at weirs equipped with movable shutters often have to be confined on one side by a solid wall (partition wall in Fig. 4.27); cf. also Fig. 4.28. Fish ramps at gently sloping weirs can be given a inclined lateral filling, to prevent the formation of dead corners (cf. Fig. 4.27).

If the entire discharge passes through the fish ramp, the guide current is always clearly directed. It is therefore possible to place the entrance to the ramp further downstream. Fish ramps usually join the headwater at the weir crest, which has technical advantages, for diverting water during construction for example. The upstream water inlet (i.e. the fish pass exit[#]) may need to be designed with a narrowed cross-section to limit discharges through the ramp, particularly during flooding.

The width of the ramp should be a function of the available discharge, but should not be less than b = 2.0 m.

[#] remark by the editor



Weir with movable shutters

fixed weir

Figure 4.27: Positioning of fish ramps at dams

Figure 4.28:
In this example, the fish ramp takes the place of the left-hand weir bay, the total discharge up to MQ (mean discharge) being sent through the fish ramp. The ramp is designed in the form of a rough channel with perturbation boulders arranged offset. The body of the ramp is a rockfill construction. A low wall made of stones separates the fish ramp from the unobstructed weir area. Krewelin weir, Dölln Stream (Brandenburg).

Figure 4.29:
Position of a fish ramp at the main weir of a bypass power station. The total minimum discharge is normally sent through the fish ramp, so that water only flows over the weir at higher discharges.

Eitorf fish ramp on the Sieg (North Rhine Westphalia).

4.3.2.2 Longitudinal section

The general requirements of fish ramp design can be defined as follows:

- mean depth of water: h = 30 to 40 cm;
- slope: I < 1:20 to 1:30;
- flow velocity: v_{max} = 1.6 to 2.0 m/s;
- bottom substrate: many interstitial gaps, rough, continuous, connection to the bottom of the river bed;
- shelters, deep zones and resting pools to facilitate upstream migration.

Fish ramps require slopes of 1:20 or less. One exception is the rough-channel pool pass described in section 4.3.2.7, which can have a slope up to 1:10.

Longer sections with gentle slopes and with deeper resting pools are recommended, particularly in the case of ramps longer than 30 m.

4.3.2.3 Body of the ramp

The construction types usually used for the bottom sills are:

- rockfill construction (loose construction);
- block-stone construction (conventional Schauberger ramp in dressed and ordered construction); or
- dispersed construction (bar construction).

These can also be transposed to fish ramps, with occasional slight modifications; cf. section 4.1 and Figure 4.3.

For fish ramps, dressed stone is only used in exceptional cases. Generally, the substructure consists of crushed rockfill, which is put in layers in accordance with the rules for base layers or is built up on geotextile material or possibly a sealing layer. Building the entire ramp body from solid material increases costs but may be necessary for constructional or stability reasons. In this case, the surface layer of the concrete ramp body should be roughened by embedding a layer of gravel or rubble into the concrete before it sets.

Ramps of the bar construction type are very frequent. Individual deeply embedded boulder bars are arranged to form cascades. The basins between the boulder bars can be filled with available indigenous bottom material and left to natural dynamics for pool formation and silting. In sandy-bottomed rivers, the basins must be covered with riprap (a filling of rocks), since otherwise the pools would become too deep after scouring during heavy discharges. The resulting ramp corresponds to a rockfill ramp with boulder sills.

Problems can arise with rockfill ramp bodies when the river carries little water, as water may be lost through seepage through the rockfill. In extreme cases this may lead to the ramp crest running dry, so that the ramp is unable to function as a fish pass. In rivers that carry a lot of sedimentary material, and where the ramp crest is at the level of the headwater bottom, self-sealing takes place relatively quickly through washed-in sediments. Self sealing may take a very long time if the ramp crest is high and no sedimentary material is carried by the water, in which case sand and gravel can be artificially washed-in to fill the gaps.

A wedge-shaped or parabolic cross-section is recommended for ramps where there are varying discharges. This cross section concentrates the small discharges during low-water periods, while allowing, at times of high discharges, shallower regions to form at the sides where flow velocities are then correspondingly lower.

4.3.2.4 Big boulders and boulder sills

With the usual gentle ramp slopes of 1:20 and 1:30, and despite a rough bottom, it is not possible to keep flow velocities below the maximum permissible limits. For this reason, additional elements that reduce flow velocity and increase water depth are incorporated into the slopes of the fish ramps. Again, large boulders are the most suitable for this purpose.

As for bypass channels, the following may be used with fish ramps, too:

- Single, large, perturbation boulders around which the water flows, increasing the roughness of the ramp and providing resting places and shelters for fish (cf. Figure 4.19), or
- Irregular boulder bars that extend transversely over the entire ramp width. The water can flow either through or over these bars, which form pool structures (cf. Figure 4.20).

The design corresponds to that given in section 4.2.2.4 for bypass channels. Boulder bars have the advantage of providing adequate water depths in the basins even at low discharges, and of retaining fine sediments.

The hydraulic calculation is described in section 4.4.

4.3.2.5 Bank protection

The banks of fish ramps must be protected in a competent manner to withstand the high flow velocities to which they are continuously exposed. Boulder sills and perturbation boulders require special measures to secure them and prevent erosion by the flow, which would otherwise endanger the functional efficiency and stability of the installation. The banks must be stabilized by riprap or set blocks and the protection must extend above the mean water line. Above this line, the slopes can be secured with live plants. Examples are given in Fig. 4.18, combinations of these also being possible.

4.3.2.6 Stabilized zone downstream of the fish ramp

The stability of a fish ramp is endangered by scouring, where pools form at the base of the ramp and initiate retrogressive erosion. This must be counteracted by securing the river bottom just downstream of the ramp. The most convenient way to do this is to use multi-layered rock fills, possibly with a base layer substructure.

The length of the downstream zone that must be secured corresponds to that for bottom ramps or slides (GEBLER, 1990, KNAUSS, 1979, PATZNER, 1982, WHITTAKER & JÄGGI, 1986). Where riverbeds are resistant to erosion, the minimum length of the secured bottom zone is between 3 to 5 m. In the case of sandy river bottoms endangered by erosion GEBLER (1990) recommends that the downstream zone be secured for distances corresponding to 7 to 10 times the ramp height,

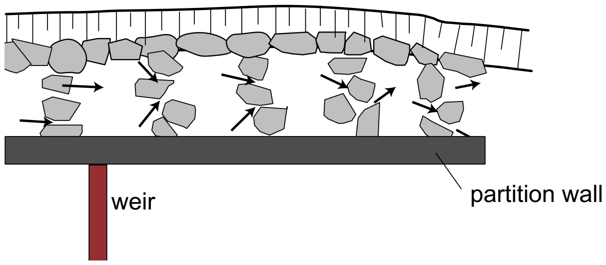


Figure 4.30: Rough-channel pool pass (plan)

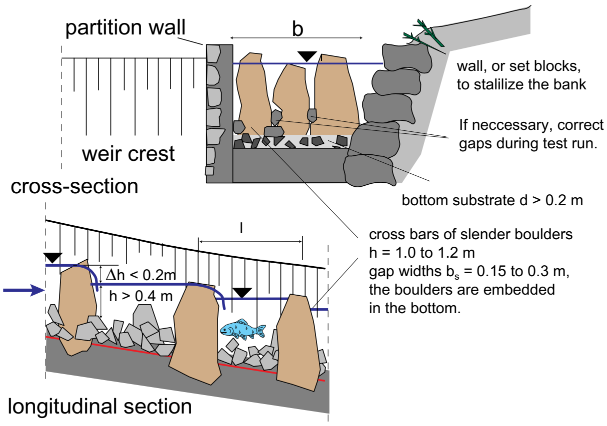


Fig. 4.31: Rough-channel pool pass (channel cross-section and longitudinal section)

with the grain size of the rockfill material being graded downstream (cf. Fig. 4.4). It is also recommended that a pool should be constructed at the base of the ramp as a calming basin.

4.3.3 Special cases

4.3.3.1 Rough-channel pool pass

A rough-channel pool pass is a combination of a technical fish pass and a fish ramp, in which the pool cross-walls are substituted by columnar rocks set on edge. This arrangement allows appreciably greater water depths to be obtained and a steeper slope (up to maximum 1:10) to be used than with conventional fish ramps. A decisive feature in this case is that the differences in water level between the pools must not exceed $\Delta h = 0.2$ m, to maintain the maximum permissible flow velocities of $v_{max} = 2.0$ m/s. As a rule, a rough-channel pool pass requires a solid masonry or concrete partition wall that separates it from the body of the weir (cf. Fig. 4.30).

This type of fish pass is particularly useful for rhithronic streams where there is little space available for the construction.

The width of the channel should not be less than 1.5 m and the clear distance between the boulder bars should be 1.5 to 2.5 m. The minimum water depth required is h = 0.4 m.

The bottom of the channel should only be constructed in concrete if heavy flood discharges are expected. A rockfill bottom is better.

Large, slender boulders (quarry-stones), embedded in the bottom layer of the pass, are used to build the transverse bars (Figure 4.31). Depending on the expected discharges the boulders are embedded approximately 0.4 m in the rockfill bottom, embedded into the channel concrete before it sets or set on a concrete sill. The boulders must be embedded in such a way that water only flows around them, and not over them. The clear width of the opening between the boulders should not be less than 0.20 m, to enable larger fish to ascend and to reduce the risk of clogging with debris.

The boulders must be offset in both the longitudinal and the transverse directions to allow the discharge to better fan-out and for better dissipation of energy in the pools. The discharge jets should always impinge on a boulder of the next transverse bar downstream and should not shoot through the next bar in order not to form a short-circuit current.

The characteristics of such irregular structures cannot be calculated exactly beforehand and there is a risk that the fish pass would probably not immediately function well without testing and modifying. It is therefore all the more important to carry out intensive testing during the construction phase as a result of which the arrangement of the boulders in the transverse bars can be improved.

4.3.3.2 Pile pass

Another special form of fish ramp is the so-called "pile pass" (Fig. 4.32) in which wooden piles reduce flow velocity sufficiently to allow for the upstream migration of fish (GEITNER & DREWES, 1990). This variant is particularly recommended if large rocks are not to be used because they would not match the natural characteristics of the river.

In a pile pass piles are arranged, either in rows or offset at intervals of 5 to 10 times the pile diameter, and rammed into the ramp body or embedded in the concrete in the case of a solid substructure. The piles should be 10 to 30 cm in diameter. The length of the piles must be such that water only flows around, and not over, them at normal water levels. To improve their self-cleaning, it is recommended that the piles should be inclined slightly in the

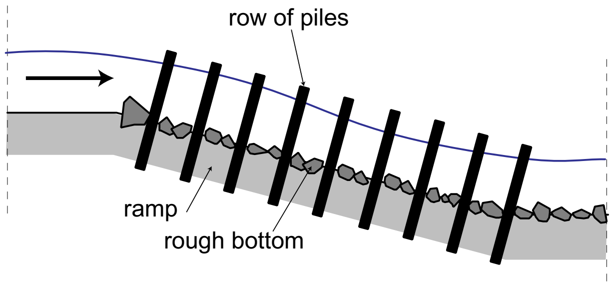


Fig. 4.32: Pile pass (diagrammatic longitudinal section)

direction of flow, so that they are overflowed for a short time during flooding.

In contrast with other constructions, pile passes are relatively insensitive to fluctuating headwater levels, if the piles are long enough. In accordance with the law of linear resistance, flow velocities remain identical with different water depths on the ramp.

4.3.4 Overall assessment

Fish ramps are "close-to-nature" constructions and characterised by the following features:

- They are suitable for retrofitting of low fixed-weir installations.
- They can be passed even by small fish and fry and by the benthic invertebrates.
- They are also suitable for downstream migration of fish.
- They have a natural-looking, visually attractive design.
- They require little maintenance in comparison with other constructions.
- They are not easily clogged; deposits of flotsam and flood debris do not immediately affect the efficiency of the installation.
- Their guide currents are satisfactory and easily located by fish.
- They offer habitat for rheophilic species.

Their disadvantages are:

- Sensitivity to fluctuating headwater levels.
- The large discharges necessary for their operation.
- The large amount of space they occupy.

4.3.5 Examples

ESELSBRÜCKE FISH RAMP			
Details of the river		**Details of the fish ramp**	
River:	Elz, Baden-Württemberg, carries sedimentary material	Width:	b = 2.5 to 3.5 m
		Slope:	I = 1 : 20
Discharge:	MQ = 2.0 m^3/s	Length:	l = 30 m
	HQ_{100} = 147 m^3/s	Water depth:	h = 0.2 to 0.4 m
Height of fall:	h = 1.20 m	Max. flow velocity:	v_{max} = 1.5 m/s
Dam:	Fixed oblique weir	Discharge:	Q = 0.3 to 0.4 m^3/s
Function:	Protection sill	Year of construction:	1993

Description of the construction:

The fish ramp at the Eselsbrücke weir on the Elz River was incorporated in the upstream area of the weir that is oblique to the river axis. The ramp was well blended into the landscape and the existing weir construction by placing it between the existing bank slope and the body of the weir.

An incision approximately 4 m wide was made in the weir crest to connect the ramp with the headwater. The skeleton of the ramp body consists of ten crossbars made of boulders (h = 1.0 to 1.5 m) arranged in groups. The area between the crossbars was filled with a mixture of river stones and gravel. Limited dynamic activity resulting in pool formation and gravel deposits is allowed in the intermediate basins.

Figure 4.33:
Eselsbrücke fish ramp on the Elz (view from tailwater)

The inclined ramp, that is shallow, blends well into the embankment and the existing weir construction.

DATTENFELD FISH RAMP

Details of the river		Ramp data	
Watercourse:	Sieg, NRW	Width:	b = 10 m
Discharge:	MNQ = 3.0 m^3/s	Slope:	I = 1 : 20
	MQ = 21.0 m^3/s	Length:	l = 50 m
	HHQ = 612 m^3/s	Discharge:	Q = 2.0 m^3/s
Barrage:	Solid weir sill	Max. flow velocity:	v_{max} = 1.5 – 2.0 m/s
Height:	h = 1.80 m	Year of construction:	1987
Width:	b = 90 m	Responsible:	StAWA# Bonn

Description of the construction:

The fish ramp has been integrated into the angle between the right riverbank and the existing solid weir sill. The body of the ramp was erected as a solid concrete structure with embedded quarry-stones and roughened with a layer of coarse gravel embedded in the wet top layer of concrete before it set. In addition, large perturbation boulders (diameter up to 80 cm, spaced in such a way as to leave a clear distance of approx. 1.5 m between them) reduce the flow velocity and create shelters for fish as they ascend the ramp. The ramp has rather shallow water towards the bank that allows even the weaker fish species and benthic fauna to ascend.

Figure 4.34:
Dattenfeld/Sieg fish ramp (general view of the bottom sill with incorporated fish ramp)

Figure 4.35:
View from tailwater

StAWA: Staatliche Ämter für Wasser- und Abfallwirtschaft [Government Offices for Water and Waste Management] (remark by the editor)

DELMENHORST FISH RAMP

Details of the river		Ramp data	
Watercourse:	Delme, Lower Saxony	Width:	b = 2.4 to 4.5 m
Discharge:	MNQ = 0.3 m^3/s	Slope:	I = 1 : 41.5
	MQ = 1.0 m^3/s	Length:	l = 27 m
	MHQ = 5 m^3/s	Water depth:	h = 0.30 – 0.7 m
Fall head:	h ≈ 0.6 m	Max. flow velocity:	v_{max} = 1.3 – 1.4 m/s
Use:	Formerly for water abstraction	Year of construction:	1993
		Responsible:	Ochtumverband

Details of construction

One of three existing evacuation gates of the weir was replaced with a gently sloped fish ramp. The full discharge runs through the ramp up to mean low-water flow, and water spills over the weir only at greater discharges.

The ramp is installed in the headwater area of the weir so that the outlet into (i.e. fish entrance from[#]) the tailwater lays immediately at the weir foot, adjacent to the overflow. A concrete wall was constructed to confine the ramp on the mid-river side upstream of the weir. The ramp consists of crossbars formed of large boulders, arranged at intervals of 4 to 5.5 m. The boulders lie on gabions. Differences in water level of ca. 10 cm occur at the crossbars. Trough-shaped pools form between the crossbars. Both the pools and the passages between the boulders are covered with a continuous layer of coarse gravel and stones, about 25 cm thick, which form interstitial spaces.

The ramp can be closed off for maintenance by means of a sluice gate in the intake area through which the water flows onto the ramp and which, at the same time, keeps out debris.

Figure 4.36:
Delmenhorst fish ramp.

View of the headwater end shortly before completion. The gently sloped ramp is covered with an uninterrupted substrate layer of gravel and stones. With the ramp built in the headwater area of the weir and the outlet (fish entrance[#]) situated immediately adjacent to the weir, the formation of "dead corners" is avoided. Rough-surfaced, gently sloped ramps of this type can be negotiated by the entire river fauna without restriction.

[#] remark by the editor

UHINGEN ROUGH-CHANNEL POOL PASS

Details of the river		**Fish pass data**	
Watercourse:	Fils, Baden-Württemberg	Discharge:	$Q = 0.34\ m^3/s$
Construction type:	Tube weir	Width:	b = 1.90 m
Height:	$h_{tot} = 3.6$ m	Slope:	I = 1 : 9
Discharge:	$MQ = 9.8\ m^3/s$	Length:	l = 32 m
	$HQ_{100} = 284\ m^3/s$	Water depth:	h = 0.6 to 0.8 m
Use:	Water power	Year of construction:	1989

Details of construction

The Fils is a hydraulically modified, rubble-carrying upland stream, with a slope of I = 2 ‰, a bottom width of b = 10 to 15 m, and a stony to gravely bottom.

The fish pass was connected to the existing left-bank wall and separated from the weir body by a low concrete partition wall. The boulders, placed on edge, are embedded into the concrete foundation, upon which was laid a substrate layer of coarse gravel, ca. 0.20 m thick and containing a few larger rocks. The boulder bars are spaced at between 1.65 and 3.15 m. The initial concern that widely varying water depths (and flow velocities) would appear at the individual cross-bars due to the irregular discharge cross-sections was not confirmed in the trial run. Although some extra work on the installation, involving enlarging or plugging of slots, was necessary, the water depths and the differences in water levels laid from the beginning within the specified limits.

Figure 4.37:
Uhingen/Fils rough-channel pool pass

View from tailwater end.

FISH RAMP AT THE SPILLENBURG WEIR

Details of the river		Fish pass data	
Watercourse:	Ruhr, NRW	Discharge:	Q = 1 m^3/s
Discharge:	MNQ = 20 m^3/s	Width:	b = 10 m
	MQ = 70 m^3/s	Slope:	I = 1 : 25
	HHQ = 2300 m^3/s	Length:	l = ca. 102 m
Construction type:	Two-stepped, fixed weir	Water depth:	h = 0.6 to 1.0 m
Height:	h = 2.6 m	Year of construction:	1993
Use:	Water power, drinking water	Responsible:	StAWA# Herten

Details of construction

The fish ramp was built at the left flank of the Spillenburg Weir with a difference in level of ca. 2.60 m at low water. Steel berms provide the lateral boundary of the installation; they also served as floodwater protection during the period of construction. The berms were covered with coarse rubble and are no longer visible.

The fish ramp is divided into 17 pools (length l = 3 to 4 m) formed of boulder bars consisting of large boulders (each weighing up to 1.5 t). The boulders are placed directly on the ramp body and lean against one another. The pools are filled with a 20 cm thick layer of gravel and stones. Concrete was not used deliberately. The discharge is controlled by a regulatable intake structure.

Figure 4.38: Setting the boulder bars

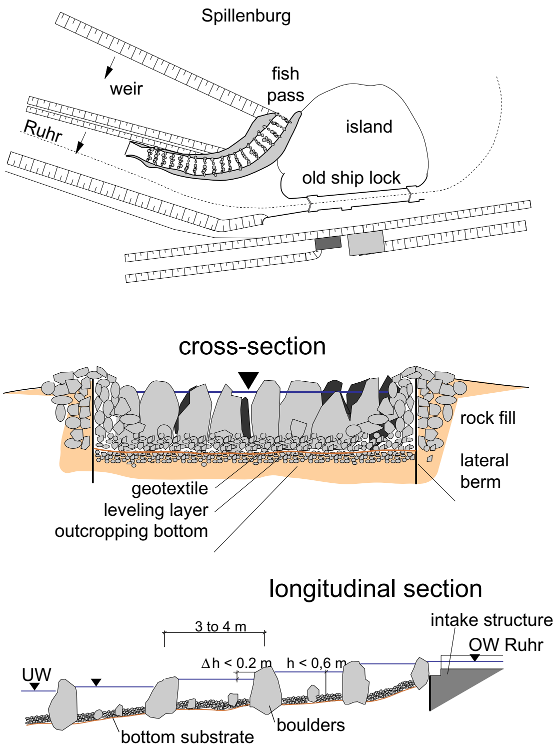


Figure 4.39: Layout and ramp design

StAWA: Staatliche Ämter für Wasser- und Abfallwirtschaft [Government Offices for Water and Waste Management] (remark by the editor)

FISH RAMP AT THE SPILLENBURG WEIR

Figure 4.40: Spillenburg weir; fish ramp under construction

The crossbars were laid from the intake structure to the tailwater. During the trial run, the water depths in the pools were corrected by plugging or enlarging gaps in the boulder sills and it was paid attention to not exceed a maximum water-level difference of Δh = 20 cm.

Figure 4.41: Spillenburg weir; fish ramp after completion

The Department for Fisheries of the LÖBF/LAfAO NRW confirmed the functioning of the construction in May 1994. Already a few months after completion, a rich variety of benthic species including mussels, snails, caddis fly and dragon fly larvae had colonized the ramp.

4.4 Hydraulic design

A distinction must be made between the two basic types of discharge in the hydraulic design of fish passes:

a) **Service discharges**: These are understood to include the normal discharge range, which is exceeded, or may not be not reached at all, on only a few days in the year and for which the functioning of the fish pass has to be guaranteed. The fish pass must be designed in such a way that the water depths that fish need for ascending are respected and that the permissible flow velocities are not exceeded for these service discharges.

b) **Critical discharge**: This is a flooding discharge that only recurs at intervals of several years flooding, but for which the fish pass must be designed so that its stability is maintained. As fish can anyhow not ascend during these heavy discharges, this factor does not need to be taken into consideration for the fish migration. The critical discharge for the fish pass can be limited or adjusted with appropriate water intake (fish pass exit[#]) structures or regulatory devices.

4.4.1 Flow formulae

The methods currently recommended for hydraulic design calculations of running waters have been compiled in the DVWK-Guidelines 220/1991 “Hydraulic calculations of running waters”.

The calculation of mean flow velocity in open channels is based upon the Darcy-Weisbach flow formula:

$$v_m = \frac{1}{\sqrt{\lambda}}\sqrt{8\,g\,r_{hy}\,I} \qquad (4.1)$$

$$\text{where} \quad r_{hy} = \frac{A}{l_u} \qquad (4.1a)$$

The resistance coefficient λ is calculated for running waters with a rough bottom and under steady, uniform flows (normal flow) according to the formula

$$\frac{1}{\sqrt{\lambda}} = -2 \log \frac{k_s/r_{hy}}{14.84} \qquad (4.2)$$

(Validity range: $k_s < 0.45\ r_{hy}$),

in which the equivalent sand roughness diameter k_s is replaced for calculation by the average rock diameter d_s, in the case of a rockfill bottom, and by grain size diameter d_{90} in the case of a mixed bottom substrate.

[#] remark by the editor

SCHEUERLEIN (1968) gives a function for the resistance coefficient for turbulent discharge in rough channels and on block stone ramps with a dressed and ordered stone base, which, disregarding the air content of the water and an assumed packing factor of 0.5 for the dressed and ordered stones, can be written in the following form:

$$\frac{1}{\sqrt{\lambda}} = -3.2 \log \left[(0.425 + 1.01\ I)\ \frac{k}{h_m}\right] \qquad (4.3)$$

Validity range: I = 1:8 to 1:15,
d_s = 0.6 to 1.2 m

The roughness k of the dressed and ordered stones can be estimated as

$$k \approx \frac{1}{3} \text{ to } \frac{1}{2}\, d_s$$

From the mean flow velocity v_m and the flow surface area A, the discharge Q is obtained as

$$Q = v_m \cdot A \qquad (4.4)$$

4.4.2 Flow resistance of perturbation boulders

In bypass channels and fish ramps with embedded perturbation boulders set as shown in Figure 4.42, the influence of the bottom roughness is masked by the flow resistance of the boulders. The resistance coefficient λ_{tot} in Equation (4.1) can then be calculated from the following formula, cf. ROUVÉ (1987):

$$\lambda_{tot} = \frac{\lambda_s + \lambda_o\,(1 - \epsilon_o)}{(1 - \epsilon_v)} \qquad (4.5)$$

in which is

$$\epsilon_v = \frac{\Sigma V_s}{V_{tot}} = \frac{\text{immersed vol. of perturbation boulders}}{\text{total volume } A \cdot l} \qquad (4.5a)$$

$$\epsilon_o = \frac{\Sigma A_{o,s}}{A_{o,tot}} = \frac{\text{surface area of perturbation boulders}}{\text{total basal area } l_u \cdot l} \qquad (4.5b)$$

$$\lambda_s = 4\,c_w\,\frac{\Sigma A_s}{A_{o,tot}} \qquad (4.5c)$$

where $c_w \approx 1.5$ is the form drag coefficient and $A_s = d_s h^*$ the wetted area of the perturbation boulders (4.5d)

where the variable h^* becomes the average water depth h_m if the water flows only around the boulders

or becomes the boulders height h_s for boulders that are completely submerged.

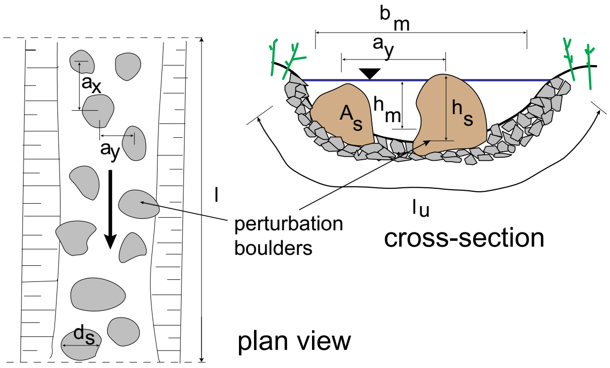


Fig. 4.42: Bypass channel with perturbation boulders

The resistance coefficient of the bottom λ_o can be determined approximately from the hydraulic radius r_{hy} of the total cross-section according to Equation (4.2). It is low in comparison with the resistance coefficient of the perturbation boulders.

For practical applications, it is usually sufficient to disregard ϵ_v and ϵ_o in Equation (4.5) and calculate the overall resistance coefficient from the superposition of the individual resistances from

$$\lambda_{tot} = \lambda_s + \lambda_o \qquad (4.6)$$

where $\lambda_s = c_W \dfrac{4\,A_s}{a_x\,a_y}$ (resistance coefficient of perturbation boulders) (4.6a)

and $A_s \approx d_s \cdot h^*$ (4.6b)

with d_s, a_x, a_y as in Figure 4.42.

a_x and a_y represent the average spacing between the boulders in the direction of flow (a_x) and across the flow (a_y), while, in small rough channels with only one boulder for each cross-section, a_y must be replaced by the channel width b.

For pile passes, c_w can be put to c_w = 1.0 (GEITNER & DREWES, 1990).

The mean flow velocity is again obtained from Equation (4.1) and the discharge from Equation (4.4).

The maximum flow velocities in the cross-sections between the boulders are decisive in allowing fish to pass, and can be calculated approximately from the formula

$$v_{max} = \frac{v_m}{1 - \dfrac{\Sigma A_s}{A_{tot}}} \qquad (4.7)$$

where A_{tot} = unobstructed flow cross-section (without perturbation boulders)

and ΣA_s = sum of the wetted areas of all the boulders within an extremely constricted cross-section

The selected slopes, boulder spacing and boulder diameters should be such that, on average, subcritical flow appears. Changes in the flow pattern must only be allowed in the narrow gaps between the boulders if at all.

Given the present state of knowledge the validity of these calculations, and particularly of the above-mentioned value for $c_w \approx 1.5$, has to be limited to the following ranges:

Boulder spacing	$a_x = a_y = 1.5$ to $3\,d_s$,
	$a_y - d_s > 0.3$ m,
Water depth	$h_m/h_s < 1.5$,
Slope	I = 1:20.

Remarks

Apart from the shape of the boulders, the form drag coefficient c_w in Equations (4.5c) and (4.6a) is decisively influenced by the effect of the flow patterns that occur behind the boulders that lie just upstream. The resistance coefficient also changes if the boulders are submerged. The few available data on these problems show values both larger and smaller than c_w = 1.5. However, general calculation methods, such as those that ditto determine the resistance coefficients of wood around which water flows, cannot yet be specified. A considerable need for research exists here. A trial run is, therefore, always required.

An example of calculation

At the main weir of a bypass power station, a fish ramp is to be built over which the required minimum flow is Q = 1.2 m^3/s. The ramp is to have a slope of 1:25 (I = 0.04) and a water depth of h = 0.40 m. The body of the ramp is to be built of quarry-stones, whose roughness is estimated at k_s = 0.12 m. The flow velocity should be reduced and fish shelters created by perturbation boulders that have an edge length of d_s = 0.6 m. The ramp will have a trapezoidal cross-section as shown in Figure 4.43. Therefore, the following characteristic baseline data are:

Flow area: $A = 2.6 \cdot 0.4 + 2 \cdot 0.4^2 = 1.36\ m^2$

Wetted perimeter: $l_u = 2.60 + 2 \cdot 0.4\sqrt{1 + 2^2} = 4.39$ m

Hydraulic radius: $r_{hy} = \dfrac{A}{l_u} = \dfrac{1.36}{4.39} = 0.31$ m

Ramp width at water level:

$$b_{sp} = 2.6 + 2 \cdot 2 \cdot 0.4 = 4.20\ \text{m}$$

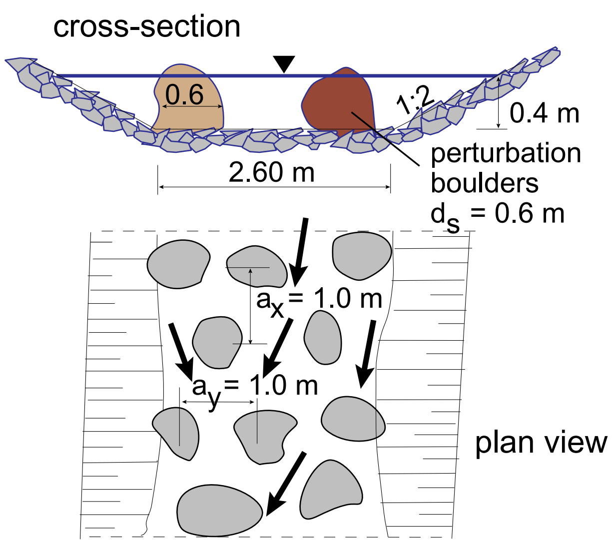


Fig. 4.43: Sketch to illustrate the example of calculation

The perturbation boulders should be placed with average axial distances of $a_x = a_y = 1.0$ m as shown in Figure 4.43. For a channel section l = 10 m long, about 28 boulders are needed.

Each individual perturbation boulder has a wetted surface of

$$A_s \approx 0.6 \cdot 0.4 = 0.24 \text{ m}^2$$

As the calculation is made for a section l = 10 m long, the volume ratios and surface area ratios are:

$$\epsilon_v = \frac{28 \frac{\pi}{4} d_s^2 h}{l A} = \frac{28 \frac{\pi}{4} 0.6^2 0.4}{10 \cdot 1.36} = 0.233$$

$$\epsilon_o = \frac{28 \frac{\pi}{4} d_s^2}{l \cdot l_u} = \frac{28 \frac{\pi}{4} 0.6^2}{10 \cdot 4.36} = 0.18.$$

Based on $\Sigma A_s = 28 \cdot 0.24 = 6.72$ m²

and $A_{o,tot} = l \cdot l_u = 10 \cdot 4.39 = 43.9$ m²

the resistance coefficient of the perturbation boulders is calculated as

$$\lambda_s = 4\, c_w \frac{\Sigma A_s}{A_{o,tot}} = 4 \cdot 1.5 \frac{6.72}{43.9} = 0.92.$$

Taking into account the bottom roughness, the resistance coefficient is calculated according to Equation (4.2) as follows:

$$\frac{1}{\sqrt{\lambda_o}} = -2 \log \frac{0.12/0.31}{14.84} = 3.16 \rightarrow \lambda_o = 0.10.$$

Hence the overall resistance coefficient is λ_{tot} according to Equation (4.5)

$$\lambda_{tot} = \frac{\lambda_s + \lambda_o (1 - \epsilon_o)}{1 - \epsilon_v} = \frac{0.92 + 0.1(1 - 0.18)}{1 - 0.233} = 1.31.$$

The mean flow velocity is obtained from Equation (4.1) as

$$v_m = \sqrt{\frac{8\, g\, r_{hy}\, I}{\lambda_{tot}}} = \sqrt{\frac{8 \cdot 9.81 \cdot 0.31 \cdot 0.04}{1.31}} = 0.86 \text{ m/s}$$

and hence the discharge:

$$Q = v_m \cdot A = 0.86 \cdot 1.36 = 1.17 \text{ m}^3/\text{s} \approx 1.20 \text{ m}^3/\text{s}.$$

Hence, as shown here, the ramp can cope with the discharge as required in the exercise statement.

The maximum flow velocity will appear in the most constricted flow cross-sections where three perturbation boulders are imbedded in a line. From Equation (4.7) is obtained:

$$v_{max} = \frac{v_m}{1 - \frac{\Sigma A_s}{A_{ges}}} = \frac{0.86}{1 - \frac{3 \cdot 0.4 \cdot 0.6}{1.36}} = 1.83 \text{ m/s}$$

$v_{max} < v_{perm} = 2.0$ m/s (v_{perm} = hightest permissible water velocity[#]).

To predict the type of flow that occurs on the ramp (in the unobstructed cross-section), the Froude number is calculated:

$$Fr^2 = \frac{v_m^2\, b_{sp}}{g\, A_{tot}} = \frac{0.86^2\, 4.20}{9.81 \cdot 1.36} = 0.233$$

$$\rightarrow Fr = 0.48 \qquad (4.8)$$

As the Froude number is Fr < 1, the status is that of subcritical flow.

In the most constricted cross-section, where

$$b_e = b_{sp} - 3 \cdot d_s = 4.2 - 3 \cdot 0.6 = 2.4 \text{ m}$$

$$A_e = A_{tot} - \Sigma A_s = 1.36 - 3 \cdot 0.24 = 0.64 \text{ m}^2$$

the Froude number becomes:

$$Fr_e^2 = \frac{v_{max}^2\, b_e}{g\, A_e} = \frac{1.83^2 \cdot 2.4}{9.81 \cdot 0.64} = 1.28$$

$$\rightarrow Fr_e = 1.13. \qquad (4.8a)$$

[#] remark by the editor

This means that supercritcal flow already appears. But since the Froude number is $Fr_e < 1.7$, no pronounced jump occurs. The energy transformation must be brought about through the stream jet striking the next perturbation boulder beneath the constriction.

For comparison:

The simplified calculation approach according to Equation (4.6) yields quite similar results.

When the resistance coefficient of the bottom is $\lambda_o = 0.10$ as already determined, and

$$\lambda_s = 4\, c_w \frac{A_s}{a_x\, a_y} = 4 \cdot 1.5\ \frac{0.4 \cdot 0.6}{1.0 \cdot 1.0} = 1.44 \text{ and}$$

$$\lambda_{tot} = \lambda_s + \lambda_o = 1.54$$

a mean flow velocity follows of

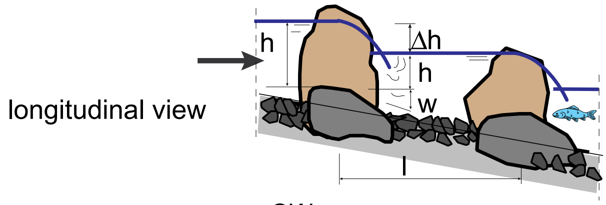
$$v_m = \sqrt{\frac{8\, g\, r_{hy}\, I}{\lambda_{tot}}} = \sqrt{\frac{8 \cdot 9.81 \cdot 0.31 \cdot 0.04}{1.54}} = 0.79 \text{ m/s}$$

and a maximum value of $v_{max} = 1.68$ m/s as well as a discharge of $Q = 1.08\ m^3/s$.

The differences compared with the first result amount to only about 8%.

4.4.3 Design calculation of boulder sills

Boulder sills are composed of boulders and form a system of pools due to their retention effect. The boulders are placed on gaps in the crossbars, i.e. the flow passes only through the clear sections between the boulders. Where low discharges occur and where channels are relatively wide, it is often necessary to partially close the gaps between the larger boulders - as sketched in Figure 4.44 - by putting bottom sills formed of flat stones. In this



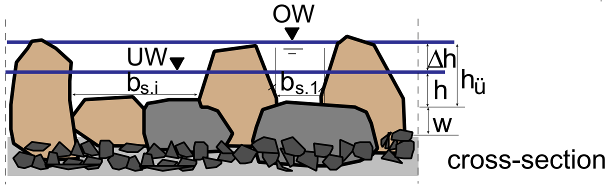


Fig. 4.44: Hydraulic design calculation for bypass channels and ramps with boulder sills (schematic diagram)

way, higher retention and a greater water depth can be achieved during low flows.

In conformity with the hydraulic laws, the characteristics of flows that go over or through a boulder sill correspond to those of the flow over a fixed weir, whereby the two basic cases of complete (no-drowned condition) and incomplete (drowned condition) flow have to be distinguished.

The limit between complete and incomplete overtopping flow is determined primarily by the ratio h/h_{head} but also by the shape of the sill, cf. PREISSLER/BOLLRICH (1992), Chapter 9.

For preliminary design calculation, it is sufficient to determine the flow using the Poleni formula:

$$Q = \frac{2}{3}\, \mu\, \sigma\, \Sigma b_s\, \sqrt{2g}\, h_{head}^{3/2} \qquad (4.9)$$

where Σb_s – the sum of the unobstructed flow widths.

Figure 4.45:
Fish stream next to the Lech dam of Kinsau
The stsmeep slope is broken up by crossbars made of boulders. The bottom of the basins between the sills is not reinforced, enabling scoured pools to be formed.

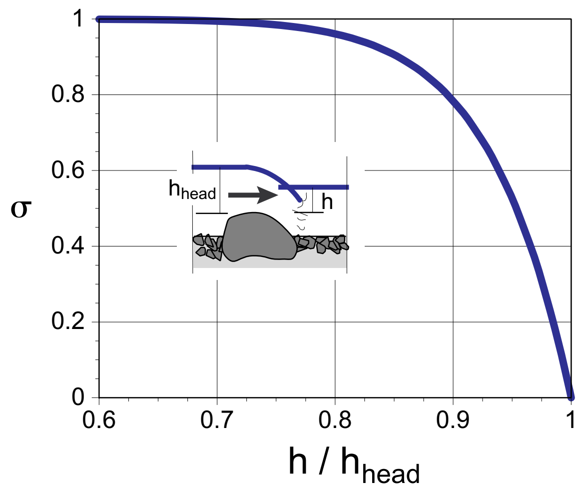


Figure 4.46: Drowned-flow reduction factor σ

Where there are clear cross-sections of varying heights, or where the boulder sill is submerged across its full width (i.e. including the large boulders), the flow Q must be determined section by section. With regard to the spillway coefficient μ, the values known for a sharp-edged, wide-crested weir, or a rounded weir crest, can be used depending in each case upon the type of sill and the stone material used. In any case, the limits of validity of the values or formulae must be strictly taken into consideration. In general, the following can be recommended:

Broad, sharp-edged rocks, crushed material:

$\mu \approx 0.5$ to 0.6

Rounded stones, e.g. fieldstones:

$\mu = 0.6$ to 0.8

The drowned-flow reduction factor σ takes account of the influence of the tailwater level h (i.e. the water level downstream of the overflowed boulder) and can be taken from Figure 4.46. The values are about the same as those for a bear-trap weir or for a broad-crested weir, cf. PREISSLER/BOLLRICH (1992). In the case of complete (no-drowned condition) discharge, this coefficient is $\sigma = 1.0$.

The maximum flow velocities appearing at the boulder sills are governed by the difference in water level Δh and amount to

$$v_{max} = \sqrt{2g\Delta h}. \qquad (4.10)$$

The size and depth of pools between the sills should guarantee low-turbulence flow so that migrating fish find enough shelter and opportunities to recover from their swimming efforts. The guide value for the volumetric power dissipation is E = 150 to 200 W/m³, and can be calculated from the following formula

$$E = \frac{\rho g \Delta h Q}{b h_m l_w} = \frac{\rho g \Delta h Q}{A l_w} \qquad (4.11)$$

where h_m = mean water depth in the pools

b = mean pool width

A = mean pool cross-section

l_w = unobstructed pool length, $l_w \approx l - d_s$.

At boulder sills made from columnar rocks placed on edge without a ground sill (cf. Figure 4.47) as in rough-bottomed channel pool passes, flow changes occur in the narrow cross-sections between the boulders at times of low tailwater levels or when the gaps are quite narrow. In these cases, the headwater depth that results for each particular step can also be determined by comparing the energy levels:

The minimum energy level necessary to carry the discharge Q through the clear cross-sections amounts to

$$h_{E,min} = \frac{3}{2}\sqrt[3]{\frac{Q^2}{g\Sigma b_s^2}} \qquad (4.12)$$

From the comparison of the energy level in the narrows with the energy level in the headwater

$$h_{E,o} = h_o + \frac{v_o^2}{2g} = h_{E,min} + h_v \qquad (4.13)$$

and taking into account the head loss h_v in relation to the critical depth

$$h_v = \zeta\,\frac{v_{gr}^2}{2g} = \frac{\zeta}{3}\,h_{E,min} \qquad (4.14)$$

it results the energy level in the headwater above the weir sill as

$$h_{E,o} = (1 + \zeta/3)\,h_{E,min}. \qquad (4.15)$$

For the inlet-loss coefficient ζ, the value $\zeta = 0.5$ may be assumed, which applies in the case of sharp-edged inlets.

In this calculation, the headwater depth is independent of the water level below the sill.

[#] remark by the editor

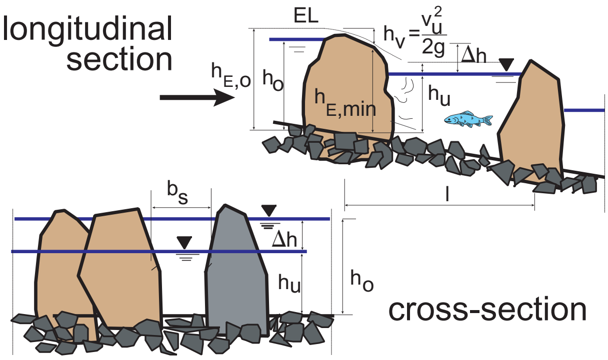


Figure 4.47: Flow at a boulder sill

An example of calculation

A bypass channel at a dam in a potamon reach of a river can be subjected to a minimum of $Q_{min} = 0.1\ m^3/s$ for low-water flows and at most to $Q_{max} = 0.31\ m^3/s$. Boulder sills are incorporated in the channel so that a pool systems forms. At low flows, a water level between 0.30 and 0.40 m is needed in the fish pass.

The water-level difference is set to $\Delta h = 0.10$ m and the boulder sill spacing to l = 2.5 m. The slope is therefore calculated as

$$I = \frac{\Delta h}{l} = \frac{0.1}{2.50} = 1:25 \text{ or } 4\%.$$

The maximum flow velocity is obtained from

$$v_{max} = \sqrt{2g\Delta h} = \sqrt{19.62 \cdot 0.10} = 1.40 \text{ m/s}$$

and is thus lower than the permissible flow velocity

$$v_{permissible} = 2.0 \text{ m/s}.$$

The boulder sills consist of fieldstones of $d_s = 0.6$ m in diameter and must be set in such a way as to concentrate the low-water discharge. The clear cross-sections are partially closed with flat stones that should be submerged by a water cushion (nappe) of at least $h_{head} = 0.2$ m.

In the clear cross-sections, stones of $d_s =$ ca. 0.4 m are embedded in the bottom in such a way as to rise about 20 cm above the bottom. This leads to a head of

$$h_{head} = 0.4 - 0.2 = 0.2 \text{ m}.$$

Since the $h / h_{head} = 0.10/0.20 = 0.5$, according to Figure 4.46 a free-flow discharge with $\sigma = 1.0$ can be assumed, so that the necessary width for the opening with a spillway coefficient $\mu = 0.5$ (for relatively sharp-edged boulders) is calculated from Equation (4.9) as

$$\Sigma bs = \frac{Q_{min}}{\frac{2}{3}\mu\,\sigma\sqrt{2g}\,h_o^{3/2}} = \frac{0.1}{\frac{2}{3}0.5 \cdot 1.0\sqrt{19.62} \cdot 0.2^{3/2}}$$
$$\approx 0.75 \text{ m}$$

The spaces between the stones are arranged alternating left and right in order to provide a meandering pool flow. Division into two openings, each ca. 0.4 m wide is also possible. The larger boulders next to the gap are to be placed in such a way that the sill is 0.4 m high and the pools are filled even at low flows. The large boulders, embedded to a depth of 20 cm in the bottom, must therefore have a diameter of about 60 cm.

The bottom of the channel has 2.5 times the width of the clear areas between the stones in order to allow the openings to be arranged in staggered parallel formation so that no short-circuit flow can develop in the pools. The bottom width will therefore be

$$b = 2.5 \cdot 0.75 \approx 1.9 \text{ m},$$

from which the overall width of the sill for a slope of 1:2 is calculated as

$$b = 1.9 + 2 \cdot 2 \cdot 0.4 = 3.50 \text{ m}.$$

The cross-section of the entire channel resulting from the construction is sketched in Figure 4.48.

It is important to know the water level at maximum flow to determine the height of the bank protection. The corresponding head then produced must be determined by trials, since no straightforward solution can be suggested because of the diverse patterns of the spillway profile.

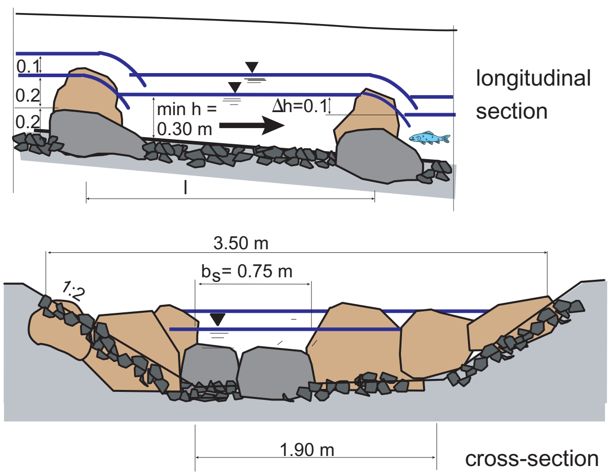


Fig. 4.48: Sketch to illustrate the example of calculation

After several trials, the calculations indicate a water-level increase of about 0.10 m.

Supposing that the head h_{head} is

$$h_{head} = 0.2 + 0.1 = 0.30 \text{ m}$$

and the drowned-flow reduction factor is $\sigma \approx 1.0$ for $h/h_{head} = 0.20/0.30 = 0.66$ according to Figure 4.46, the discharge Q in the gaps is calculated as

$$Q = \frac{2}{3}\,\mu\,\sigma\,\Sigma b_s \sqrt{2g}\, h_{head}^{3/2}$$

$$= \frac{2}{3}\, 0.5 \cdot 1.0 \cdot 0.75\, \sqrt{19.62} \cdot 0.30^{3/2} = 0.18 \text{ m}^3/\text{s}.$$

Over the remaining width of the weir sill of $b = 3.50 - 0.75 = 2.75$ m, where $h_{head} = 0.10$ m and $\mu = 0.5$ (no flow reduction by submerge, since $h = 0$) a discharge of

$$Q = \frac{2}{3} \cdot 0.5 \cdot 2.75\, \sqrt{19.62} \cdot 0.10^{3/2} = 0.13 \text{ m}^3/\text{s}$$

is carried through, so the total discharge amounts to

$$Q_{tot} = 0.182 + 0.128 = 0.31 \text{ m}^3/\text{s}.$$

Since the water-level differences in this example do not change, as compared with low discharge, the same maximal flow velocities of $v_{max} = 1.40$ m/s occur even at maximum discharge. Only the mean flow velocities in the pools change. At low-water and with a mean water depth of $h_m = (0.3 + 0.4)/2 = 0.35$ m, they amount to

$$v_{m,min} = \frac{Q_{min}}{A} = \frac{0.1}{1.9 \cdot 0.35 + 2 \cdot 0.35^2} = 0.11 \text{ m/s}$$

while at maximum discharge they increase to

$$v_{m,max} = \frac{Q_{max}}{A} = \frac{0.31}{1.9 \cdot 0.45 + 2 \cdot 0.45^2} = 0.25 \text{ m/s}.$$

The low mean flow velocities in the pools result in a relatively low-turbulence pool flow and allow finer sediments to settle at least in the low-flow peripheral areas. Bottom protection is nevertheless necessary, owing to the much greater stresses that occur in the spillway areas.

The turbulence conditions in the pools are estimated according to Equation (4.11). At $Q_{max} = 0.31$ m³/s and with

$$A = b \cdot h_m + m \cdot h_m^2 = 1.90 \cdot 0.45 + 2 \cdot 0.45^2 = 1.26 \text{ m}^2$$

and $l_w = l - d_s = 2.50 - 0.60 = 1.90$ m

the volumetric power dissipation results as

$$E = \frac{\rho g Q \Delta h}{A l_w} = \frac{9810 \cdot 0.31 \cdot 0.1}{1.26 \cdot 1.90} = 127 \text{ W/m}^3.$$

$$< E_{permissible} = 150 \text{ to } 200 \text{ W/m}^3$$

4.4.4 Critical discharge over bottom ramps and slopes

For bottom ramps and slopes of the rockfill-type, WHITTAKER and JÄGGI (1986) consider the following equation as a criterion of stability

$$q_{permissible} = 0.257 \sqrt{g \frac{\rho_s - \rho_w}{\rho_w}}\, I^{-7/6}\, d_{65}^{3/2} \qquad (4.16)$$

Figure 4.49:
Test run at the Eitorf-Unkelmühle/Sieg fish ramp
Precise design calculation of irregular boulder sills of this kind is not possible. The optimum arrangement of the boulders was therefore initially determined here with the aid of sandbags. Only after this test, the boulders were permanently embedded. Test runs of this kind must be considered as being an essential part of the construction process and their costs must therefore be accounted for already at the planning stage.

Since $d_{65} \approx d_S/1.06$ and ρ_S = 2700 kg/m^3, the formula can be written in the form

$$q_{permissible} = 0.307 \sqrt{g}\ I^{-7/6}\ d_S^{3/2} \qquad (4.16a)$$

Equation (4.16) already contains a safety margin of 20%.

Block-stone ramps can be subjected to much greater loading stress compared with rockfill bottom steps. According to GEBLER (1990), there is yet no known validated stability criterion. The experiments by WHITTAKER and JÄGGI gave an increase of the permissible discharge by a factor 1.7 to 2.0 for dressed and ordered boulders, compared with Equation (4.16). It must be pointed out, however, that the permissible impingement is greatly influenced by the quality of the work (e.g. faults in the block paving), particularly for block-stone ramps, and other causes of failure such as scour in the tailwater, slope erosion, etc., also influence the stability of the structure.

The stable foothold of exposed individual rocks (perturbation boulders, boulder sills) has to be proved separately. Impacting forces, both the hydraulic pressures due to differences of water levels Δh and the forces due to the maximum flow velocities, must be taken into account here.

4.4.5 Trial runs

Hydraulic design calculations of natural-looking bypass channels and fish ramps can always only be considered as preliminary estimates. The reason lies, firstly in the desired (and also aimed at) diversity of the constructional materials (e.g. boulders) used, the cross-sections, flow conditions, etc., and secondly in the fact that up to now only incomplete studies and results are available. Hence, there are uncertainties in the selection of the coefficients (e.g. roughness, discharge coefficients, intake losses) in the design formulae. Nevertheless, the hydraulic design calculation (preliminary approximation) must be done in order to estimate the order of size of the required boulders and cross-sections as well as the anticipated flow velocities and discharge volumes. Owing to the imponderables, trial runs are always necessary in which observance of the threshold values and planning targets regarding discharge, flow velocities and water depths can be checked and, where applicable, corrected. Trial runs should also be carried out for varying discharges, i.e. on several different dates, since the hydraulic conditions, both in the fish pass and in the development of the guide current in the tailwater, vary very widely. In particular, if inherent dynamic developments are permitted, checks should be carried out and, if necessary, improvements made even at later stages, i.e. during the regular operational period.

During the trial run, the following planning targets should be checked in particular:

- Flow patterns and water depths: very shallow sections, areas with very high turbulence, short-circuit flows and detached jets must be avoided.
- The maximum flow velocities must not exceed 2.0 m/s, particularly at the critical locations (i.e. narrow cross-sections, submerged boulder sills).
- Differences of water level at drops and sills: $\Delta h < 0.2$ m.

5 Technical fish passes

Technical fish passes include the following types:

- Pool passes
- Vertical slot passes
- Denil passes (counter flow passes)
- Eel ladders
- Fish locks
- Fish lifts

This section describes only the common types of technical fish pass, whose hydraulic and biological effectiveness have been adequately studied.

5.1 Pool pass

5.1.1 Principle

The principle of a pool pass consists in dividing up a channel leading from the headwater to the tailwater by installing cross-walls to form a succession of stepped pools. The discharge is usually passed through openings (orifices) in the cross-walls and the potential energy of the water is dissipated, step-by-step, in the pools (Figure 5.1).

Fish migrate from one pool to the next through openings in the cross-walls that are situated at the bottom (submerged orifices) or at the top (notches). The migrating fish encounter high flow velocities only during their passage through the cross-walls, while the pools with their low flow velocities offer shelter and opportunities to rest. A rough bottom is a prerequisite to make pool passes negotiable for benthic fauna.

5.1.2 Design and dimensions

5.1.2.1 Plan view

The design of pool passes is usually straight from headwater to tailwater. However, curved passes or passes that are folded so as to wind-back once on themselves by 180°, or even several times (Figure 5.2), resulting in a shorter structure, are

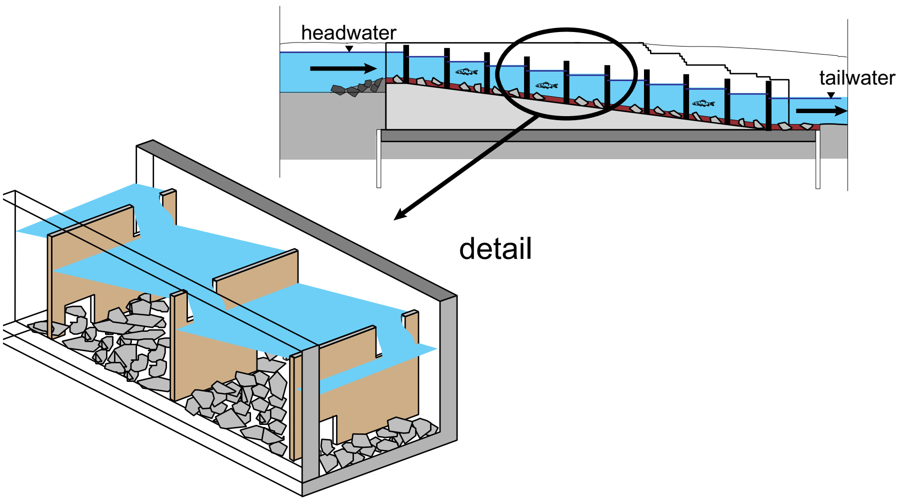


Figure 5.1: Conventional pool pass (longitudinal section and pool structure) (modified and supplemented after JENS, 1982)

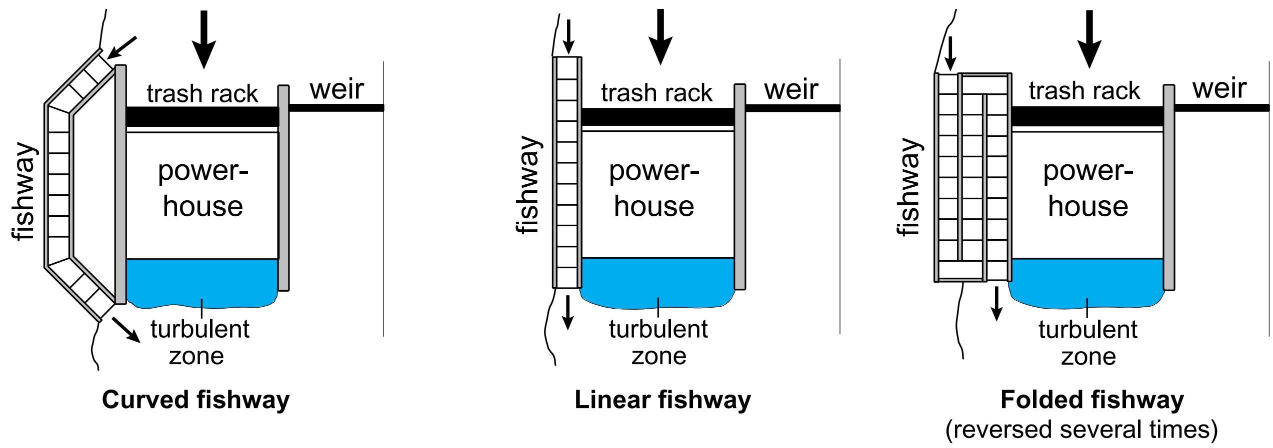


Figure 5.2: Pool passes (plan view) (modified and supplemented after LARINIER, 1992a)

also used. Wherever possible, the water outlet (downstream entrance to the fish pass#) below the weir or turbine outlet must be located in such a way that dead angles or dead-ends are not formed. Basic principles, similar to those outlined in Chapter 3, apply here to regulate the distance of the fish pass entrance in relation to the weir or the turbine outlet.

An alternative design and arrangement of the pools is shown in Figure 5.3.

5.1.2.2 Longitudinal section

Differences in water level between individual pools govern the maximum flow velocities. They are therefore a limiting factor for the ease with which fish can negotiate the pass. In the worst case, the difference in water level (Δh) must not exceed 0.2 m; however, differences in level of $\Delta h = 0.15$ m at the normal filling level of the reservoir are more suitable. The ideal slope for a pool pass is calculated from the difference in water level and length of the pools (l_b):

$$I = \Delta h / l_b \qquad (5.1)$$

where l_b is as shown in Figure 5.4,

so that values of $I = 1{:}7$ to $I = 1{:}15$ are obtained for the slopes if the value l_b ranges from 1.0 m to 2.25 m. Steeper slopes can only be achieved by making the pools shorter if the permissible differences in water-level are respected. However, this results in considerable turbulence in the pools and should be avoided if possible.

remark by the editor

The number of pools needed (n) is obtained from the total head to be overcome (h_{tot}) and the permissible difference in water level between two pools (Δh) (Figure 5.4):

$$n = \frac{h_{tot}}{\Delta h} - 1 \qquad (5.2)$$

where the total height h_{tot} is obtained from the difference between the maximum filling level of the reservoir (maximum height) and the lowest tailwater level upon which the design calculation for the fish pass is to be based.

5.1.2.3 Pool dimensions

Pool pass channels are generally built from concrete or natural stone. The partition elements (partition cross-walls) can consist of wood or prefabricated concrete.

The pool dimensions must be selected in such a way that the ascending fish have adequate space to move and that the energy contained in the water is dissipated with low turbulence. On the other hand, the flow velocity must not be reduced to the extent that the pools silt up. A volumetric dissipated power of 150 W/m^3 should not be exceeded to ensure that pool flows are not turbulent. A volumetric dissipated power of 200 W/m^3 is permissible in the salmonid zone (LARINIER 1992a).

The pool size must be chosen as to suit the behavioural characteristics of the potential natural fish fauna and should match the size and expected number of migrating fish. Table 5.1 gives the recommended minimum dimensions for pool sizes and the design of the cross-walls taken from

Figure 5.3:
A pool pass made of clinker bricks, with alternating pools, at a mill dam in Hude on the Berne (Lower Saxony). The construction fits in well with the general picture of the historical mill.

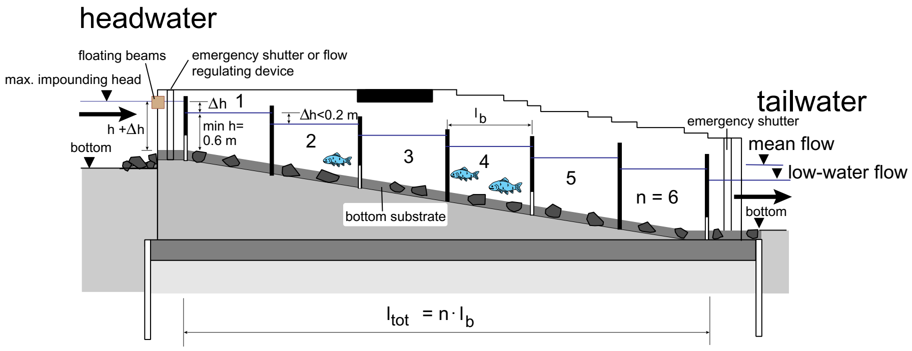


Figure 5.4:
Longitudinal section through a pool pass (schematic)

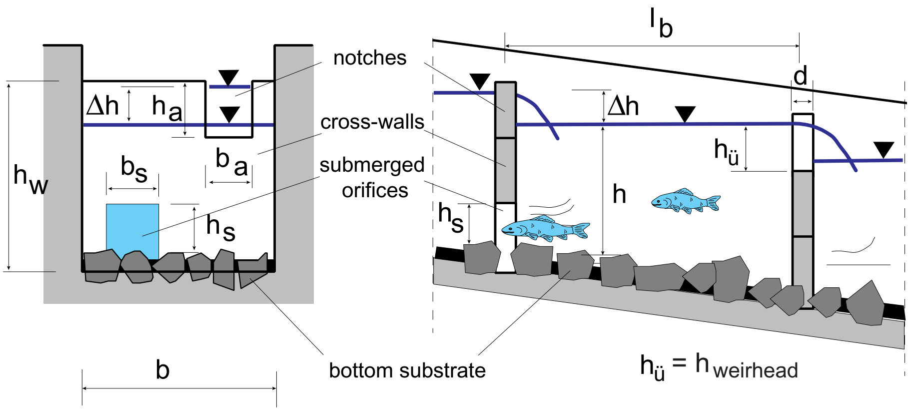


Figure 5.5:
Pool-pass terminology

various literature sources and adapted to the hydraulic design criteria and empirical values for functioning fish passes (see Figure 5.5 for definitions of the technical terms). The smaller pool dimensions apply to smaller watercourses and the larger values to larger watercourses. An alternative type of fish pass must be considered if the recommended pool lengths and discharges cannot be achieved.

The bottom of the pools must always have a rough surface in order to reduce the flow velocity in the vicinity of the bottom and make it easier for the benthic fauna and small fish to ascend. A rough surface can be produced by embedding stones closely together into the concrete before it sets.

5.1.2.4 Cross-wall structures

5.1.2.4.1 Conventional pool pass

Conventional pool passes are characterised by vertical cross-walls that stand at right angles to the pool axis (cf. Figures 5.1 and 5.5) and that may be solid (concrete or masonry) or wood. Wooden cross-walls facilitate later modification but they have to be replaced after a few years.

The cross-walls have submerged openings that are arranged in alternating formation at the bottom of the cross-wall (dimensions as in Table 5.1) through which fish can ascend by swimming into the next pool. The openings reach to the bottom of the pool and allow to create a continuous rough-surfaced bottom when the substrate is put in.

The importance of surface openings (notches) is usually overestimated as ascending fish will invariably first try to migrate upstream by swimming and only exceptionally will try to surmount an obstacle by leaping over it. The turbulence arising from the detached jets coming out of surface openings adversely affect the flow conditions in the pools. Moreover, with varying headwater levels, submerged cross-walls cause problems in the optimisation of discharges. Nevertheless, if surface orifices are provided, their lower edge should still be submerged by the water level of the downstream pool in order to avoid plunging flows and thus allow fish to swim over the obstacle.

Recommended dimensions for orifices and notches are given in Table 5.1.

In general, submergence of cross-walls should be avoided wherever possible so that water flows only through the orifices (or surface notches). Submerged cross-walls at the water outlet (fish pass entrance#) have a particularly negative effect as thus adequate guide currents rarely form.

remark by the editor

Table 5.1 Recommended dimensions for pool passes

Fish species to be considered	Pool dimensions[1)] in m			Dimensions of submerged orifices in m		Dimensions of the notches[3)] in m		Discharge[4)] through the fish pass m^3/s	Max. difference in water level[6)] Δh in m
	length l_b	width b	water depth h	width b_S	height h_S[2)]	width b_a	height h_a		
Sturgeon[5)]	5 – 6	2.5 – 3	1.5 – 2	1.5	1	-	-	2.5	0.20
Salmon, Sea trout, Huchen	2.5 – 3	1.6 – 2	0.8 – 1.0	0.4 – 0.5	0.3 – 0.4	0.3	0.3	0.2 – 0.5	0.20
Grayling, Chub, Bream, others	1.4 – 2	1.0 – 1.5	0.6 – 0.8	0.25 – 0.35	0.25 – 0.35	0.25	0.25	0.08 – 0.2	0.20
upper trout zone	> 1.0	> 0.8	> 0.6	0.2	0.2	0.2	0.2	0.05 – 0.1	0.20

Remarks

1) The larger pool dimensions correspond to larger submerged orifices.
2) h_s – clear orifice height above bottom substrate.
3) If a pass with both top notches and submerged orifices is planned, the larger pool dimensions should be applied.
4) The discharge rates were determined for $\Delta h = 0.2$ m by using the formulae shown in section 5.1.3. The lower value relates to the smaller dimensions of submerged orifices in pools without top notches; the higher discharge is obtained for the larger submerged orifices plus top notches ($\psi = 0.65$).
5) Pool dimensions for the sturgeon are taken from SNiP (1987), since there is no other data available with respect to this fish species.
6) The difference in water level refers to the difference in level between pools.

5.1.2.4.2 Rhomboid pass

The rhomboid pass differs from the conventional pool pass in that the cross-walls are arranged obliquely to the pool axis and point downstream (cf. Figures 5.6 and 5.7). Since successive cross-walls alternate in their attachment to the channel walls (i.e. one from the right channel wall, one from the left channel wall), each pool has one long side and one short side. The length of the shorter side should not be less than 0.3 m and that of the longer side should be at least 1.8 m. Submerged orifices are always put at the upstream end of the cross-wall while surface notches are always in the downstream corner (JENS, 1982).

The angle of inclination of the cross-walls relative to the bottom of the pass is approximately 60° and the angle between the cross-walls and the pool axis is 45 to 60°. This gives the cross-walls a very irregular shape in the form of a rhomboid, hence the name “rhomboid pass”. Separate moulds are need for building the right and left side cross-walls since they are not mirror images and they are inclined in opposite directions.

Otherwise, the same recommendations apply with regard to the average dimensions of the pools and orifices and the water depths as for the conventional pool passes shown in Table 5.1.

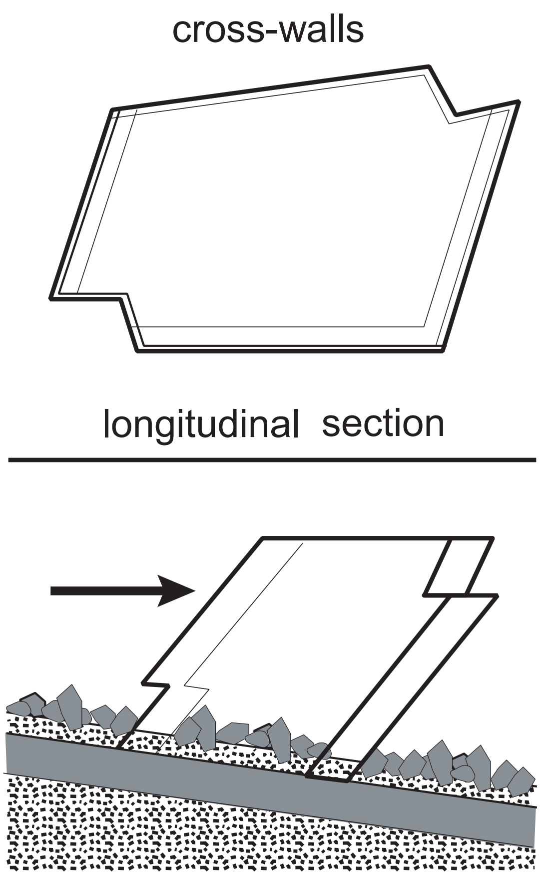


Fig. 5.6: Cross-wall design of a rhomboid pass (after JENS, 1982)

Fig. 5.7: Example of a rhomboid pass (Moselle weir Lehmen, view from tailwater)

The advantages of this design are more favourable flow characteristics in the pools and improved self-cleaning. The inclined cross-walls act as guides leading the ascending fish to the next orifice.

5.1.2.4.3 Humped fish pass

The humped fish pass, developed by Schiemenz, is a special form of the pool pass in which the orifices are designed as widening streamlined channels, cf. Figure 5.8 (HENSEN & SCHIEMENZ, 1960). Unlike other pool passes the orifices are not offset to one another but are aligned. In hydraulic model experiments, the shape of the channels has been optimised to the extent that virtually no eddies or rollers form in the pools. The resulting flow in the pool is always directed which makes it easier for the fish to find their way through the pass.

Humped fish passes require long pools and allow for only small water-level differences of $\Delta h = 0.14$ m between pools. Therefore, humped fish passes are only appropriate if:

- low heads have to be overcome and
- sufficient space is available for such long constructions.

Experience with humped fish passes indicates that they are also suitable for fish species that are weak swimmers. If a rough bottom is incorporated, the pass can also ensure passage of benthic fauna. The major disadvantages of this type of fish pass are the extensive space required and technical demands for the shape of the streamlined channel orifices.

5.1.3 Hydraulic design

The following parameters are crucial and must be respected if pool passes are to function correctly:

- flow velocities in the orifices must not exceed the threshold value of $v_{max} = 2.0$ m/s;
- discharge in the fish pass and
- volumetric power dissipation should not exceed $E = 150$ W/m^3 in general, or $E = 200$ W/m^3 within the salmonid region, in order to ensure low-turbulence flows in the pools.

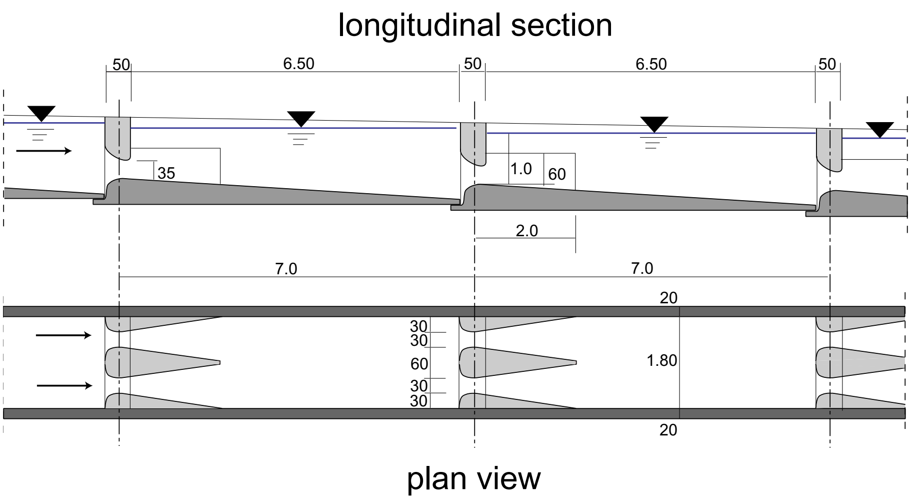


Figure 5.8: Design and dimensions of the pools of a humped fish pass at the Geesthacht dam on the river Elbe (measurements in cm or m) (after HENSEN & SCHIEMENZ, 1960)

Another humped fish pass is to be found in Gifhorn on the Oberaller, which is smaller, having a width of 0.75 m and only one central submerged orifice of 25 × 25 cm.

Maximum flow velocities occur within the orifices and can be calculated from the formula

$$v_s = \sqrt{2g\Delta h} \tag{5.3}$$

Equation (5.3) gives a permissible water-level difference at the cross-walls of $\Delta h = 0.2$ m if the upper threshold value $v_{max} = 2.0$ m/s is respected.

The equation

$$Q_s = \psi A_s \sqrt{2g\Delta h} \tag{5.4}$$

where $A_s = h_s b_s$ (for terms see Figure 5.5) (5.4a)

should be used to determine the discharge in the orifices. The discharge coefficient is influenced by the design of the orifices and by the bottom substrate and can be estimated as $\psi = 0.65$ to 0.85.

The discharge over the top notches can be calculated from

$$Q_a = \frac{2}{3}\,\mu\,\sigma\,b_a\sqrt{2g}\;h_{weirhead}^{3/2} \tag{5.5}$$

where

$h_{weirhead}$ is the difference in the water level between headwater and tailwater, cf. Figure 5.5

μ is the discharge coefficient ($\mu \approx 0.6$), and

σ is the drowned-flow reduction factor.

After LARINIER (1992a), the drowned-flow reduction factor σ, by which the influence of the tailwater of the respective downstream pool is expressed, can be calculated from

$$\sigma = \left[1 - \left[1 - \frac{\Delta h}{h_{weirhead}}\right]^{1.5}\right]^{0.385} \tag{5.6}$$

which is valid for the range: $0 \le \frac{\Delta h}{h_{weirhead}} \le 1$,

for $\Delta h > h_{weirhead}$, $\sigma = 1$

The spillway and outflow coefficients in Equations (5.4) and (5.5) can only be approximate values, as they depend upon the shape of the orifices. If necessary, they must be determined more precisely.

The maximum velocities of the jet coming from top notches can likewise be calculated from Equation (5.3).

To ensure a flow with low turbulence and adequate energy conversion within the pools, the volumetric dissipated power should not exceed $E = 150$ to 200 W/m^3. The power density can be estimated from

$$E = \frac{\rho g \Delta h Q}{b h_m (l_b - d)} \tag{5.7}$$

in which the total discharge $Q = Q_s + Q_a$ must be entered for Q.

Some specific characteristics must be taken into account in the hydraulic design calculations of humped fish passes. These are made necessary by the incomplete energy conversion in the pools and must be looked up in the specialized literature (HENSEN & SCHIEMENZ, 1960).

Example of calculation for a conventional pool pass

Calculations are to be made for a conventional pool pass at a dam. The water level differences between headwater and tailwater fluctuate between $h_{tot} = 1.6$ m and $h_{tot} = 1.2$ m for the discharges that have to be used as basis for the design, cf. Figure 5.10. The river is classified as potamon, with the typical potamonic ichthyofauna (chub, bream, etc.). Large salmonids such as sea trout or salmon are not anticipated.

The pool dimensions are selected from Table 5.1 as follows:

Pool width $b = 1.4$ m

minimum water depth $h = 0.6$ m.

The surface of the pool bottoms is roughened using river boulders as shown in Figure 5.9.

The cross-walls are to have only bottom orifices, with a clear orifice span of $b_s = h_s = 0.3$ m, cf. Figure 5.9. Top notches are not planned for.

The maximum water level difference must not exceed $\Delta h_{max} = 0.2$ m so that, according to Equation (5.2), the number of pools needed is

$$n = \frac{h_{tot}}{\Delta h} - 1 = \frac{1.6}{0.2} - 1 = 7 \text{ pools.}$$

With higher tailwater levels, the water-level difference falls to

$$\Delta h_{min} = \frac{1.2}{8} = 0.15 \text{ m.}$$

According to Equation (5.3), the flow velocity in the orifices is calculated for a $\Delta h = 0.2$ m (low water conditions) as

$$v_s = \sqrt{19.62 \cdot 0.2} = 1.98 \text{ m/s}$$

and for $\Delta h = 0.15$ m

$$v_s = \sqrt{19.62 \cdot 0.15} = 1.71 \text{ m/s;}$$

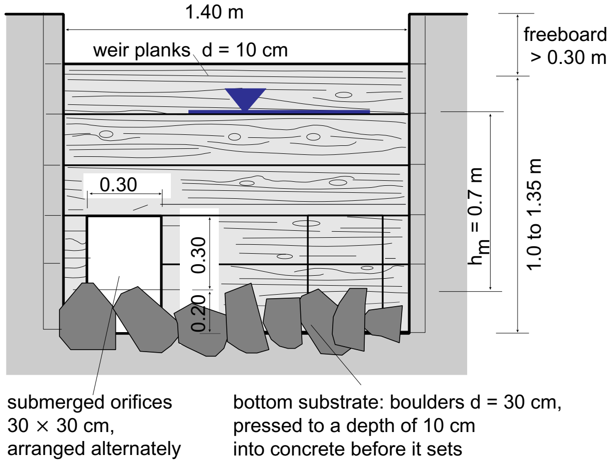


Figure 5.9: Cross-section through the pools

the flow velocity is thus always lower than the permissible maximum of v_{max} = 2.0 m/s.

According to Equation (5.4), with an assumed coefficient ψ = 0.75, the discharges amount to

$$Q_{s.max} = \psi\, A_s \sqrt{2g\Delta h} = 0.75 \cdot 0.3^2 \cdot 1.98$$
$$= 0.134\ m^3/s$$

at low-water, and drop at higher tailwater levels to

$$Q_{s,\,min} = 0.75 \cdot 0.3^2 \cdot 1.71 = 0.115\ m^3/s.$$

Following from Equation (5.7) where E = 150 W/m^3 at a minimal mean water depth of

$$h_m = h + \Delta h/2 = 0.6 + 0.2/2 = 0.7\ m$$

and a plank thickness of d = 0.1 m, a pool length of

$$(l_b - d) = \frac{\rho g \Delta h Q}{E b h_m} = \frac{9.81 \cdot 1000 \cdot 0.134 \cdot 0.20}{150 \cdot 1.40 \cdot 0.7}$$

$$\rightarrow \quad l_b = 1.89 \approx 1.90\ m$$

is required in order to create low-turbulence flow through the pool. The longitudinal section is shown in Figure 5.10. At a water depth of 1.0 m, a bottom substrate layer of 20 cm and Δh = 0.15 m, the height of the downstream cross-wall is

$$h_w = 1.0 + 0.20 + 0.15 = 1.35\ m$$

and the height of the upstream wall

$$h_w = 0.8 + 0.20 = 1.0\ m.$$

The height of the intermediate cross-walls is stepped down by 5 cm each.

5.1.4 Overall assessment

Pool passes are among the oldest types of fish passes and they have certainly proved their worth wherever the design, layout and maintenance was appropriate. Pool passes are suitable for maintaining the possibility of migration at dams for both strongly swimming fish, and for bottom-oriented and small fish. In pool passes a continuous rough bottom can be constructed whose spaces offer opportunities for ascent to the benthic fauna.

The relatively low water requirements of between 0.05 and 0.5 m^3/s for normal orifice dimensions and differences in water level are an advantage.

On the other hand, the high maintenance requirements of pool passes are disadvantageous, as there is a high risk of the orifices being obstructed by debris. Experience has shown that many pool passes are not functional during most of the time simply because the orifices are clogged by debris. Pool passes, therefore, require regular, maintenance and cleaning, at least at weekly intervals.

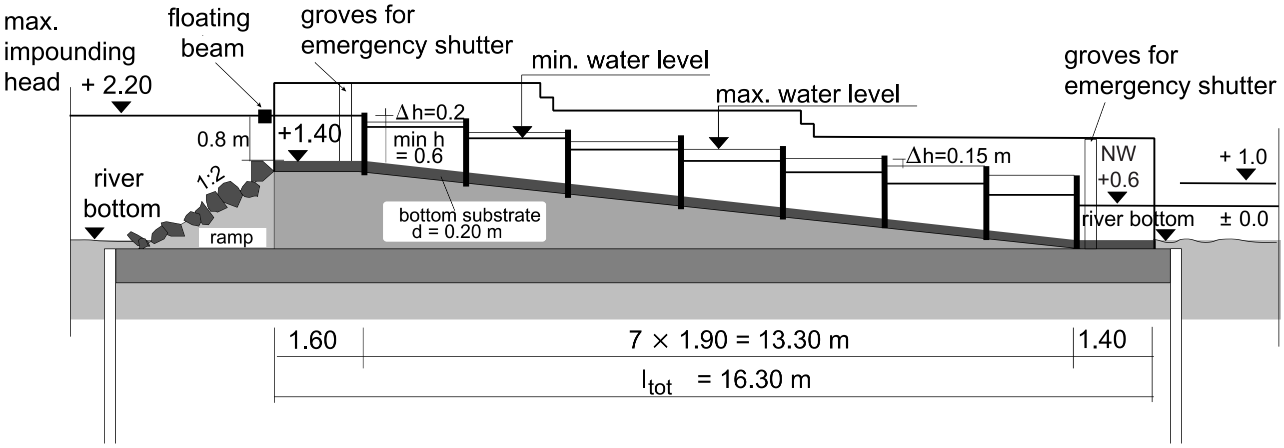


Figure 5.10: Longitudinal section through pool pass (sketch accompanying example of calculation)

5.1.5 Examples

POOL PASS AT KOBLENZ

Details of the dam		Details of the fish pass	
River:	Moselle, Rhineland-Palatinate	Pool width:	b = 1.80 m
Use:	Water power generation, navigation (shipping)	Pool length:	$l_b \approx 2.60$ m
		Number of pools:	n = 24
Flows:	$NQ_{1971/80} = 20\ m^3/s$	Water depth:	h = 1.0 m
	$MQ_{1931/90} = 313\ m^3/s$	Total length:	$l_{tot} = 102$ m
	$HQ_{1993} = 4165\ m^3/s$	Slope:	$I \approx 1 : 12$
Fall head:	$h_F = 5.30$ m	Cross-walls:	Concrete walls with top notches and bottom orifices 30 × 30 cm
Year of construction:	1945-54		
Responsible:	Federal Waterway Authorities/ Moselle Hydroelectric Company		

Figure 5.11: The Coblenz/Moselle fish pass (view from tailwater)

The fish pass of this dam, that entered into operation in 1951, is situated at the side of the power station on the right bank of the Moselle. The functioning of the pass has been checked by GENNERICH (1957), PELZ (1985) and others. Although a large number of fish were able to negotiate the pass, many more were caught in the immediate vicinity of the turbine outlets, apparently because they were unable to find the entrance to the pass. Tests showed that the distance of about 45 m between the fish pass entrance and the turbine outlets, which is due to the great length of ca. 102 m of the pass, is to be blamed.

POOL PASS AT DAHL

Details of the dam		Details of the fish pass	
River:	Lippe, at kilometer 99.0, NRW	Width:	b = 1.0 m
Flows:	MNQ = 12.3 m^3/s	Total length:	l_{tot} = 46.0 m
	MQ = 32.3 m^3/s	Slope:	I = 1 : 11 to 1 : 24
	MHQ = 179 m^3/s	Construction	
Type:	Block stone ramp	characteristics:	Prefabricated concrete parts with bottom orifices and top notches
Height of step	h_{tot} = 2.6 m		
Responsible:	Lippeverband, Dortmund		
		Year of construction:	1985

Description of construction:

The bottom sill has been changed to a rough block stone ramp with berms at the headwater and tailwater ends. The pass was integrated into the ramp that was constructed along the undercut left bank; prefabricated concrete parts with grooves, into which the cross-walls were inserted, were used to construct the pool pass. The cross-walls have alternating bottom orifices of 25 × 25 cm and top notches.

Data on functioning

Monitoring and fish counts by RUPPERT & SPÄH (1992) proved that fish can negotiate the pass. However, ascent by benthic invertebrates is hardly possible because of the smooth concrete bottom.

Fig. 5.12: Dahl pool pass (shortly before going into operation)

Fig. 5.13: Dahl pool pass in operation (view from tailwater)

5.2 Slot passes

5.2.1 Principle

The slot pass, or vertical slot pass, was developed in North America and has been widely used there since the middle of the twentieth century (CLAY, 1961; BELL, 1973; RAJARATNAM *et al.*, 1986). This type of structure has also been used increasingly in the Federal Republic of Germany over the last few years.

The slot pass is a variation of the pool pass whereby the cross-walls are notched by vertical slots extending over the entire height of the cross-wall; see Figure 5.14. The cross-walls may have one or two slots depending on the size of the watercourse and the discharge available. In the one-slot design, the slots are always on the same side (in contrast to the conventional pool pass where the orifices are arranged on alternate sides).

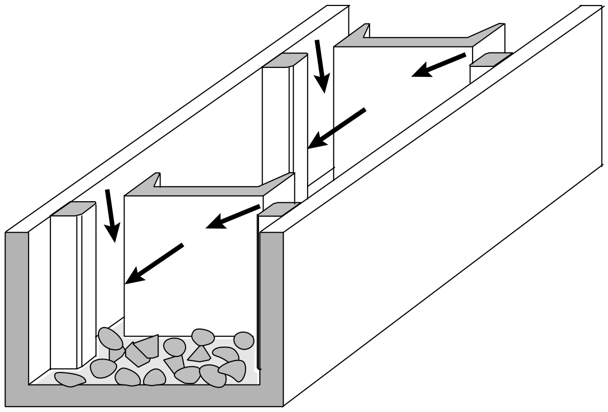


Fig. 5.14: Example of a slot pass with two slots (diagrammatic)

5.2.2 Design and dimensions

5.2.2.1 Plan view

The same principles as those outlined for conventional pool passes apply to the correct positioning of a slot pass and the location of its entrance at a dam, cf. section 5.1.

5.2.2.2 Longitudinal section

The longitudinal section of a slot pass corresponds to that of a conventional pool pass as described in section 5.1; see also Figures 5.18 and 5.23.

The characteristics for bottom height at the fish pass entrance and exit, and the water depth, outlined in section 5.2.3 should be observed.

5.2.2.3 Pool dimensions

In particular, slot width and the number of slots (one or two), and the resulting discharge, determine the pool dimensions required. As with pool passes, it is only possible to attain low-turbulence flow in the pools if the pool size guarantees a volumetric power dissipation of $E < 200\ W/m^3$ (LARINIER, 1992a). The pool dimensions given in Table 5.2 have been shown to be suitable both in laboratory tests and in practical experiments (KATOPODIS, 1990; GEBLER, 1991; LARINIER, 1992a). Readers are referred to Figure 5.16 for the relevant terminology. The dimensions quoted refer to slot passes with one slot. Where two slots are planned, the width of the pool should be doubled accordingly, thereby making the sidewall opposite the slot the axis of symmetry.

Figure 5.15:
Slot pass at the Bergerac weir on the Dordogne (France)

($h_{tot} = 4.0$ m, $b = 6.0$ m, $l_b = 4.5$ m, $l_{tot} = 73$ m, $Q = 2.2$ to $7\ m^3/s$, additional 0 to $6\ m^3/s$ through a bypass channel, year of construction 1984).

This type of construction has proven excellent both for large salmonids and the economically significant allis shad *(Alosa alosa)* as well as for cyprinids.

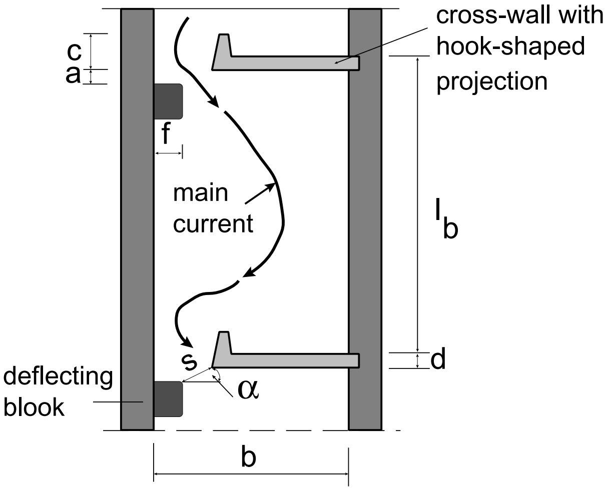


Fig. 5.16: Dimensions and terminology for slot passes with one slot only (plan view)

According to GEBLER (1991), the minimum dimensions for slot passes with slot widths of s = 0.15 to 0.17 m should be l_b = 1.9 m and b = 1.2 m.

5.2.2.4 Structural characteristics

The most important characteristic of a slot pass is its slot width (s), which has to be chosen on the basis of the fish fauna present and the discharge available; see Table 5.2. For brown trout, grayling, cyprinids and small fish, slot widths of s = 0.15 to 0.17 m are sufficient. Where large salmonids are to be accommodated (for example salmon, sea trout, and huchen), and in larger rivers with correspondingly high discharges, larger slot widths of s = 0.3 m to 0.6 m are recommended with correspondingly bigger pool dimensions in accordance with Table 5.2. However, in individual cases, slot widths of s = 0.20 m might also suffice, if the necessary high discharges were not available for example. The possible effects on the flow regime in the pools must be considered if the slot widths are modified compared to those shown in Table 5.2.

The shape of the cross-walls must be such that no short-circuit current, that would pass through the pools in a straight line from slot to slot, is formed but rather a main current is created that curls back on itself so as to utilise the entire pool volume for low-turbulence energy conversion. Such current regimes are encouraged by incorporating a hook-shaped projection into the cross-walls that has the effect of deflecting the flow in the area in front of the slot aperture. The slot boundary on the wall side consists of a staggered deflecting block. The distance “a” (see Fig. 5.16) by which the deflecting block is staggered compared to the cross-wall creates a slot current that is deflected by the angle α to direct the main current towards the centre of the pool. According to GEBLER (1991), the distance “a” should, be chosen in such a way that the resulting angle is at least 20° in smaller fish passes. In passes with larger slot widths, larger angles of between α = 30° to 45° are recommended (LARINIER, 1992a, RAJARATNAM, 1986).

Table 5.2 shows the recommended values for the design of cross-walls. The relevant terminology can be found in Figure 5.16.

It has been proved from models and field tests that the current regime required in the pools cannot be

Table 5.2: Minimum dimensions for slot passes with one slot only (dimensions in m) (According to GEBLER, 1991, and LARINIER, 1992a)

Fish fauna to be considered		Grayling, bream, chub, others		Sturgeon
		Brown trout	Salmon, sea trout, huchen	
Slot width	s	0.15 – 0.17	0.30	0.60
Pool width	b	1.20	1.80	3.00
Pool length	l_b	1.90	2.75 – 3.00	5.00
Length of projection	c	0.16	0.18	0.40
Stagger distance	a	0.06 – 0.10	0.14	0.30
Width of deflecting block	f	0.16	0.40	0.84
Water level difference	h	0.20	0.20	0.20
Min. depth of water	h_{min}	0.50	0.75	1.30
Required discharge[1]	Q in m^3/s	0.14 – 0.16	0.41	1.40

[1] calculated for Δh = 0.20 m and h_{min}

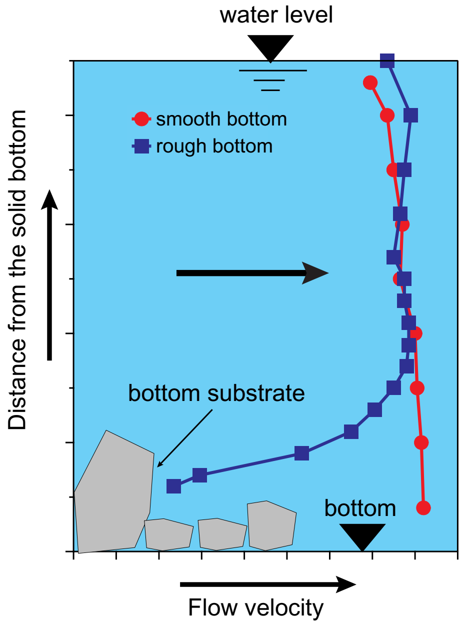


Fig. 5.17: Flow velocity distribution in the slot, comparison between smooth and rough bottom (after GEBLER, 1991).

guaranteed if the recommended values are not respected.

Prefabricated concrete components or wood are appropriate building materials for the cross-walls. As a constructional requirement with wooden cross-walls, frames or steel carriers set in the concrete bottom are needed as abutments. The deflecting block can easily be set in the form of a piece of squared timber, standing on its edge and fastened to the wall. Depending on the construction method chosen, the cross-walls may be installed either as true verticals or perpendicular to the bottom.

The cross-walls should be sufficiently high so that at mean discharge the water does not flow over them.

5.2.2.5 Bottom substrate

The slot pass makes it possible to create a continuous bottom substrate throughout the whole fish ladder. The material used for the bottom must have a mean grain diameter of at least d_{50} = 60 mm. Where possible the material should be the same as the natural bottom substrate of the watercourse. The minimum thickness of the bottom layer is about 0.2 m. It is advisable to embed several large stones, that form a support structure, into the bottom concrete before the concrete sets whereas the finer substrate can then be loosely added.

In addition to facilitating ascent for benthic fauna as described earlier, the bottom substrate considerably reduces flow velocities near the bottom and in the slots. Figure 5.17 shows that the considerable reduction in flow velocities can be largely attributed to the effect of the bigger stones. These protected areas make it possible for species with low swimming performance, such as loach, gudgeon or bullhead, to migrate upwards through the pass.

It is important to ensure that the bottom substrate of the fish pass is connected to the bottom substrate of the watercourse. If the bottom of the fish pass is higher than the river bottom, it should be connected to the river bottom by rock fill.

5.2.3 Hydraulic calculation

The following should be monitored under all operating conditions:

- water depths;
- flow velocities in the slot (critical values);
- discharges and
- power density for the volumetric power dissipation in the pools.

The water depths directly below a cross-wall as determined from the average level of the bottom substrate, should be large enough to prevent flushing discharge in the slot. This can be guaranteed by the following conditions:

$$h_u > h_{gr} \quad \text{or} \qquad (5.8)$$

$$v_{max} > v_{gr} \qquad (5.8a)$$

where $$h_{gr} = \sqrt[3]{\frac{Q^2}{g s^2}} \qquad (5.8b)$$

$$v_{max} = \sqrt{2g\Delta h} \qquad (5.8c)$$

$$v_{gr} = \sqrt{g h_{gr}} \qquad (5.8d)$$

The minimum water depth (measured directly below the slots) at Δh = 0.20 m, is approximately $h_u = h_{min}$ = 0.5 m. The following procedure is suggested to guarantee this depth under all operating conditions (cf. Figure 5.18):

- The lowest headwater level is the decisive factor in determining the bottom level at the water intake (fish pass outlet#). The surface of the substrate before the first pool (coming from

remark by the editor

upstream) is at a level that is determined by the headwater level minus (h_{min} + Δh).

- The low-water level (NW), that is the lowest level for most of the year (except for maybe a few days), determines the tailwater level. The level of the surface of the bottom substrate of the last pool downstream (water outlet/fish pass entrance) should be set to NW – h_{min}.

At these headwater and tailwater levels the water depth is the same in all pools and the water level differences between two successive pools are the same throughout the pass. This assumption is the worst-case scenario for those impoundments where the maximum headwater level is constant. The number "n" of pools required is found from the equation

$$n = \frac{h_{tot}}{\Delta h} - 1 \quad (5.2)$$

where again Δh ≤ 0.20 m should be used as the threshold value for the difference in water level.

The maximum flow velocity v_{max} occurs in the slots and is related to the maximum difference in water level Δh by

$$v_s = \sqrt{2g\Delta h}. \quad (5.3)$$

Discharges in slot passes are determined by the hydraulic conditions in the slots and can be estimated using the equation (5.9):

$$Q = \frac{2}{3}\,\mu_r\, s\,\sqrt{2g}\; h_o^{3/2} \quad (5.9)$$

where $\mu_r = f\,(h_u/h_o)$ as shown in Fig. 5.22.

The coefficient μ_r was established from test results from laboratory trials (RAJARATNAM, 1986 and GEBLER, 1991) and field measurements (KRÜGER 1993). The coefficient can be determined from

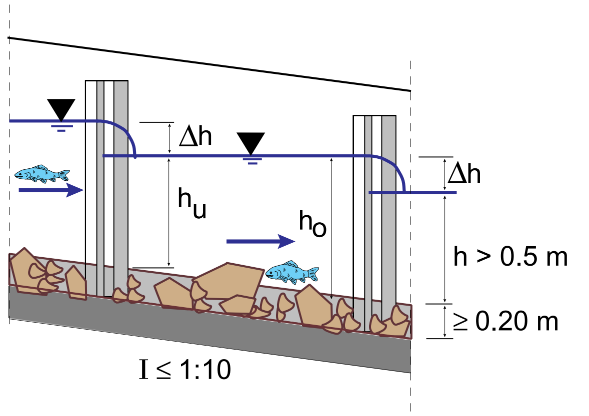


Fig. 5.19: Detail of slot pass (schematic longitudinal section)

Figure 5.22. Here the values cover a range from s = 0.12 to 0.30 m, h_u = 0.35 to 3.0 m and Δh = 0.01 to 0.30 m. If larger slot dimensions are to be used, trials with scale models are recommended.

Equation 5.9 has been used to construct Figure 5.21 for slot widths s = 17 cm and for Δh = 0.20 m and Δh = 0.15 m. Therefore the discharge can be directly read off for these cases.

Discharge calculations are more complex if different headwater and tailwater levels are being considered, for example, if the lower pools have a greater water depth due to specific tailwater conditions (e.g. backwater influences from below) or if there are different headwater levels (e.g. on fixed weirs or dams). Very different water depths then occur at the cross-walls, leading to varying differences in water level, comparable with a dam filling or draw-down line. Discharge calculation can then only be attempted by iteration through the following procedure: First, the discharge must be estimated by assuming a mean water level difference at the most upstream (first) cross-wall.

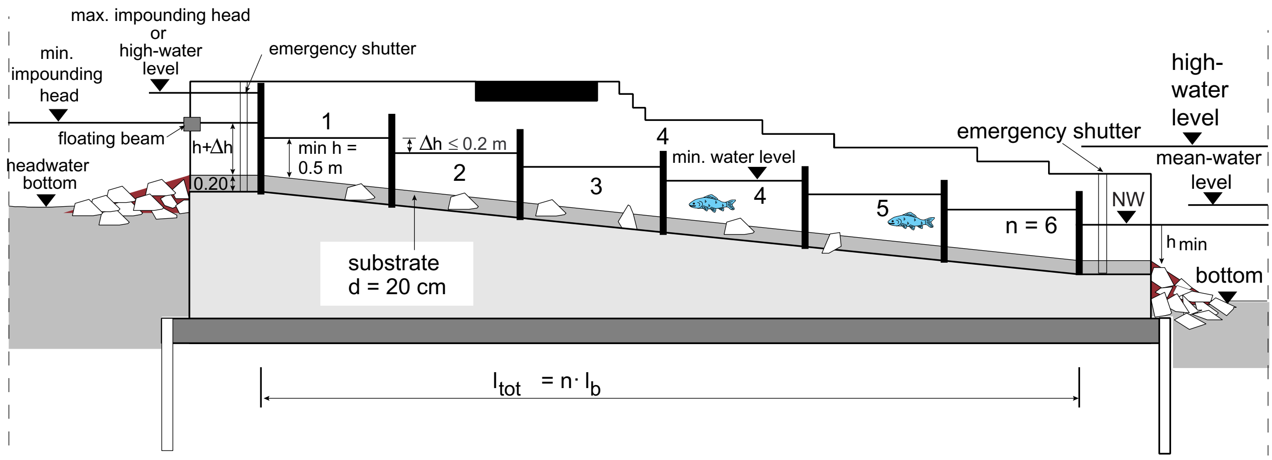


Figure 5.18: Longitudinal section through a slot pass (schematic)

Figure 5.20: Slot current in a slot pass

The current must emerge diagonally from the slot to prevent short-circuit current in the pool (lower Puhlstrom dam/Unterspreewald).

Using this estimated discharge, the headwater depth h_o can be found step-by-step for each cross-wall, starting the calculation from the last, downstream cross-wall. This calculation can also only be solved by iteration, as μ_r is a function of h_u/h_o. If the estimated value for the discharge was correct, the calculated value h_o at the first (upper) cross-wall must correspond to the headwater level. If this is not so, the calculation must be repeated using a different estimated discharge.

In order to guarantee low-turbulence current in the pools, the power density for the volumetric power dissipation in the pools should not exceed the threshold value of E = 200 W/m^3 given by LARINIER (1992a). The volumetric power dissipation is given by the formula:

$$E \approx \frac{\rho g \Delta h Q}{b h_m (l_b - d)} \qquad (5.7)$$

Example of calculation for a slot pass:

A weir is to be fitted with a slot pass. The headwater level varies between 61.95 m (summer headwater level) and 62.10 m (winter headwater level). The relevant tailwater low-water level is 60.60 m with the bottom of the watercourse being at 60.00 m; the downstream fish pass bottom should lie at the same level as the bottom of the river. There is no need to consider large salmonids when planning the fish pass.

The discharge, flow velocity and turbulence conditions in the pass should be determined for the minimum and maximum headwater level.

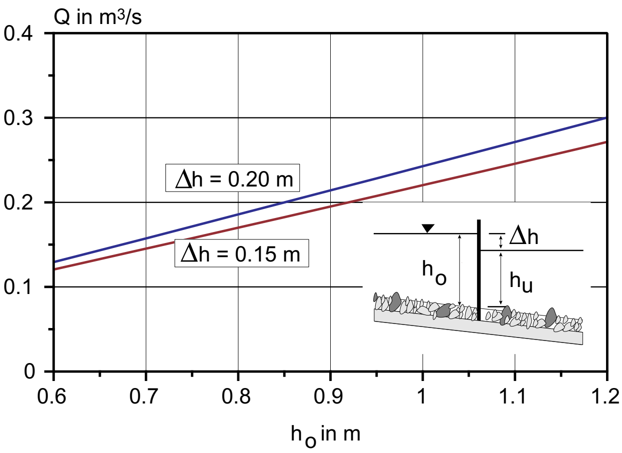


Fig. 5.21: Water discharge in the slot pass with a slot width of s = 17 cm

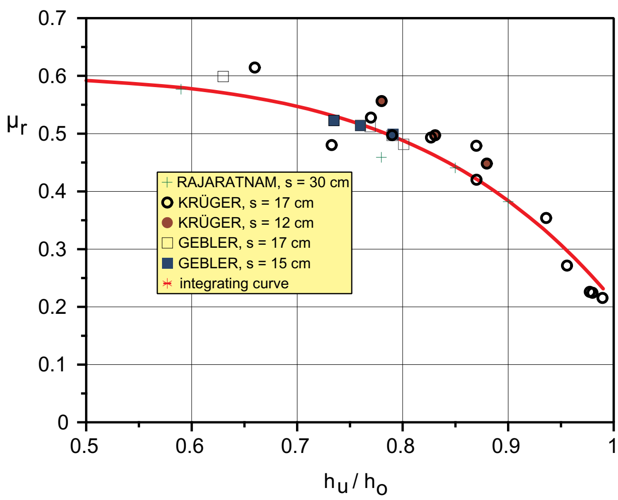


Fig. 5.22: Discharge coefficient $\mu_r = f(h_u/h_o)$ in Equation (5.9) for sharp-edged slot boundaries.

The dimensions are selected as follows in accordance with Table 5.2:

- slot width: $s = 0.17$ m;
- pool length: $l_b = 1.90$ m;
- pool width: $b = 1.40$ m.

Figure 5.24 shows one proposal for the design of the installations (i.e. cross-walls).

With the maximum difference between headwater and tailwater being $h_{tot} = 62.1 - 60.6 = 1.50$ m and a permissible water level difference of $\Delta h = 0.2$ m (Table 5.2), the number of pools to be constructed is calculated from equation (5.2):

$$n = \frac{h_{tot}}{\Delta h} - 1 = \frac{1.5}{0.2} - 1 = 6.5 \approx 7 \text{ pools.}$$

However, further calculation shows that at least 8 pools, i.e. nine cross-walls, are required so as not to exceed the permissible water level difference at high headwater level (winter level).

Therefore, the overall length of the pass, including an anterior and a posterior chamber (each of length 1.0 m), is:

$$l_{tot} = 8 \cdot 1.90 + 2 \cdot 1.0 = 17.20 \text{ m.}$$

The pools contain a 0.2 m thick bottom substrate layer. The minimum water depth is chosen as $h = 0.60$ m in the fish pass to achieve the same flow regimes in all pools at lower headwater levels, while the total difference between headwater and tailwater is apportioned equally to all cross-walls. From

$$\min h_{tot} = 61.95 - 60.6 = 1.35 \text{ m}$$

$$\text{and } \Delta h = 1.35/9 = 0.15 \text{ m}$$

the level of the water inlet (fish pass exit) on the headwater side, related to the upper edge of the substrate, becomes:

$$z_{e,substrate} = 61.95 - (0.6 + 0.15) = 61.2 \text{ m}$$

and the level of the solid fish pass bottom in the headwater inlet (fish pass exit) becomes:

$$z_{e,bottom} = 61.2 - 0.2 = 61.0 \text{ m.}$$

At low headwater levels, the same water level differences and water depths occur at each cross-wall. The maximum flow velocity in the slots is then

$$v_s = \sqrt{2g\Delta h} = \sqrt{19.62 \cdot 0.15} = 1.72 \text{ m/s}$$

$$< \text{permissible } v_s = 2.0 \text{ m/s.}$$

From Fig. 5.21 the approximate value $Q = 0.16$ m^3/s can be read off for $h_o = 0.75$ m and $\Delta h = 0.15$ m and is confirmed by the detailed calculation:

$$h_o = 0.75 \text{ m}, \; h_u = 0.6 \text{ m},$$

$$h_u/h_o = 0.6/0.75 = 0.80$$

Figure 5.22 gives $\mu_r = 0.49$

$$Q = \frac{2}{3}\, \mu_r\, s \sqrt{2g}\, h_o^{3/2}$$

$$= \frac{2}{3}\, 0.49 \cdot 0.17 \sqrt{19.62} \cdot 0.75^{3/2} = 0.16 \text{ m}^3\text{/s.}$$

Calculating the volumetric dissipated power tests the turbulence conditions in the pools. As the calculation shows, the threshold value of $E = 200$ W/m^3 is not exceeded with $h_m = h_u + \Delta h/2 = 0.6 + 0.15/2 = 0.675$ and

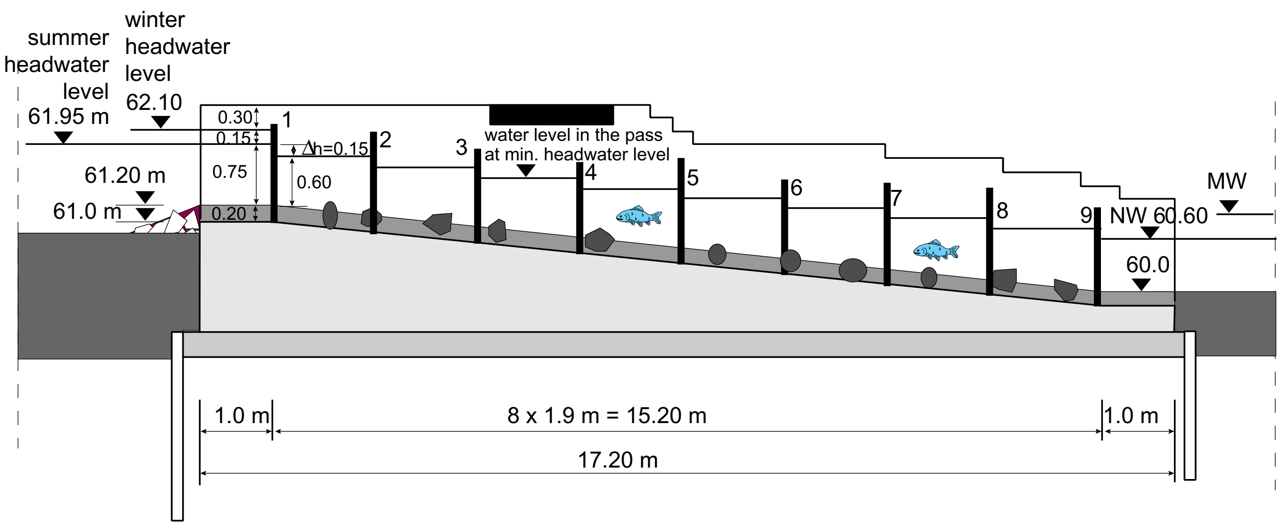


Figure 5.23: Sketch accompanying the example of calculation (longitudinal section through the slot pass)

Table 5.3: Water levels and flow velocities at high headwater level

Cross-wall no.	1	2	3	4	5	6	7	8	9
Elevation of the bottom above sea level	61.20	61.05	60.90	60.75	60.60	60.45	60.30	60.15	60.00
h_u in m	0.75	0.75	0.75	0.75	0.73	0.72	0.70	0.66	0.60
h_o in m	0.90	0.90	0.90	0.90	0.89	0.88	0.87	0.85	0.81
Δh in m	0.15	0.15	0.15	0.16	0.16	0.16	0.17	0.19	0.21
v_s in m/s	1.72	1.72	1.72	1.77	1.77	1.77	1.83	1.93	**2.03 critical !!**

Water level in pool	HW = 62.10	61.95	61.80	61.65	61.49	61.33	61.17	61.00	60.81	TW = 60.60

$$E_{vorh} = \frac{\rho g \Delta h Q}{b h_m (l_b - d)}$$

$$= \frac{1000 \cdot 9.81 \cdot 0.160 \cdot 0.15}{1.40 \cdot 0.675 \cdot (1.90 \cdot 0.7)} = 138 \text{ W/m}^3.$$

The flow calculation must be done by iteration at high headwater level according to the algorithm given:

The test calculation shows that for high headwater levels there will be a $\Delta h_1 = 0.15$ m at the first cross-wall, hence with

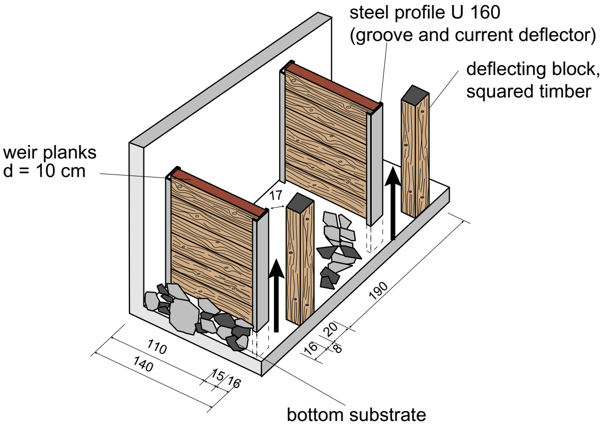


Fig. 5.24: Proposed design for cross-walls of a slot pass.

The weir planks are held on both sides in U-profiles whilst the central steel profile simultaneously assumes the function of the hooked projection for diverting the current. The width of the central steel profile should therefore be greater (b = 16 cm) (according to KRÜGER *et al*, 1994b).

$h_{o,1} = 0.90$ m and $h_{u,1} = 0.75$ m

$h_{u,1}/h_{o,1} = 0.75/0.9 = 0.833$ giving $\mu_r = 0.46$

a discharge of

$$Q = \frac{2}{3}\, 0.46 \cdot 0.17 \sqrt{19.62} \cdot 0.9^{3/2} = 0.197 \text{ m}^3/\text{s}$$

can be calculated. Because the discharge is dependent on h_o and the coefficient μ_r is dependent on h_u/h_o, no explicit solution is possible and the water levels corresponding to this discharge in the pools can only be found by iteration. To this end, Δh is estimated at each cross-wall thereby defining μ_r; then Equation 5.9 is used to calculate the headwater depth h_o for the discharge Q. The result of the iteration is shown in Table 5.3.

The turbulence conditions are only determined for the most downstream pool since this is where the highest water level difference occurs. With $h_m = (0.81 + 0.66)/2 = 0.735$, the volumetric power dissipation in the eighth pool is

$$E_{vorh} = \frac{\rho g Q \Delta h_8}{b h_m (l_b - d)} = \frac{1000 \cdot 9.81 \cdot 0.197 \cdot 0.19}{1.40 \cdot 0.735 \cdot (1.90 - 0.1)}$$

$$= 198 \text{ W/m}^3 < E_{permissible} = 200 \text{ W/m}^3$$

which is just less than the permissible $E = 200$ W/m^3.

The calculation shows that for high headwater levels there are already critical flow velocities of $v \approx 2$ m/s at the lower cross-wall, which is the reason for inserting eight, rather than seven, pools. Were there only seven pools there would be a maximum flow velocity of $v_s = 2.17$ m/s at the lower cross-wall. This example shows that especially varying headwater levels demand careful testing of the hydraulic conditions in slot passes in order to avoid the risk of wrongly dimensioning the pass.

5.2.4 Overall assessment

Slot passes (vertical slot passes) are well suited to guarantee ascent by both fish species that are weak swimmers and small fishes.

Other advantages are:

- Vertical apertures that stretch over the whole height of the cross-walls are suited to the swimming behaviour of both bottom-living and open-water fish.
- Reduction in flow velocities near the bottom of the slots also allows low performance fish to ascend. A prerequisite for this is the installation of a bottom substrate with some larger perturbation boulders.
- Suitable for use even with varying headwater levels.
- Not sensitive to varying tailwater levels.
- Benthic invertebrate fauna can also migrate if the bottom substrate has continuous interstitial spaces.
- Because the orifices extend vertically over the total height of the cross-walls the slot pass is less susceptible to clogging than traditional fish pass designs. Partial clogging of the discharge cross-section does not cause complete loss of function.
- This type of construction is suitable both for use in small streams with low discharge and for use in larger rivers.
- Slot passes can cope with discharges from just over 100 l/s to several m^3/s.

In view of these advantages slot passes should be preferred to conventional pool passes. Present knowledge indicates that slot passes should be given preference over other technical fish passes.

5.2.5 Example

NEU LÜBBENAU SLOT PASS

Details of bottom step		Details of fish pass	
Watercourse:	Spree at km 165.3 Unterspreewald, Brandenburg	Dam height:	h_{tot} = 1.2 to 1.4 m
		Slot width:	s = 0.17 m
		Number of pools:	n = 9
Flows:	MQ = 5.5 m^3/s	Pool width:	b = 1.0 and 1.4 m
	MNQ = 1.5 m^3/s	Length of pool:	l_b = 1.6 to 1.9 m
Year of construction:	1992	Overall length:	l_{tot} = 19.2 m
Function:	Weir		

Design

The pool dimensions are generous with b = 1.4 m and l_b = 1.9 m except that the upper three pools are of reduced width (b = 1.0 m) for constructional reasons. Analogous to Figure 5.24, the cross-walls are made of 10 cm thick dam planks held on both sides in vertical steel carriers (U-profiles). The diversion blocks are squared timbers vertically dowel-jointed onto the sidewall.

The fish pass is situated between the weir and the ship lock, almost in the centre of the river, which is generally considered a disadvantage. The initial fears that the fish might have difficulties in finding the entrance to the pass have not been substantiated although the narrow width (15 m) of the Spree may be the true determining factor in avoiding failure. A location on the left bank of the Spree would certainly have been better. Unfortunately, also only a few large perturbation boulders have been set into the bottom of the pass and these cannot substitute for a continuous rough bottom substrate.

Fish counts have confirmed that fish pass functions well. The numbers of ascending fish were considerable, i.e. over 10 000 fish in both periods April/May 1993 and 1994, and with peaks of more than 1 800 fish/day (KRÜGER *et al.*, 1994b).

Figure 5.25:
Slot pass at the Spree dam at Neu Lübbenau/ Unterspreewald (view from tailwater)

5.3 Denil pass

5.3.1 Principle

Around the turn of the nineteenth century the Belgian engineer G. Denil developed a fish pass which was then named a “counter flow pass”, because of the way it worked, and today is called “Denil pass” after its inventor (DENIL, 1909).

The fish pass consists of a linear channel, in which baffles are arranged at regular and relatively short intervals, angled against the direction of flow (Figure 5.26). The backflows formed between these baffles dissipate considerable amounts of energy and, because of their interaction, allow a relatively low flow velocity in the lower part of the baffle cutouts (Figure 5.28). This allows the Denil pass to have a steep slope, relative to other types of fish passes, and to overcome small to medium height differences over relatively short distances.

The compact construction of the Denil pass and the possibility of prefabricating the pass in dry conditions and installing it once assembled makes this type of construction particularly suitable for retrofitting of existing dams, that do not have a fishway, and for use where there is not much space.

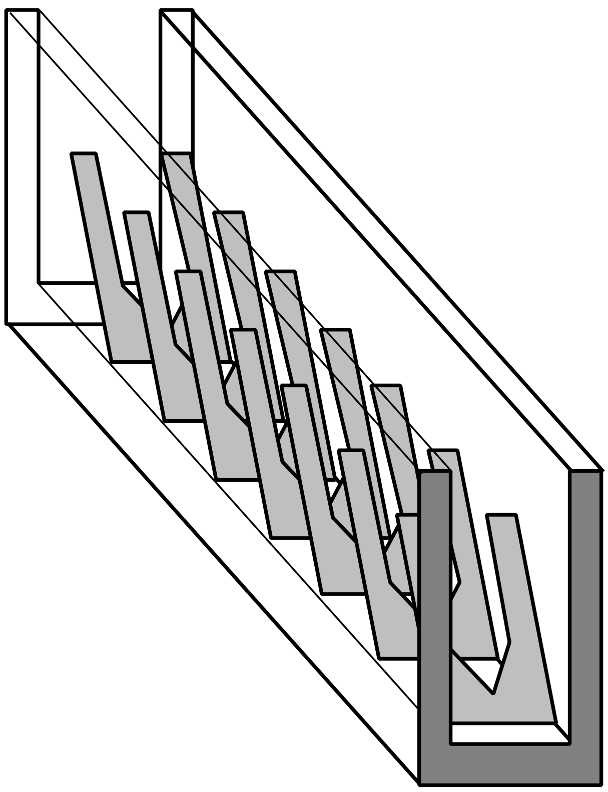


Fig. 5.26: Denil pass (schematic) (modified after LONNEBJERG, 1980)

The original fish passes designed by Denil had concave-shaped baffles. Starting from this prototype numerous variations were developed in subsequent years (see LARINIER 1992b for comparisons). Of these the so-called “standard Denil pass”, with U-shaped sections in the baffles as shown in Figure 5.27, proved to be the most functional. Today, Denil passes are almost exclusively of this standard type so that the description that follows can be restricted to the standard Denil pass.

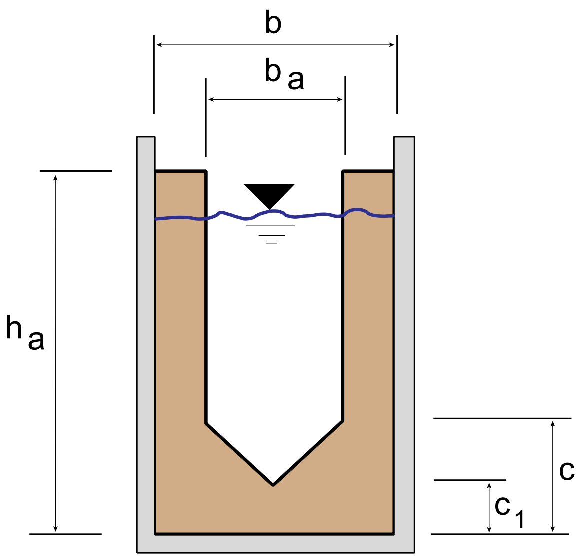


Fig. 5.27: Baffles in a Denil pass (standard Denil, terminology) (modified after LONNEBJERG, 1980).

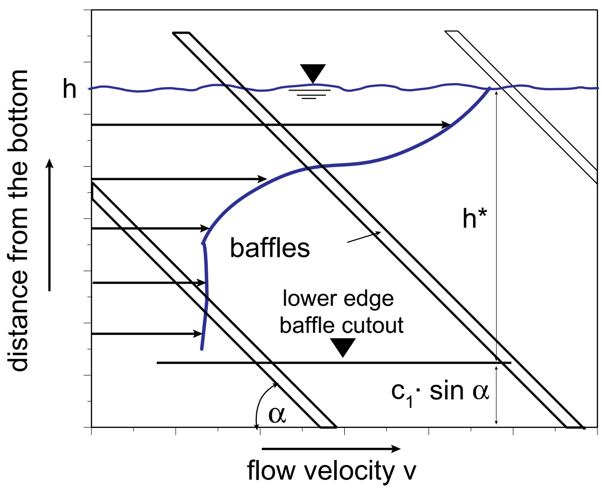


Fig. 5.28: Characteristic velocity distribution in a Denil pass (modified after KRÜGER, 1994a).

Figure 5.29:
Denil pass with intermediate resting pools. View from headwater, Gollmitzer mill/Strom at Prenzlau (Brandenburg)

Figure 5.30:
Denil pass made of wood Gifhorn/Ise (Lower Saxony)

5.3.2 Design and dimensions

5.3.2.1 Plan view

The channel is always straight in plan. Bends are not allowed as they have a negative influence on the current characteristics. Changes of direction can only be achieved by using intermediate pools.

Fish must ascend a Denil pass in one episode of continued swimming, since they cannot rest between the baffles. Too great a length of pass will, therefore, select for larger and stronger swimming species. As a result, the channel length must be chosen in accordance with the swimming performance of fish with low stamina. A resting pool (cf. Figure 5.29) must be built every 6-8 m for cyprinids or every 10-12 m for salmonids. The dimensions of such resting pools must be chosen in a way that the imported energy is transformed into low-turbulence flow, and that adequate resting zones are formed. A natural-looking design can be arranged for the resting pools, which can mimic small, natural, vegetated waterbodies. The volumetric power dissipation (power density for conversion of hydraulic energy) of the resting pools should be less than $E = 25\text{-}50\ W/m^3$.

The same principles apply to the positioning of the outlets of Denil passes as apply to pool passes.

5.3.2.2 Longitudinal section

The usual slopes for the channel are between $I = 1:5$ (20%) and 1:10 (10%). The width and permissible slope of the channel are interdependent if the hydraulic conditions that favour the ascent of fish are to be guaranteed. According to LARINIER (1983), the guideline values as shown in Table 5.4 can be recommended.

Table 5.4: Guide values for channel widths and slopes in Denil passes (LARINIER, 1983)

Fish fauna to be considered	Channel width b in m	Recommended slopes I as %	1 : n	Water discharge[1)] Q in m^3/s for $h^*/b_a = 1.5$
Brown trout, Cyprinds and others	0.6	20.0	1 : 5	0.26
	0.7	17.0	1 : 5.88	0.35
	0.8	15.0	1 : 6.67	0.46
	0.9	13.5	1 : 7.4	0.58
Salmon Sea trout and Huchen	0.8	20.0	1 : 5	0.53
	0.9	17.5	1 : 5.7	0.66
	1.0	16.0	1 : 6.25	0.82
	1.2	13.0	1 : 7.7	1.17

Note: [1]) Calculated according to Equation (5.10) with the recommended dimensions of the cross-walls according to Table 5.5

Table 5.5: Guide values for the design of baffles in a Denil pass depending on the selected channel width, after LONNEBJERG (1980) and LARINIER (1992b)

		Tolerance range	Recommended guide values
Baffle width	b_a/b	0.5 – 0.6	0.58
Baffle spacing	a/b	0.5 – 0.9	0.66
Distance between the lowest point of the cutout and the bottom	c_1/b	0.23 – 0.32	0.25
Depth of the triangular section	c_2/c_1	2	2

5.3.2.3 Channel

The channel of a Denil pass is either made of concrete or wood (Figure 5.30). Its clear width must be determined as a function of the discharge available and the fish species expected.

If large salmonids are included in the potential natural fish fauna the channel width should be between b = 0.8 m and 1.2 m. Channel widths of between b = 0.6 and 0.9 m are sufficient if only brown trout and cyprinids are expected. It is also possible to lay two or more channels next to one another in parallel if adequate discharge is available.

5.3.2.4 Cross-channel structures

The baffles are preferably made of wood and only in rare cases of metal. All edges should be well rounded to avoid injury to the fish as they ascend.

The baffles are inclined in upstream direction at an angle of $\alpha = 45^o$ compared to the channel bottom and have a U-shaped section that is triangular in its lower part. The dimensions b_a, c_1 and c_2 that define the baffle cutouts and the distance "a" between the baffles are dependent on the width of the channel and may only be varied within low tolerance ranges as they have a considerable effect on the current conditions. Denil passes are very sensitive to changes in these dimensions, making it advisable to stick to the prescribed geometry. The validity of the model calculations given in section 5.3.3 is absolutely restricted to the dimensions of the standard Denil pass described here. The values in Table 5.5 can be used as guidelines for designing baffles.

5.3.2.5 Water inlet[#] and water outlet[##] of the pass

The water flow should always reach the inlet (fish pass exit) from the direction that represents an upstream prolongation of the channel axis. Narrows and bends before the inlet have a negative effect on the flow conditions. There should be some

[#] i.e. fish pass exit (remark by the editor)
[##] i.e. fish pass entrance (remark by the editor)

means to close off the channel at the water inlet to make maintenance work on the channel easier.

The Denil channel must project sufficiently far into the tailwater that the outlet (fish pass entrance) is at least at the level of water in the channel even at low water. During higher tailwater levels, the backwater influence is displaced further into the channel, without having any great effect on the current patterns in the fish pass.

The water outlet of a Denil fish pass should, where possible, be connected to the bottom of the watercourse to help fish species that migrate along the bottom to better find the entrance into the pass. In shallow watercourses the bottom must be secured using gravel or rubble; this is, however, in fact usually anyhow required and done by constructing calming basins or secured downstream bottom zones.

5.3.3 Hydraulic calculations

Hydraulic calculations for Denil passes are only possible with the help of empirical approaches. Individual tests show that the correct range of validity of the results must be strictly observed and that extrapolation into other geometric or slope conditions is highly uncertain. Therefore, it is here again mentioned explicitly that the calculations below are only applicable to the standard Denil pass of given dimensions.

The water depth in the Denil pass is affected by the water level at the entrance and by entry losses. In practice, the diagram (Figure 5.32) given by LONNEBJERG (1980) is sufficiently precise. Here h_o refers to the level of the lower edge of the first baffle section (first baffle upstream) whilst h* describes the water depth perpendicular to the channel bottom, measured from the water surface down to the lower edge of the baffle sections, (cf. Figure 5.31). The value of h* should not be less than 0.35 m and should ensure that $h^*/b_a = 1.5$ to 1.8, for maximum discharge, since the velocity pattern according to Figure 5.28 is no longer guaranteed at greater water depths.

The flow characteristics in Denil passes have been investigated by LARINIER (1978), LONNEBJERG (1980), RAJARATNAM (1984) and KRÜGER (1994), to name but a few. The results again show the susceptibility of Denil passes to changes in geometry (cf. also KATOPODIS 1990). The discharge through a standard Denil pass which respects the recommended channel and baffle dimensions shown in Tables 5.4 and 5.5 can be calculated by using the KRÜGER's (1994) equation:

$$Q = 1.35\, b_a^{2.5} \sqrt{g\, I} \left(\frac{h^*}{b_a} \right)^{1.584} \qquad (5.10)$$

The discharge required for the Denil pass is shown in Table 5.4 as a function of channel width and slope.

Hydraulic model tests are recommended to find the optimum design where the geometric characteristics to be used differ from the standard Denil pass.

As already mentioned, resting pools must be built after every 6 to 8 m of channel length (after approximately 10 m for salmonids) where large height differences are to be overcome. The pool volume must be large enough to allow a low-turbulence dissipation of the imported flow energy. The chosen pool size should therefore be such that the following condition is fulfilled:

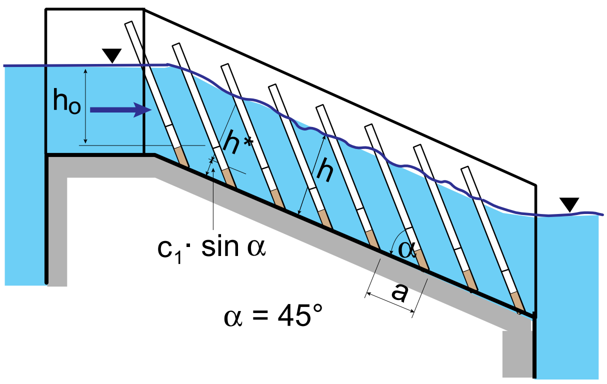


Fig. 5.31: Denil pass (longitudinal section, sketch illustrating the construction principle and terminology) (modified after LARINIER, 1992b).

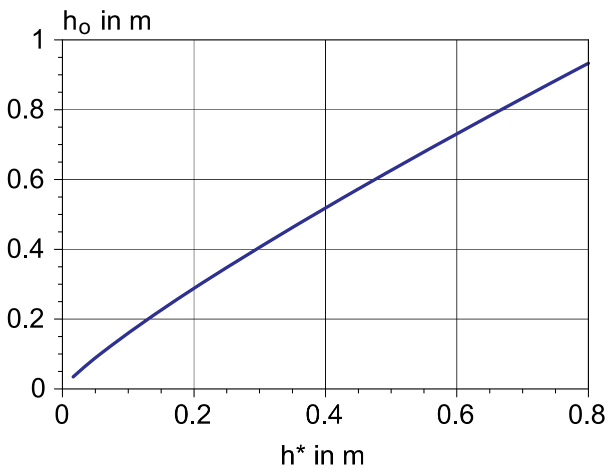


Fig. 5.32: Relation of $h^* = f(h_o)$ (modified after LONNEBJERG, 1980)

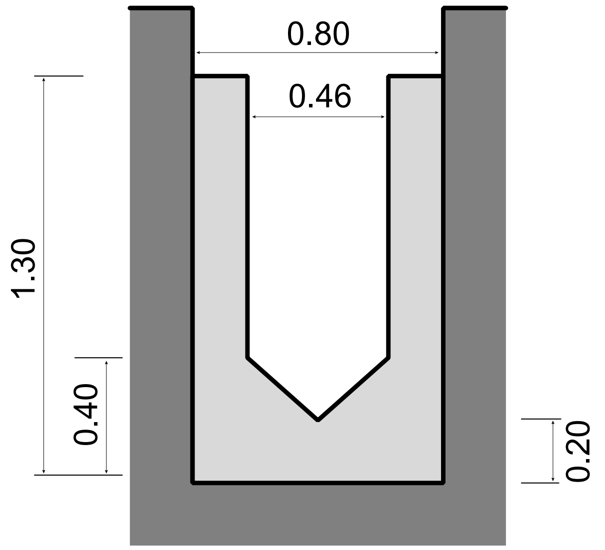


Fig. 5.33: Dimensions of the baffles

$$E = \frac{\frac{\rho}{2} Qv^2}{b_m h_m l_b} < 25 \text{ to } 50 \text{ W/m}^3 \qquad (5.11)$$

where b_m, h_m, l_b are the mean width, water depth and length of the resting pools and $v = Q/(h^* \cdot b_a)$.

It is difficult to prove the permissible flow speed in a Denil pass. The velocity distribution given in Figure 5.28 must be guaranteed by correct design of the baffles.

Example of calculation:

A dam with a maximum difference in water level of 3.0 m between headwater and tailwater is to be fitted with a Denil pass. The fish pass should be tailored to suit both cyprinids and the huchen. The headwater level can be held constant at + 63.0 m under all likely operating conditions. The lowest tailwater level is at + 60.0.

The channel width of b = 0.8 m is chosen from Table 5.4 and the slope of the channel is to be

$$I = 15\% = 1 : 6.66.$$

The baffle spacing (a) is obtained from:

$$a = 0.66 \cdot b = 0.66 \cdot 0.8 = 0.53 \text{ m}.$$

Two intermediate pools are required to overcome a height difference of 3 m, thus the total channel length is divided into three channels with a length of l = 6.75 m each (cf. Figure 5.34). The water depth in both intermediate pools should be about $h_m = 1.20$ m.

The dimensions of the baffles are chosen in accordance with Table 5.5 and are shown in Figure 5.33:

The value of h* is determined by

$$h^* = 1.5 \cdot b_a = 1.5 \cdot 0.46 = 0.7 \text{ m}.$$

Therefore, the height of the baffles is

$$h_a = 0.7/\sin 45° + 0.2 + 0.1 \text{ (freeboard)} = 1.29 \approx 1.3 \text{ m}.$$

Figure 5.32 gives the inflow water level

$$h_o = 0.83 \text{ m}$$

so the bottom height of the first baffle is calculated from

$$h_1 = h_0 + c_1 \cdot \sin(\alpha + \arctan I) \qquad (5.12)$$

$$h_1 = 0.83 + 0.2 \cdot \sin(45° + 8.53°) = 0.99 \approx 1.0 \text{ m}.$$

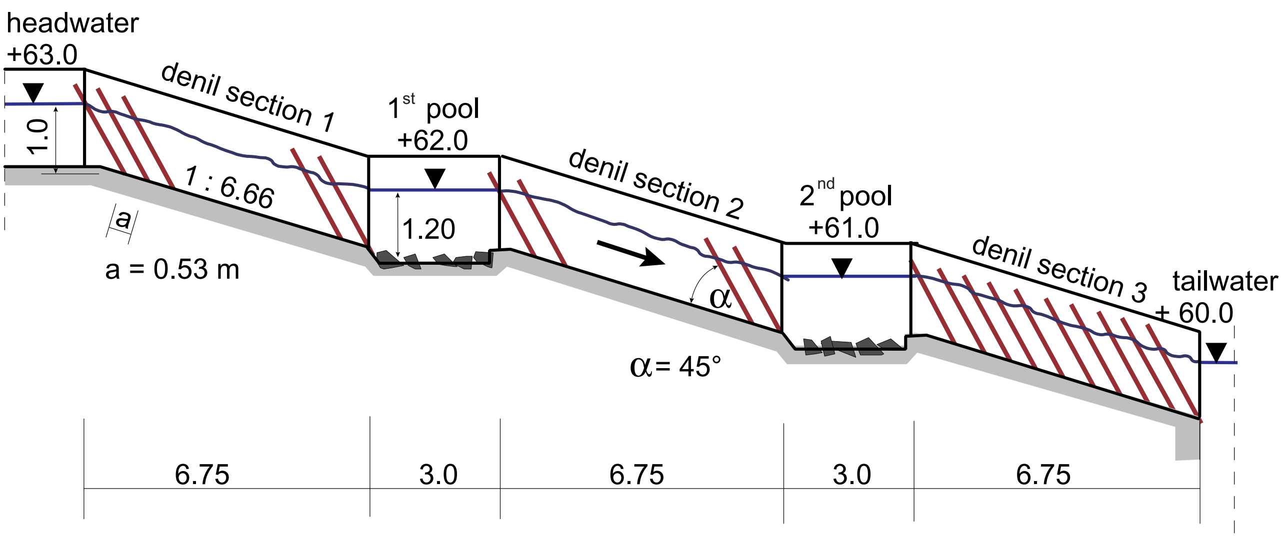


Figure 5.34: Longitudinal section of the fish pass

The discharge is calculated by using equation (5.10):

$$Q = 1.35\ b_a^{2.5}\sqrt{g\ I}\ \left(\frac{h^*}{b_a}\right)^{1.584}$$

$$= 1.35 \cdot 0.46^{\ 2.5}\sqrt{9.81 \cdot 0.15}\ \left(\frac{0.7}{0.46}\right)^{1.584}$$

$$Q = 0.457\ m^3/s.$$

The dimensions of the resting pools can be found using equation (5.11). With E = 35 W/m^3 and the flow velocity

$$v = Q/A \approx \frac{Q}{b_a \cdot h^*} = 1.42\ m/s$$

the necessary area "A_{nec}" of the resting pool is then:

$$A_{nec} = l_b \cdot b_m = \frac{\frac{\rho}{2}\ Qv^2}{h_m \cdot E} = \frac{\frac{1000}{2} \cdot 0.457 \cdot 1.42^2}{35 \cdot 1.20}$$

$$= 10.97\ m^2.$$

The pool width of b_m = 4.0 m and pool length of l_b = 3.0 m give a base area of 12.0 m^2. The diagram in Figure 5.34 shows a longitudinal section of the fish pass.

5.3.4 Overall assessment

The Denil pass is characterized by the following advantages:

- It can have steep slopes with resulting low space requirements;
- There is the possibility of prefabricating the channel elements;
- It can easily be used to retrofitted existing dams;
- It is not susceptible to variations in tailwater level;
- It usually forms a good attraction current in the tailwater.

The disadvantages of this type of construction are:

- High susceptibility to variations in the headwater levels. In practice, only variations of a few centimetres, with a maximum of about 20 cm, are permitted;
- Relatively high discharges needed compared to other construction types;
- Clogging with debris can easily upset its functioning. Denil passes require regular inspection and maintenance.

The success of Denil passes has been adequately proven, in particular for salmonids, and cyprinids such as the barbel, that have a lower swimming performance, by counting numbers of ascending fish. On the other hand, the monitoring that has been carried out to date shows that small fish and fish of low swimming performance have only a restricted possibility to pass through, especially when the length of the structure is too long. There is, therefore, a selection for larger, stronger swimming species and individuals.

Likewise, ascent by microorganisms and invertebrate benthic fauna must be rated impossible.

For these reasons Denil passes should only be used if other structures cannot be built, for example due to lack of space.

5.3.5 Example

UNKELMÜHLE DENIL PASS

Details of the dam		Details of fish pass	
Watercourse:	Sieg, NRW,	Width:	b = 0.64 and 0.74 m
Flows:	MNQ = 1.5 m^3/s	Length:	l = 6.60 and 9.50 m
	MQ = 22 m^3/s	Slope:	I = 1 : 4.5
	HHQ = 700 m^3/s	Fall Head:	h_F = 3.2 m
Use:	Water power	Discharge:	Q = 0.3 to 0.38 m^3/s
Year of construction:	1930	Responsible:	StAWA Bonn
Operator:	RWE-Energie AG		

Design

An existing traditional pool pass around the powerhouse of the hydropower station at Unkelmühle, that had been built in 1930, was replaced by a Denil pass under the control of the StAWA, Bonn, as the former fish pass was not functioning properly owing to the small dimensions of the pools and the slope being too steep. The new pass consists of two Denil channels connected by a resting pool, which was built as an impervious, reinforced concrete trough with stone rubble cladding and planted with aquatic vegetation. The upper channel is 6.60 m long and the lower 9.50 m and both have a slope of 1 : 4.5. The channels are made of reinforced concrete with wooden cladding to which the wooden baffles are fixed. The fish pass is fed by a discharge of 300 to 380 l/s.

Ascending fish can be observed through an under-water viewing window in the observation chamber at the edge of the resting pool. An installation that can accommodate a fish trap for monitoring purposes has been fitted to the water inlet of the upper channel (fish pass exit[#]).

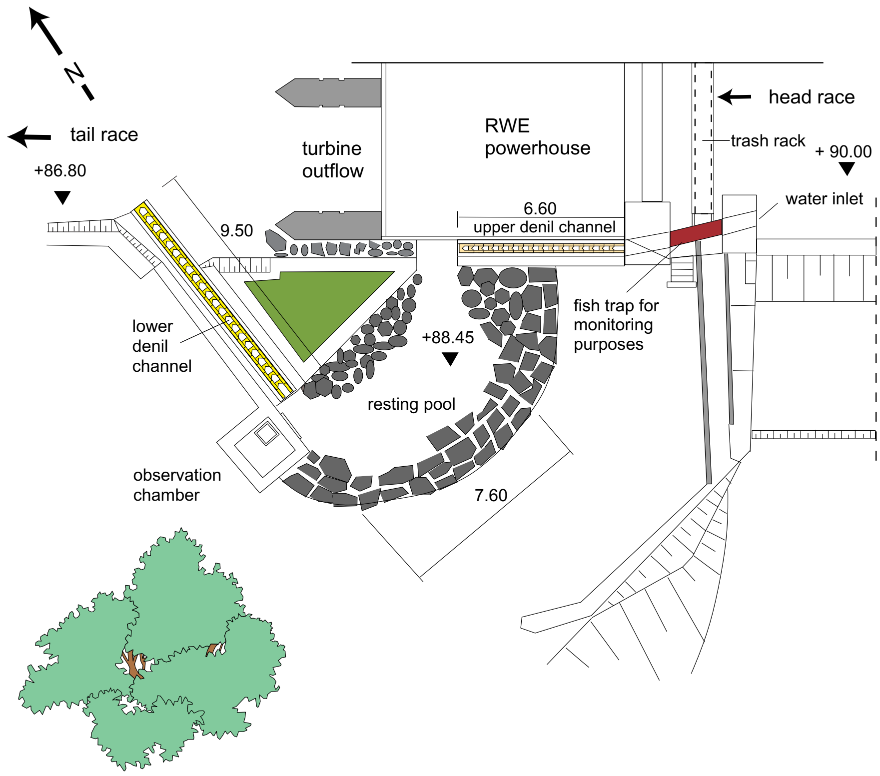


Figure 5.35: Fish pass at the hydroelectric power station Unkelmühle/Sieg (NRW)

[#] remark by the editor

Example (continued)

Figure 5.36:
View of the lower Denil channel and the resting pool above.

The attraction current that affects a large area of the tailrace is clearly visible; it is responsible for the ease with which the entrance of the pass is detected by fish.

Figure 5.37:
View of the lower Denil channel.

The concrete channel is covered with wood to which the baffles are fitted that have a U-shaped cutout. The high turbulence water-air mixture on the surface misleads the observer as there are much lower flow velocities near the bottom area of the channel.

Figure 5.38:
Sea lamprey *(Petromyzon marinus)* from the Sieg.

Data on efficiency:

LUBIENIECKI et al. (1993) tested the efficiency of the fish pass from May 1991 to May 1992 using the fish trap to monitor fish migration. The numbers of ascending fish were to some extent surprising. On some 200 control days over 1000 ascending barbel were found. Monitoring also showed that other fish species were ascending the pass in only very small numbers. A particular success in 1993 was finding that sea lampreys were ascending the pass. This species died out 40 years ago in the River Sieg but new fishways had made it possible to recolonize the Sieg.

5.4 Eel ladders

5.4.1 Peculiarities of eel migration

The eel, being a catadromous migrant fish, lives in almost all standing and flowing waters connected to the sea. It grows in fresh water until sexual maturity and then migrates down the river to the sea in the silver phase, presumably to spawn in the Sargasso Sea.

The post-larval eels (so-called glass eels) reach the coast of Europe in two to three years and penetrate from there into inland waters. The ascending eels with a body length of 7 to 25 cm are certainly in a position to overcome small obstacles with rough surfaces, small cracks or fissures. However, the ability of young eels to ascend is frequently overestimated and many weird and wonderful climbing aids, such as vertically positioned bundles of brushwood etc, have proven unsuccessful. Therefore, mitigation facilities specially attuned to the performance of glass eels can be useful in addition to existing fish passes, particularly in the estuary area of rivers where the ascending eels are still very small. Eels of larger body lengths also use the more common types of fish pass so that separate eel ladders are not required there.

5.4.2 Design

Two principle types of design are common:

1. Pipes are laid through the body of a weir, often close to the river bottom, in which bundles of brushwood, fascines or other baffles are placed to lower the flow velocity. The baffles are often attached to a chain, so that they can be pulled

Figure 5.39:
Eel *(Anguilla anguilla)*

Figure 5.40:
Rhomboid pass and eel ladder on the Sauer dam at Rosport (Rhineland-Palatinate).

View from headwater.

The eel ladder, in which brushwood bundles are placed, is paralleling the bank-side wall of the rhomboid pass.

out and replaced. The eel has to wind its way through the built-in devices to overcome the obstacle to migration. This type of device has not been found suitable in practice since the tubes become quickly clogged with debris; this is very difficult to discover (the pipe is completely beneath the water) and just as difficult to remedy.

2. Relatively small and flat open channels, which pass from tailwater to headwater and are made of concrete, steel or plastic in which various fittings are placed that help eel in winding upwards. According to JENS (1982), brush-type structures have proven to be most suited to this purpose. However, brushwood, gravel and grids are also used as built-in devices. These channels should have a cover as protection against predators such as rats and gulls.

The way in which the eel ladders are laid out ensures that water only trickles through them, so they are just moistened. This means that they cannot be used for the ascent of other fish species, nor is this intended.

The exit of an eel ladder must always be at the bank. Connection with the bottom is not required as glass eels migrate in the surface-water layer. It should be noted that the small discharges through an eel ladder are barely sufficient to provide an adequate guide current and, if necessary, additional water supply, e.g. through a bypass, has to be provided to create sufficient attraction.

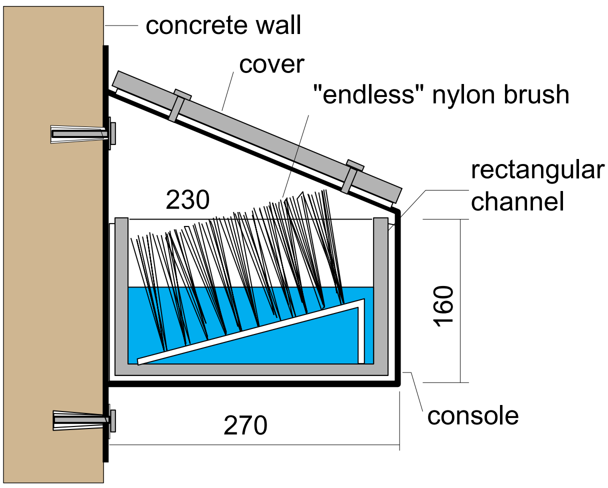


Fig. 5.41: The eel ladder at the Zeltingen dam on the Moselle (Rhineland-Palatinate) is adapted to the specific migratory behaviour of the eel. The ladder consists of a channel in which an endless plastic brush is laid to help the eel moving upstream by winding its way through the brush. Also this eel ladder was constructed in combination with a conventional pass and parallels the side of this pass (after JENS, 1982).

Because of the low swimming performance of the young eel, the exit of the pass into the headwater must at all costs be placed in an area with gentle current; under no circumstances it should be placed just close to the screens of the turbine inlets.

5.4.3 Overall assessment

Eel ladders are only suitable for allowing upstream migration of eels. Due to its selectiveness, an eel ladder on its own is not sufficient for mitigation if also other fish species have to pass the obstacle as the eel ladder would not allow them to do so. Eel ladders are specially recommended in the estuary areas of rivers in addition to the other technical fish passes (pool passes, Denil passes etc) to specifically allow young eel to migrate upstream.

5.5 Fish lock

The use of fish locks as mitigation devices has been known for quite some time now and has been applied especially in the Netherlands, Scotland, Ireland and Russia (van DRIMMELEN, 1966; JENS, 1982). Some fish locks exist on the Rivers Saar and Sieg in Germany.

The structure of a fish lock is similar to a ship lock (see Figures 5.42 and 5.43). Both essentially consist of a lock chamber as well as a lower inlet and an upper outlet structure with closing devices. However, there are some differences as far as the functioning is concerned which also make it clear that a ship lock, over and above its actual purpose, is not normally sufficient to sustain fish migrations nor can it replace a fish pass. In particular, the lack of a permanent guide current, the short opening times of the sluice gates, the high turbulence in the chamber during filling procedures and the position of the lock at the dam only exceptionally allow fishes to find their way through a ship lock.

However, it is possible in exceptional cases to consider whether the operating mode of the ship lock can be modified temporarily (e.g. during the main migration season for glass eels or salmonids) to facilitate the ascent of fish.

5.5.1 Principle

The functional principle of a fish lock is shown in Figure 5.42. It is possible to distinguish four operating phases:

1. The lock is idle. The lower gate is open and the water level in the chamber is at the level of the tailwater. The fish must now be shown the way from the tailwater into the lock chamber by a guide current. To this end either the upper sluice gate is slightly opened or a guide current is produced by sending water through a bypass (i.e. pipeline) that ends at the entrance to the lock chamber. The fish gather in the chamber.
2. The lock chamber is being filled. The lower sluice gate is closed; the upper one is slowly opened fully. The flow coming from the headwater leads the fish in the chamber to the upper exit.
3. The water level in the chamber is equal to that of the headwater. Water is passed into the tailwater through a slot in the lower sluice gate or a special pipe, whereby an attraction current is produced at the exit to the headwater. The fish find their way out of the chamber.
4. The lock chamber is emptied after closing the upper and opening the lower sluice gates. The lock is again in an idle state.

The timing of the operating modes is done automatically. Usually there are half-hourly to hourly operating intervals. The most efficient rhythm and, if applicable, the necessary seasonal adjustments, can only be determined through monitoring controls.

5.5.2 Design

The design of the chambers and closing devices is variable and largely depends on the specific local conditions. When designing the chamber bottom there should be measures to prevent fish being left in areas that become dry. To this end, the chamber bottom can have a stepped design (Figure 5.43) or just be inclined (Figure 5.42). The chamber dimensions should clearly be larger than the pools of conventional fish passes as many more fish must remain in the chamber for a longer time. The construction of a rough bottom is possible in principle. Chambers that are open to the top are desirable.

The guide current may be produced, or intensified, by sending water through a bypass (cf. Figure 5.43). The cross section of the water outlet of the anterior chamber should be dimensioned in such a way that an effective guide current is guaranteed in the range between v = 0.9 and maximum of 2.0 m/s (on average v = 1.2 m/s). When designing the influxes and discharges for the filling and emptying phases of the lock chamber care should be taken that the mean flow velocities

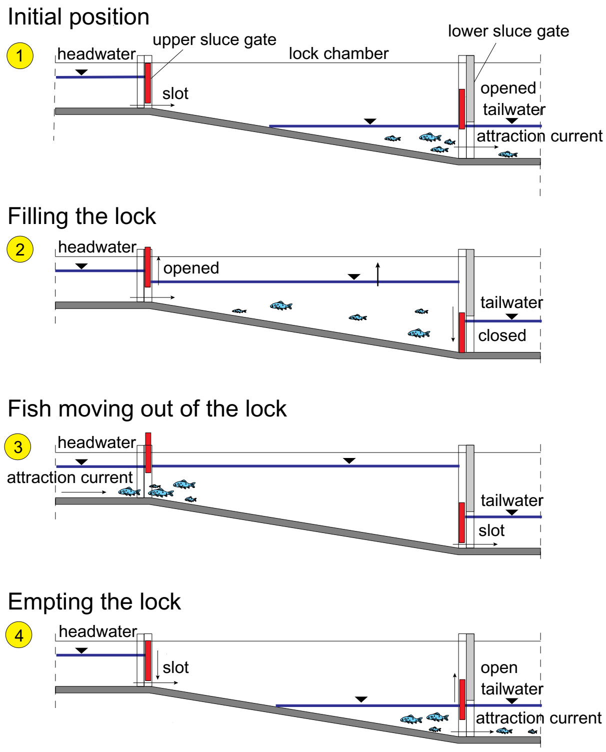


Fig. 5.42: How a fish lock works (schematic longitudinal section)

do not exceed 1.5 m/s at any time or in any place within the chamber and that the water level in the chamber rises or falls at less than 2.5 m/min (SNiP, 1987).

With regard to the position of the fish lock at the dam and the location of the entrance and the exit, the same criteria apply as for other fish passes. Because of their compact structure fish locks can, for example, be housed in partition piers.

5.5.3 Overall assessment

Fish locks have an advantage as alternatives to traditional technical fish ladders if

- There is not much space and
- There are very large height differences to overcome.

Equally the fish lock offers structural advantages if very large (e.g. sturgeon) or low performance fish species have to be taken into consideration.

It is not possible at present to exclude a selective effect with regard to the ease with which they are passed by invertebrates, bottom-living fish and small fish.

The moving parts, drive and control systems require increased maintenance efforts compared with traditional fish passes.

5.5.4 Example

SCHODEN FISH LOCK

Details of the dam		Details of the fish lock	
Watercourse:	Saar, Rhineland-Palatinate	Fall head:	h_F = 5.70 m
Flows:	MNQ = 19 m^3/s	Chamber width:	b = 1.0 m
(from 1946/93	MQ = 80 m^3/s	Length:	l = 34 m
data series)	HHQ = 1 230 m^3/s	Year of construction:	1981
Use:	Water power, ship navigation	Operator:	WSA Saarbrücken
Control flow:	Q = 2 × 30 m^3/s	Responsible:	RWE Energie AG

Structural design:
During the development of the Saar as a waterway for shipping, a fish lock was constructed on the Schoden dam. This was incorporated in the partition pier between the powerhouse and the weir. The entrance to the lock is located near to the turbine outlet. The entrance into the fish lock has a cross section of 0.65 × 0.80 m and is submerged. On the headwater side, the exit releases fish into the impoundment.

A hydraulically activated rolling gate serves to close off the lock towards the tailwater while towards the headwater the lock chamber is sealed off by a dam shutter. A fish trap can be installed between the shutter and the exit for monitoring purposes.

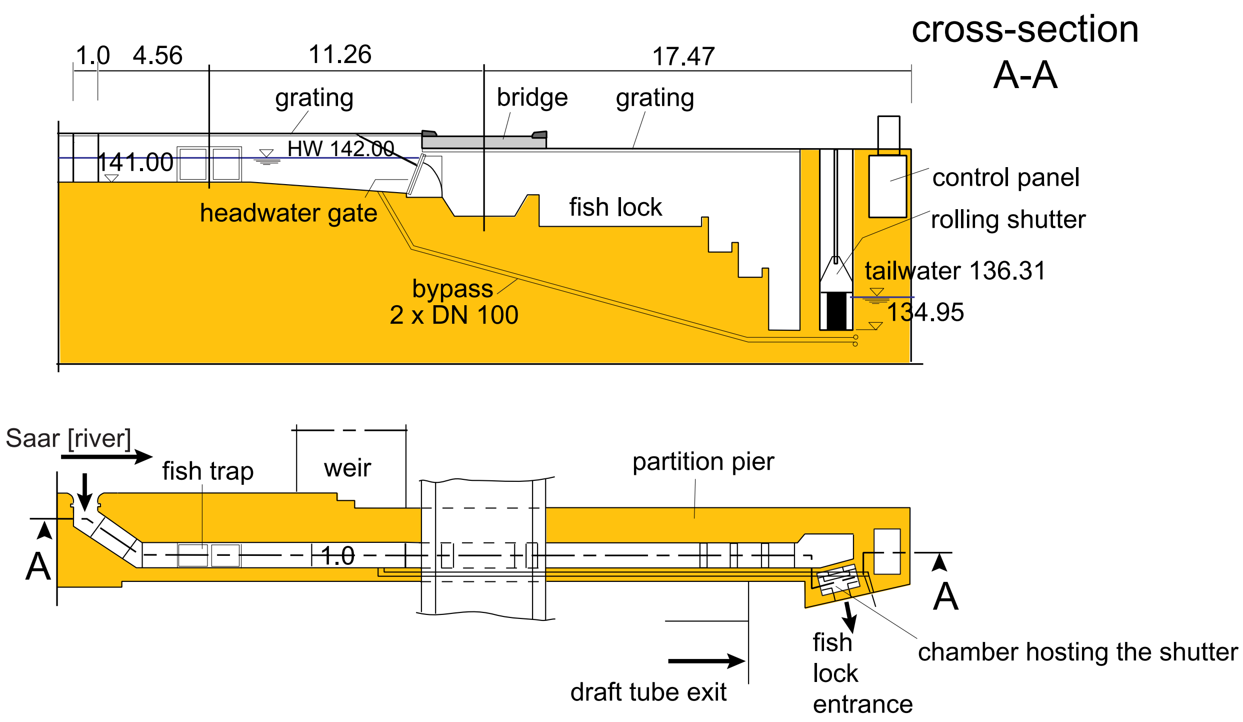


Figure 5.43: Longitudinal section and plan view of the Schoden fish lock (Saar)

Example (continued)

SCHODEN FISH LOCK

Data on effectiveness:

Fish monitoring in the lock carried out by the district authority in Treves confirm the effectiveness of the fish lock. In all, in the period from 15.4.1992 to 18.7.1992, over 50 000 fish moved through the lock (KROLL, 1992, oral presentation at the symposium on “Long distance migratory fish in rivers regulated by dams”, held at Koblenz on 16 and 17 November 1992). Tests regarding the effects of different turbine operation modes on the effectiveness of the fish lock showed no significant differences in numbers of fish entering the lock, regardless of whether only the turbine near the lock was in operation, or only the one on the bank side, or both turbines together.

Figure 5.44: The Schoden/Saar fish lock (view of the weir installation)

The lock is installed in the partition pier between the weir and the powerhouse (see the arrow).

5.6 Fish lift

5.6.1 Principle

Where there are considerable height differences (> 6 to 10 m) and little water available there are restrictions on the applicability of conventional fish passes, due to the building costs, the space requirement and, not least, the physiological abilities and the performance of the fish. Where great heights are to be overcome, solutions have been developed to carry fish from the tailwater to the headwater using a lift.

A trough is used as a conveyor and is either equipped with a closable outlet gate or can be tilted. When in the lower position, the trough is sunk into the bottom. Fish have to be attracted towards the fish lift by a guide current. In addition, a sliding and collapsible grid gate located in front of the lift, may serve to push the fish into the lift and thus above the transport trough. The lower gate of the lift closes on a regular cycle. The fish gathered above the trough can no longer escape, are “caught” by the rising trough and conveyed to the top. Here a watertight connection may be made to the upper water level or else the trough is simply tipped out above the headwater level into a funnel. Along with the water from the trough the fish reach the upper channel where, once again, there must be a clear attraction current.

The regular cycle is determined according to actual migratory activity. The operation is usually automatic.

5.6.2 Structure

Figure 5.45 shows in a diagrammatic sketch the structure of a fish lift as constructed both on the east coast of the United States and in France (LARINIER, 1992c).

The same principles apply to the positioning of a fish lift as for conventional fish passes.

5.6.3 Overall assessment

- Little space is required, and large height differences can be overcome with such fish lifts, e.g. even at high dams. However, the structural expenditure is considerable.
- Since the fish are conveyed upstream passively, fish lifts are suitable for species with low swimming performance as well as for the transportation of large fishes.
- Fish lifts are not suited for the upstream migration of invertebrates and the downstream migration of fish.
- Large variations in the tailwater always mean design problems in providing an adequate guide current.
- The expenditure on maintenance for fish lifts is higher than for traditional fish passes.

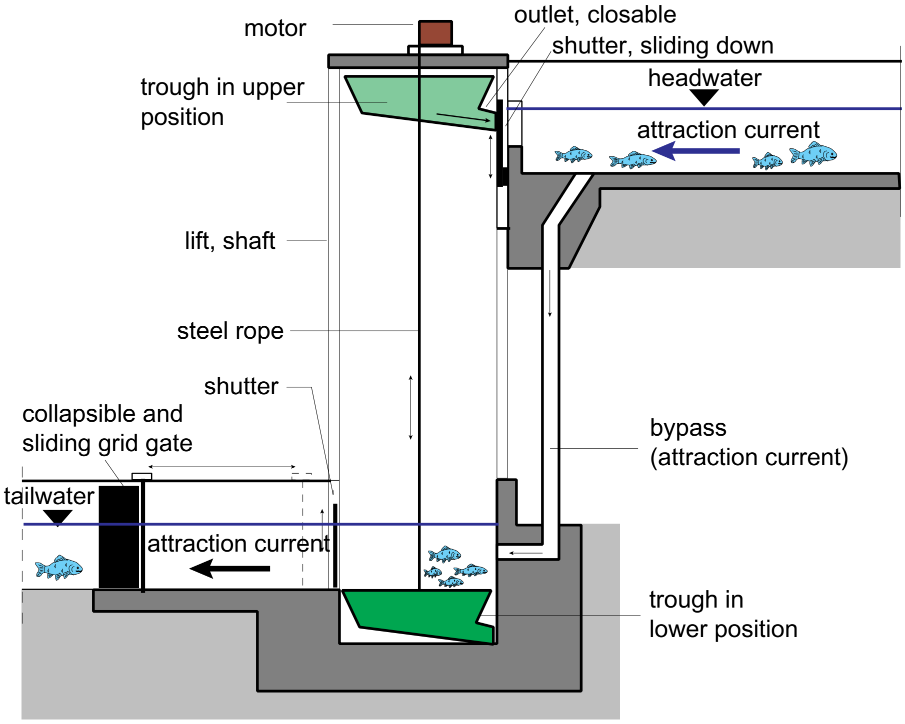


Figure 5.45: Schematic view of the structure of a fish lift and functional principle (modified after LARINIER, 1992c).

5.6.4 Example

TUILIÈRES FISH LIFT

Details of the dam		**Details of the fish lift**	
Watercourse:	Dordogne, France	Lift height:	h = 10 m
Use:	Water power	Transport trough volume:	$V = 3.5\ m^3$
Flow:	$Q = 285\ m^3/s$	Guide current:	$Q = 4\ m^3/s$
Fall head:	$h_F = 12$ m	Link to headwater:	Slot pass, $l_{tot} = 70$ m
Energy production by:	EDF		h = 2.0 m, $Q = 1.0\ m^3/s$
		Year of construction:	1990

Functional data:

Proof was obtained by video monitoring that more than 100 000 fishes used the lift in the period 11 May to 28 July 1989. The lift is not only accepted by large salmonids and allis shad but also by cyprinids, sea and river lamprey etc. The slot pass link to the headwater is equipped with an observation window from which the fish can be easily observed as they swim upstream.

Figure 5.46:
Tuilières fish lift. The lift is located on the right hand side directly adjacent to the turbine outlets and conveys fish 10 m high into an intermediate pool whence the last two metres of difference in height are overcome by a slot pass.

Figure 5.47:
The lower entrance to the Tuilières fish lift

The collapsible grid gate is closed and then pushes the fish, that have gathered in the antechamber, towards the transport trough before this trough is lifted. The gate considerably improves the efficiency of the installation.

The opening of the canal, through which the water necessary for operating the slot pass ($Q = 1\ m^3/s$) is led, can be seen at the top right of the photo. At the same time, this additional water improves the attraction towards the lift.

6 Monitoring of fish passes

Provision of structural prerequisites for monitoring the functioning of fish passes should be made for all new installations that must observe current water legislation. Particularly where there is considerable divergence from the guidelines in this book, approving authorities should have the possibility to order a control of functioning. The following presents exclusively the methodology for the assessment of monitoring of upstream migrations; monitoring of downstream migration is not dealt with at this point.

6.1 Objective of monitoring

The objective of monitoring is to prove explicitly that the fish pass entrance can be found and the fish pass negotiated by fish. Monitoring goes beyond checking the construction against the planning directives and construction certification, as well as beyond the obligatory trial run (see Chapter 4.4.5), which is required particularly for the more natural looking constructions. It also goes beyond routine maintenance (see Chapter 3.8). New fish passes that have been constructed in accordance with the guidelines in this instruction booklet, should be assumed to function well in principle.

Experience shows that actual constructions frequently diverge from the recommendations in these Guidelines because of local circumstances. It is then often difficult to fully assess the effects of any possible impairment of function. In such cases, possibilities for monitoring and structural improvements to the pass should be incorporated in the project as early as at the approval procedure stage. Monitoring is also recommended for newly built fish passes when there is no, or only inadequate, experience with the operation of the (new) type of construction chosen, or if the pass is unique because of its dimensions (e.g. very high water discharges or fall heads). The methods described below can also be applied to monitoring of existing fish passes.

While sufficiently tested methods for monitoring upstream migration of fish exist, it is generally very difficult to prove the efficiency of upstream migration of benthic invertebrates in fish passes. The invertebrates' differing colonisation strategies mean that proof of their migration has usually to be restricted to recording colonisation within the fish pass itself. Present knowledge indicates that the existence of continuous bottom substrate alone can be invoked as an indicator of the possibility of upstream migration of invertebrates.

Most fisheries laws prohibit catching fish in fish passes. If research necessitates the capture of fish from a fish pass, an exemption permit must be requested prior to fishing. Granting of this permit is only possible if the owner of the fishery is in agreement prior to any fishing action. Usually the management of monitoring should be entrusted to fisheries experts.

6.2 Methods

The timing and duration of testing are of great significance to the reliability of any control of functioning. This should preferably take place during the main migration periods, which can differ regionally due to local particularities and weather conditions.

The following biological and technical elements should be considered when drafting a monitoring strategy and later when assessing the functioning of the fish pass:

- The potential natural fish fauna of the watercourse and the actual qualitative and quantitative composition of fish stocks in the headwater and tailwater of each dam. In addition, similar assessments should be made of the benthic invertebrate fauna.
- The unrestricted ascent of all migratory developmental stages of the relevant fish species.
- The current state of connectivity of the water system.
- The general requirements for planning and construction of the fish pass as set out in these Guidelines.
- If necessary, proposals for optimising the fish pass should be made.

Control of the functioning of the fish pass requires not only the obligatory counting of all fish that have negotiated the fishway but also the assessment of a number of other parameters and baseline conditions. These data are used to appraise the efficiency of the pass by comparing the monitoring results with the natural migratory activity of the fish fauna in the stretch of water being investigated. The additional data include:

- Counting ascending fish, classified by species and size groups, data on sexual maturity.

- Data on water level and discharge trends (increasing or decreasing water discharges), weather, turbidity of the water or degree of transparency.
- Details of lunar phase with reference to the migratory activity of the fish, particularly during eel migration.
- Measurement of current velocities and discharge in the fish pass.
- Measuring oxygen content and water temperature,
- Determining fish stocks in the headwater and tailwater taking into account stocking measures in each of the stretches of water.
- Noting other relevant details of the fish such as disease or injury.
- Assessing the overall condition of the fish pass and its level of maintenance.
- Recording any modifications of the environmental conditions of the river and recording particular events such as maintenance measures, fish mortalities etc, that may have bearings on the migratory activity in the fish pass.

It is recommended that already during construction of the pass provision be made for built-in trapping chambers or at least lifting devices for the use of mobile fish traps to be installed directly at the outlet of the pass. This is particularly necessary in technical passes to test ascent of fish in the pass. The methods for controlling the functioning of the pass should be appropriate to the type of pass. If necessary, several methods may have to be combined to balance out the different disadvantages of the individual methods. Various traditional methods are listed below, which, when used in the appropriate manner, can help to provide reliable data on the functioning of the fish pass.

6.2.1 Fish traps

The standard method for testing both natural-looking and technical passes is trapping the fish. Traps can be used provided that the cross section of the pass can be completely blocked off by the fish trap and that there is a tight connection to the bottom. The fish trap should be installed immediately at the water intake of the pass (i.e. the fish pass exit#; Figure 6.1) and can be built as a box, pedestal or special fish trap according to local circumstances. Box traps are the most appropriate for use in pool or slot passes, their size being determined by the dimension of the pools. The traps should be set in the uppermost pool. Control traps, which are, for example, set in resting pools or which are not set immediately at the water intake do not give any definite proof that fish can negotiate the total length of the pass.

The fish trap should be made of robust, dark, plastic yarn with maximum mesh size of 10 – 12 mm to allow the catch of young fish during the control. Box traps consist of a light aluminium frame, whose sides are filled with either plastic netting or coated wire mesh.

Control tests with traps require intensive care by trained staff. Fish may be injured as a result of high density in the trap, particularly in times of increased migratory activity. Frequent emptying can prevent this. The fish are removed from the trap, measured and their parameters recorded according to the defined programme, and released into the headwater. Since the trap, in the way it is set, prevents migration downstream from the headwater into the fish pass, this method provides reliable data on upstream movement.

6.2.2 Blocking method

This method involves blocking-off the water intake of the fish pass (i.e. fish pass exit#) with a net or grid to prevent fish swimming in from the headwater. All fish are then removed from the fishway, either by electro-fishing or by drying the pass. Control fishing, which is carried out after a certain time, reveals then the fish that have entered the fish pass from the tailwater.

This method can be applied at all passes that provide places for the fish to rest. It is, therefore, not suitable for Denil passes. Problems arise particularly from clogging of the blocking device by debris and floating solids.

Test fishing in a fish pass using conventional methods or electro-fishing is not suitable as a function control unless the water intake of the fish pass (i.e. the fish pass exit#) is first blocked off. It is otherwise, impossible to determine from which direction the fish migrated into the pass, i.e. whether they came from the tailwater or headwater.

6.2.3 Marking

Marking of fish can be used to control the functioning of the more natural fish passes and is often used to study migrations in aquatic systems. Marking of fish must be reported to, or approved by, the appropriate authorities. There are many

remark by the editor

Figure 6.1:
Fish trapping to monitor the functioning of the fish ramp at the Pritzhagener Mill on the Stöbber (Brandenburg)

Figure 6.2:
Salmon marked with red tattooing dye and released into the Mühlbach, a tributary of the Lahn (Rhineland-Palatinate), in the framework of a repopulation programme.

Figure 6.3:
Electro-fishing for monitoring purposes on the fish ramp at the Unkelmühle weir in the Sieg River (North Rhine-Westphalia)

different methods for marking fish, such as the use of coded marks (tags) or dye injections (Figure 6.2), each of which has distinct advantages and disadvantages.

When using this method autochthonous fish, that is caught in the relevant waterbody, is marked and released into the tailwater of the dam being investigated. Control of the functioning of the fish pass then consists of proving the presence of marked fish in the water intake area (fish exit area[#]) of the pass or in the headwater. Information about the recapture of the marked fish can be gained either directly by using conventional methods, such as fish traps or electro-fishing, or through the notification by anglers of any marked fish caught. Since the recapture rate is generally low, large numbers of various species and sizes must be marked for release into the tailwater. The relationship between the total number of all fish marked and the number recaptured must be taken into account when assessing the results.

6.2.4 Electro-fishing

Electro-fishing is frequently used for qualitative and quantitative investigation of fish stocks. Under the influence of an electric field in the water any fish present first swim towards the anode (galvanotaxis) and are then anaesthetised for a short period (galvanonarcosis), which allows them to be captured. The fish can then be investigated as to species, size category etc. (Figure 6.3). If the electro-fishing equipment is used correctly the fish are not injured. Electro-fishing (in Germany[##]) must only be carried out by specially trained persons and requires the approval of the relevant authority and the agreement of the holder of the fishing rights.

Electro-fishing gives qualitative and semi-quantitative estimates of the fish stock in the headwater and tailwater of dams. The determination of stock size can be used to assess the ascent activity of the fish fauna at the time of monitoring and also constitutes the basis for estimating the functionality of the fish pass (see section 6.3). In combination with other methods, such as blocking the water inlet to the fish pass or marking, electro-fishing gives the possibility of proving that fish manage to negotiate the pass.

6.2.5 Automatic counting equipment

Automatic counting equipment allows the ascending fish to be observed without disturbing them. The various methods are based on different principles, including movement sensors, light barriers or video control, and many are still largely in the exploratory stage. Optical systems can only be applied if there is sufficient viewing depth. Light barriers and movement sensors only allow the fish to be counted without distinguishing species or size. A more sophisticated combination of video monitoring and image processing systems allows a differential assessment of the functionality of the fish pass (TRAVADE & LARINIER, 1992).

In most cases the application of automatic counting equipment presupposes separate observation chambers, devices or installations mostly at the water intake (fish exit[#]) of the pass. If these methods are to be used, provision must be made at an early stage in planning, before building the fish pass. Expenditure on regular checks and maintenance of automatic counting equipment is high.

6.3 Assessment of results

The assessment of the results of controls of the functioning of fish passes presupposes detailed recording of data. In addition to locality-specific data for the river stretch and other factors that may influence the test results, data on the methodology used, including the duration of exposure of the fish traps or the cycle of emptying these traps, are required for correct assessment.

Unrestricted functioning and complete failure of a fish pass are both easy to demonstrate, but proof of restricted or selective functioning for specific species or sizes is considerably more difficult. Proof of the full functioning of a pass by the analysis and assessment of fish ascent figures should be carried out using the following criteria:

- Results of monitoring are to be assessed in relation to the main periods of migration that are specific to species and waterbody. Here, concomitant factors such as discharge conditions, temperature, moon phase etc, should be considered.
- Fish migrating through the fish pass are to be assessed in relation to the stock densities in the headwater and tailwater of the dam. This can be done by comparing the results of the fish pass monitoring with the natural dominance relationships (as percentage data) and the size range of the species actually present in the water.

According to the general requirements defined in Chapter 3, a fish pass can be recognised as functional if all species of the potential natural fish

[#] remark added by the editor
[##] "in Germany" was added by the editor

fauna, in the different stages of development and in numbers that reflect their relative abundance in the watercourse, can find the fish pass entrance and negotiate the pass. However, this frequently presents methodological problems because:

- Usually not all species of the potential natural fish fauna are represented in the water,
- In particular the presence of small fish species is difficult to prove with traditional methods such as fish traps,
- Species that are extremely rare in the river may not be detected during monitoring, although these species may in principle be able to negotiate the pass.

Therefore, it is now allowed to believe that a fish pass functions well if:

- It can be proved that all fish species actually present in the affected river stretch, in their different stages and relative abundance, can find the entrance and negotiate the pass. The pass can be considered functional even for extremely rare species or species that are not recorded because of the methodological difficulty to catch them, if other species with the same ratio of body size to pass dimensions and similar swimming performance are able to negotiate the pass.
- The plausibility that the fish pass entrance can be detected and the pass be negotiated must also be given for species of fish of the potential natural fish fauna that are currently not represented in the population of the watercourse.

7 Legal requirements

The relevant laws must be observed when planning, building and operating fishways. As set out in Article 70 of the Constitutional Law of the Federal Republic of Germany, inland fisheries are subject to the jurisdiction of each *Land* (Federal State). Therefore, each of the *Länder* (Federal States) has its own fishery act, which usually differs widely in a number of points from similar acts of the other *Länder*. All federal fishery acts contain details on the construction and operation of fishways, that can be implemented directly and independently of other regulations or laws.

On the other hand, as regards the Water Law, there exists a higher-ranking skeleton law, the *Wasserhaushaltsgesetz* (Water Resources Policy Law) (WHG). This contains in § 1a, Subsection 1, the principle that waterbodies should be managed in such a way that they add to the well-being of the general public and also benefit individuals where this does not interfere with the public good. The subsection also states that all negative influences must be avoided. According to §§ 4,8 unfavourable effects on waters deriving from uses that require permission or approval are to be prevented or compensated for.

This principle is also in accordance with § 8 and § 20 of the Federal Law on Nature Conservation and the relevant Nature Conservation Acts of the *Länder*. The proposal of Council's Guidelines on the ecological quality of waterbodies, that was submitted by the Commission of the European Union, includes the provision that migratory fish species may not be impeded by human activities.

7.1 New installations

The Water Law requires that the necessary permissions or planning procedure approvals be sought from the relevant authorities prior to building dams or weirs in waterways. Such constructions usually represent a substantial structural modification of the waterbody in the sense of § 31 WHG, in that they lead to an essential change in habitats, so that Planning Permission Hearings in accordance with § 31, Subsection 1, must be undertaken. In addition, complementary law regulations of the *Land* have, of course, also to be respected.

According to the annex (here Point 6) of § 3 of the *UVP*[#] Law (Environmental Impact Assessment Law), planning procedures that are to be carried out according to § 31 WHG [Water Resources Policy Law] require an Environmental Impact Assessment (UVP).

The Environmental Impact Assessment includes the determination, description and assessment of the impacts of a planned action on people, animals and plants, soil, water, air, climate and landscape, including their mutual interactions in each case, as well as their impacts on cultural property and other goods.

In the context of the Environmental Impact Assessment, conservation or restoration of longitudinal connectivity is usually an aim, although fishery laws of some *Länder* provide formal exceptions with regard to building fishways.

The fisheries requirements also have to be considered where an approval, licensing or agreement procedure has to be carried out instead of Planning Permission Hearings. Within the framework of the relevant laws the planning procedure should balance the interests of fisheries with the benefits associated with the project that is object of the application.

7.2 Existing installations

The legal situation for existing dams and weirs is different if modifications are carried out that do not require approval as here, in first instance, the old laws, conferred with their ancillary clauses, apply. An amendment of the old laws is usually not possible without the agreement of the holder of the right, as defined by the guarantee of ownership under Article 14 of the Constitutional Law. These old rights may, however, be revoked in accordance with § 15 WHG in return for compensation where considerable disadvantage to the general well-being can be expected from a continued use. Most Fishing Acts of the *Länder* offer the possibility to oblige the owner of a dam to retrofit it with a fish pass if the building costs and any possible compensation claims are met by the third party insisting on the construction.

In Hesse, North Rhine-Westphalia, Rhineland-Palatinate, Saxony-Anhalt and Thuringia, the *Land* can only insist on retrofitting an obstruction with a pass if the measure has a reasonable cost/benefit ratio and a reasonable ratio of cost-to-production-power of the liable party. If the liable party cannot afford to pay, the *Land* has to care for the provision of an appropriate part of the funding of retrofitting.

[#] remark by the editor: UVP = Umweltverträglichkeitsprüfung (Environmental Impact Assessment)

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9 Table of symbols and signs used

Symbol	Unit	Used for
a	m	Distance between baffles in Denil passes; stagger distance of the deflecting block relative to the cross-wall in slot passes
A	m^2	Area, flow section
A_{tot}, A_{ges}	m^2	Total flow section
A_o	m^2	Base area
A_s	m^2	Cross-section of submerged orifice in pool passes; wetted area of an immersed object (e.g. a perturbation boulder)
a_x, a_y	m	Distance between perturbation boulders, (a_x) in longitudinal direction and (a_y) in lateral direction
b	m	Width, channel width
b_a	m	Width of baffle section in Denil passes; width of notches in pool passes
b_m	m	Mean width
b_s	m	Width of submerged orifice in pool passes; width of gaps (for discharge) in a boulder sill (cascaded ramp)
$b_{So,}$ b_{bot}	m	Bottom width
b_{Sp}	m	Width of waterbody at its surface
c	m	Length of hook-shaped projection in slot passes
c_1, c_2	m	Height of triangular section of baffles in Denil passes
c_w	-	Form drag coefficient
d	m	Thickness, e.g. of substrate layer; thickness of wall in pool and slot passes
d_S	m	Boulder or stone diameter
d_{90}	m	Grain diameter for 90% mass sieving
E	W/m^3	Volumetric power dissipation
f	m	Width of deflecting block in slot passes
Fr	-	Froude number
g	m/s^2	Acceleration due to gravity, $g = 9.81\ m/s^2$
h	m	Height or water depth, generally the minimum water depth
h^*	m	In Denil passes: distance from the deepest point of the cutout section of the baffle to the bottom of the channel, measured perpendicular to the bottom
h_a	m	Height of notches in pool passes; height of baffles in Denil passes
h_E	m	Energy level
$h_{E,min}$	m	Minimum energy level
h_F	m	Fall head
h_{gr}	m	Limiting depth, water depth for discharges with minimum energy level
h_m	m	Mean water depth
h_o	m	Water depth above a dam, or above a cross-wall or sill (be aware of reference level!)
h_s	m	Height of submerged orifice in pool passes (measured from bottom surface or substrate surface)
h_u	m	Water depth below a dam, or below a cross-wall or sill (be aware of reference level!)
$h_ü$	m	Weirhead (sometimes as $h_{weirhead}$)
h_v	m	Losses in energy level caused by discharges
h_w	m	Height of cross-walls in pool passes
I	-	Slope
k	m	Absolute roughness
k_s	m	Equivalent sand roughness

Symbol	Unit	Used for
l	m	Length, distance
l_b	m	Pool length
l_u	m	Actual length of the wetted channel cross-section
n	-	Number of pools
Q	m^3/s	Discharge or flow
Q_a	m^3/s	Discharge through the notches in pool passes
Q_s	m^3/s	Discharge through the submerged orifices in pool passes
r_{hy}	m	Hydraulic radius, $r_{hy} = A / l_u$
s	m	Slot width in slot passes
V	m^3	Volume
v	m/s	Flow velocity
v_{gr}	m/s	Flow velocity at critical flow depth
v_m	m/s	Mean flow velocity
v_{max}	m/s	Maximum flow velocity
v_s	m/s	Maximum flow velocity in the slot or in the submerged orifice
w	m	Height of weir, height of sill
x,y,z	-	Axes in Cartesian coordinate system
α	°	Angle
Δh	m	Water level difference, e.g. between pools
ϵ_v	-	Volume ratio
ϵ_o	-	Area ratio
λ	-	Resistance coefficient in Darcy-Weisbach flow law
λ_{tot}, λ_{ges}	-	Total resistance coefficient
λ_o	-	Resistance coefficient due to bottom roughness
λ_s	-	Resistance coefficient due to perturbation boulders or similar objects
μ	-	Spillway coefficient for calculating spillover
μ_r	-	Discharge coefficient in slot passes
ρ	kg/m^3	Density (of water), $\rho = 1000\ kg/m^3$
ρ_s	kg/m^3	Density of stone, $\rho_s \approx 2700\ kg/m^3$
σ	-	Backwater coefficient, takes account of the influence of the tailwater level
ψ	-	Outflow coefficient
ζ	-	Loss coefficient

Hydrological information and abbreviations

Abbreviation	Meaning
OW	Headwater: water level above a dam
UW	Tailwater: water level below a dam
MNW, MNQ	Mean low-water level and mean low-water discharge
MW, MQ	Mean water level and mean discharge
MHW, MHQ	Mean high-water level and mean high-water discharge
HW, HQ	High water level and high water discharge
$\underline{n}$W, $\underline{n}$Q	Water level/discharge not reached on n days in the year
$\bar{n}$W, $\bar{n}$Q	Water level/discharge exceeded on n days in the year
HHW, HHQ	Highest known water level, highest known discharge

10 GLOSSARY

Abiotic factors: Non-living chemical and physical factors, e.g. geology, temperature, water balance, that influence biological systems and biocoenoses. – See: *biotic factors.*

Adult: An organism from the time it reached sexual maturity.

Allochthonous: Living organisms or dead material that is exotic to the environment from which it was sampled. – See: *autochthonous*.

Autochthonous: Living organisms or dead material that is indigenous to the environment from which it was sampled. – See: *allochthonous*.

Autotrophic: Characterizing the physiological mechanism of green plants and many microorganisms, whereby the organism grows using photosynthesis to convert inorganic matter (minerals, CO_2, NH_4) to organic matter.

Benthic zone: Bottom of a body of water. Benthic organisms live on or in the bottom. The biocoenosis of this habitat is termed “benthos”; the biocoenosis of bottom-dwelling invertebrate species is termed “benthic invertebrate fauna”.

Biocoenosis: Living community of plants and animals of a specific living space (biotope). – See: *ichthyocoenosis*.

Biotic factors: Factors pertaining to the living environment, e.g. nutrition, competition, parasites etc., that influence biological systems. See: a*biotic factors*.

Biotope: Space (habitat) occupied by a living community (biocoenosis) of plants and animals with its own specific environmental conditions.

Bypass: A means of conducting water and organisms around the main channel. In these Guidelines often used in the sense of a means to supply additional attraction current.

Bypass power station, synonym with **channel power station:** A bypass power station is a hydroelectric power station that lies on a bypass channel (water is deviated from the main channel into an artificial turbine canal. In general, the river course is artificially shortened by the bypass in order to achieve a greater fall or head for the generation of electricity. Water is extracted from the main channel by means of the bypass and conveyed to the hydroelectric power station.

Critical discharge: Water volume per unit of time, which is decisive for defining the dimensions of a fish pass. Unit: [m^3/s].

Directional current: Current without cross-currents.

Diversional hydropower station: A hydroelectric power station where the exploitable fall or head, as existing at the dam structure, is increased as a result of the diversion.

Draft tube: Funnel-shaped opening that constitutes the connection from the turbine rotor to the tailwater in reaction turbines of hydropower stations and that delays the water coming out of the turbine, thus reducing its flow velocity.

Energy dissipation: The withdrawal of potential and/or kinetic energy from the water discharge energy and its transformation into heat. – See: *volumetric power dissipation*.

Eurytypic: Organisms that can tolerate very different environmental conditions and thus changes in their living space (habitat). – See: *stenotypic*.

Flow transition: Change of water depths from turbulent to laminar flow or conversely. The transition from laminar to turbulent is always steady, while the change from turbulent to laminar always shows a disturbance in the surface water level in the form of a hydraulic jump.

Gabions: Cuboid wire baskets filled with stones that are mainly used for revetting riverbanks above and below water.

Habitat: The normal living space occupied by a species of plant or animal within an ecosystem.

Ichthyocoenosis: Community of living fish. – See: *biocoenosis*.

Interstitial: Water-filled spaces within the river sediments forming the river bottom or adjacent to it.

Invertebrates: Collective term for animals without backbones.

Invertivorous fish: Fish species that feed on invertebrates, whether aquatic, flying or terrestrial. – See: *invertebrates*.

Kelts: Salmon returning to the sea after spawning.

Olfactory orientation: Orientation of many fish species results from a highly developed sense of smell.

Parr: A young salmon living in freshwater.

Phytoplankton: Small to very small algae that live passively in fresh or salt water and manufacture their own nutrition by photosynthesis (i.e. they are autotrophic).

Piscivorous fish: Fish species that feed on other fish.

Planktivorous fish: Fish species that feed on plankton.

Population: The totality of all individuals of one species in a specific living area that reproduce sexually with one another over many generations and are thus genetically linked.

Sluice: Device for relief, flushing or emptying the impoundment behind a dam.

Sluice gate: Constructional, adjustable element installed at weirs, reservoirs and hydroelectric power stations to regulate the flow of water. Sluices are generally made of rectangular steel plates sliding or rolling in lateral guide grooves.

Smolts: Young salmon, with typical silvery colour, migrating to the sea.

Spillover jet: A water jet passing over a real spillway, either falling free or flowing along the spillway back as a gushing jet

Stenotypic: Stenotypic species are very sensitive to changes in their living conditions. – See: *eurytypic*.

Stock: Genetically distinct community of individuals of one species in a specific living area.

Volumetric power dissipation: Amount of energy per unit of volume that is dissipated in the pools of a fish pass. The hydraulic energies are no longer available for further discharge. It is a measure of the turbulence conditions in a pool. Unit: [W/m^3 pool volume]. – See: *energy dissipation*.

Photo credit:

Baumann, A.:	Figure 4.2
BAWAG:	Figures 4.21, 4.26, 4.45
Gebler, R.-J.:	Figures 4.33, 4.37, 5.40
Heinrichsmeier, G.:	Figures 4.38, 4.39, 4.40, 4.41
Krüger, F.:	Figures 2.9, 2.11, 3.1, 3.2, 3.14, 4.9, 4.10, 4.11, 4.17, 4.24, 4.28, 5.7, 5.15, 5.20, 5.25, 5.29, 5.30, 5.36, 5.37, 5.38, 5.39, 6.1
Lippeverband:	Figures 5.12, 5.13
Marmulla, G.:	Figures 4.29, 4.34
Mathis, R.:	Figure 2.15
RWE AG:	Figures 3.3, 5.11, 5.44
Schaa, W.:	Figure 4.49
Schwevers, U.:	Figures 2.6, 2.7, 2.8, 2.12, 2.13, 5.46, 5.47, 6.2, 6.3
Städtler, E.:	Figure 4.35
Steidl, J.:	Figure 4.15
Stolzenburg, H.:	Figure 2.14
Surhoff, P.:	Figures 4.22, 4.36, 5.3
Touschek, A.:	Figure 4.13

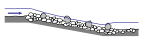
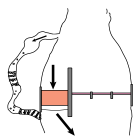
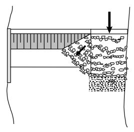
Graphic design by Krüger, F. and Schaa, W.

Appendix: Overview of the most frequently used construction types of fish passes

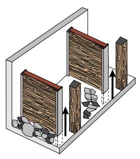
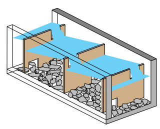
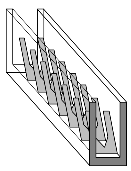
The various fish passes are classified by functional and ecological aspects, but no account is taken of local geographical factors that may limit the use of some structures.

*Where measurements are given, they are only minimum requirements.

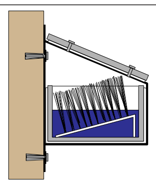
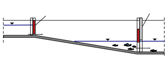
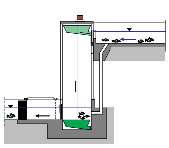
Close-to-nature types of structures

Type	Sketch	Principle	Dimensions* and discharge	Range of application	Advantages and disadvantages	Effectiveness
Bottom ramps and slopes (sect. 4.1)		Ramps and slopes are structures that have a rough surface and extend over the entire width of the river. Loose rockfill constructions and dispersed constructions are favoured.	The ramps are as wide as the river (b = width of river), their slope normally < 1:15. If the main body of the ramp is steeper, then at least the marginal areas must be less steep. Height h > 0.2 m. Discharge must be q > 100 l/s m. Construction in several layers and with secured downstream bottom.	Recommended where a previous use has been abandoned and where the headwater level needs no longer be regulated. Used for the modification of steep drops and fixed (very steep) weirs, as a protective sill to hinder erosion.	There is a danger of drying out at low discharge, so sealing may be necessary. Relatively low costs. They blend well into the landscape, look natural, require little maintenance. No problems with attraction currents, so can easily be found by fish.	They are passable in both directions by all aquatic fauna. Long term silting of the impoundment restores also upstream the typical flow velocities and substrate conditions.
Bypass channels (sect. 4.2)		Offer an alternative route round a dam with a natural-looking stream bypassing the impoundment.	b > 1.2 m; h > 0.20 m; < 1:20. The bypass should extend up to the upstream limit of the backwater. Discharge must be at least q = 100 l/s m.	Suitable for all barriers and heads if there is sufficient space, particularly useful for retrofitting existing installations. They are not suitable when impounding heads vary; in the latter case, inlet constructions for water regulation might be necessary.	Their financial cost is low, their demand for space high! Deep cuts into the surrounding terrain may be necessary or combination with other technical structures. Bridges or underpasses are often required.	They are passable for all aquatic fauna, provide living space for rheophilic species, are the only fish pass that can bypass the whole area of the dam and the impoundment, blend well into the landscape.
Fish ramps (sect. 4.3)		Ramps with gentle slopes and a rough surface; integrated into the weir structure. Their body may be of rockfill, with perturbation boulders or boulder sills to reduce flow velocities.	b > 2 0 m; h > 0.3 to 0.4 m; = 1:20 or less. Necessary discharge q approximately 100 l/s m.	They can be used to overcome heights not greater than about 3 metres. Used at fixed weir sills, and at multi-bay weirs as a substitute for a weir bay. They are not suitable for variable impounding heads.	Their construction is often technically demanding, with a need for high structural stability. There is a danger of drying out at low water, therefore sealing may be necessary. Require little maintenance; good self-cleaning during floods. Good attraction current.	They are passable for all aquatic fauna in both directions, i.e. upstream and downstream.

Technical structures

Type	Sketch	Principle	Dimensions* and discharge	Range of application	Advantages and disadvantages	Effectiveness
Slot passes (sect. 5.2)		Slot passes are generally concrete channels with cross-walls of concrete or wood and with one or two vertical slots that extend over the whole height between the cross-wall and the lateral bounds.	Pool dimensions: l_b > 1.90 m; b > 1.20 m; h > 0.5 m; Slot width: s > 0.17 m. Discharge can be from Q = 140 l/s up to several cubic metres per second.	Used for small and medium heads, suitable for variable impounding heads. Can be used for small streams and large rivers. The minimum tailwater depth must be h > 0.5 m.	Relatively high discharges can be sent through, thus good attraction currents can form. More reliable than conventional pool passes because of the lower risk of clogging of the slots.	They are currently the best type of technical fish pass, being suitable for all species of fish and are passable for invertebrates if a continuous bottom substrate is built in.
Pool passes (sect. 5.1)		Are generally concrete channels with cross-walls of wood or concrete which are fitted with submerged orifices and top notches on alternate sides.	Pool dimensions depend on the river zone; l_b > 1.4 m; b > 1.0 m; h > 0.6 m. Submerged orifices: b_S/h_S > 25 · 25 cm Discharge Q = 80 to 500 l/s.	Used for small and medium heads, at melioration dams and at hydroelectric power stations.	Only relatively low discharges allowed; there is great risk of clogging with debris.	Suitable for all species of fish if the dimensions of the pools and orifices are chosen as a function of the fish size that can be expected to occur. There might not be sufficient attraction current at low discharges.
Denil passes (sect. 5.3)		Wooden or concrete channel with sectioned baffles (usually of wood) that are U-shaped, and are set at an angle of 45° against the flow direction.	Channels: b = 0.6 to 0.9 m; h > 0.5 m; < 1:5; Q > 250 l/s. Channel lengths can be 6 to 8 metres; resting pools are required for heights > 1.5 to 2 m.	Suitable for small heads, particularly for retrofitting of old milldams when there is not much space.	Relatively high discharges; should not be used for variable headwater levels; not sensitive to varying tailwater levels; need little space; cheap; good formation of attraction current.	According to present knowledge, less suitable for weak swimmers or small fish. Selective. Benthic fauna cannot pass.

Special constructions

Type	Sketch	Principle	Dimensions* and discharge	Range of application	Advantages and disadvantages	Effectiveness
Eel ladders (sect. 5.4)		Generally, eel ladders are small channels with brush-type fittings, layers of brushwood or gravel, with water just trickling through them; also "eel pipes" that are led through the weir body and are filled with brushwood or brush-type material.	Channel: b = 30 to 50 cm; h = 15 to 25 cm. Slopes usually 1:5 to 1:10, but can be steeper.	Often used as a bypass in pool passes, but only useful where migration of glass eels and elvers occurs; in general not strictly necessary if there is another fish pass.	Low construction costs, only little space required, only low discharges needed.	Only suitable for glass eels and elvers. Eel pipes are not proven satisfactory because of their tendency to become clogged and the difficulty in maintenance. On their own, they are not sufficient to connect upstream and downstream habitats and cannot guarantee free passage for all fish.
Fish locks (sect. 5.5)		A pit-shaped chamber with controllable closures at headwater and tailwater openings. The attraction current is formed by controlling the sluice gate openings or by sending water through a bypass.	Their dimensions can vary, with minimum chamber width and water depth being similar to those in a pool pass. Water quantity requirements depend on chamber size, cycle intervals for lock operation and required intensity of attraction current.	Used for high heads, and where space or available water discharge is limited.	Planning and construction is often technically demanding. Require high efforts in maintenance and operating, high construction and service costs, low water consumption. Useful where very large fish (e.g. sturgeon) are to be taken into consideration.	According to present knowledge, suitable for salmonids and fish with weak swimming capacities. Less suitable for bottom-living and small fish.
Fish lifts (sect. 5.6)		Lifting device with transport trough and mechanical drive to hoist fish from tailwater to headwater; connection to headwater through a channel; water sent through a bypass creates attraction current.	Dimensions variable, volume of transport trough about 2 to 4 m^3. Continuous flow through a bypass needed to create attraction current.	Used for same situations as fish locks, but often the only type of pass that can be built for heights greater than 10 metres, e.g. at high dams.	Need little space. Planning and construction is often technically demanding. Require high efforts in maintenance and operating, high construction and service costs.	According to present knowledge, suitable for salmonids and fish with weak swimming capacities. Less suitable for bottom-living and small fish. Not suitable for macrozoobenthic fauna or for downstream migration of fish.

Many fish species undertake more or less extended migrations as part of their basic behaviour. Amongst the best known examples in Europe are salmon (*Salmo salar*) and sturgeon (*Acipenser sturio*), which often swim several thousands of kilometres when returning from the sea to their spawning grounds in rivers. In addition to these long-distance migratory species other fish and invertebrates undertake more or less short-term or small-scale migrations from one part of the river to another at certain phases of their life cycles.

Fish passes are of increasing importance for the restoration of free passage for fish and other aquatic species in rivers as such devices are often the only way to make it possible for aquatic fauna to pass obstacles that block their up-river journey. The fish passes thus become key elements for the ecological improvement of running waters. Their efficient functioning is a prerequisite for the restoration of free passage in rivers. However, studies of existing devices have shown that many of them do not function correctly. Therefore, various stakeholders, e.g. engineers, biologists and administrators, have declared great interest in generally valid design criteria and instructions that correspond to the present state-of-the-art of experience and knowledge.

Fishways can be constructed in a technically utilitarian way or in a manner meant to emulate nature. Bypass channels and fish ramps are among the more natural solutions, while the more technical solutions include conventional pool-type passes, slot passes, fish lifts, hydraulic fish locks and eel ladders. Comprehensive monitoring is crucial.

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