FISH PASSES

DESIGN, DIMENSIONS AND MONITORING

FAO FIAT PANIS

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.

Jiansan JIA
Chief, Inland Water Resources and
Aquaculture Service (FIRI)
Fishery Resources Division
Fisheries Department, FAO

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:

ADAM, Beate	Dr., Dipl.-Biol., Institut für angewandte Ökologie (Institute for Applied Ecology), Kirtorf-Wahlen
BOSSE, Rainer	Dipl.-Ing., RWE Energie AG, Bereich Regenerative Stromerzeugung (KR) (Rhenish-Westphalian Electricity Board, Department for Regenerative Electric Power Generation (KR)), Essen
DUMONT, Ulrich	Dipl.-Ing., Ingenieurbüro Floecksmühle (Floecksmühle Consulting Engineers), Aachen
GEBLER, Rolf-Jürgen	Dr.-Ing., Ingenieurbüro Wasserbau und Umwelt (Hydraulic Engineering and Environment Consulting Engineers), Walzbachtal
GEITNER, Verena	Dipl.-Ing., Ingenieurbüro Prein-Geitner (Prein-Geitner Consulting Engineers), Hildesheim
HASS, Harro	Dipl.-Biol., Fischereidirektor, Niedersächsisches Landesamt für Ökologie, Dezernat Binnenfischerei (Lower Saxony Regional Authority for Ecology, Department for Freshwater Fishery), Hildesheim
KRÜGER, Frank	Dr.-Ing., Landesumweltamt Brandenburg, Referat Gewässergestaltung, Wasserbau und Hochwasserschutz (Brandenburg Regional Environmental Authority, Department for River Design, Hydraulic Engineering and Flood Protection), Frankfurt/Oder
RAPP, Robert	Dr.-Ing., Abteilungsdirektor, Bayerische Wasserkraftwerke AG BAWAG (Bavarian Hydroelectric Company BAWAG), Munich

[1] to the original German publication

SANZIN, Wolf-Dieter	Dr., Dipl.-Biol., Regierungsdirektor, Bayerisches Landesamt für Wasserwirtschaft (Bavarian Regional Authority for Water Management), Munich
SCHAA, Werner	Dipl.-Ing., Regierungsbaudirektor, Staatliches Umweltamt Köln, Außenstelle Bonn (State Agency for Water and Waste Management – District of Cologne, Branch Office Bonn), Bonn, (President of this Technical Committee)
SCHWEVERS, Ulrich	Dr., Dipl.-Biol., Institut für angewandte Ökologie (Institute for Applied Ecology), Kirtorf-Wahlen
STEINBERG, Ludwig	Dipl.-Biol., Oberregierungsrat, Landesanstalt für Ökologie, Bodenordnung und Forsten/Landesamt für Agrarordnung Nordrhein-Westfalen, Dezernat für Fischerei (North Rhine-Westphalian Agency for Ecology, Land and Forestry/North Rhine-Westphalian Office for Agricultural Development in Recklinghausen (LÖBF), Department for Fisheries at Kirchhundem-Albaum), Kirchhundem-Albaum (Vice-President of this Technical Committee).

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).

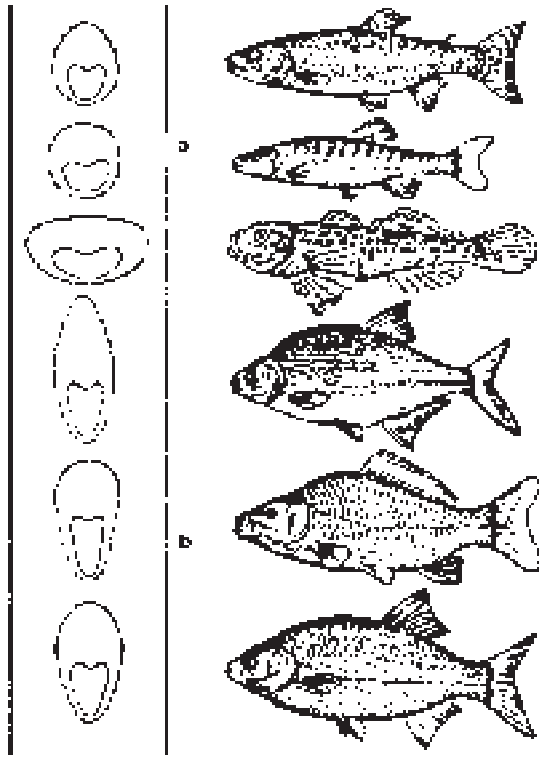

Fig. 2.1: Adaptations of body forms of fish to different flow velocities (from SCHUA, 1970)
(a) Species occurring in the fast flowing upper reaches of streams: brown trout, minnow, bullhead;
(b) Species occurring in slow flowing river regions: bream, carp, rudd.

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).

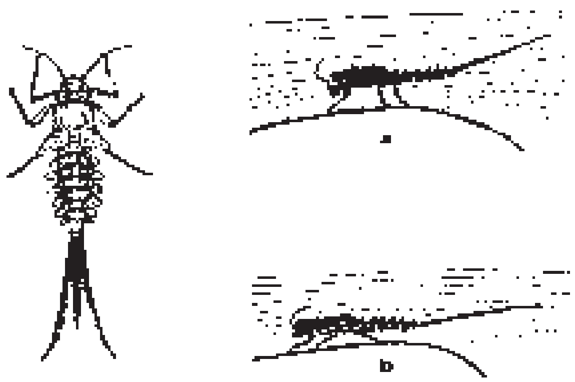

Fig. 2.2: Body posture of mayfly larvae of the genus Baetis (from SCHUA, 1970)
(a) in weak currents
(b) in strong currents

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.

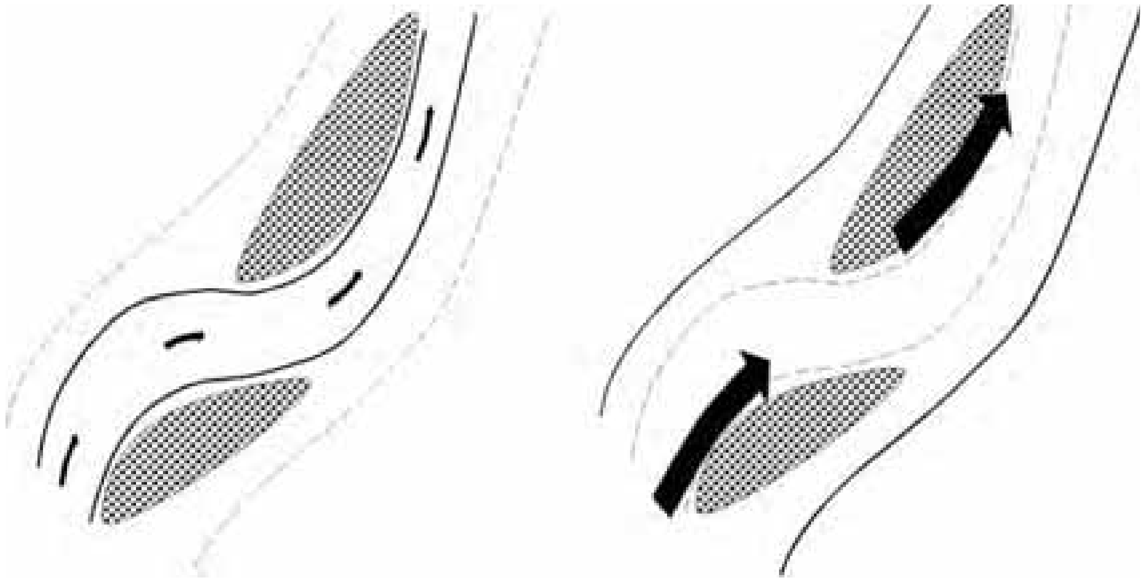

Fig.2.3: Changes in flow characteristics in a river at different discharge conditions
(a) at low water level: slow velocities; the water flows round obstacles
(b) at high water level: high velocities; the water flows over obstacles

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.

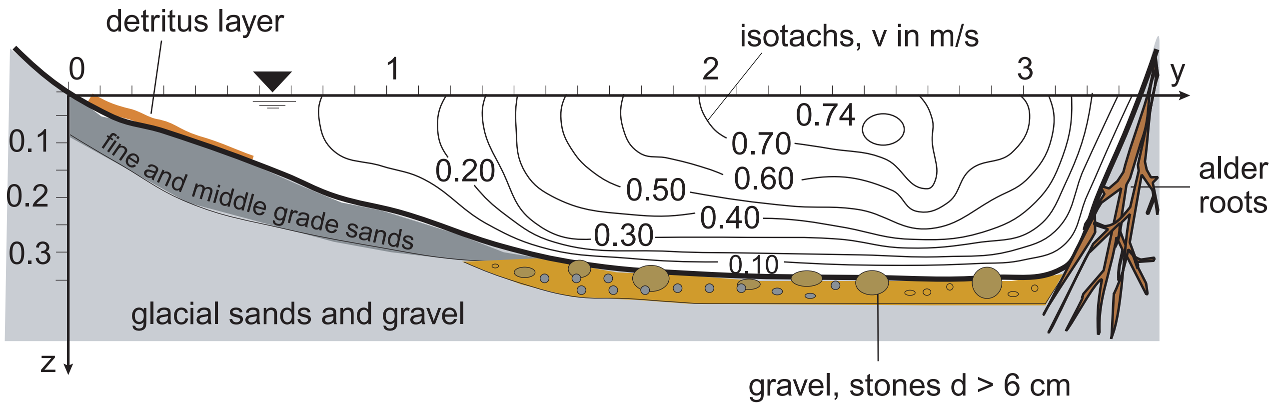

Fig. 2.4: Substrate distribution depending on flow velocity

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 10°C 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 0°C in winter and 20°C 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.

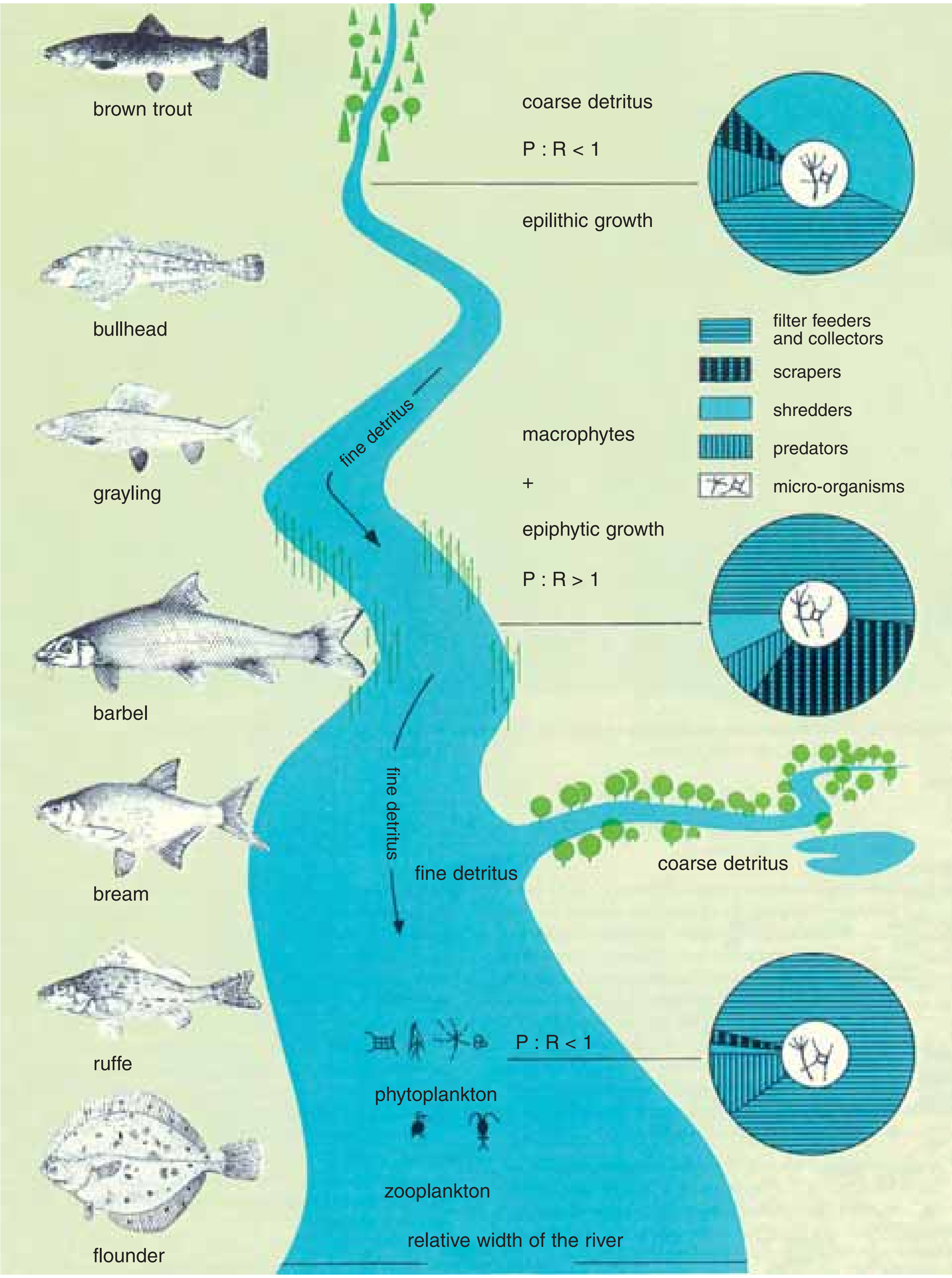

Figure. 2.5 River Continuum Concept: Alteration of structural and functional characteristics of running water biocoenoses as a function of the width of the river (From: Bavarian Regional Office for Water Management, 1987)
P = primary production; R = respiratory activity; P/R = ratio of primary production 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)*	main	main	secondary			
Bullhead *(Cottus gobio)*	main	main	main			
Brook lamprey *(Lampetra planeri)*	main	main	main			
Stone loach *(Noemach. barbatulus)*		main	main	secondary	secondary	
Minnow *(Phoxinus phoxinus)*		secondary	main	secondary		
Stickleback *(Gasterosteus aculeatus)*		secondary	main	main	main	main
Grayling *(Thymallus thymallus)*			main	secondary		
Riffle minnow *(Alburnoides bipunct.)*			main	main		
Dace *(Leuciscus leuciscus)*			main	main	secondary	secondary
Gudgeon *(Gobio gobio)*			main	main	main	main
Chub *(Leuciscus cephalus)*			main	main	main	main
Roach *(Rutilus rutilus)*			main	main	main	main
Barbel *(Barbus barbus)*			secondary	main		
Nase *(Chondrostoma nasus)*			secondary	main		
Bleak *(Alburnus alburnus)*				main	main	main
White bream *(Blicca bjoerkna)*				main	main	main
Perch *fluviatilis)*				main	main	main
Pike *(Esox lucius)*				main	main	main
Bream *(Abramis brama)*				secondary	main	main
Ruffe *(Gymnoceph. cernua)*				secondary	main	main
Orfe *(Leuciscus idus)*				secondary	main	main
Rudd *(Scardinius erythrophthalamus)*					main	main
Carp *(Cyprinus carpio)*					main	main
Tench *(Tinca tinca)*					main	main
Anadromous species						
Sea trout *(Salmo trutta f. trutta)*		main	main	secondary	secondary	secondary
Salmon *(Salmo salar)*		secondary	main	secondary	secondary	secondary
River lamprey *(Lampetra fluviatilis)*			main	secondary	secondary	secondary
Sea lamprey *(Petromyzon marinus)*		secondary	secondary	secondary	secondary	
Allis shad *(Alosa alosa)*				main	secondary	secondary
Twaite shad *(Alosa fallax)*				main	main	secondary
Sturgeon *(Acipenser sturio)*				secondary	main	main
Catadromous species						
Eel *(Anguilla anguilla)*			secondary	main	main	main
Flounder *(Platichthys flesus)*				secondary	main	main

main = Main distribution area of reproductive populations

secondary = Secondary distribution area of reproductive populations

Table 2.2: River zoning (after ILLIES, 1961)

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

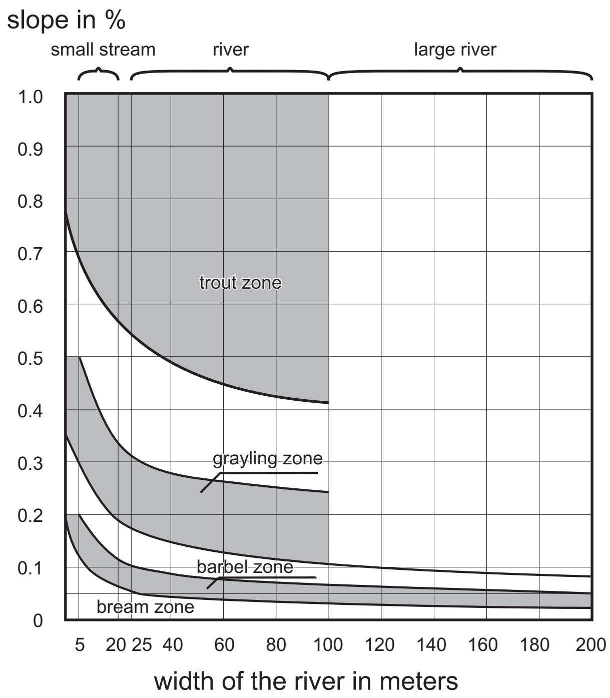

Fig. 2.10 Graphical representation of the relations between slope, river width and river zoning for determination of indicator fish zones (modified from HUET, 1959). The typical core zones are shown in grey; the zones lying between the grey fields are transitional zones. However, these transitions take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

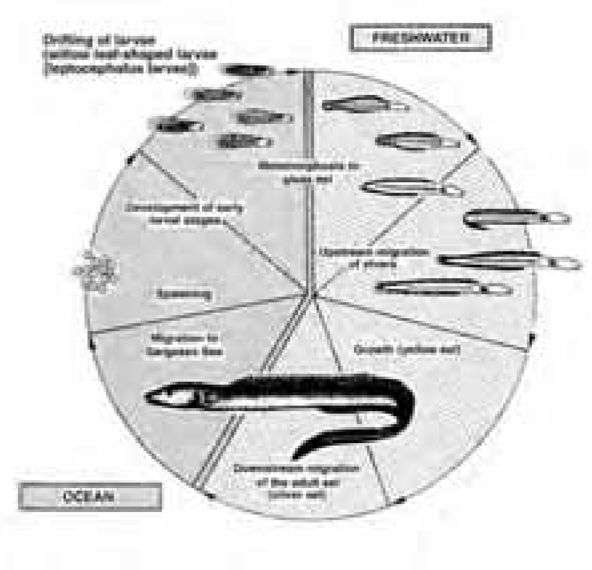

Fig. 2.16: Life cycle of catadromous migratory fish: example of the eel *(Anguilla anguilla)*

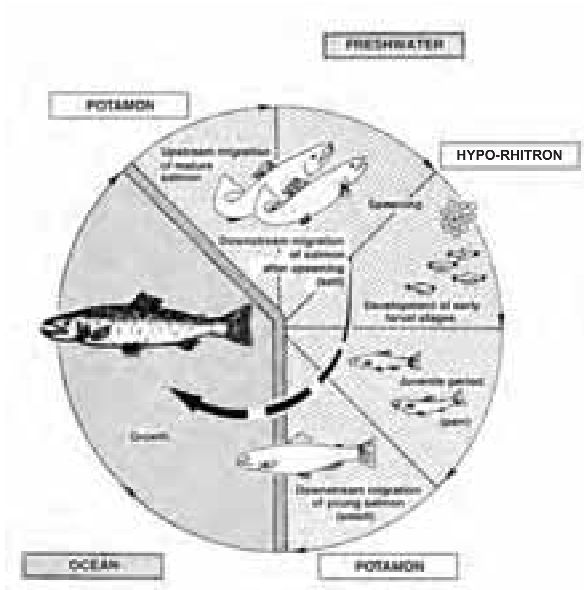

Fig. 2.17: Life cycle of anadromous migratory fish: example of the salmon *(Salmo salar)*

- 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.

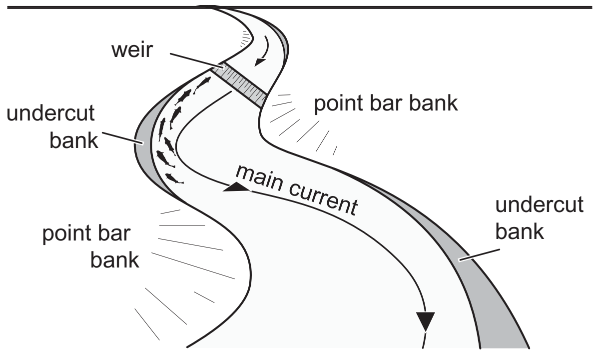

Fig. 3.4: Diagram showing the flow pattern in a river with undercut banks and point bar banks. Fish swimming in or along the main current will arrive at the weir along the side of the undercut bank. Consequently, a fish pass should be positioned as closely as possible to the point where the fish meet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

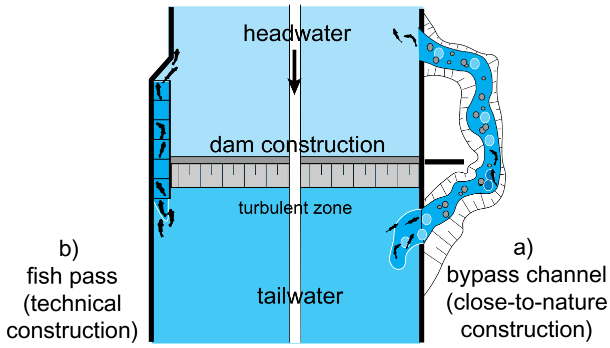

Fig. 3.5: a) Optimum position of a bypass channel and
b) optimum position of a technical fish pass:

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

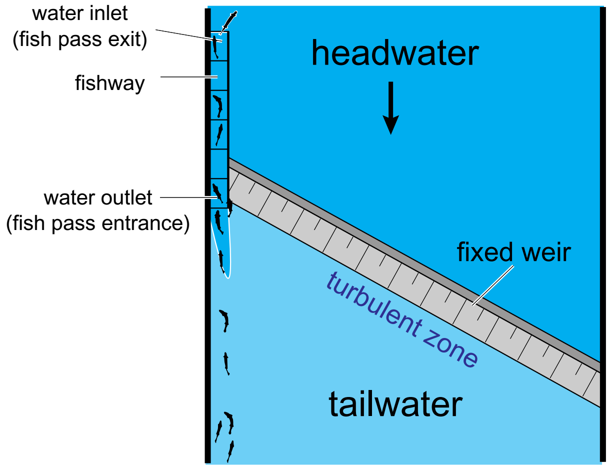

Fig. 3.6: Fish moving upstream gather in the narrow angle between the weir and the bank. This is the most suitable location for the construction of a fish pass (after LARINIER, 1992d).

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

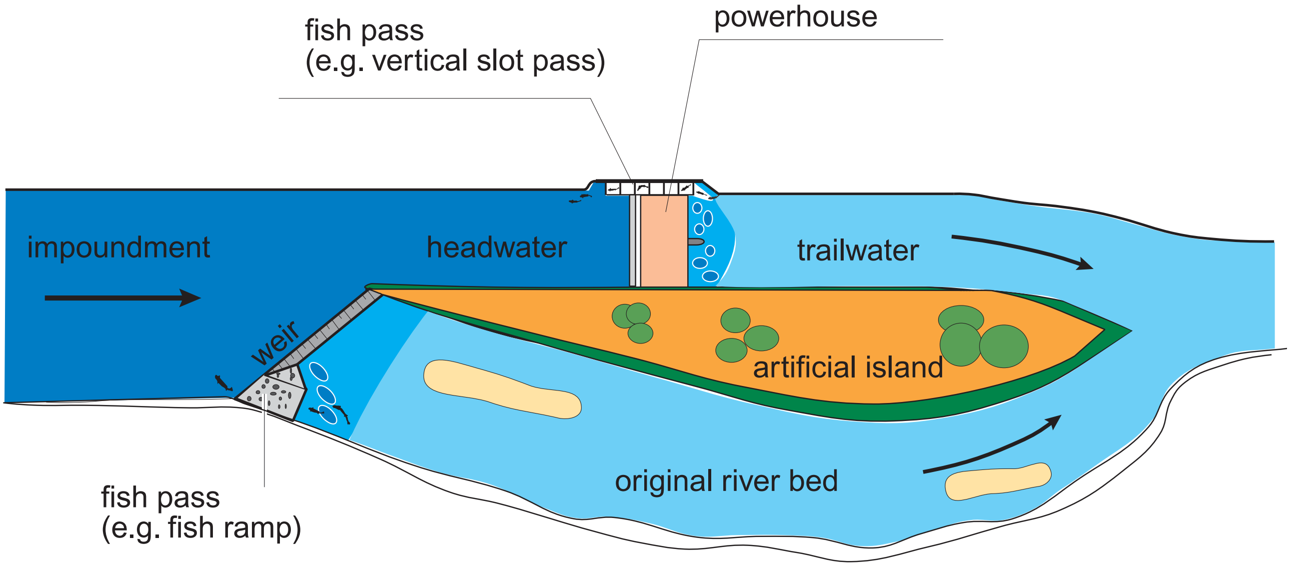

Figure 3.7: Ensuring longitudinal connectivity at a bypass hydroelectric power station through construction of two fish passes, i.e. one directly at the hydropower plant and the other at the weir.

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

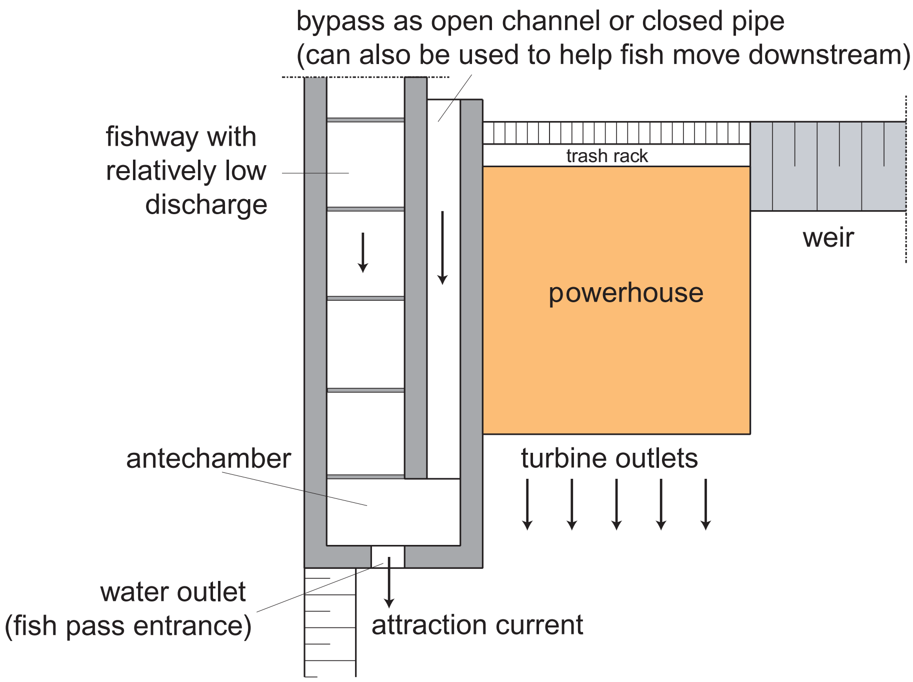

Figure 3.8:
Additional discharge is sent through a bypass into an antechamber downstream of the first pool of the fish pass to increase the attraction current at the fish entrance

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

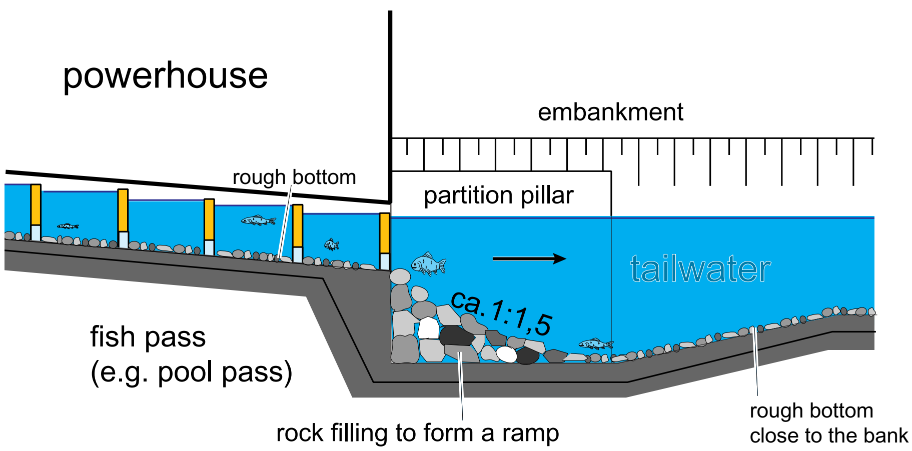

Figure 3.9:
Underwater rockfill ramp connecting the fish pass entrance with the river bottom

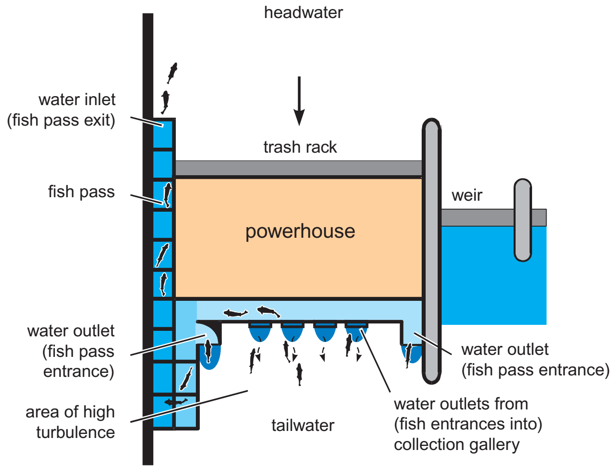

Fig. 3.10: Diagram of an American hydroelectric power station with a collection gallery (after LARINIER, 1992d)

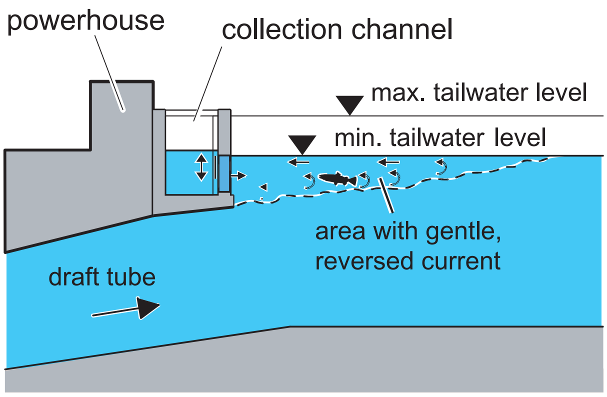

Fig. 3.11: Cross-section through a collection gallery (after LARINIER, 1992d)

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

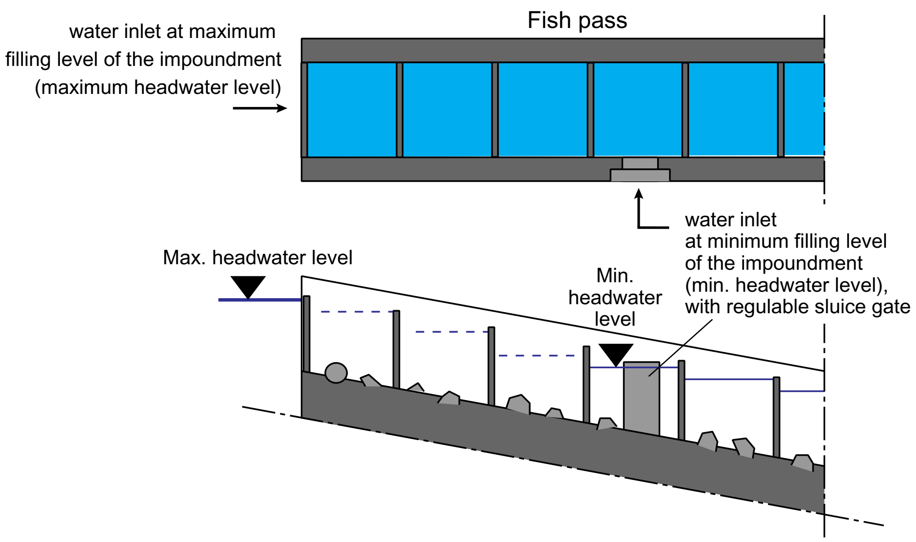

Figure 3.12:
At the side of the impoundment, several water inlets (fish exits[#]) at different levels guarantee that fish can leave the fish pass even at varying (lower) headwater levels.

[#] 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

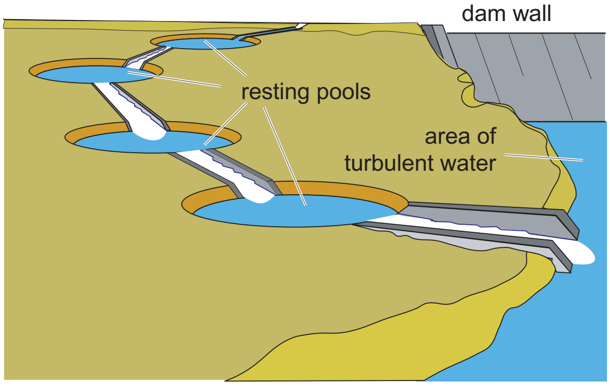

Fig. 3.13: Technical fish pass with resting pools, bypassing the obstacle in a bent design (modified from TENT, 1987)

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.