5 Technical fish passes

Technical fish passes include the following types:

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

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

5.1 Pool pass

5.1.1 Principle

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

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

5.1.2 Design and dimensions

5.1.2.1 Plan view

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

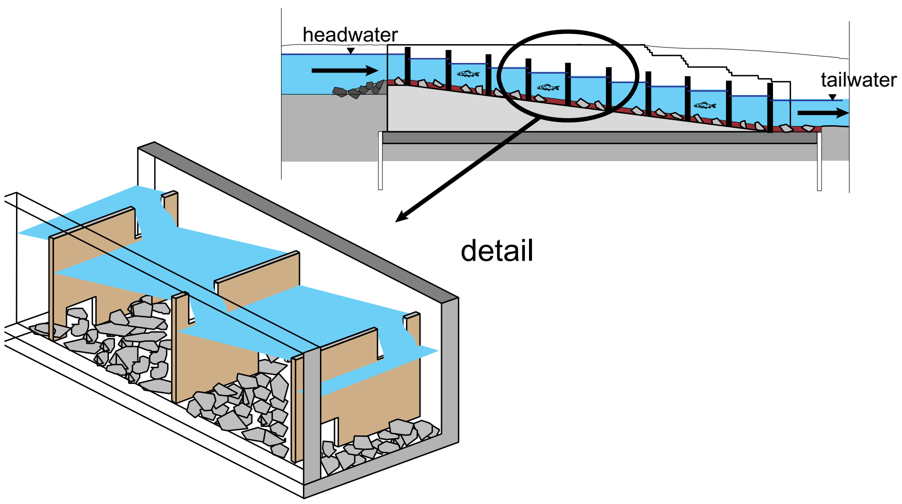

Figure 5.1: Conventional pool pass (longitudinal section and pool structure) (modified and supplemented after JENS, 1982)

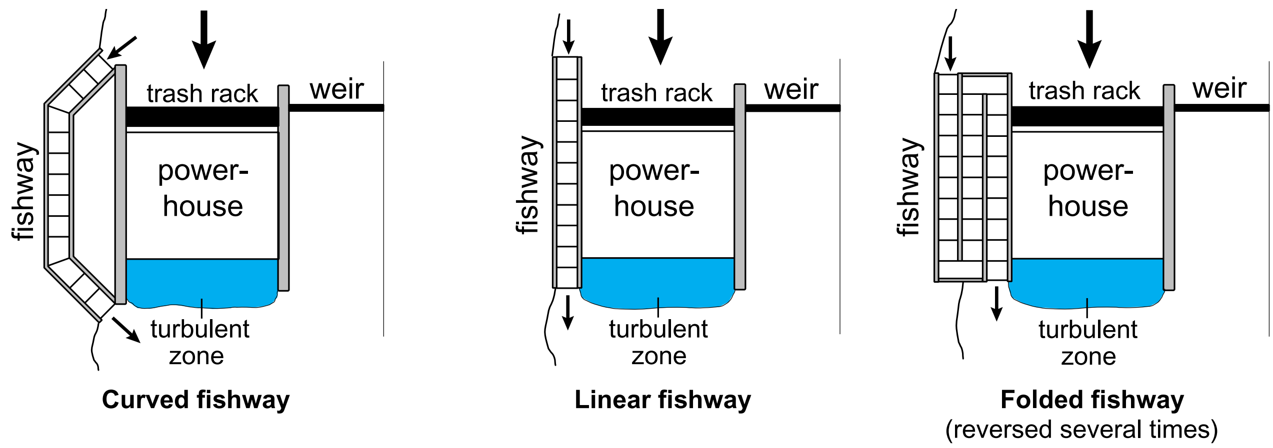

Figure 5.2: Pool passes (plan view) (modified and supplemented after LARINIER, 1992a)

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

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

5.1.2.2 Longitudinal section

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

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

where l_b is as shown in Figure 5.4,

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

remark by the editor

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

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

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

5.1.2.3 Pool dimensions

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

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

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

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

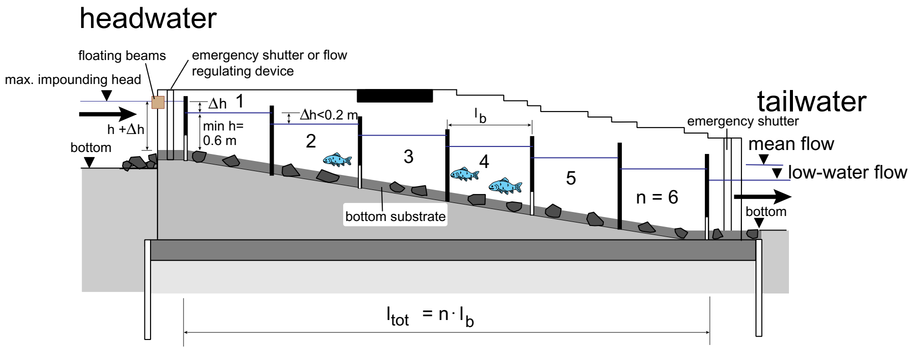

Figure 5.4: Longitudinal section through a pool pass (schematic)

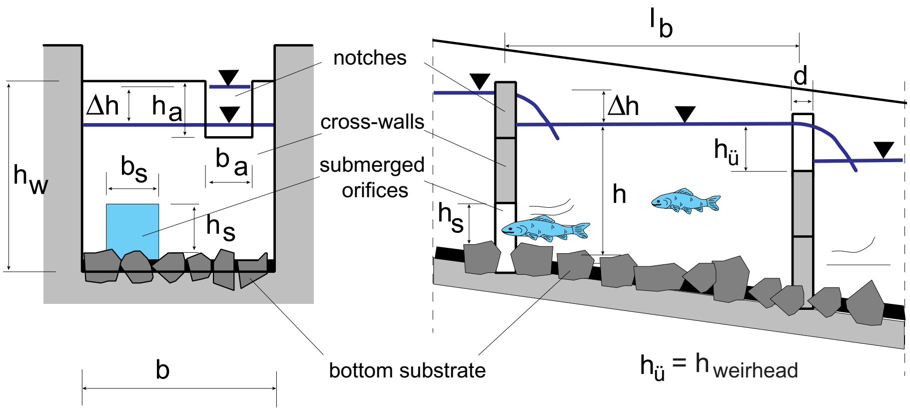

Figure 5.5: Pool-pass terminology

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

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

5.1.2.4 Cross-wall structures

5.1.2.4.1 Conventional pool pass

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

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

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

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

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

remark by the editor

Table 5.1 Recommended dimensions for pool passes

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

Remarks

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

5.1.2.4.2 Rhomboid pass

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

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

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

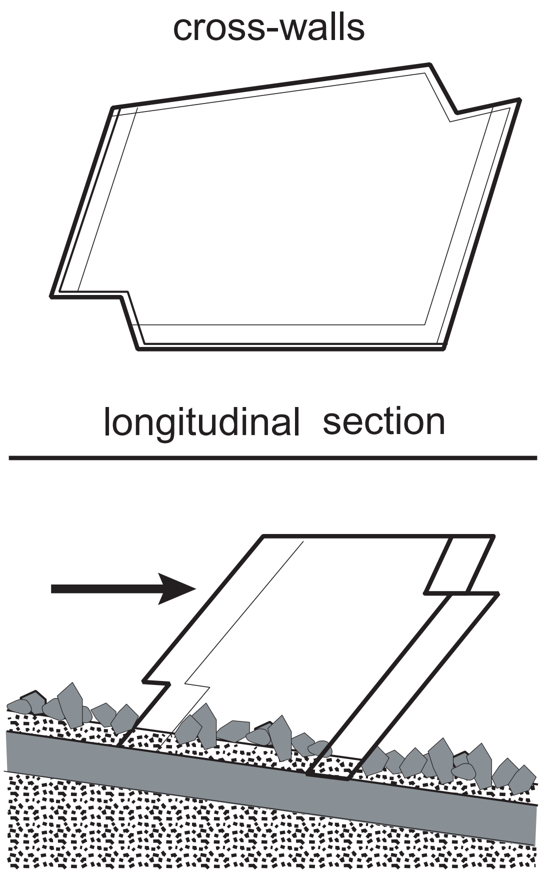

Fig. 5.6: Cross-wall design of a rhomboid pass (after JENS, 1982)

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

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

5.1.2.4.3 Humped fish pass

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

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

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

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

5.1.3 Hydraulic design

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

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

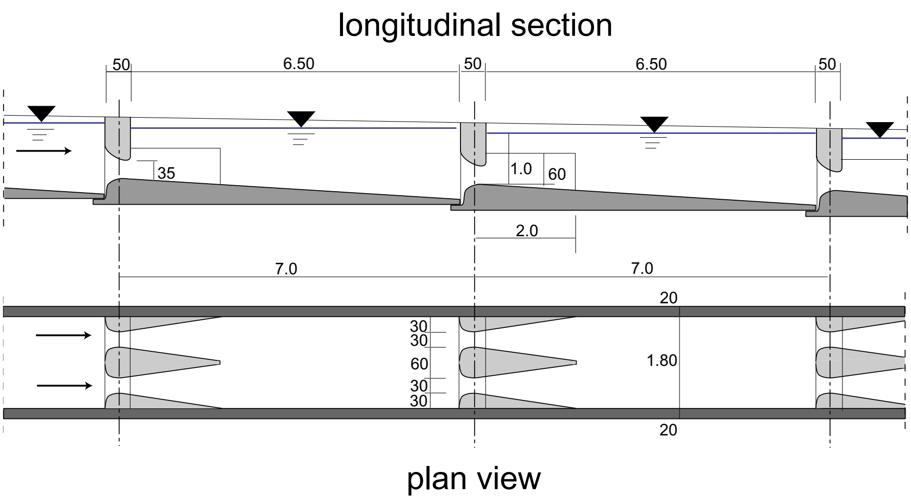

Figure 5.8: Design and dimensions of the pools of a humped fish pass at the Geesthacht dam on the river Elbe (measurements in cm or m) (after HENSEN & SCHIEMENZ, 1960)

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

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

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

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

The equation

$$Q_s = \psi A_s \sqrt{2g\Delta h} \qquad (5.4)$$

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

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

The discharge over the top notches can be calculated from

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

where

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

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

σ is the drowned-flow reduction factor.

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

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

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

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

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

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

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

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

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

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

Example of calculation for a conventional pool pass

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

The pool dimensions are selected from Table 5.1 as follows:

Pool width b = 1.4 m

minimum water depth h = 0.6 m.

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

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

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

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

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

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

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

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

and for Δh = 0.15 m

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

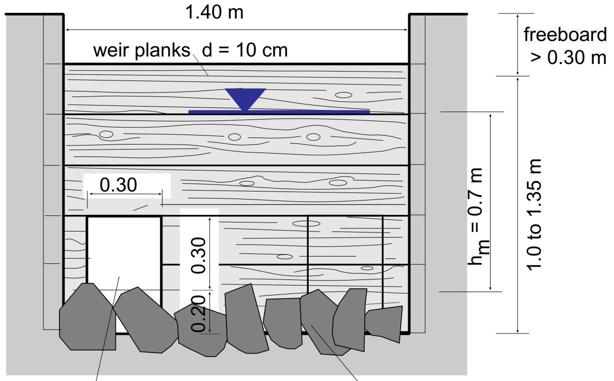

Figure 5.9: Cross-section through the pools

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

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

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

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

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

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

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

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

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

$$\rightarrow \quad l_b = 1.89 \approx 1.90 \text{ m}$$

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

$$h_w = 1.0 + 0.20 + 0.15 = 1.35 \text{ m}$$

and the height of the upstream wall

$$h_w = 0.8 + 0.20 = 1.0 \text{ m}.$$

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

5.1.4 Overall assessment

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

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

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

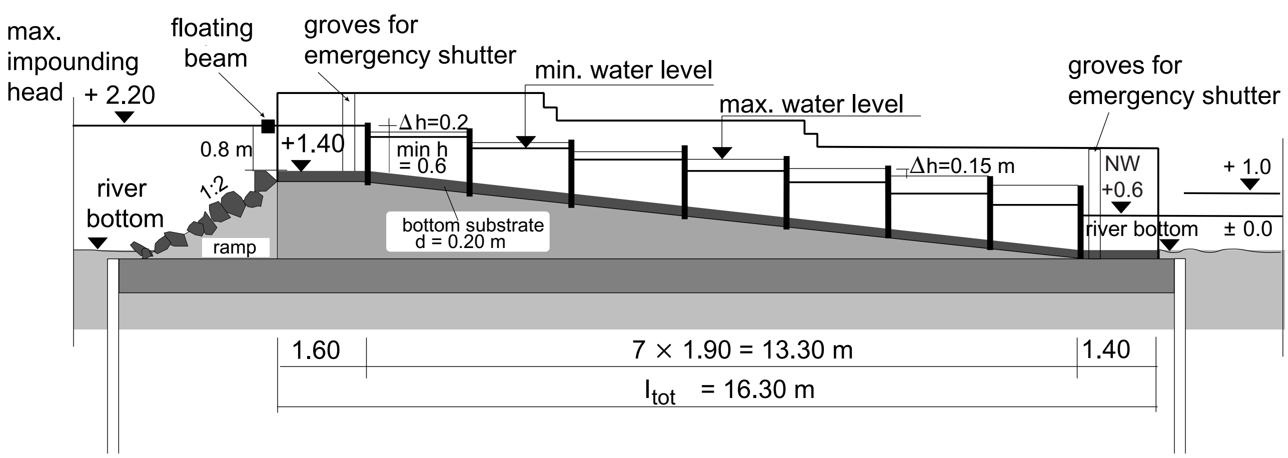

Figure 5.10: Longitudinal section through pool pass (sketch accompanying example of calculation)

5.1.5 Examples

POOL PASS AT KOBLENZ			
Details of the dam		**Details of the fish pass**	
River:	Moselle, Rhineland-Palatinate	Pool width:	b = 1.80 m
Use:	Water power generation, navigation (shipping)	Pool length:	$l_b \approx 2.60$ m
		Number of pools:	n = 24
Flows:	$NQ_{1971/80} = 20$ m³/s	Water depth:	h = 1.0 m
	$MQ_{1931/90} = 313$ m³/s	Total length:	$l_{tot} = 102$ m
	$HQ_{1993} = 4165$ m³/s	Slope:	$I \approx 1 : 12$
Fall head:	$h_F = 5.30$ m	Cross-walls:	Concrete walls with top notches and bottom orifices 30 × 30 cm
Year of construction:	1945-54		
Responsible:	Federal Waterway Authorities/ Moselle Hydroelectric Company		

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

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

POOL PASS AT DAHL

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

Description of construction:

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

Data on functioning

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

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

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

5.2 Slot passes

5.2.1 Principle

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

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

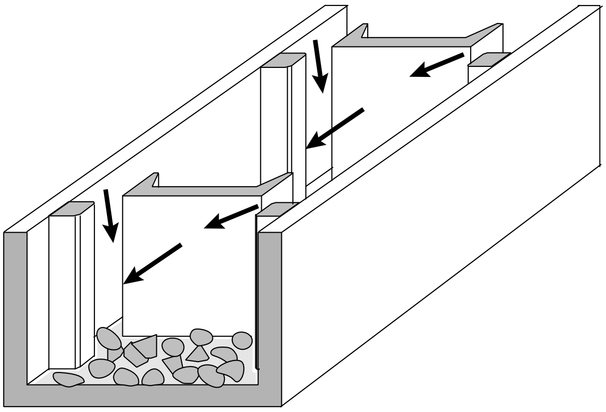

Fig. 5.14: Example of a slot pass with two slots (diagrammatic)

5.2.2 Design and dimensions

5.2.2.1 Plan view

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

5.2.2.2 Longitudinal section

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

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

5.2.2.3 Pool dimensions

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

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

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

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

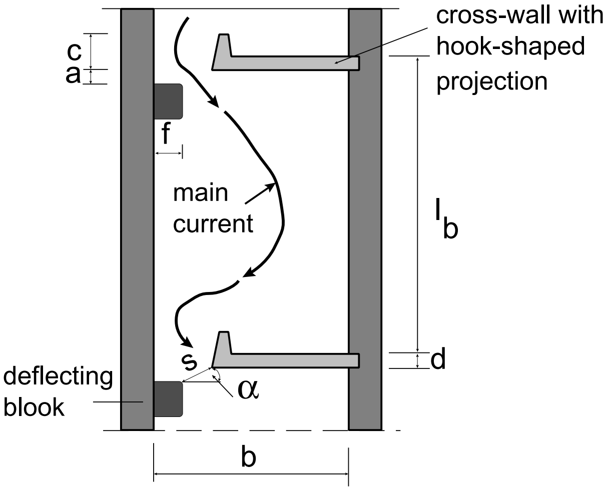

Fig. 5.16: Dimensions and terminology for slot passes with one slot only (plan view)

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

5.2.2.4 Structural characteristics

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

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

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

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

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

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

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

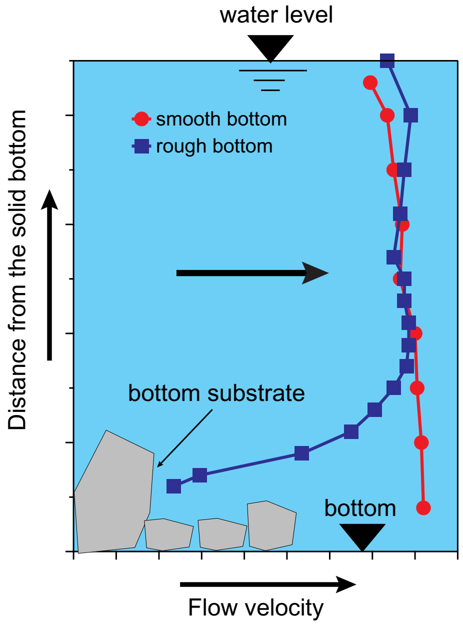

Fig. 5.17: Flow velocity distribution in the slot, comparison between smooth and rough bottom (after GEBLER, 1991).

guaranteed if the recommended values are not respected.

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

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

5.2.2.5 Bottom substrate

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

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

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

5.2.3 Hydraulic calculation

The following should be monitored under all operating conditions:

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

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

$$h_u > h_{gr} \quad \text{or} \tag{5.8}$$

$$v_{max} > v_{gr} \tag{5.8a}$$

where

$$h_{gr} = \sqrt[3]{\frac{Q^2}{g s^2}} \tag{5.8b}$$

$$v_{max} = \sqrt{2g\Delta h} \tag{5.8c}$$

$$v_{gr} = \sqrt{g h_{gr}} \tag{5.8d}$$

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

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

remark by the editor

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

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

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

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

where again $\Delta h \leq 0.20$ m should be used as the threshold value for the difference in water level.

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

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

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

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

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

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

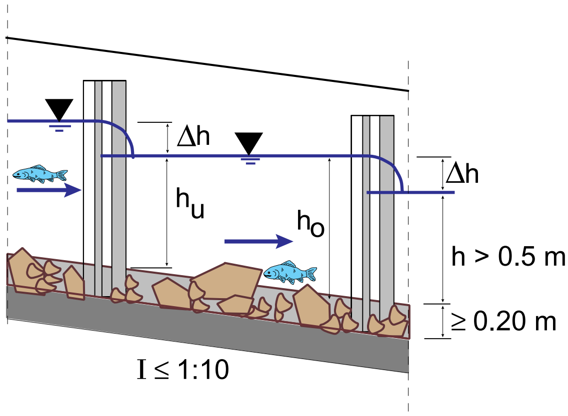

Fig. 5.19: Detail of slot pass (schematic longitudinal section)

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

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

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

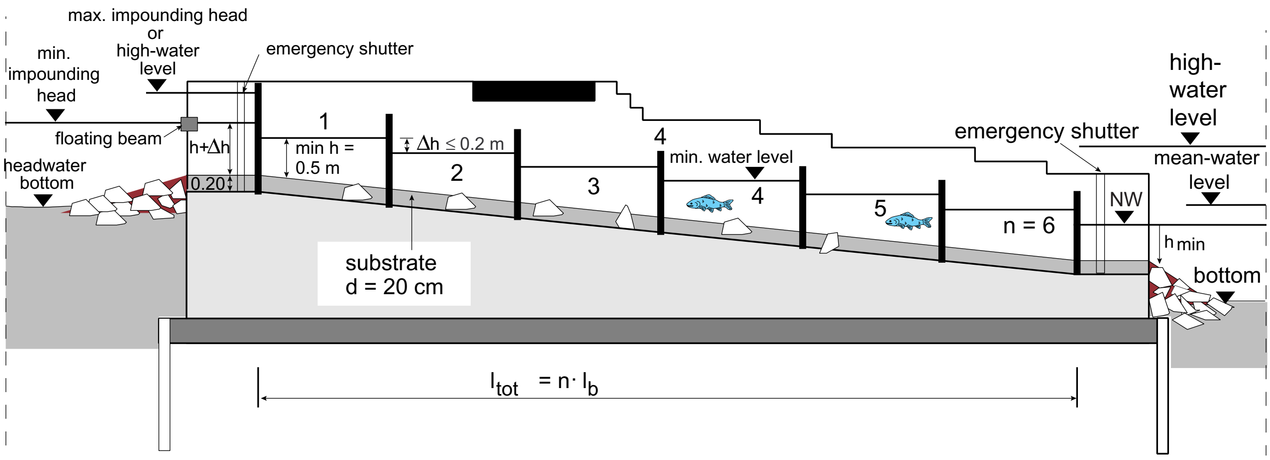

Figure 5.18: Longitudinal section through a slot pass (schematic)

Figure 5.20: Slot current in a slot pass

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

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

In order to guarantee low-turbulence current in the pools, the power density for the volumetric power dissipation in the pools should not exceed the threshold value of E = 200 W/m³ given by LARINIER (1992a). The volumetric power dissipation is given by the formula:

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

Example of calculation for a slot pass:

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

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

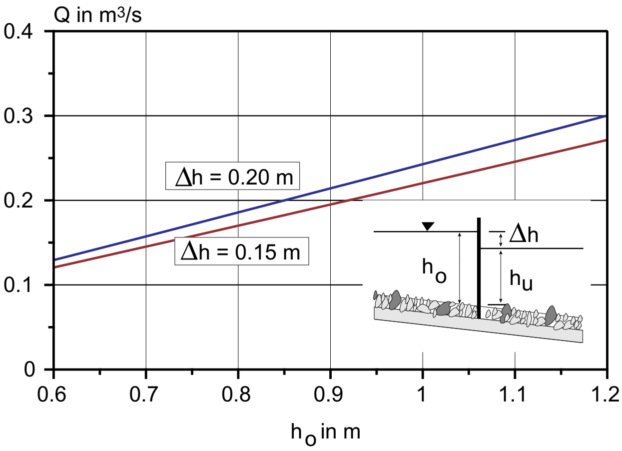

Fig. 5.21: Water discharge in the slot pass with a slot width of s = 17 cm

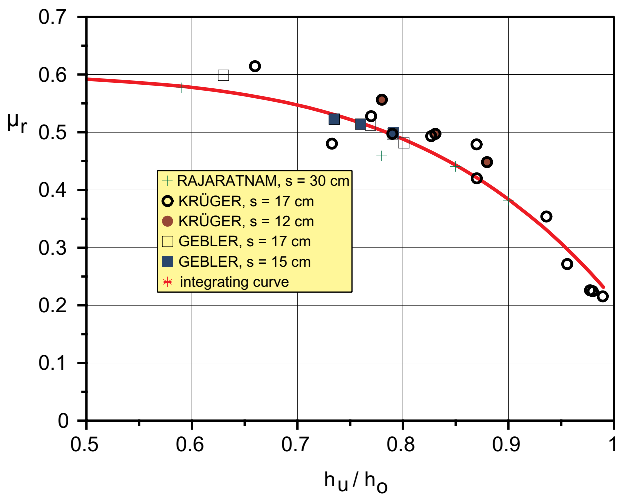

Fig. 5.22: Discharge coefficient $\mu_r = f(h_u/h_o)$ in Equation (5.9) for sharp-edged slot boundaries.

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

Figure 5.22 gives $\mu_r = 0.49$

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

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

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

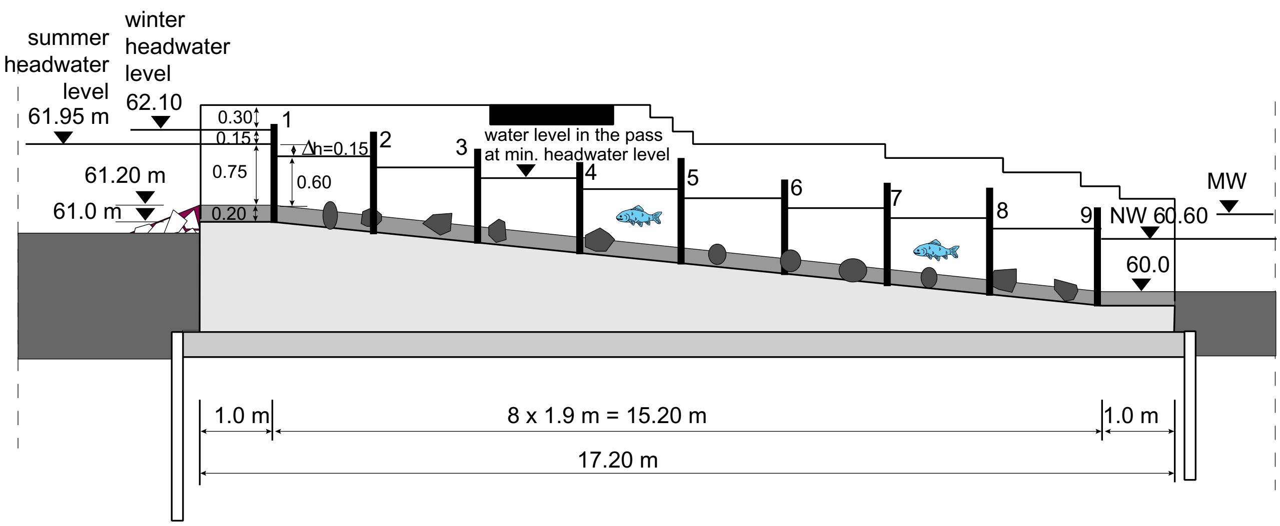

Figure 5.23: Sketch accompanying the example of calculation (longitudinal section through the slot pass)

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

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

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

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

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

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

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

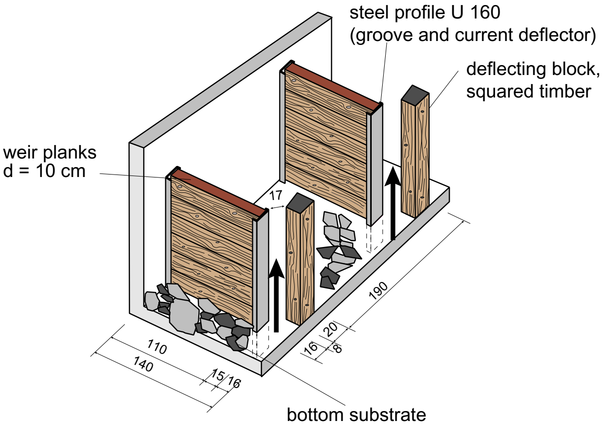

Fig. 5.24: Proposed design for cross-walls of a slot pass.

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

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

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

a discharge of

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

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

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

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

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

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

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

5.2.4 Overall assessment

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

Other advantages are:

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

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

5.2.5 Example

NEU LÜBBENAU SLOT PASS

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

Design

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

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

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

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

5.3 Denil pass

5.3.1 Principle

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

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

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

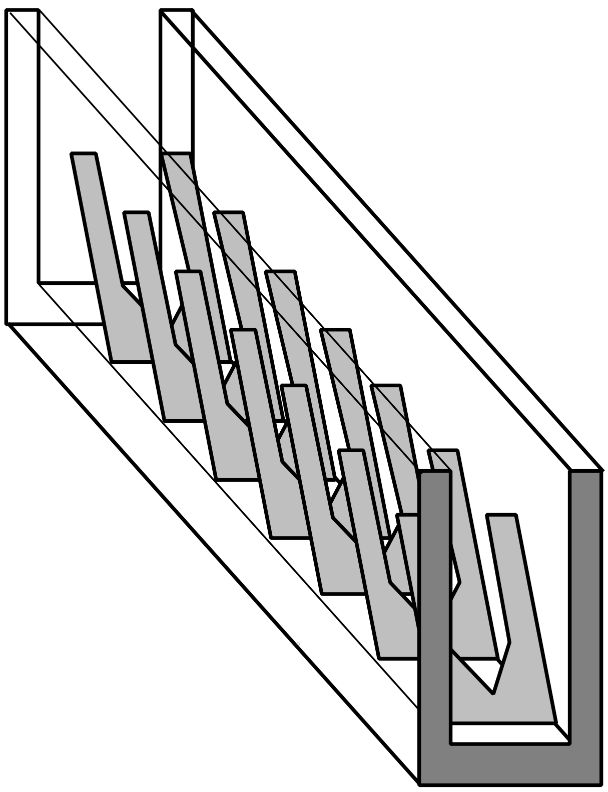

Fig. 5.26: Denil pass (schematic) (modified after LONNEBJERG, 1980)

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

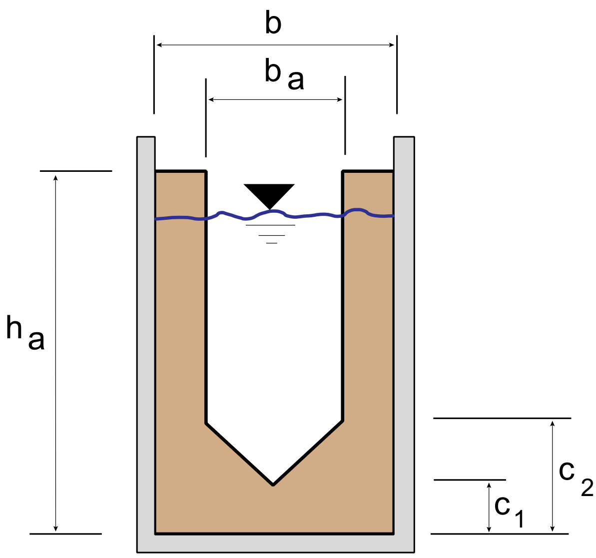

Fig. 5.27: Baffles in a Denil pass (standard Denil, terminology) (modified after LONNEBJERG, 1980).

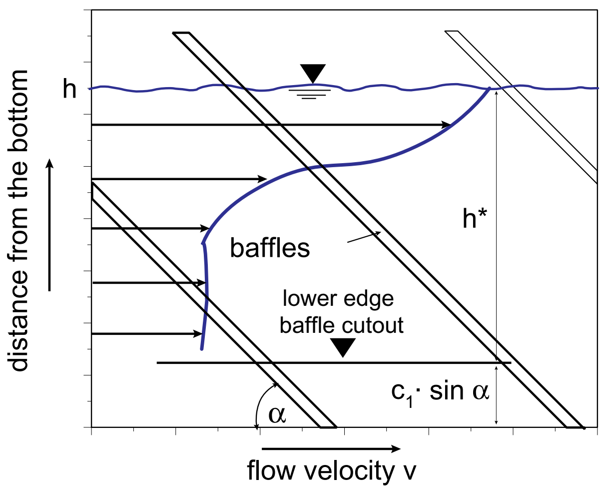

Fig. 5.28: Characteristic velocity distribution in a Denil pass (modified after KRÜGER, 1994a).

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

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

5.3.2 Design and dimensions

5.3.2.1 Plan view

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

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

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

5.3.2.2 Longitudinal section

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

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

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

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

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

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

5.3.2.3 Channel

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

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

5.3.2.4 Cross-channel structures

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

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

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

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

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

[##] i.e. fish pass entrance (remark by the editor) means to close off the channel at the water inlet to make maintenance work on the channel easier.

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

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

5.3.3 Hydraulic calculations

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

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

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

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

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

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

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

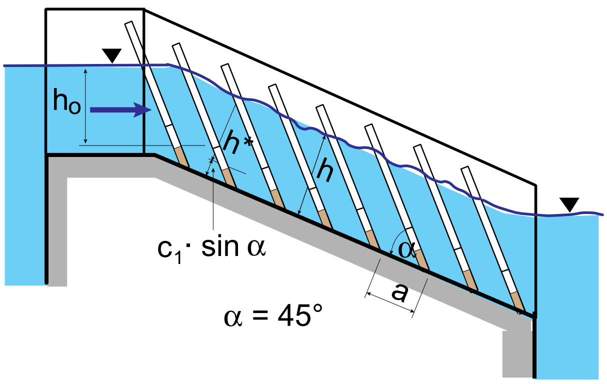

Fig. 5.31: Denil pass (longitudinal section, sketch illustrating the construction principle and terminology) (modified after LARINIER, 1992b).

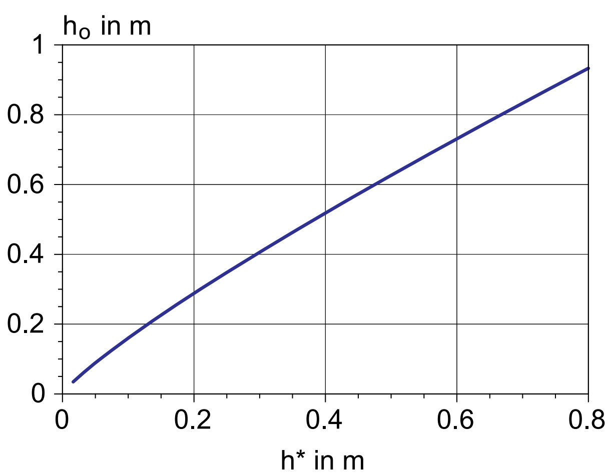

Fig. 5.32: Relation of $h^* = f(h_o)$ (modified after LONNEBJERG, 1980)

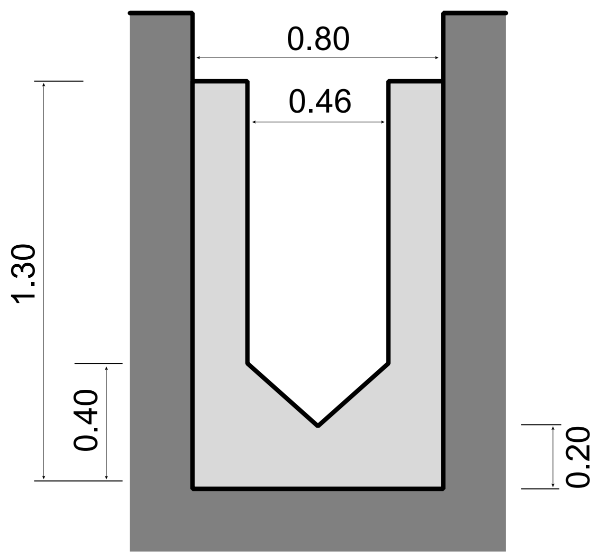

Fig. 5.33: Dimensions of the baffles

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

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

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

Example of calculation:

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

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

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

The baffle spacing (a) is obtained from:

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

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

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

The value of h* is determined by

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

Therefore, the height of the baffles is

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

Figure 5.32 gives the inflow water level

$$h_o = 0.83 \text{ m}$$

so the bottom height of the first baffle is calculated from

$$h_1 = h_0 + c_1 \cdot \sin(\alpha + \arctan I) \quad (5.12)$$

$$h_1 = 0.83 + 0.2 \cdot \sin(45° + 8.53°) = 0.99 \approx 1.0 \text{ m}.$$

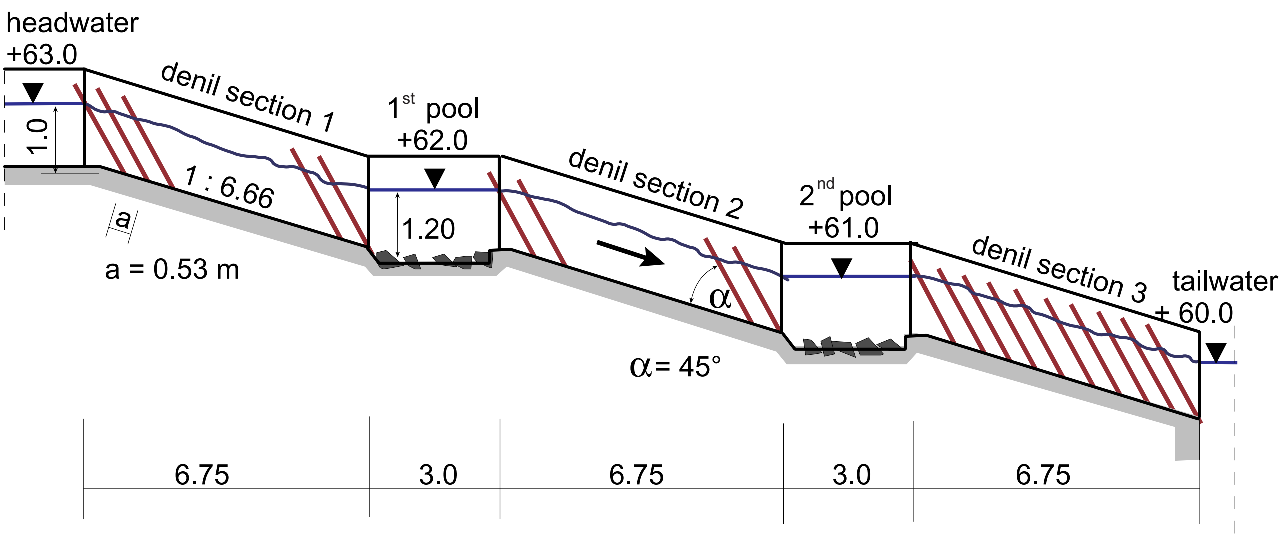

Figure 5.34: Longitudinal section of the fish pass

The discharge is calculated by using equation (5.10):

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

$$= 1.35 \cdot 0.46^{\ 2.5}\sqrt{9.81 \cdot 0.15}\ \left(\frac{0.7}{0.46}\right)^{1.584}$$

$$Q = 0.457\ m^3/s.$$

The dimensions of the resting pools can be found using equation (5.11). With E = 35 W/m^3 and the flow velocity

$$v = Q/A \approx \frac{Q}{b_a \cdot h^*} = 1.42\ m/s$$

the necessary area "A_{nec}" of the resting pool is then:

$$A_{nec} = l_b \cdot b_m = \frac{\frac{\rho}{2}\,Qv^2}{h_m \cdot E} = \frac{\frac{1000}{2} \cdot 0.457 \cdot 1.42^2}{35 \cdot 1.20}$$

$$= 10.97\ m^2.$$

The pool width of b_m = 4.0 m and pool length of l_b = 3.0 m give a base area of 12.0 m^2. The diagram in Figure 5.34 shows a longitudinal section of the fish pass.

5.3.4 Overall assessment

The Denil pass is characterized by the following advantages:

- It can have steep slopes with resulting low space requirements;
- There is the possibility of prefabricating the channel elements;
- It can easily be used to retrofitted existing dams;
- It is not susceptible to variations in tailwater level;
- It usually forms a good attraction current in the tailwater.

The disadvantages of this type of construction are:

- High susceptibility to variations in the headwater levels. In practice, only variations of a few centimetres, with a maximum of about 20 cm, are permitted;
- Relatively high discharges needed compared to other construction types;
- Clogging with debris can easily upset its functioning. Denil passes require regular inspection and maintenance.

The success of Denil passes has been adequately proven, in particular for salmonids, and cyprinids such as the barbel, that have a lower swimming performance, by counting numbers of ascending fish. On the other hand, the monitoring that has been carried out to date shows that small fish and fish of low swimming performance have only a restricted possibility to pass through, especially when the length of the structure is too long. There is, therefore, a selection for larger, stronger swimming species and individuals.

Likewise, ascent by microorganisms and invertebrate benthic fauna must be rated impossible.

For these reasons Denil passes should only be used if other structures cannot be built, for example due to lack of space.

5.3.5 Example

UNKELMÜHLE DENIL PASS

Details of the dam		Details of fish pass	
Watercourse:	Sieg, NRW,	Width:	b = 0.64 and 0.74 m
Flows:	MNQ = 1.5 m^3/s	Length:	l = 6.60 and 9.50 m
	MQ = 22 m^3/s	Slope:	I = 1 : 4.5
	HHQ = 700 m^3/s	Fall Head:	h_F = 3.2 m
Use:	Water power	Discharge:	Q = 0.3 to 0.38 m^3/s
Year of construction:	1930	Responsible:	StAWA Bonn
Operator:	RWE-Energie AG		

Design

An existing traditional pool pass around the powerhouse of the hydropower station at Unkelmühle, that had been built in 1930, was replaced by a Denil pass under the control of the StAWA, Bonn, as the former fish pass was not functioning properly owing to the small dimensions of the pools and the slope being too steep. The new pass consists of two Denil channels connected by a resting pool, which was built as an impervious, reinforced concrete trough with stone rubble cladding and planted with aquatic vegetation. The upper channel is 6.60 m long and the lower 9.50 m and both have a slope of 1 : 4.5. The channels are made of reinforced concrete with wooden cladding to which the wooden baffles are fixed. The fish pass is fed by a discharge of 300 to 380 l/s.

Ascending fish can be observed through an under-water viewing window in the observation chamber at the edge of the resting pool. An installation that can accommodate a fish trap for monitoring purposes has been fitted to the water inlet of the upper channel (fish pass exit[#]).

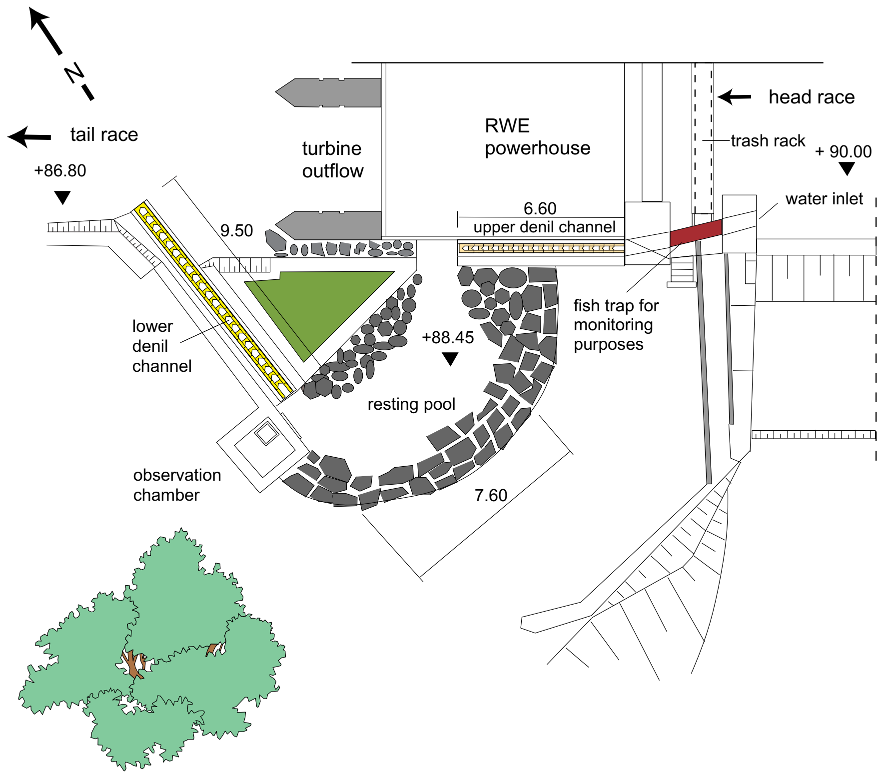

Figure 5.35: Fish pass at the hydroelectric power station Unkelmühle/Sieg (NRW)

[#] remark by the editor

Example (continued)

Figure 5.36:
View of the lower Denil channel and the resting pool above.

The attraction current that affects a large area of the tailrace is clearly visible; it is responsible for the ease with which the entrance of the pass is detected by fish.

Figure 5.37:
View of the lower Denil channel.

The concrete channel is covered with wood to which the baffles are fitted that have a U-shaped cutout. The high turbulence water-air mixture on the surface misleads the observer as there are much lower flow velocities near the bottom area of the channel.

Figure 5.38:
Sea lamprey *(Petromyzon marinus)* from the Sieg.

Data on efficiency:

LUBIENIECKI et al. (1993) tested the efficiency of the fish pass from May 1991 to May 1992 using the fish trap to monitor fish migration. The numbers of ascending fish were to some extent surprising. On some 200 control days over 1000 ascending barbel were found. Monitoring also showed that other fish species were ascending the pass in only very small numbers. A particular success in 1993 was finding that sea lampreys were ascending the pass. This species died out 40 years ago in the River Sieg but new fishways had made it possible to recolonize the Sieg.

5.4 Eel ladders

5.4.1 Peculiarities of eel migration

The eel, being a catadromous migrant fish, lives in almost all standing and flowing waters connected to the sea. It grows in fresh water until sexual maturity and then migrates down the river to the sea in the silver phase, presumably to spawn in the Sargasso Sea.

The post-larval eels (so-called glass eels) reach the coast of Europe in two to three years and penetrate from there into inland waters. The ascending eels with a body length of 7 to 25 cm are certainly in a position to overcome small obstacles with rough surfaces, small cracks or fissures. However, the ability of young eels to ascend is frequently overestimated and many weird and wonderful climbing aids, such as vertically positioned bundles of brushwood etc, have proven unsuccessful. Therefore, mitigation facilities specially attuned to the performance of glass eels can be useful in addition to existing fish passes, particularly in the estuary area of rivers where the ascending eels are still very small. Eels of larger body lengths also use the more common types of fish pass so that separate eel ladders are not required there.

5.4.2 Design

Two principle types of design are common:

1. Pipes are laid through the body of a weir, often close to the river bottom, in which bundles of brushwood, fascines or other baffles are placed to lower the flow velocity. The baffles are often attached to a chain, so that they can be pulled

Figure 5.39:
Eel *(Anguilla anguilla)*

Figure 5.40:
Rhomboid pass and eel ladder on the Sauer dam at Rosport (Rhineland-Palatinate).

View from headwater.

The eel ladder, in which brushwood bundles are placed, is paralleling the bank-side wall of the rhomboid pass.

out and replaced. The eel has to wind its way through the built-in devices to overcome the obstacle to migration. This type of device has not been found suitable in practice since the tubes become quickly clogged with debris; this is very difficult to discover (the pipe is completely beneath the water) and just as difficult to remedy.

2. Relatively small and flat open channels, which pass from tailwater to headwater and are made of concrete, steel or plastic in which various fittings are placed that help eel in winding upwards. According to JENS (1982), brush-type structures have proven to be most suited to this purpose. However, brushwood, gravel and grids are also used as built-in devices. These channels should have a cover as protection against predators such as rats and gulls.

The way in which the eel ladders are laid out ensures that water only trickles through them, so they are just moistened. This means that they cannot be used for the ascent of other fish species, nor is this intended.

The exit of an eel ladder must always be at the bank. Connection with the bottom is not required as glass eels migrate in the surface-water layer. It should be noted that the small discharges through

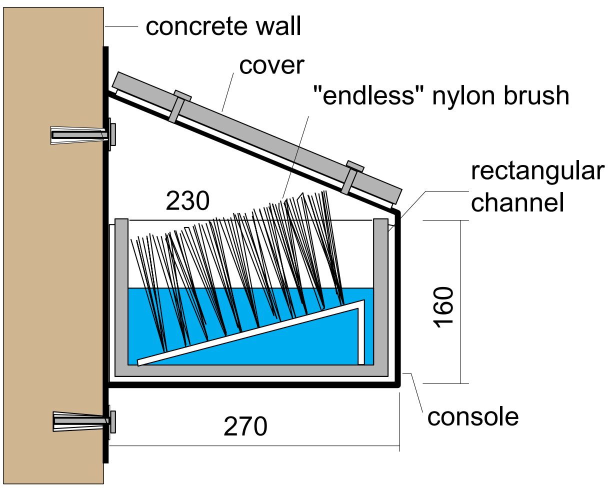

Fig. 5.41: The eel ladder at the Zeltingen dam on the Moselle (Rhineland-Palatinate) is adapted to the specific migratory behaviour of the eel. The ladder consists of a channel in which an endless plastic brush is laid to help the eel moving upstream by winding its way through the brush. Also this eel ladder was constructed in combination with a conventional pass and parallels the side of this pass (after JENS, 1982).

an eel ladder are barely sufficient to provide an adequate guide current and, if necessary, additional water supply, e.g. through a bypass, has to be provided to create sufficient attraction.

Because of the low swimming performance of the young eel, the exit of the pass into the headwater must at all costs be placed in an area with gentle current; under no circumstances it should be placed just close to the screens of the turbine inlets.

5.4.3 Overall assessment

Eel ladders are only suitable for allowing upstream migration of eels. Due to its selectiveness, an eel ladder on its own is not sufficient for mitigation if also other fish species have to pass the obstacle as the eel ladder would not allow them to do so. Eel ladders are specially recommended in the estuary areas of rivers in addition to the other technical fish passes (pool passes, Denil passes etc) to specifically allow young eel to migrate upstream.

5.5 Fish lock

The use of fish locks as mitigation devices has been known for quite some time now and has been applied especially in the Netherlands, Scotland, Ireland and Russia (van DRIMMELEN, 1966; JENS, 1982). Some fish locks exist on the Rivers Saar and Sieg in Germany.

The structure of a fish lock is similar to a ship lock (see Figures 5.42 and 5.43). Both essentially consist of a lock chamber as well as a lower inlet and an upper outlet structure with closing devices. However, there are some differences as far as the functioning is concerned which also make it clear that a ship lock, over and above its actual purpose, is not normally sufficient to sustain fish migrations nor can it replace a fish pass. In particular, the lack of a permanent guide current, the short opening times of the sluice gates, the high turbulence in the chamber during filling procedures and the position of the lock at the dam only exceptionally allow fishes to find their way through a ship lock.

However, it is possible in exceptional cases to consider whether the operating mode of the ship lock can be modified temporarily (e.g. during the main migration season for glass eels or salmonids) to facilitate the ascent of fish.

5.5.1 Principle

The functional principle of a fish lock is shown in Figure 5.42. It is possible to distinguish four operating phases:

1. The lock is idle. The lower gate is open and the water level in the chamber is at the level of the tailwater. The fish must now be shown the way from the tailwater into the lock chamber by a guide current. To this end either the upper sluice gate is slightly opened or a guide current is produced by sending water through a bypass (i.e. pipeline) that ends at the entrance to the lock chamber. The fish gather in the chamber.
2. The lock chamber is being filled. The lower sluice gate is closed; the upper one is slowly opened fully. The flow coming from the headwater leads the fish in the chamber to the upper exit.
3. The water level in the chamber is equal to that of the headwater. Water is passed into the tailwater through a slot in the lower sluice gate or a special pipe, whereby an attraction current is produced at the exit to the headwater. The fish find their way out of the chamber.
4. The lock chamber is emptied after closing the upper and opening the lower sluice gates. The lock is again in an idle state.

The timing of the operating modes is done automatically. Usually there are half-hourly to hourly operating intervals. The most efficient rhythm and, if applicable, the necessary seasonal adjustments, can only be determined through monitoring controls.

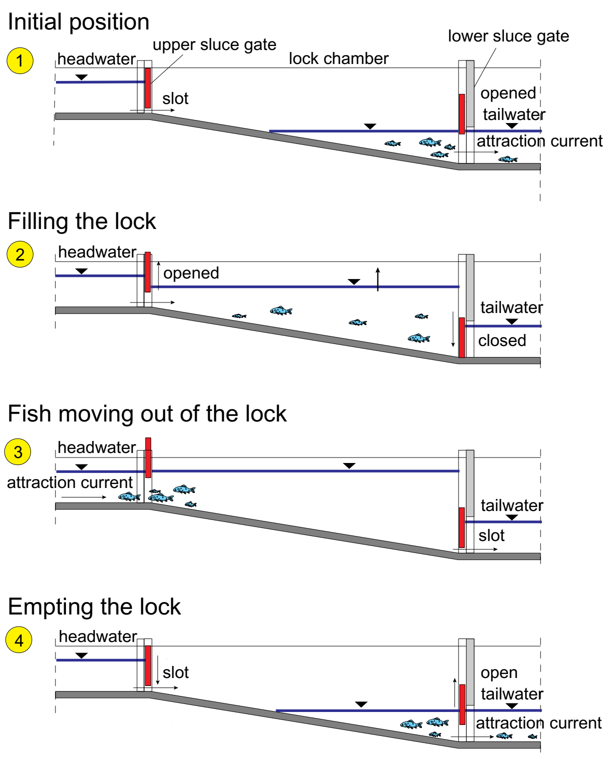

Fig. 5.42: How a fish lock works (schematic longitudinal section)

5.5.2 Design

The design of the chambers and closing devices is variable and largely depends on the specific local conditions. When designing the chamber bottom there should be measures to prevent fish being left in areas that become dry. To this end, the chamber bottom can have a stepped design (Figure 5.43) or just be inclined (Figure 5.42). The chamber dimensions should clearly be larger than the pools of conventional fish passes as many more fish must remain in the chamber for a longer time. The construction of a rough bottom is possible in principle. Chambers that are open to the top are desirable.

The guide current may be produced, or intensified, by sending water through a bypass (cf. Figure 5.43). The cross section of the water outlet of the anterior chamber should be dimensioned in such a way that an effective guide current is guaranteed in the range between v = 0.9 and maximum of 2.0 m/s (on average v = 1.2 m/s). When designing the influxes and discharges for the filling and emptying phases of the lock chamber care should be taken that the mean flow velocities do not exceed 1.5 m/s at any time or in any place within the chamber and that the water level in the chamber rises or falls at less than 2.5 m/min (SNiP, 1987).

With regard to the position of the fish lock at the dam and the location of the entrance and the exit, the same criteria apply as for other fish passes. Because of their compact structure fish locks can, for example, be housed in partition piers.

5.5.3 Overall assessment

Fish locks have an advantage as alternatives to traditional technical fish ladders if

- There is not much space and
- There are very large height differences to overcome.

Equally the fish lock offers structural advantages if very large (e.g. sturgeon) or low performance fish species have to be taken into consideration.

It is not possible at present to exclude a selective effect with regard to the ease with which they are passed by invertebrates, bottom-living fish and small fish.

The moving parts, drive and control systems require increased maintenance efforts compared with traditional fish passes.

5.5.4 Example

SCHODEN FISH LOCK

Details of the dam		**Details of the fish lock**	
Watercourse:	Saar, Rhineland-Palatinate	Fall head:	h_F = 5.70 m
Flows:	MNQ = 19 m^3/s	Chamber width:	b = 1.0 m
(from 1946/93	MQ = 80 m^3/s	Length:	l = 34 m
data series)	HHQ = 1 230 m^3/s	Year of construction:	1981
Use:	Water power, ship navigation	Operator:	WSA Saarbrücken
Control flow:	Q = 2 × 30 m^3/s	Responsible:	RWE Energie AG

Structural design:
During the development of the Saar as a waterway for shipping, a fish lock was constructed on the Schoden dam. This was incorporated in the partition pier between the powerhouse and the weir. The entrance to the lock is located near to the turbine outlet. The entrance into the fish lock has a cross section of 0.65 × 0.80 m and is submerged. On the headwater side, the exit releases fish into the impoundment.

A hydraulically activated rolling gate serves to close off the lock towards the tailwater while towards the headwater the lock chamber is sealed off by a dam shutter. A fish trap can be installed between the shutter and the exit for monitoring purposes.

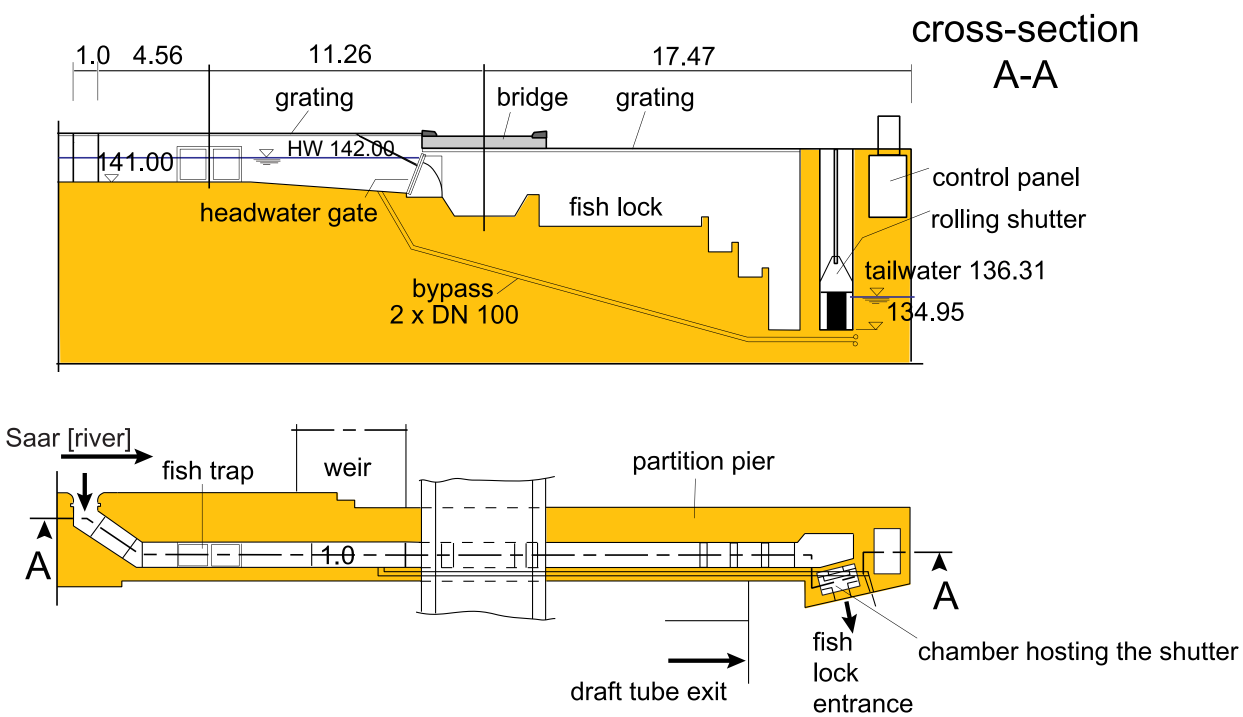

Figure 5.43: Longitudinal section and plan view of the Schoden fish lock (Saar)

Example (continued)

SCHODEN FISH LOCK

Data on effectiveness:

Fish monitoring in the lock carried out by the district authority in Treves confirm the effectiveness of the fish lock. In all, in the period from 15.4.1992 to 18.7.1992, over 50 000 fish moved through the lock (KROLL, 1992, oral presentation at the symposium on "Long distance migratory fish in rivers regulated by dams", held at Koblenz on 16 and 17 November 1992). Tests regarding the effects of different turbine operation modes on the effectiveness of the fish lock showed no significant differences in numbers of fish entering the lock, regardless of whether only the turbine near the lock was in operation, or only the one on the bank side, or both turbines together.

Figure 5.44: The Schoden/Saar fish lock (view of the weir installation)

The lock is installed in the partition pier between the weir and the powerhouse (see the arrow).

5.6 Fish lift

5.6.1 Principle

Where there are considerable height differences (> 6 to 10 m) and little water available there are restrictions on the applicability of conventional fish passes, due to the building costs, the space requirement and, not least, the physiological abilities and the performance of the fish. Where great heights are to be overcome, solutions have been developed to carry fish from the tailwater to the headwater using a lift.

A trough is used as a conveyor and is either equipped with a closable outlet gate or can be tilted. When in the lower position, the trough is sunk into the bottom. Fish have to be attracted towards the fish lift by a guide current. In addition, a sliding and collapsible grid gate located in front of the lift, may serve to push the fish into the lift and thus above the transport trough. The lower gate of the lift closes on a regular cycle. The fish gathered above the trough can no longer escape, are "caught" by the rising trough and conveyed to the top. Here a watertight connection may be made to the upper water level or else the trough is simply tipped out above the headwater level into a funnel. Along with the water from the trough the fish reach the upper channel where, once again, there must be a clear attraction current.

The regular cycle is determined according to actual migratory activity. The operation is usually automatic.

5.6.2 Structure

Figure 5.45 shows in a diagrammatic sketch the structure of a fish lift as constructed both on the east coast of the United States and in France (LARINIER, 1992c).

The same principles apply to the positioning of a fish lift as for conventional fish passes.

5.6.3 Overall assessment

- Little space is required, and large height differences can be overcome with such fish lifts, e.g. even at high dams. However, the structural expenditure is considerable.
- Since the fish are conveyed upstream passively, fish lifts are suitable for species with low swimming performance as well as for the transportation of large fishes.
- Fish lifts are not suited for the upstream migration of invertebrates and the downstream migration of fish.
- Large variations in the tailwater always mean design problems in providing an adequate guide current.
- The expenditure on maintenance for fish lifts is higher than for traditional fish passes.

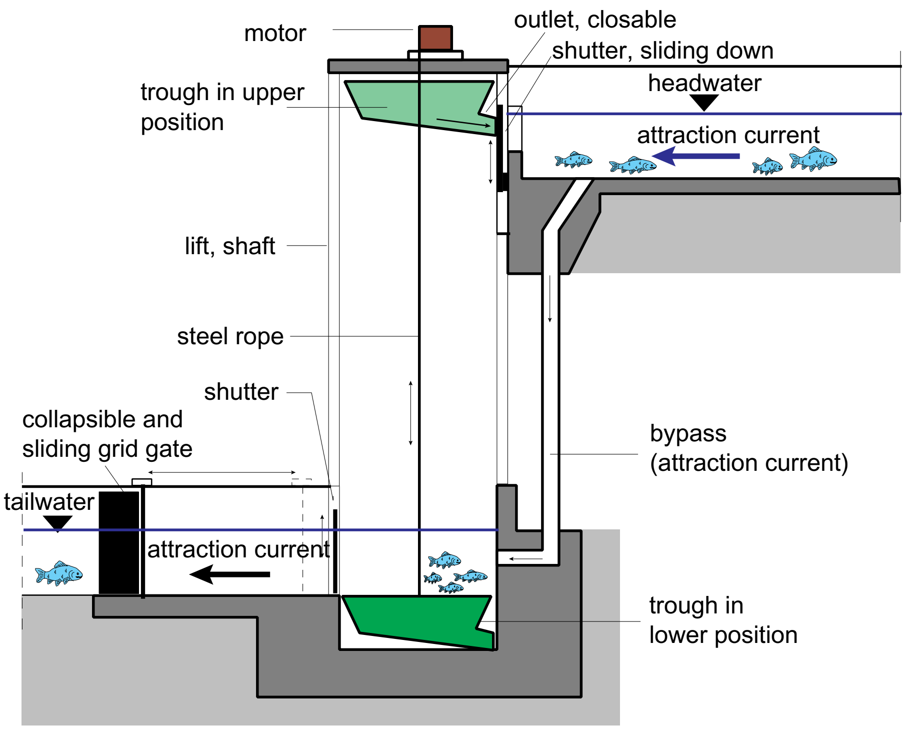

Figure 5.45:
Schematic view of the structure of a fish lift and functional principle (modified after LARINIER, 1992c).

5.6.4 Example

TUILIÈRES FISH LIFT

Details of the dam		Details of the fish lift	
Watercourse:	Dordogne, France	Lift height:	h = 10 m
Use:	Water power	Transport trough volume:	V = 3.5 m^3
Flow:	Q = 285 m^3/s	Guide current:	Q = 4 m^3/s
Fall head:	h_F = 12 m	Link to headwater:	Slot pass, l_{tot} = 70 m
Energy production by:	EDF		h = 2.0 m, Q = 1.0 m^3/s
		Year of construction:	1990

Functional data:

Proof was obtained by video monitoring that more than 100 000 fishes used the lift in the period 11 May to 28 July 1989. The lift is not only accepted by large salmonids and allis shad but also by cyprinids, sea and river lamprey etc. The slot pass link to the headwater is equipped with an observation window from which the fish can be easily observed as they swim upstream.

Figure 5.46:
Tuilières fish lift. The lift is located on the right hand side directly adjacent to the turbine outlets and conveys fish 10 m high into an intermediate pool whence the last two metres of difference in height are overcome by a slot pass.

Figure 5.47:
The lower entrance to the Tuilières fish lift

The collapsible grid gate is closed and then pushes the fish, that have gathered in the antechamber, towards the transport trough before this trough is lifted. The gate considerably improves the efficiency of the installation.

The opening of the canal, through which the water necessary for operating the slot pass (Q = 1 m^3/s) is led, can be seen at the top right of the photo. At the same time, this additional water improves the attraction towards the lift.

6 Monitoring of fish passes

Provision of structural prerequisites for monitoring the functioning of fish passes should be made for all new installations that must observe current water legislation. Particularly where there is considerable divergence from the guidelines in this book, approving authorities should have the possibility to order a control of functioning. The following presents exclusively the methodology for the assessment of monitoring of upstream migrations; monitoring of downstream migration is not dealt with at this point.

6.1 Objective of monitoring

The objective of monitoring is to prove explicitly that the fish pass entrance can be found and the fish pass negotiated by fish. Monitoring goes beyond checking the construction against the planning directives and construction certification, as well as beyond the obligatory trial run (see Chapter 4.4.5), which is required particularly for the more natural looking constructions. It also goes beyond routine maintenance (see Chapter 3.8). New fish passes that have been constructed in accordance with the guidelines in this instruction booklet, should be assumed to function well in principle.

Experience shows that actual constructions frequently diverge from the recommendations in these Guidelines because of local circumstances. It is then often difficult to fully assess the effects of any possible impairment of function. In such cases, possibilities for monitoring and structural improvements to the pass should be incorporated in the project as early as at the approval procedure stage. Monitoring is also recommended for newly built fish passes when there is no, or only inadequate, experience with the operation of the (new) type of construction chosen, or if the pass is unique because of its dimensions (e.g. very high water discharges or fall heads). The methods described below can also be applied to monitoring of existing fish passes.

While sufficiently tested methods for monitoring upstream migration of fish exist, it is generally very difficult to prove the efficiency of upstream migration of benthic invertebrates in fish passes. The invertebrates' differing colonisation strategies mean that proof of their migration has usually to be restricted to recording colonisation within the fish pass itself. Present knowledge indicates that the existence of continuous bottom substrate alone can be invoked as an indicator of the possibility of upstream migration of invertebrates.

Most fisheries laws prohibit catching fish in fish passes. If research necessitates the capture of fish from a fish pass, an exemption permit must be requested prior to fishing. Granting of this permit is only possible if the owner of the fishery is in agreement prior to any fishing action. Usually the management of monitoring should be entrusted to fisheries experts.

6.2 Methods

The timing and duration of testing are of great significance to the reliability of any control of functioning. This should preferably take place during the main migration periods, which can differ regionally due to local particularities and weather conditions.

The following biological and technical elements should be considered when drafting a monitoring strategy and later when assessing the functioning of the fish pass:

- The potential natural fish fauna of the watercourse and the actual qualitative and quantitative composition of fish stocks in the headwater and tailwater of each dam. In addition, similar assessments should be made of the benthic invertebrate fauna.
- The unrestricted ascent of all migratory developmental stages of the relevant fish species.
- The current state of connectivity of the water system.
- The general requirements for planning and construction of the fish pass as set out in these Guidelines.
- If necessary, proposals for optimising the fish pass should be made.

Control of the functioning of the fish pass requires not only the obligatory counting of all fish that have negotiated the fishway but also the assessment of a number of other parameters and baseline conditions. These data are used to appraise the efficiency of the pass by comparing the monitoring results with the natural migratory activity of the fish fauna in the stretch of water being investigated. The additional data include:

- Counting ascending fish, classified by species and size groups, data on sexual maturity.

- Data on water level and discharge trends (increasing or decreasing water discharges), weather, turbidity of the water or degree of transparency.
- Details of lunar phase with reference to the migratory activity of the fish, particularly during eel migration.
- Measurement of current velocities and discharge in the fish pass.
- Measuring oxygen content and water temperature,
- Determining fish stocks in the headwater and tailwater taking into account stocking measures in each of the stretches of water.
- Noting other relevant details of the fish such as disease or injury.
- Assessing the overall condition of the fish pass and its level of maintenance.
- Recording any modifications of the environmental conditions of the river and recording particular events such as maintenance measures, fish mortalities etc, that may have bearings on the migratory activity in the fish pass.

It is recommended that already during construction of the pass provision be made for built-in trapping chambers or at least lifting devices for the use of mobile fish traps to be installed directly at the outlet of the pass. This is particularly necessary in technical passes to test ascent of fish in the pass. The methods for controlling the functioning of the pass should be appropriate to the type of pass. If necessary, several methods may have to be combined to balance out the different disadvantages of the individual methods. Various traditional methods are listed below, which, when used in the appropriate manner, can help to provide reliable data on the functioning of the fish pass.

6.2.1 Fish traps

The standard method for testing both natural-looking and technical passes is trapping the fish. Traps can be used provided that the cross section of the pass can be completely blocked off by the fish trap and that there is a tight connection to the bottom. The fish trap should be installed immediately at the water intake of the pass (i.e. the fish pass exit[#]; Figure 6.1) and can be built as a box, pedestal or special fish trap according to local circumstances. Box traps are the most appropriate for use in pool or slot passes, their size being determined by the dimension of the pools. The traps should be set in the uppermost pool. Control traps, which are, for example, set in resting pools or which are not set immediately at the water intake do not give any definite proof that fish can negotiate the total length of the pass.

The fish trap should be made of robust, dark, plastic yarn with maximum mesh size of 10 – 12 mm to allow the catch of young fish during the control. Box traps consist of a light aluminium frame, whose sides are filled with either plastic netting or coated wire mesh.

Control tests with traps require intensive care by trained staff. Fish may be injured as a result of high density in the trap, particularly in times of increased migratory activity. Frequent emptying can prevent this. The fish are removed from the trap, measured and their parameters recorded according to the defined programme, and released into the headwater. Since the trap, in the way it is set, prevents migration downstream from the headwater into the fish pass, this method provides reliable data on upstream movement.

6.2.2 Blocking method

This method involves blocking-off the water intake of the fish pass (i.e. fish pass exit[#]) with a net or grid to prevent fish swimming in from the headwater. All fish are then removed from the fishway, either by electro-fishing or by drying the pass. Control fishing, which is carried out after a certain time, reveals then the fish that have entered the fish pass from the tailwater.

This method can be applied at all passes that provide places for the fish to rest. It is, therefore, not suitable for Denil passes. Problems arise particularly from clogging of the blocking device by debris and floating solids.

Test fishing in a fish pass using conventional methods or electro-fishing is not suitable as a function control unless the water intake of the fish pass (i.e. the fish pass exit[#]) is first blocked off. It is otherwise, impossible to determine from which direction the fish migrated into the pass, i.e. whether they came from the tailwater or headwater.

6.2.3 Marking

Marking of fish can be used to control the functioning of the more natural fish passes and is often used to study migrations in aquatic systems. Marking of fish must be reported to, or approved by, the appropriate authorities. There are many

[#] remark by the editor

Figure 6.1:
Fish trapping to monitor the functioning of the fish ramp at the Pritzhagener Mill on the Stöbber (Brandenburg)

Figure 6.2:
Salmon marked with red tattooing dye and released into the Mühlbach, a tributary of the Lahn (Rhineland-Palatinate), in the framework of a repopulation programme.

Figure 6.3:
Electro-fishing for monitoring purposes on the fish ramp at the Unkelmühle weir in the Sieg River (North Rhine-Westphalia)

different methods for marking fish, such as the use of coded marks (tags) or dye injections (Figure 6.2), each of which has distinct advantages and disadvantages.

When using this method autochthonous fish, that is caught in the relevant waterbody, is marked and released into the tailwater of the dam being investigated. Control of the functioning of the fish pass then consists of proving the presence of marked fish in the water intake area (fish exit area[#]) of the pass or in the headwater. Information about the recapture of the marked fish can be gained either directly by using conventional methods, such as fish traps or electro-fishing, or through the notification by anglers of any marked fish caught. Since the recapture rate is generally low, large numbers of various species and sizes must be marked for release into the tailwater. The relationship between the total number of all fish marked and the number recaptured must be taken into account when assessing the results.

6.2.4 Electro-fishing

Electro-fishing is frequently used for qualitative and quantitative investigation of fish stocks. Under the influence of an electric field in the water any fish present first swim towards the anode (galvanotaxis) and are then anaesthetised for a short period (galvanonarcosis), which allows them to be captured. The fish can then be investigated as to species, size category etc. (Figure 6.3). If the electro-fishing equipment is used correctly the fish are not injured. Electro-fishing (in Germany[##]) must only be carried out by specially trained persons and requires the approval of the relevant authority and the agreement of the holder of the fishing rights.

Electro-fishing gives qualitative and semi-quantitative estimates of the fish stock in the headwater and tailwater of dams. The determination of stock size can be used to assess the ascent activity of the fish fauna at the time of monitoring and also constitutes the basis for estimating the functionality of the fish pass (see section 6.3). In combination with other methods, such as blocking the water inlet to the fish pass or marking, electro-fishing gives the possibility of proving that fish manage to negotiate the pass.

6.2.5 Automatic counting equipment

Automatic counting equipment allows the ascending fish to be observed without disturbing them. The various methods are based on different principles, including movement sensors, light barriers or video control, and many are still largely in the exploratory stage. Optical systems can only be applied if there is sufficient viewing depth. Light barriers and movement sensors only allow the fish to be counted without distinguishing species or size. A more sophisticated combination of video monitoring and image processing systems allows a differential assessment of the functionality of the fish pass (TRAVADE & LARINIER, 1992).

In most cases the application of automatic counting equipment presupposes separate observation chambers, devices or installations mostly at the water intake (fish exit[#]) of the pass. If these methods are to be used, provision must be made at an early stage in planning, before building the fish pass. Expenditure on regular checks and maintenance of automatic counting equipment is high.

6.3 Assessment of results

The assessment of the results of controls of the functioning of fish passes presupposes detailed recording of data. In addition to locality-specific data for the river stretch and other factors that may influence the test results, data on the methodology used, including the duration of exposure of the fish traps or the cycle of emptying these traps, are required for correct assessment.

Unrestricted functioning and complete failure of a fish pass are both easy to demonstrate, but proof of restricted or selective functioning for specific species or sizes is considerably more difficult. Proof of the full functioning of a pass by the analysis and assessment of fish ascent figures should be carried out using the following criteria:

- Results of monitoring are to be assessed in relation to the main periods of migration that are specific to species and waterbody. Here, concomitant factors such as discharge conditions, temperature, moon phase etc, should be considered.
- Fish migrating through the fish pass are to be assessed in relation to the stock densities in the headwater and tailwater of the dam. This can be done by comparing the results of the fish pass monitoring with the natural dominance relationships (as percentage data) and the size range of the species actually present in the water.

According to the general requirements defined in Chapter 3, a fish pass can be recognised as functional if all species of the potential natural fish

[#] remark added by the editor
[##] "in Germany" was added by the editor

fauna, in the different stages of development and in numbers that reflect their relative abundance in the watercourse, can find the fish pass entrance and negotiate the pass. However, this frequently presents methodological problems because:

- Usually not all species of the potential natural fish fauna are represented in the water,
- In particular the presence of small fish species is difficult to prove with traditional methods such as fish traps,
- Species that are extremely rare in the river may not be detected during monitoring, although these species may in principle be able to negotiate the pass.

Therefore, it is now allowed to believe that a fish pass functions well if:

- It can be proved that all fish species actually present in the affected river stretch, in their different stages and relative abundance, can find the entrance and negotiate the pass. The pass can be considered functional even for extremely rare species or species that are not recorded because of the methodological difficulty to catch them, if other species with the same ratio of body size to pass dimensions and similar swimming performance are able to negotiate the pass.
- The plausibility that the fish pass entrance can be detected and the pass be negotiated must also be given for species of fish of the potential natural fish fauna that are currently not represented in the population of the watercourse.

7 Legal requirements

The relevant laws must be observed when planning, building and operating fishways. As set out in Article 70 of the Constitutional Law of the Federal Republic of Germany, inland fisheries are subject to the jurisdiction of each *Land* (Federal State). Therefore, each of the *Länder* (Federal States) has its own fishery act, which usually differs widely in a number of points from similar acts of the other *Länder*. All federal fishery acts contain details on the construction and operation of fishways, that can be implemented directly and independently of other regulations or laws.

On the other hand, as regards the Water Law, there exists a higher-ranking skeleton law, the *Wasserhaushaltsgesetz* (Water Resources Policy Law) (WHG). This contains in § 1a, Subsection 1, the principle that waterbodies should be managed in such a way that they add to the well-being of the general public and also benefit individuals where this does not interfere with the public good. The subsection also states that all negative influences must be avoided. According to §§ 4,8 unfavourable effects on waters deriving from uses that require permission or approval are to be prevented or compensated for.

This principle is also in accordance with § 8 and § 20 of the Federal Law on Nature Conservation and the relevant Nature Conservation Acts of the *Länder*. The proposal of Council's Guidelines on the ecological quality of waterbodies, that was submitted by the Commission of the European Union, includes the provision that migratory fish species may not be impeded by human activities.

7.1 New installations

The Water Law requires that the necessary permissions or planning procedure approvals be sought from the relevant authorities prior to building dams or weirs in waterways. Such constructions usually represent a substantial structural modification of the waterbody in the sense of § 31 WHG, in that they lead to an essential change in habitats, so that Planning Permission Hearings in accordance with § 31, Subsection 1, must be undertaken. In addition, complementary law regulations of the *Land* have, of course, also to be respected.

According to the annex (here Point 6) of § 3 of the *UVP*[#] Law (Environmental Impact Assessment Law), planning procedures that are to be carried out according to § 31 WHG [Water Resources Policy Law] require an Environmental Impact Assessment (UVP).

The Environmental Impact Assessment includes the determination, description and assessment of the impacts of a planned action on people, animals and plants, soil, water, air, climate and landscape, including their mutual interactions in each case, as well as their impacts on cultural property and other goods.

In the context of the Environmental Impact Assessment, conservation or restoration of longitudinal connectivity is usually an aim, although fishery laws of some *Länder* provide formal exceptions with regard to building fishways.

The fisheries requirements also have to be considered where an approval, licensing or agreement procedure has to be carried out instead of Planning Permission Hearings. Within the framework of the relevant laws the planning procedure should balance the interests of fisheries with the benefits associated with the project that is object of the application.

7.2 Existing installations

The legal situation for existing dams and weirs is different if modifications are carried out that do not require approval as here, in first instance, the old laws, conferred with their ancillary clauses, apply. An amendment of the old laws is usually not possible without the agreement of the holder of the right, as defined by the guarantee of ownership under Article 14 of the Constitutional Law. These old rights may, however, be revoked in accordance with § 15 WHG in return for compensation where considerable disadvantage to the general well-being can be expected from a continued use. Most Fishing Acts of the *Länder* offer the possibility to oblige the owner of a dam to retrofit it with a fish pass if the building costs and any possible compensation claims are met by the third party insisting on the construction.

In Hesse, North Rhine-Westphalia, Rhineland-Palatinate, Saxony-Anhalt and Thuringia, the *Land* can only insist on retrofitting an obstruction with a pass if the measure has a reasonable cost/benefit ratio and a reasonable ratio of cost-to-production-power of the liable party. If the liable party cannot afford to pay, the *Land* has to care for the provision of an appropriate part of the funding of retrofitting.

[#] remark by the editor: UVP = Umweltverträglichkeitsprüfung (Environmental Impact Assessment)