4 Close-to-nature types of fish passes

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

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

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

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

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

4.1 Bottom ramps and slopes

4.1.1 Principle

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

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

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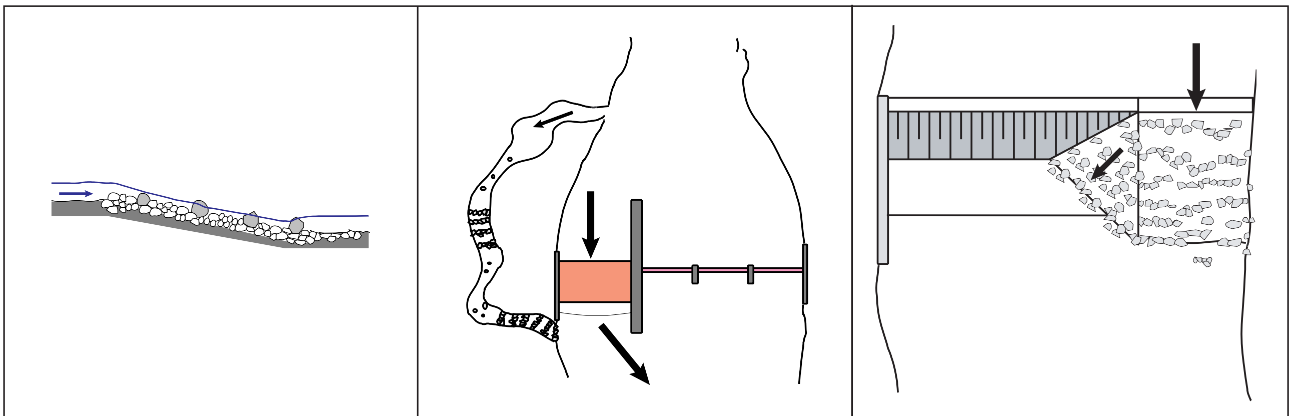


a) **Bottom ramp and slope:**	b) **Bypass channel:**	c) **Fish ramp:**
A sill having a rough surface and extending over the entire river width with as shallow a slope as possible, to overcome a level difference of the river bottom. This category also includes stabilizing structures (e.g. stabilizing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

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

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

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

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

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

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

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

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

4.1.2 Design and dimensions

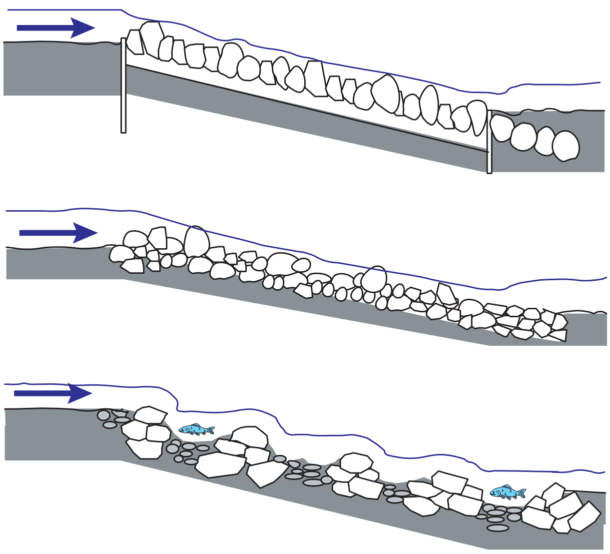
4.1.2.1 Construction styles

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

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

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

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



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

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

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

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

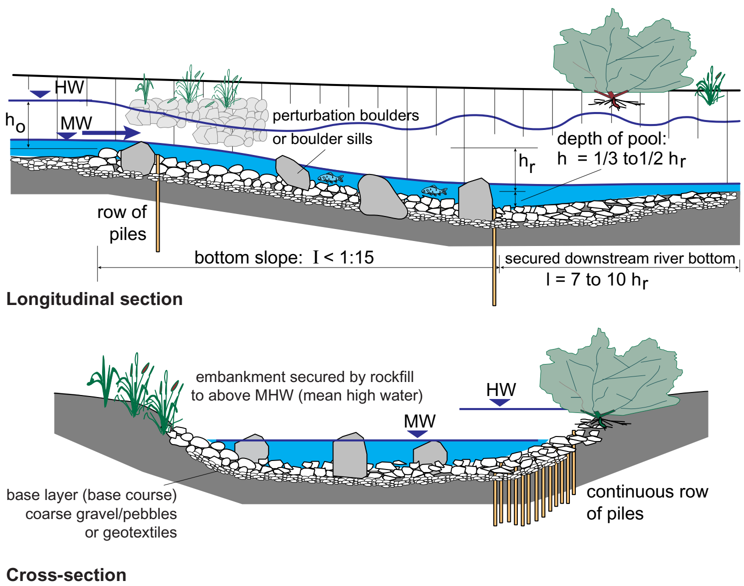


Figure 4.4:
Bottom slope as rockfill construction (modified from GEBLER, 1990)

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

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

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

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

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

All elements of the river fauna can negotiate rockfill ramps.

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

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

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

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

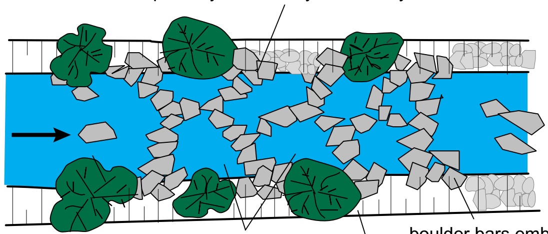


Fig. 4.5: Bottom step in boulder bar construction (plan view)

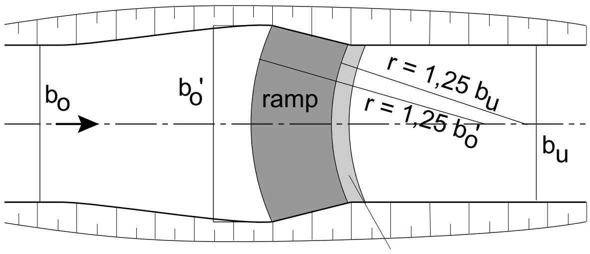


Fig. 4.6: Plan view of a curved bottom ramp (after SCHAUBERGER, 1975)

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

4.1.2.2 Plan view

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

4.1.2.3 Longitudinal section

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

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

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

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

4.1.3 Remodelling of drops

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

4.1.4 Conversion of regulable weirs into dispersed or cascaded ramps

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

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

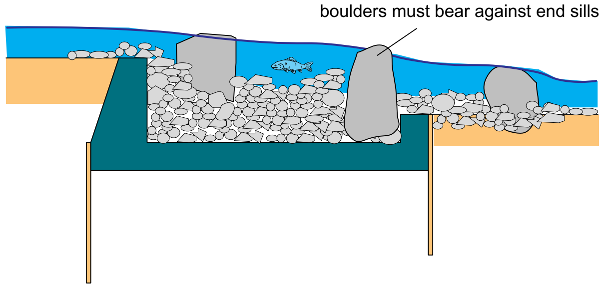


Fig. 4.7: Conversion of an artificial drop into a rough bottom slope.

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

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

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

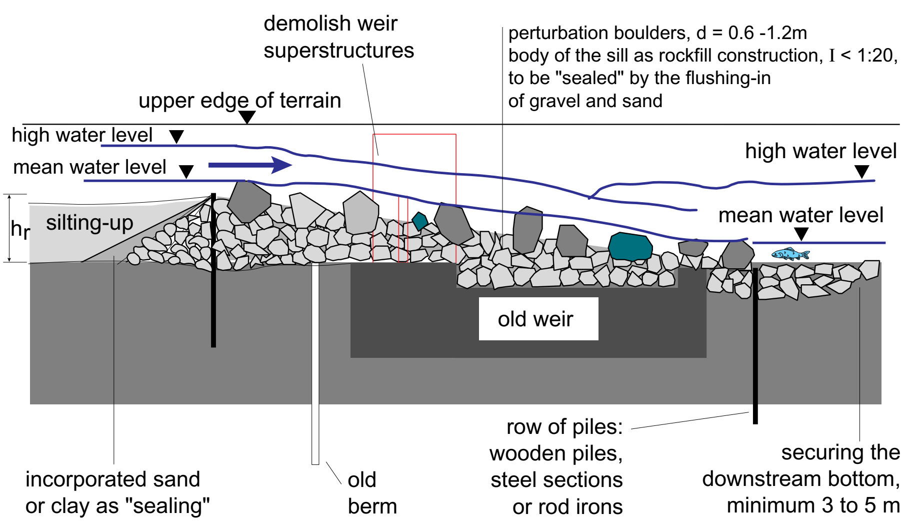


Figure 4.8
Conversion of a regulable weir into a protection sill

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

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

4.1.5 Overall assessment

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

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

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

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

4.1.6 Examples

GROSSWEIL BOTTOM RAMP

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

Constructional design:

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

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

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

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

BISCHOFSWERDER PROTECTION SILL

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

Description of construction:

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

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

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

Figure 4.11:
Bischofswerder protection sill after modification

MAXLMÜHLE BOTTOM SILL

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

Description of construction:

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

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

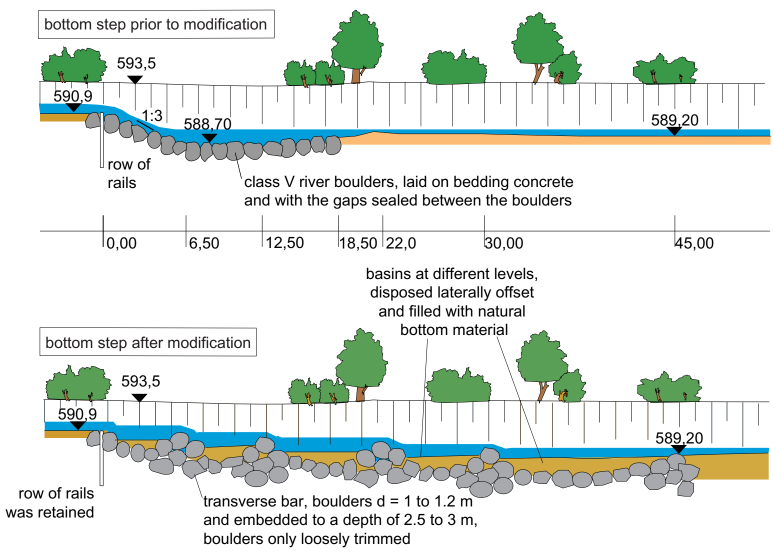


Figure 4.12:
Longitudinal section of a bottom step in the Mangfall River, boulder bar construction (diagrammatic).

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

MÜHLENHAGEN BOTTOM SILL

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

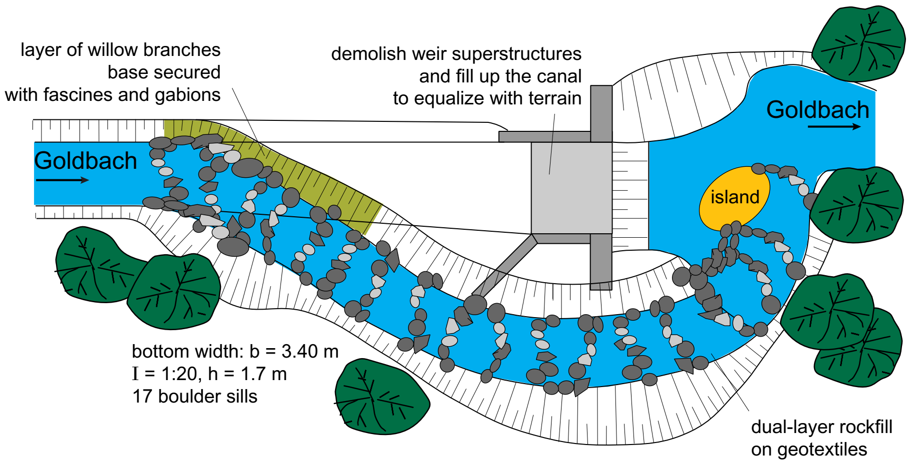


Figure 4.14: Plan view showing the position of the Mühlenhagen/Goldbach bottom ramp

Figure 4.15: Mühlenhagen/Goldbach bottom ramp

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

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

4.2 Bypass channels

4.2.1 Principle

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

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

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

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

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

4.2.2 Design and dimensions

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

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

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

Slope:

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

bottom width:

$b_{bot} > 0.80$ m;

mean depth of water:

$h > 0.2$ m;

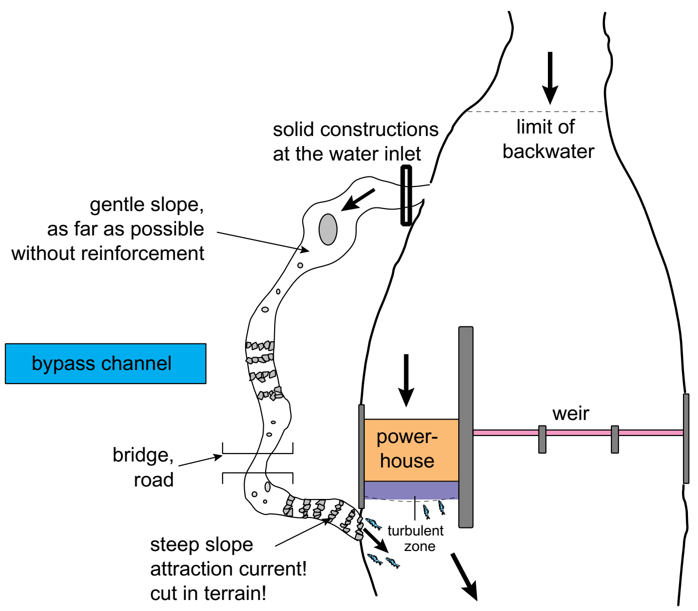


Figure 4.16:
Bypass channel.
Bypass around a dam:
example of common design

mean flow velocity:

v_m = 0.4 to 0.6 m/s

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

maximum flow velocity:

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

bottom:

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

shape:

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

cross-section

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

width-related discharge:

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

4.2.2.1 Plan view

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

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

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

4.2.2.2 Longitudinal section

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

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

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

in that particular region and require no extensive reinforcements.

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

4.2.2.3 Channel cross-section

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

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

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

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

4.2.2.4 Big boulders and boulder sills

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

The following methods can be used:

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

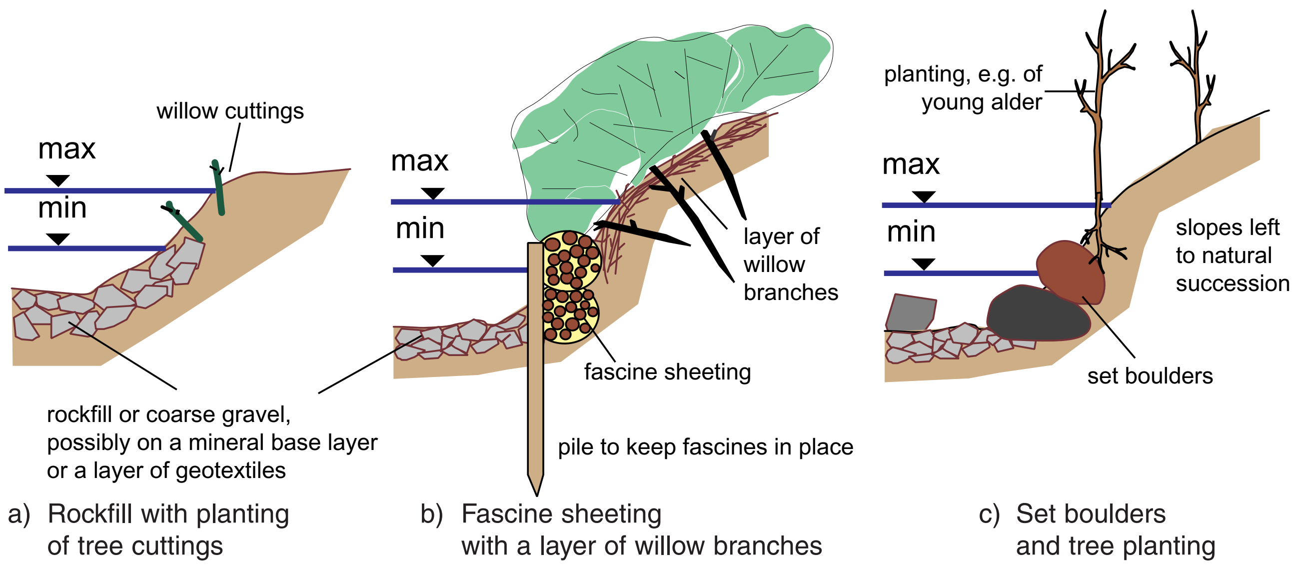


Figure 4.18: Examples for securing bottom and banks of bypass channels

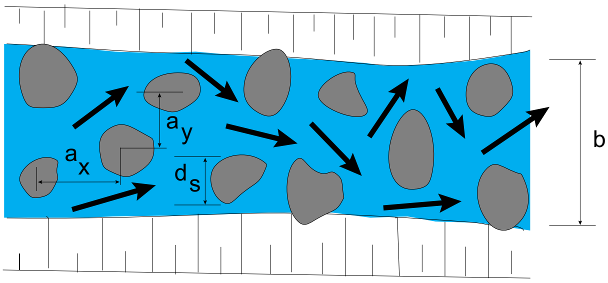


Fig 4.19: A bypass channel in which perturbation boulders have been placed

ax = ay = 2 to 3 ds

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

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

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

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

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

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

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

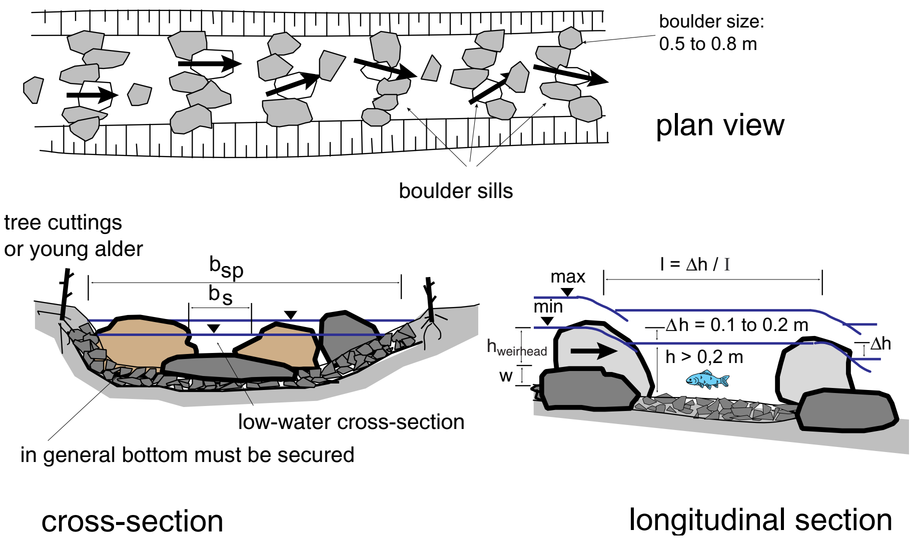


Fig 4.20: Boulder sills for breaking the slope in a bypass channel

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

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

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

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

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

4.2.2.6 Crossings

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

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

4.2.3 Overall assessment

The most important advantages of bypass channels are as follows:

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

remark by the editor

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

These advantages are counterbalanced by the following disadvantages:

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

4.2.4 Examples

VARREL BÄKE STREAM BYPASS CHANNEL

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

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

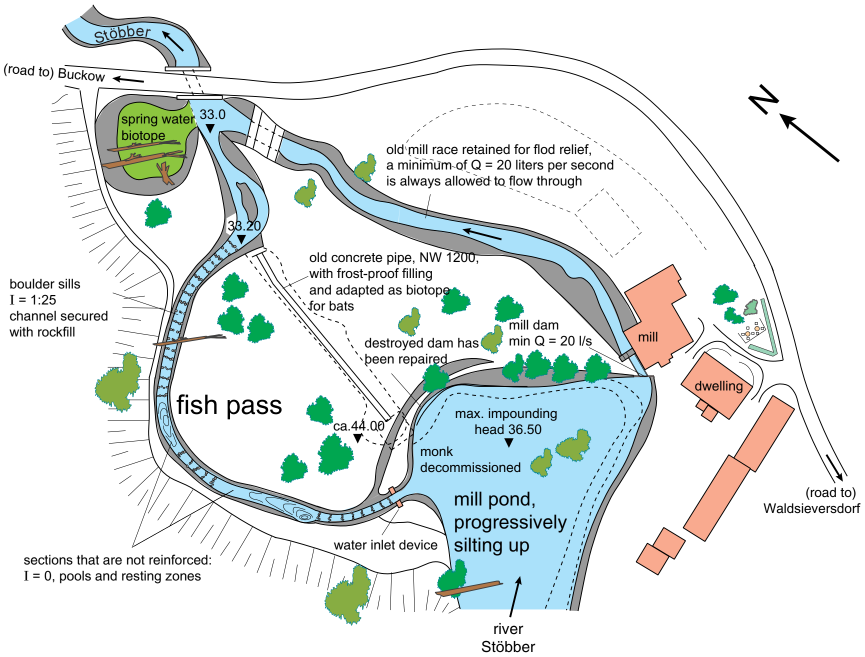
Although the abandoned mill dam is no longer used for hydropower generation, it had to be preserved for reasons of bottom stabilisation and the maintenance of the ground water levels. Water for feeding the fishponds is diverted at a location upstream of the mill dam. With discharges up to MNQ (mean low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

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

SEIFERT'S MILL BYPASS CHANNEL

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

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



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

Figure 4.24:
Bypass channel at Seifert's Mill

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

KINSAU BYPASS CHANNEL

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

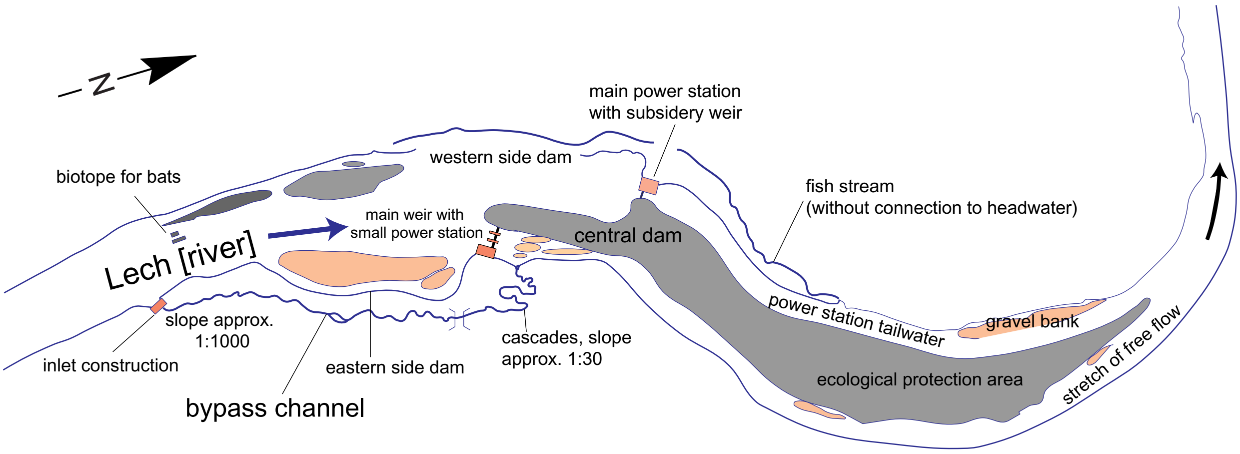


Figure 4.25: Sketch of position

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

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

4.3 Fish ramps

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

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

4.3.1 Principle

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

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

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

4.3.2 Design and dimensions

4.3.2.1 Plan view

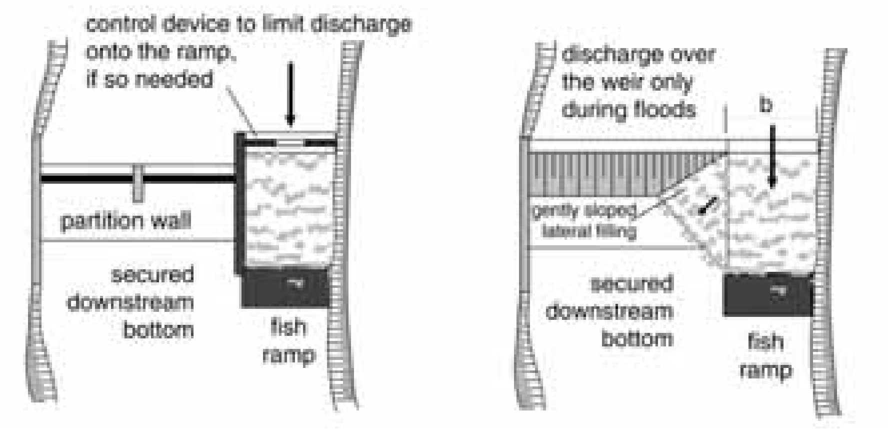
As a rule, fish ramps are set by riverbanks and the bank that receives the greater portion of the current is the most favourable. The upper, acute angle should be selected for the construction of the fish ramp at submerged weirs standing obliquely in the river. An existing empty evacuation channel or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

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

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

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

[#] remark by the editor



Weir with movable shutters   fixed weir

Figure 4.27: Positioning of fish ramps at dams

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

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

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

4.3.2.2 Longitudinal section

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

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

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

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

4.3.2.3 Body of the ramp

The construction types usually used for the bottom sills are:

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

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

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

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

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

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

4.3.2.4 Big boulders and boulder sills

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

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

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

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

The hydraulic calculation is described in section 4.4.

4.3.2.5 Bank protection

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

4.3.2.6 Stabilized zone downstream of the fish ramp

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

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

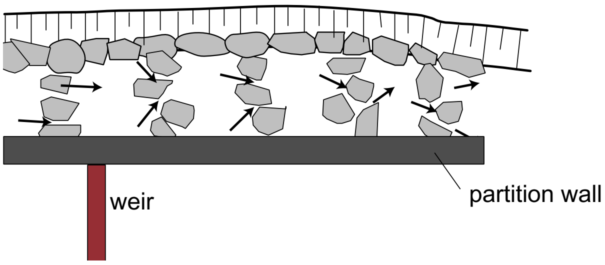


Figure 4.30: Rough-channel pool pass (plan)

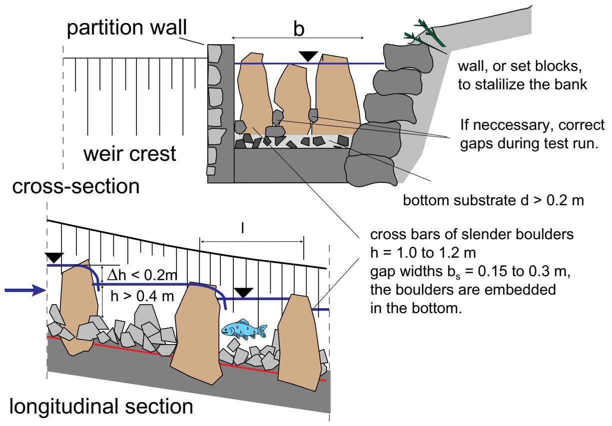


Fig. 4.31: Rough-channel pool pass (channel cross-section and longitudinal section)

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

4.3.3 Special cases

4.3.3.1 Rough-channel pool pass

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

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

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

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

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

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

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

4.3.3.2 Pile pass

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

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

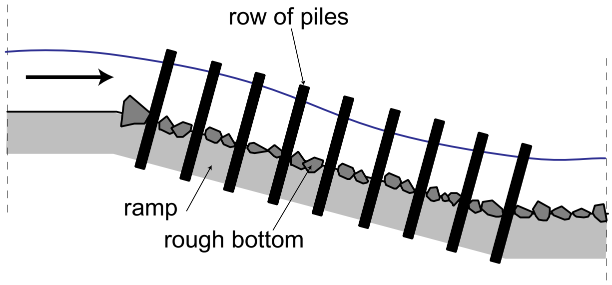


Fig. 4.32: Pile pass (diagrammatic longitudinal section)

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

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

4.3.4 Overall assessment

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

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

Their disadvantages are:

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

4.3.5 Examples

ESELSBRÜCKE FISH RAMP

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

Description of the construction:

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

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

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

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

DATTENFELD FISH RAMP

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

Description of the construction:

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

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

Figure 4.35: View from tailwater

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

DELMENHORST FISH RAMP

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

Details of construction

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

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

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

Figure 4.36:
Delmenhorst fish ramp.

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

[#] remark by the editor

UHINGEN ROUGH-CHANNEL POOL PASS

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

Details of construction

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

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

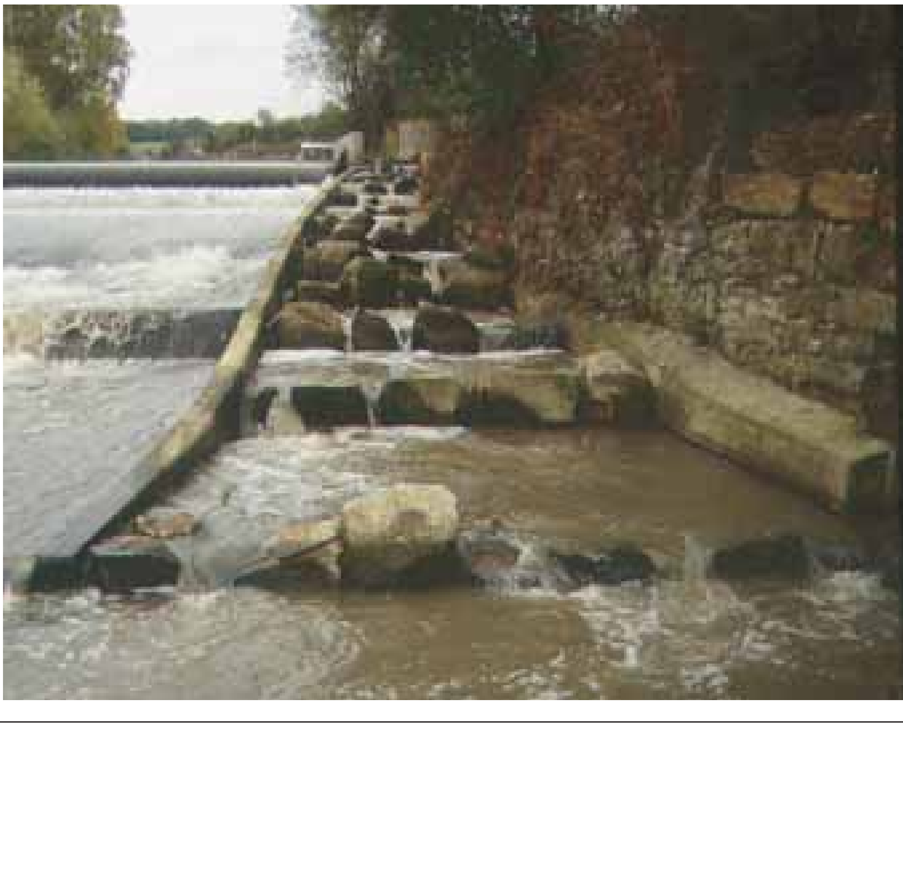


Figure 4.37:
Uhingen/Fils rough-channel pool pass

View from tailwater end.

FISH RAMP AT THE SPILLENBURG WEIR

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

Details of construction

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

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

Figure 4.38: Setting the boulder bars

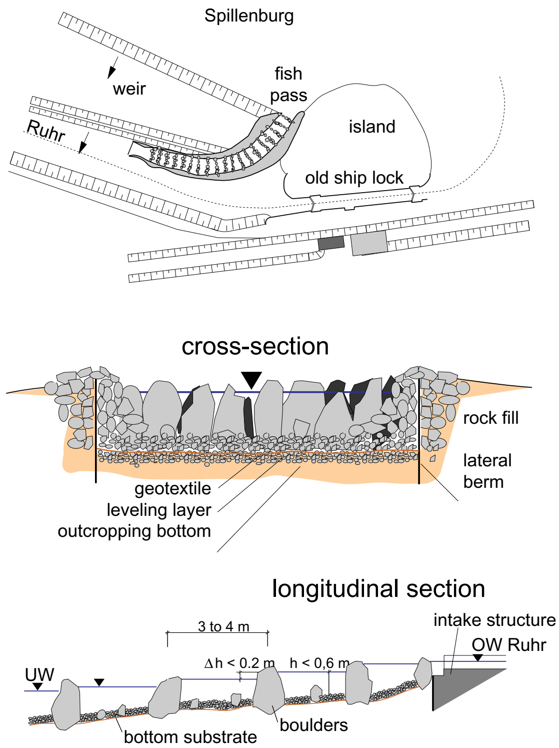


Figure 4.39: Layout and ramp design

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FISH RAMP AT THE SPILLENBURG WEIR

Figure 4.40: Spillenburg weir; fish ramp under construction

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

Figure 4.41: Spillenburg weir; fish ramp after completion

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

4.4 Hydraulic design

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

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

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

4.4.1 Flow formulae

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

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

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

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

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

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

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

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

remark by the editor

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

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

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

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

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

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

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

4.4.2 Flow resistance of perturbation boulders

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

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

in which is

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

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

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

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

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

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

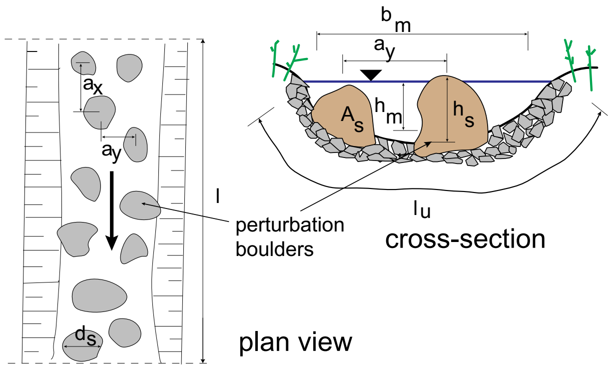

Fig. 4.42: Bypass channel with perturbation boulders

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

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

$$\lambda_{tot} = \lambda_s + \lambda_o \tag{4.6}$$

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

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

with d_s, a_x, a_y as in Figure 4.42.

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

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

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

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

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

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

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

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

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

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

Remarks

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

An example of calculation

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

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

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

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

Ramp width at water level:

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

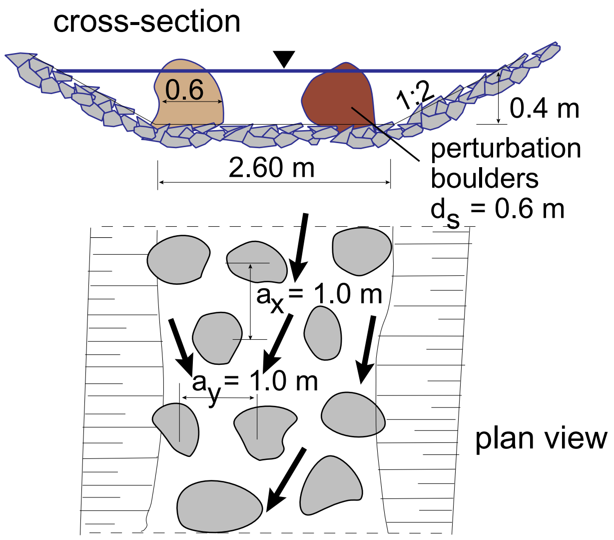

Fig. 4.43: Sketch to illustrate the example of calculation

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

Each individual perturbation boulder has a wetted surface of

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

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

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

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

Based on $\Sigma A_s = 28 \cdot 0.24 = 6.72 \text{ m}^2$

and $A_{o,tot} = l \cdot l_u = 10 \cdot 4.39 = 43.9 \text{ m}^2$

the resistance coefficient of the perturbation boulders is calculated as

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

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

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

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

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

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

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

and hence the discharge:

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

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

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

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

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

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

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

$$\rightarrow Fr = 0.48 \tag{4.8}$$

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

In the most constricted cross-section, where

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

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

the Froude number becomes:

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

$$\rightarrow Fr_e = 1.13. \tag{4.8a}$$

remark by the editor

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

For comparison:

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

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

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

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

a mean flow velocity follows of

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

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

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

4.4.3 Design calculation of boulder sills

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

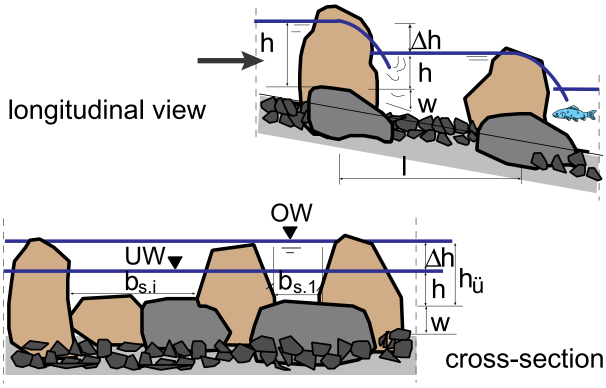

Fig. 4.44: Hydraulic design calculation for bypass channels and ramps with boulder sills (schematic diagram)

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

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

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

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

where Σb_s – the sum of the unobstructed flow widths.

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

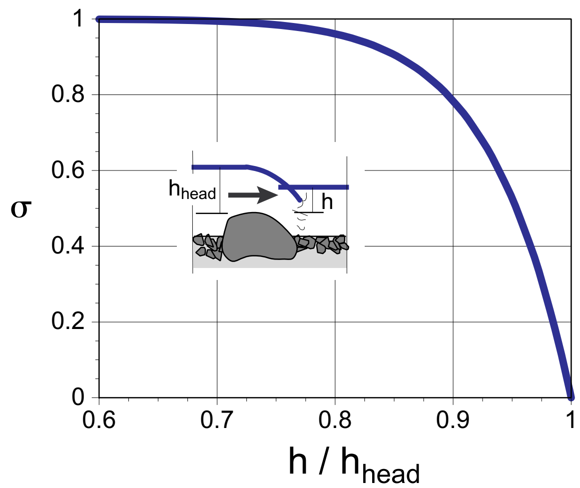

Figure 4.46: Drowned-flow reduction factor σ

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

Broad, sharp-edged rocks, crushed material:

$\mu \approx 0.5$ to 0.6

Rounded stones, e.g. fieldstones:

$\mu = 0.6$ to 0.8

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

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

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

remark by the editor

The size and depth of pools between the sills should guarantee low-turbulence flow so that migrating fish find enough shelter and opportunities to recover from their swimming efforts. The guide value for the volumetric power dissipation is E = 150 to 200 W/m^3, and can be calculated from the following formula

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

where h_m = mean water depth in the pools

b = mean pool width

A = mean pool cross-section

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

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

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

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

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

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

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

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

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

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

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

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

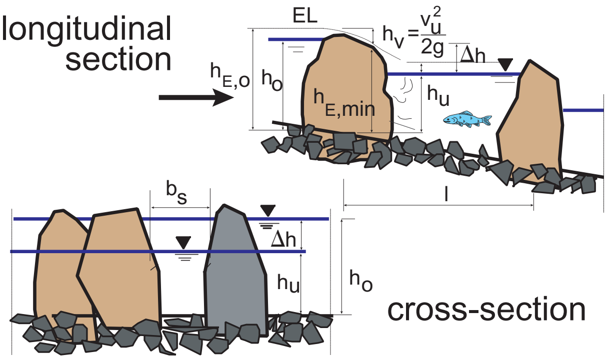

Figure 4.47: Flow at a boulder sill

An example of calculation

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

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

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

The maximum flow velocity is obtained from

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

and is thus lower than the permissible flow velocity

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

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

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

h_{head} = 0.4 - 0.2 = 0.2 m.

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

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

$$\approx 0.75 \text{ m}$$

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

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

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

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

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

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

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

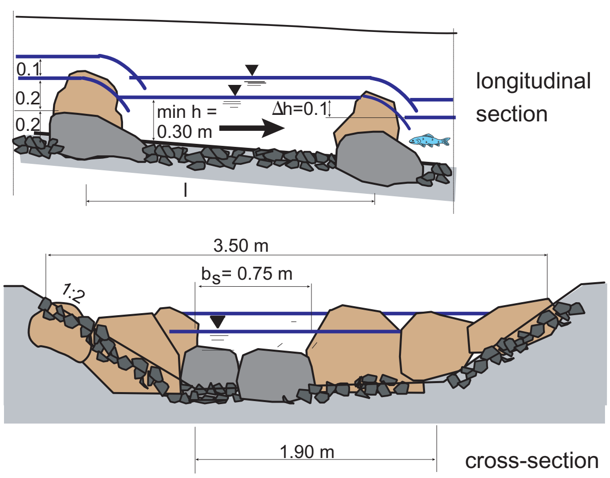

Fig. 4.48: Sketch to illustrate the example of calculation

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

Supposing that the head h_{head} is

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

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

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

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

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

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

is carried through, so the total discharge amounts to

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

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

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

while at maximum discharge they increase to

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

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

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

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

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

the volumetric power dissipation results as

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

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

4.4.4 Critical discharge over bottom ramps and slopes

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

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

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

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

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

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

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

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

4.4.5 Trial runs

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

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

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