

CHAPTER 5

POOL FISHWAYS, PRE-BARRAGES AND NATURAL BYPASS CHANNELS

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1. THE PRINCIPLE OF POOL FISHWAYS

Pool fishways, which are widely used, are a very old concept. An official study carried out in France more than two hundred years ago (PHILIPPE, 1897) revealed that there were more than one hundred pool fish passes.

Pool fishways are based on the principle of dividing the height to be passed into several small drops forming a series of pools. The passage of water from one pool to another is either by surface overflow, through one or more notches or slots, or through one or several submerged orifices situated in the wall separating two pools. Hybrid pool fish passes can often be found, for example with flow through a notch or slot or over the dividing wall, combined with submerged flow through an orifice. The profile of the surface overflow weir is generally rectangular, but in some cases can be trapezoidal, triangular or even semicircular.

The principal or critical parameters of a pool pass are the dimensions of the pools and the geometric characteristics of the cross-walls separating the pools (shapes, dimensions and heights of the weirs, notches, slots and orifices). These geometric characteristics, together with waters levels upstream and downstream of the facility, determine the hydraulic behaviour of the pass *i.e.* the flow discharge, the difference in water level from one pool to another, and the flow pattern within the pools.

2. DROPS BETWEEN POOLS AND FLOW PATTERNS IN THE POOLS

The smaller the head difference (or drop, DH) between two pools, the easier it is for the fish to pass. However, this head difference cannot be reduced too much because the number of pools required would then become prohibitive.

The maximum velocity of the flow created by the drop DH can be approximated by:

$$V = (2g DH)^{0.5}$$

where g is the acceleration due to gravity (9.81 m/s^2).

Head differences between the pools of 0.15 m, 0.30 m and 0.45 m, correspond to maximum flow velocities of approximately 1.7 m/s, 2.4 m/s and 3.0 m/s respectively.

The drops between the pools will be selected above all as a function of the swimming or leaping capacities of the species concerned.

The flow may be either “**plunging**” or “**streaming**”. In “plunging flow”, the nappe of water from the upstream weir plunges towards the floor of the pool (Figure 1). The power is dissipated by turbulent mixing, and in an hydraulic jump at the bottom of the fall. This type of flow is found whenever the downstream water level is below the crest of the traverse.

In passes with plunging flows where the downstream water level is significantly below the crest of the traverse, fish have to jump through the free falling nappe of water to pass from one pool to the other. This type of pass is generally reserved for salmonids. A drop of around 0.30 m is preferable in most plunging flow type fish passes. In some cases this may be increased up to 0.60 m for large salmonids (salmon or sea trout), and up to 0.45 m for trout. However, there is no advantage in increasing the drops too much as the volume of the pools must be similarly increased in order to dissipate the extra power correctly.

Fish passes with “plunging flows” must be avoided for shad, which are not at ease in this type of flow.

In passes with “**streaming flow**”, the jet which forms at the traverse (notch, slot) between the two pools remains at the surface. Its energy is dissipated in the downstream pool by large recirculation eddies. This type of flow occurs when the downstream water level above the crest of the weir reaches 0.5-0.6 times the upstream level above the crest of the weir (Figure 1) (LENNE, 1990). The transition between the “plunging” and the “streaming” flow is unstable and is characterised by a marked hysteresis.

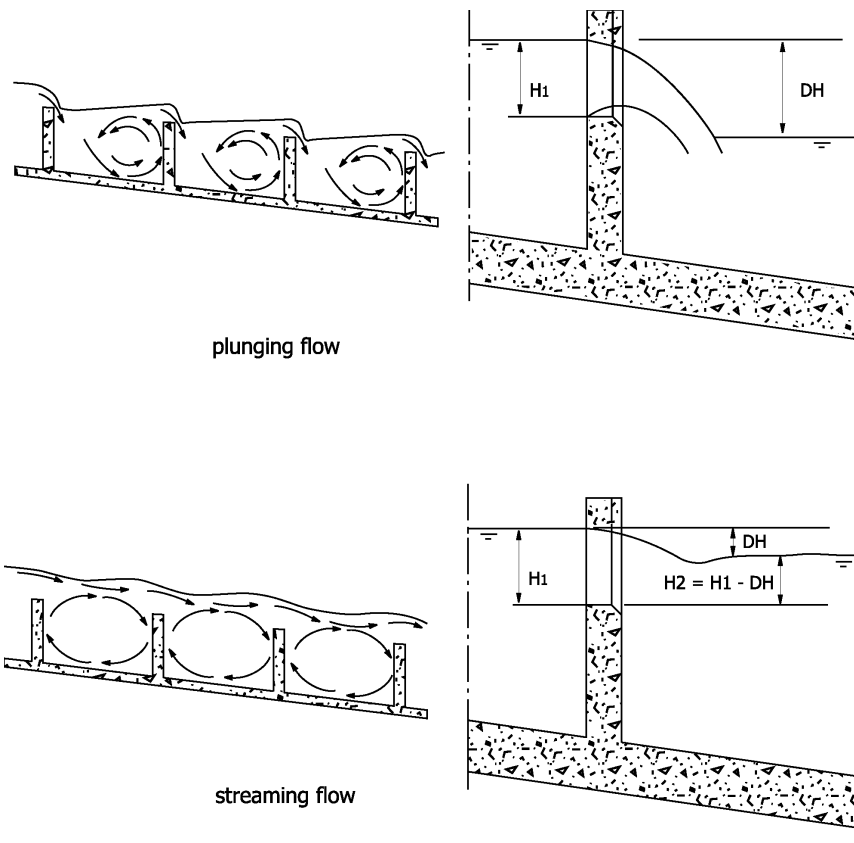


Figure 1: Plunging and streaming flow in a fishway.

In “streaming flow” passes (deep notches or vertical slots passes) or those with submerged orifices, the drops between the pools are generally 0.30-0.40 m for salmon and sea trout, around 0.30 m for trout and fast-water cyprinids (dace, barbel) and from 0.20 to 0.30 m for shad (preferably 0.25 m). For most cyprinids and piscivorous species (perch, pike) a suitable drop will be between 0.15 m and 0.25 m, being lower the smaller the size of individual or species it is required to pass.

3. SIZE OF THE POOLS

The difficulty of passage for migrators increases with the turbulence and aeration in the pools. A simple indication of the turbulence and agitation levels in the pools is given by the power dissipated per unit pool volume (volumetric dissipated power) which can be expressed as:

$$P_v = \rho g Q DH/V$$

Where:

P_v : volumetric dissipated power (watts/m³)

ρ : density of water (1000 kg/m³)

g : acceleration due to gravity (9.81 m/s²)

Q : flow discharge in the fishway (m³/s)

DH : head difference between pools (m)

V : volume of water in the pool (m³)

This criterion allows the minimum volume of water in a pool to be determined where the head difference between pools and the flow discharge in the pass are fixed, or, alternatively, the maximum flow that may pass if the head differences and volume of the pools are fixed.

200 watts/m³ is generally taken as the upper limit for volumetric dissipated power in salmon and sea trout fish passes. Higher P_v figures may be accepted if the fishway consists of a few pools only, or for very large fish facilities with discharge flows of more than several m³/s.

On the other hand, lower levels are advisable (less than 150 watts/m³) for small fishways, and for fishways designed for shad and riverine species.

The minimum volume of the pools is fixed by the flow discharge, and by the head difference between them. Pool dimensions (length, width and depth) will depend on the flow pattern, *i.e.* the nature and direction of the flows (which depend on the shape and size of the slots, orifices or notches, as well as on the water levels on both sides of each cross-wall).

The phenomenon of “short-circuiting”, *i.e.* direct passage of a high velocity jet from one pool to the next without sufficient dissipation of the kinetic energy, should be avoided. On the other hand, the jets should not hit the walls with too much velocity because this may disturb the behaviour of fish and affect the efficiency of the pass. It can induce the fish to jump, which puts them at risk of injury or even of leaping out the fishway.

In sizing the pools it is generally preferable not to stray too far from the characteristics of existing passes, which have proved to be effective. The length of a pool (L) in fishways is generally between **7d** and **12d**, d being:

- In fishways with overflow weirs, the head on the weir,

- In fishways with notches, the smallest value of either the width of the notch or the head on the notch,

- In vertical slot fishways, the width of the slot,

- In submerged orifice fishways, the diameter (when circular) or the smallest dimension (when rectangular) of the orifice.

In “plunging flow” type fishways the depth of water in the pool immediately below the fall must be an absolute minimum of at least twice the head difference between the pools to enable fish to pass easily.

The minimum length of the pools is obviously a function of the size of the fish to be given passage: it can be taken as around three times the length of the largest fish to be given passage.

In practice, the pools of most fishways for large migratory fish vary between 2.5 and 3.5 m in length.

The minimum depth of the pools depends on the species concerned. A minimum depth of around one metre is used for large migratory salmonids, whereas around 60 cm is sufficient for trout.

In practice, while these guidelines should be borne in mind, it is usually the hydraulic conditions (flow discharge, head difference between pools, flow pattern, volumetric dissipated power) which determine the minimum dimensions of the pools rather than the size of fish.

4. MINIMUM DIMENSIONS OF THE NOTCHES, ORIFICES AND SLOTS

The notches and slots in “streaming flows” fish passes must be at least 0.30-0.40 m wide for large migratory salmonids, 0.45 m for shad and 0.20 m for trout. The minimum sizes for cyprinids and other coarse fish will depend on the size of the fish concerned.

The sizes should be much greater in “plunging flow” fishways, particularly if the fish have to jump to reach the upper pool.

Whichever the species in question, even if it is small, the minimum width of fish passage must be sufficient (greater than 0.15-0.20 m) to prevent them from being easily blocked by trash.

The minimum surface area of orifices should be 0.09 to 0.10 m² for large migratory salmonids and other large fish, and 0.04 m² for trout and most cyprinids and other riverine species.

Much smaller orifices may be included in some facilities but these are not generally intended for fish passage, but rather to enable the fishway to be dewatered for maintenance operations.

5. ESTIMATION OF THE FLOW DISCHARGE IN A POOL PASS

The usual hydraulic formulae for discharge over weirs (broad or sharp-crested weirs, with or without lateral contraction, drowned or not) and through slots and orifices allow the approximate flow in a fishway to be determined as a function of its geometric

characteristics. These include dimensions and crest elevation of weirs, notches or slots; difference in elevation between two successive pools; and upstream and downstream water levels. Various conditions are shown in Figure 2 and are described below.

The flow discharge through a **submerged orifice** can be expressed by the formula:

$$Q = C_d S (2g DH)^{0.5}$$

where:

- Q : flow discharge (m³/s)
- S : area of the orifice (m²)
- g : acceleration due to gravity (9.81 m/s²)
- DH : drop between the two pools (m)
- C_d : discharge coefficient of the orifice.

The main factors affecting the discharge coefficient are the shape (circular, square, rectangular...) and the profile of the orifice (with sharp edge, chamfered, rounded upstream edge), the thickness of the cross-wall in which the orifice is situated, and the position of the orifice in the wall. Generally, the bevelling or rounding of the upstream edges give a greater coefficient of discharge. This coefficient may vary from 0.65 to over 0.85.

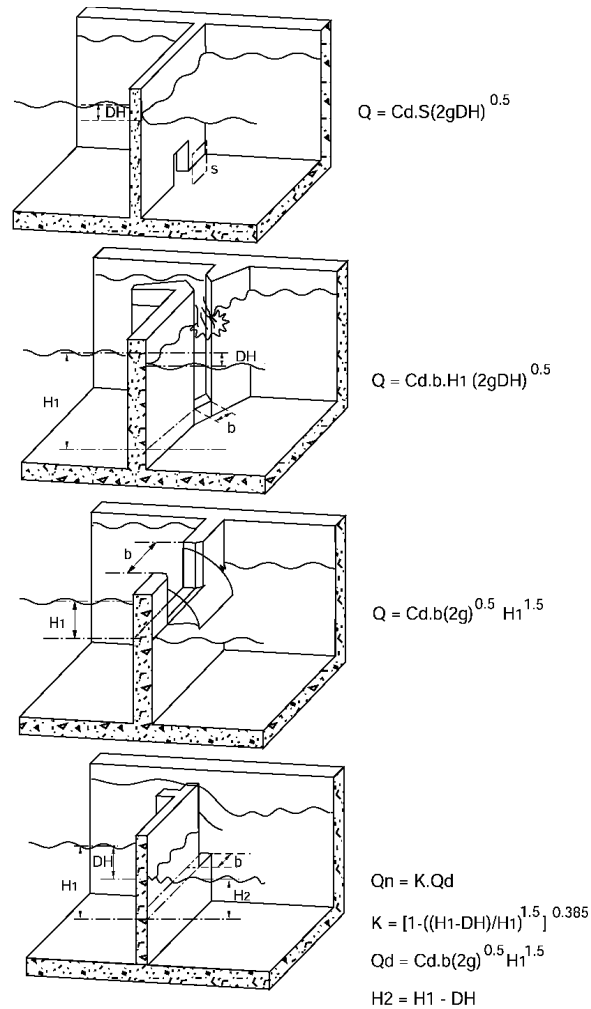


Figure 2: Geometric and hydraulic parameters for determining flow discharge in a pool-type fishway.

The flow through a **vertical slot** can be expressed by the formula:

$$Q = C_d b H_1 (2g DH)^{0.5}$$

where

Q : flow discharge (m³/s)

b : width of the slot (m)

H₁: head at the slot (m), *i.e.* the difference between the water level upstream of the slot and that of the slot crest.

g : acceleration due to gravity (9.81 m/s²)

DH : drop between the two pools (m)

C_d : discharge coefficient of the slot.

The main factors affecting the coefficient of discharge are the shape and the form of the slot. The rounding of the slot profile on the upstream edge gives a greater coefficient of discharge. This may vary from 0.65 for a sharply bevelled slot to over 0.85 when the slot is rounded.

The flow through a free-flowing **rectangular notch**, *i.e.* a non-**submerged weir**, can be expressed by the formula:

$$Q = C_d b (2g)^{0.5} H_1^{1.5}$$

where

Q : flow discharge (m³/s)

b : width of the notch (m)

g : acceleration due to gravity (9.81 m/s²)

H₁ : head at the notch (m), *i.e.* the difference between the water level elevation upstream of the notch and the elevation of the crest of the notch.

C_d : discharge coefficient.

The main factors affecting the coefficient of discharge are the profile of the notch and the thickness of the dividing wall in which the notch is situated. As with orifices and slots, the bevelling or rounding of the crest upstream give a greater coefficient of discharge. This may vary from 0.33 for a notch forming a broad-crested weir to almost 0.5 for a notch the profile of which is shaped to achieve an adherent nappe (ogee profile). In most cases, the coefficient of discharge is close to 0.4.

When the rectangular notch may be considered to be a **submerged rectangular sharp-crested weir** (*i.e.* when the level of the water in the pool immediately downstream is situated above the crest of the weir), and in the case of a moderate degree of submergence ($H_2/H_1 < 0.9$), defined by the ratio of head upstream (H₁) and downstream ($H_2=H_1-DH$) of the weir, then the discharge Q_n, may be expressed as follows:

$$Q_n = K Q_d$$

$$\text{with } Q_d = C_d b (2g)^{0.5} H_1^{0.5}$$

$$\text{and } K = [1 - ((H_1 - DH)/H_1)^{1.5}]^{0.385}$$

where:

Q_d : flow (m³/s) from the same weir under free-flow conditions (no submergence) at the same upstream head H₁

H₁ : is the upstream head at the weir (m), *i.e.* the difference between the water level elevation on the upstream side of the weir, and the crest elevation of the weir

DH : head difference between the two pools (m)

K : discharge reduction coefficient (< 1) induced by submergence.

It must be stressed that the above formulae only give an approximate flow value, because the approach conditions of the flow and the characteristics of the traverses are generally very different from those required to strictly apply formulae which were developed in laboratory conditions for flow measurement. It is also the case when, taking account of the thickness of the cross-walls separating the pools, the weirs or notches can be considered neither as "sharp crested" weir, nor as "broad crested" weirs. Rather, they should be considered as "short crested" weirs for which the coefficients of discharge are likely to vary significantly particularly in relation to changes in the head. The rugosity of the walls may also have a significant effect on the coefficients of discharge, with extreme roughness tending to reduce the contractions of the flow and consequently to increase the coefficient of discharge. Finally, the flow characteristics through the furthest upstream cross-wall are generally somewhat different (the approach velocities are lower and more homogenous) to those through the subsequent cross-walls.

In practice, however, the level of precision obtained is sufficient to specify the appropriate dimensions for the facility. However, in the case of fishways conveying the full ecological flow, which is often the case in hydro plants located on small streams, greater accuracy is required in evaluating the flow in the fish pass. In such cases it is therefore advisable to provide well-defined cross-sections, and to actually calibrate and gauge carefully the most upstream notches or orifices of the fishway.

6. SPECIFICATION OF A POOL FISHWAY

The specification of a pool fish pass at an obstruction involves determining of a number of characteristics. These include the number of pools required; the means of communication between the pools (position and geometrical characteristics of notches, slots and orifices); the elevation of the crest of the notches or slots; the elevation of the floor; and the elevation of the cross-walls and side-walls of the pass. The procedure is as follows:

1. The **drop** (or head differential) between the pools, which generally depends on the species concerned, is chosen.

2. From the maximum head difference across the obstruction, observed in most cases at low flow periods, the **number of drops (N)** is determined, and consequently the **number of pools (N-1)**.

3. The **type of traverse between the pools** is selected (geometry and dimensions of the notches, slots or orifices) depending on:

- The range of variation between upstream and downstream water levels during the migration period.
- The migratory species (minimum dimensions required according to the size of the fish, specific behaviour (**surface and/or bottom passage**), type of flow to be avoided for certain species.

4. The discharge through the pass is generally fixed for low river discharge conditions. It is usually determined in relation to the competing flow discharge of the river and the migratory species concerned. It may correspond to part or the whole of the compensation (or ecological) flow specified by statutory legislation. The minimum volumes and dimensions of the pools depend on a number of criteria including:

- The value adopted for volumetric dissipated power.

- The mode of communication between the pools (form and configuration of water jets).
- The migratory species concerned (minimum length, width and depth requirements for pools vary depending on species and size of fish).

5. From the flow discharge selected for the pass, and with reference to the upstream water level, the **dimensions and the elevation of the notches, slots, weirs and orifices** are established using the appropriate hydraulic formulae. The elevation **of the floor of the fish pass** is determined from the water depths specified for each pool to satisfy the criteria for the maximum volumetric dissipated power allowable.

6. Once the geometrical characteristics and the elevation of the fish pass have been determined for the reference level conditions, designers must check certain parameters. The head differences between pools, and the levels of turbulence and aeration in the pools (determined by the volumetric dissipated power), must remain acceptable for all upstream and downstream water levels encountered during the migration season of the species concerned. **In particular designers must verify that the fishway operates in a satisfactory hydraulic manner under the most extreme water level conditions that have been taken into account.**

Should the criteria on the maximum drops between pools or the allowable volumetric dissipated power not be observed, it will be necessary to modify the geometry of the communicating passages (weirs, notches, slots or orifices) between the pools (in order to reduce the flow and the turbulence level), or to increase the volume of the pools, or to provide a control device in the upstream section of the fishway. However, if the option of a reduction of flow discharge in the pass is considered, it must be ensured that it remains significant in relation to that in the river in order to maintain a sufficient attraction to the pass.

7. Auxiliary water may be injected, usually into the downstream pool (through a screen and at a low velocity), in order to increase the attraction of the fish pass while limiting its volume. In this case, the **size of the downstream entrance to the fishway** (width, crest elevation) must take into account the combined flow of the fishway and the auxiliary water system.

8. Once the hydraulic functioning of the fishway has been ensured, the “**backwater curve**” (*i.e.* the water levels in all the pools) can be calculated for extreme upstream and downstream water levels; this allow the height of the **cross-walls** between the pools and of the **side-walls** to be determined. Other factors than pass function, such as protection of the facility against floods or the position in the barrage, may also dictate side-walls levels.

9. If the fishway is not rectilinear *i.e.* in a straight line, but has sharp **changes of direction** (*e.g.* 180° bends) a **minimum length** equal to the length of a standard pool must be provided between the bend and the preceding cross-wall. This is to ensure that the jet coming from the slot or notch does not hit the opposite wall too violently.

10. In pools where the fishway suddenly changes direction, the right angles must be chamfered or rounded in order to prevent vertical currents from forming, which might encourage the migrators to leap out of the fishway.

7. ADAPTATION OF POOL PASSES TO VARIATIONS IN THE UPSTREAM AND DOWNSTREAM WATER LEVELS

Fluctuations in the levels upstream and downstream of an obstruction may induce major changes to the hydraulic functioning of a pool-type fish pass.

In most cases, when the flow discharge in the river increases, the downstream water level rises relatively quicker than the upstream water level, thus leading to a decrease in the total drop at the obstruction. Less frequently, the upstream and downstream water levels are subject to similar variations. Where there are adjustable discharge control facilities (e.g. sluice gates) at the obstruction, while the downstream water level is likely to rise considerably, the upstream water level can remain almost constant. The upstream water level can even drop at the obstruction during high flow, for example on navigable rivers such as the Seine and Thames rivers: the control point where the water level is maintained constant is situated far upstream of the control structure itself and the upstream water level drops at the structure, due to the increased gradient of the water surface during high flows.

How well pool fish passes tolerate variations in upstream and downstream water level, depends on the geometry of the traverses (slots, notches more or less deep, overflow weirs, orifices, etc.) between the pools:

- In the case of a fishway where the flow passes through wide surface weirs that take up a large part of the width of the cross-walls, any increase in the water level upstream will cause a very significant increase in the flow discharge. This in turn will cause a large increase in the turbulence and aeration in the pools.

- In the case of a vertical slot fishway, the flow and the volume of water in the pools increase almost linearly with the levels upstream, whilst the velocity and level of turbulence remain almost constant.

- In the case of a pass with submerged orifices, the difference in level from one side to the other of the orifice does not change significantly, and the flow remains almost constant.

The fishway will withstand variations in the water level (upstream and downstream) much better if the flow is "squeezed" through narrow and deep traverses (slots or deep notches) between pools.

When the level downstream rises more rapidly than the level upstream, as happens at most obstructions, the resulting drowning or the backwatering effect will be felt further back up the pass if a narrow and deep traverse is being used.

With wide and surface notches (generally in "plunging flow" fish passes), the effect of the variations in the downstream water level is concentrated at the entrance (downstream) drop. A rise in the downstream water level results in a rapid drowning of the entrance drop, resulting in a significant reduction in water velocity and attractivity of the fishway. A drop in the downstream water level results in an increase in the entrance drop that may make the fish facility difficult to negotiate.

In contrast, in the case of narrow notches or slots (in "streaming flow" fishways), the effects of variations in the water level downstream are distributed through several pools and this type of communication between pools is therefore more likely to accommodate variations in the downstream level. The attractivity of the pass is maintained better if the level downstream is increased, because the decrease of the entrance head differential is

less marked. On the other hand, the increase in the entrance head differential is also less significant when the downstream water level drops.

When the water level upstream remains constant, wide passages (surface weirs or notches) can be chosen for the fish. In such cases, the optimum width of the traverse between the pools is determined by the variation in the downstream water level. Where there is significant variation in the downstream water level it is necessary to limit the drowning of the downstream part of the fish pass, and to ensure sufficient velocities in the pools and at the entrance, by making the traverses deep and narrow.

In the case of significant upstream water level variations it is advisable to constrict the flow through deep notches or slots. For large facilities, the best solution is the vertical slot type fishway. When the flow through the pass is limited to 300-700 litres/second the best solution will often be pools with alternating deep side notches and submerged orifices.

8. FLOW CONTROL SECTIONS

In the case of upstream water level variation the flow discharge in a fish pass can be controlled to limit the turbulence to an acceptable level, by installing a control section upstream of the facility. There are several types of control sections. These include static (by means of a series of vertical slots or submerged orifices), mobile (by means of a series of adjustable sluices or regulating valves) or even more complex systems. Examples of the latter would include bypassing some pools, or by opening exits at various levels in the fish pass. Figure 3 illustrates some examples of control sections.

When the variation in the water level becomes significant, control must be accomplished by spreading the change across **several pools**. This is in order to avoid the creation of local hydraulic conditions (head differential between pools, velocities or turbulence) which could impede the passage of fish. Regulation using only a single sluice or gate in order to limit the flow may induce a local velocity increase and drop which can not be negotiated by fish. It is absolutely essential that the criteria for the maximum velocity, the head drops, and the volumetric dissipated power are also respected in the control section.

One solution is to install a series of sluices or gates upstream of the facility, the positions of which are carefully controlled (manually or automatically) with respect to upstream water level. This allows an almost constant flow to be maintained in the plant while guaranteeing that the fish can pass the traverse (Figure 3a).

For small facilities (100 to 200 litres/second), "plunging flow" fish passes are often used to limit the length of the pools and to enable the use of high slopes (frequently the case when designing fishways for trout at small-scale power stations). The most frequent way of limiting the variations in the flow when the level increases upstream is to use a control section consisting of several submerged orifices (Figure 3b). The area of the orifices are sized so that the maximum drop between pools never exceeds about 0.30 m, for the maximum upstream water level conditions encountered during the migration period. The drops at the control section will be lower, *i.e.* around 10 to 20 cm, during periods of low or medium upstream water level. Particular attention must be paid to the risk of the orifices becoming blocked by water-borne debris.

When the level of the water upstream varies much more than that downstream, one solution is to design the fishway (*i.e.* the number of drops and pools) for the highest upstream water level. In order to maintain a sufficient discharge in the facility when the upstream water level falls, head drops between upstream pools can be reduced or suppressed by opening sluices located in the corresponding dividing wall (Figure 3c).

Alternatively sections of fishway may be bypassed altogether by providing additional pathways, e.g. one or more exits on the sidewalls of the upper pools (Figure 3d).

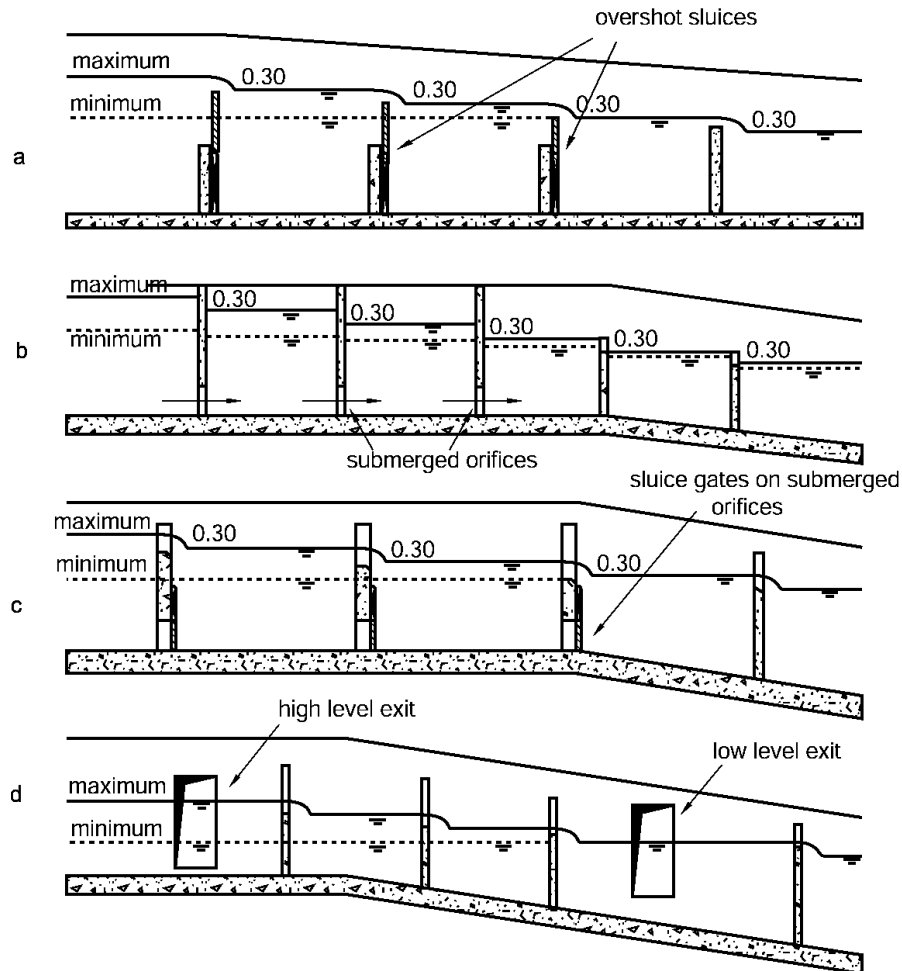


Figure 3: Schematic plans illustrating flow control sections in a fishway.

9. USEFULNESS OF POOL FISHWAYS

The pool pass appears to be the best solution when several migratory species are involved (salmon, sea trout, trout, cyprinids, etc.), since it is much less selective than the baffled fishway. Despite the limited slope which it may have, the fact that its layout can have frequent changes of direction (180° bends) makes the integration of this type of pass into existing plant relatively easy, usually in the bank.

Submerged orifice type fishways are generally of little interest and are, in practice, only rarely used. They are difficult to maintain (the orifices frequently become clogged), and the flow discharge through them tends to decrease during high flow (when the overall drop at the obstruction decreases) so that the fish may have difficulty in locating the orifice which is generally at the bottom of the pool. They cannot be used for shad.

Vertical slot type fishways have the distinct advantage that they can tolerate major variations (several m) in the upstream and downstream water levels, without requiring a control section. However, for large migrators, they can only be used where a significant flow is available (greater than $0.70 \text{ m}^3/\text{s}$ - $1 \text{ m}^3/\text{s}$) because of the minimum slot dimensions required for such fish. They allow fish passage at any depth.

Notch type fishways, whether or not they also have orifices on the floor, are currently the most common because they can be adapted to many circumstances. They accept a wide range of design flow discharge (several tens of litres/second to several m^3/s) and, if the notches are deep enough, they will accommodate relatively significant upstream water level variations without the need for regulation section.

Blocks can be set in the concrete floor of the pools in order to increase its roughness, and thus to make passage easier for small species. Similarly the side wall of the pass can be irregular to create small resting areas: special shapes for concrete or steel sheet piles can be used for wall construction.

As a guide for the designer, the geometric characteristics of several types of pool pass currently used in France and elsewhere are given below.

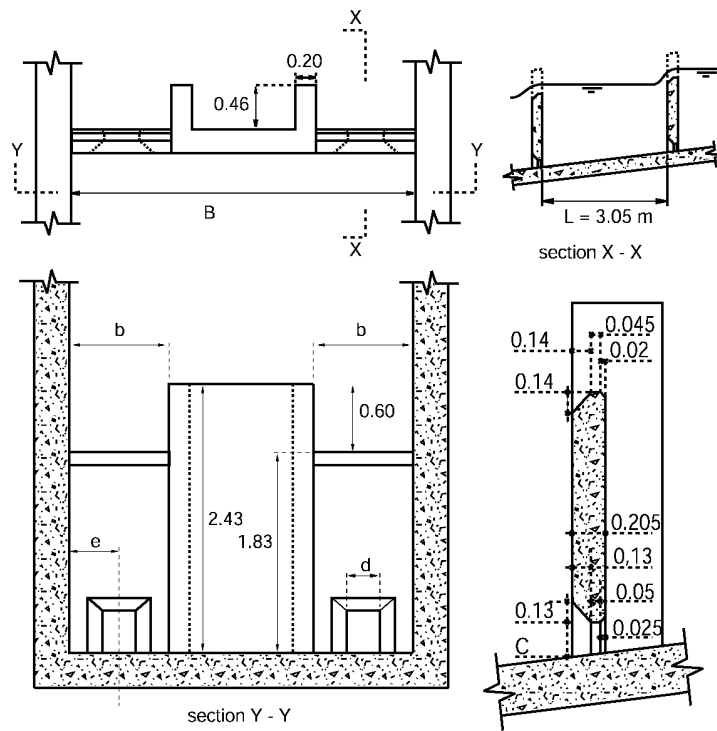
10. EXAMPLES OF POOL FISHWAYS

10.1 Ice Harbor type Fishway

This type of pass (Figure 4), which has been the subject of numerous hydraulic model studies, has often been used for salmonids on both the West Coast (in particular at the Ice Harbor Dam on the Columbia River) and East Coast of the USA (RIZZO, 1969; BELL, 1986). The minimum length of the pools is approximately 3 m, the average depth of water is 2 m, the difference in level between the pools is 0.30 m, and the slope is generally close to 10%. The flow passes through one or two side surface notches, whose width depends on the flow discharge required, and one or two orifices. The head on the weirs is approximately 0.30 m.

The width of this type of fishway may vary from 2 m in small plants to over 10 m in the largest plants, with a flow discharge of $1 \text{ m}^3/\text{s}$ to $6 \text{ m}^3/\text{s}$. The volumetric dissipated power varies roughly between $150 \text{ watts}/\text{m}^3$ and $200 \text{ watts}/\text{m}^3$. RIZZO (1986) specified a number of criteria for designing this type of pass. The coefficient of discharge of the side weir is around 0.45, and that of the orifices approximately 0.85. The width of each side weir is close to $0.312 B$, B being the width of the fishway. The size of the orifices varies from 0.09 m^2 ($0.30 \text{ m} \times 0.30 \text{ m}$) for a fishway designed for $1 \text{ m}^3/\text{s}$ to 0.2 m^2 ($0.46 \text{ m} \times 0.46 \text{ m}$) for fishways suitable for flows greater than $2 \text{ m}^3/\text{s}$. Figure 4 shows the characteristics of the pools.

The flow is "plunging" and accommodates only a slight variation in the level upstream. A control section consisting of either vertical slots, or else a series of telescopic sluices, is generally used when the level of water upstream varies.



Q (*) (m ³ /s)	B (m)	b (m)	e (m)	cxd (mXm)	Pv (*) (watts/m ³)
1.0	3.05	0.95	0.55	0.30X0.30	160
1.6	4.26	1.32	0.79	0.46X0.41	180
2.0	5.20	1.63	0.91	0.46X0.46	180

(*) flow and volumetric dissipated power for a nominal head of 0.30 m

Figure 4: Characteristics of a fishway of the “Ice Harbor” type.

This type of pass had been used for shad at some plants in North America. However experience has shown it creates a problem for shad when the design head is 0.30 m (because of the plunging jet). Several modifications have had to be made to improve the efficiency of the fish passage facilities (RIDEOUT and al. 1985) including:

- An increased head on the traverses (0.40-0.45 m) to create more surface flow.
- A reduction of the cross-section of orifices.
- Closure of every second notch in a staggered pattern in order to both prevent short-circuit of the surface jet and to decrease the flow discharge and the turbulence in pools.

With these modifications this type of pass then becomes very similar to the deep lateral, alternate notch fishway described below.

10.2 Deep side notch and submerged orifice fishway

This type of pass (Figure 5), which was developed following several studies on models, is currently used in France, mainly for salmonids. The traverses between the pools consist of side notches with bottom orifices situated opposite one another together. The position of the notches and the orifices alternates from one side of the pass to the other at

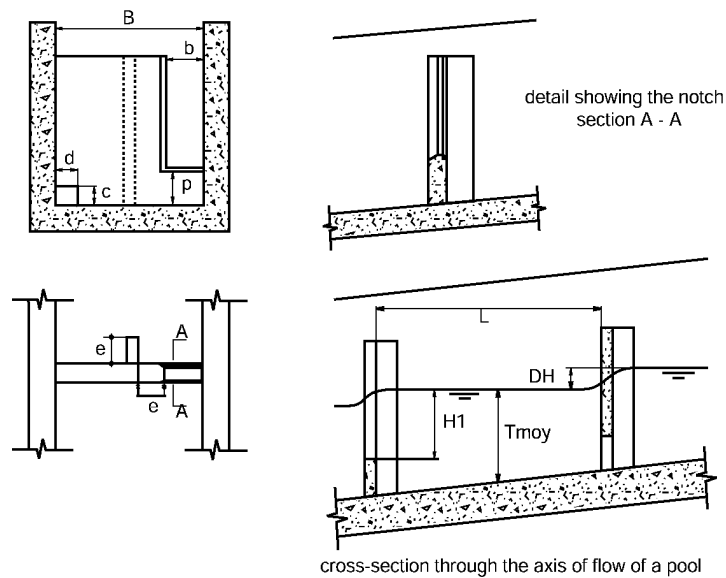
each successive dividing wall. A baffle fixed to the upstream face of the wall straightens and stabilises the flow and also reduces the contraction of the flow at the notch.

As there is a “streaming flow”, the width of the notch determines the dimensions of the pools to some extent (namely their minimum length) but their minimum volume depends on the volumetric dissipated power density required.

However, the hydraulic conditions in this type of fishway are not optimum, insofar as the whole volume of water in the pool does not contribute to the dissipation of energy. The flow from the notch remains relatively compact, forming a tube of current that hits the upstream face of the wall. A recirculation eddy, which has little effect on the power expended, forms at the side of the main current and downstream from the cross-wall.

It is therefore important to maximise the ratio between the length of the pools to the width of the notch (L/b) and to reduce the ratio between the width of the pool and the width of the notch (B/b) wherever possible. However, this is to the detriment of the overall slope and length of the facility.

Figure 5 shows the characteristics of pools designed for several different flow discharges. The drop between the pools is generally 30 cm.



Q (*) (m ³ /s)	L (m)	B (m)	Tmoy (m)	b (m)	cx d (m x m)	e (m)	P (m)	H1 (*) (m)
0.175	2.20	1.25	1.15	0.20	0.15X0.15	0.15	0.70	0.60
0.300	2.70	1.50	1.30	0.30	0.20X0.20	0.25	0.80	0.65
0.500	3.15	1.80	1.50	0.40	0.30X0.30	0.35	0.925	0.725
0.700	3.50	2.00	1.65	0.45	0.375X0.375	0.40	0.95	0.85

(*) design head and flow discharge for design head

Figure 5: Characteristics of a pool-type fishway used in France with deep side notches and submerged orifices.

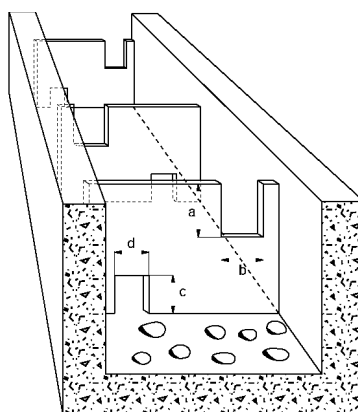
To ensure “streaming flow”, and in order to avoid the unstable regime that occurs between “streaming flow” and “plunging flow”, the minimum head at the notch must be a little more than twice the head drop between pools (*i.e.* 0.60 m for the usual drop of 0.30 m). The ratio (L/b) usually varies from 8 to 10 and (B/b) from 4 to 6.

This type of pass with streaming flow is difficult to design for very low flow discharge. Taking account of the need for minimum head and minimum slot widths (approximately 0.20 m for trout), this fishway cannot be designed for flows less than 150 litres/second. In such cases, the more classic “plunging flow” fishways with lower head and wider notches are used.

The main advantages of this type of fishway are that it is easy to construct, and that it can accommodate significant variations in the upstream water level without additional controls being necessary.

10.3 Fishway for coarse fish and trout (Germany, Switzerland)

Fishways consisting of pools with surface notches and submerged orifices have often been used in Germany and Switzerland. Figure 6 shows the characteristics of pools given by JENS (1982) for fishways for trout and coarse species in second order watercourses.



	Fishway for coarse fish	Fishway for trout
Minimum depth	0.80 m	0.60 m
Internal length	> 2.0 m	> 0.80 m
Internal width	> 0.80 m	> 0.60 m
Drop	< 0.25 m	< 0.30 m
Free space to the side walls	> 0.30 m	> 0.30 m
Notch (b x a)	0.20 x 0.25 m	> 0.20 x 0.20 m
Submerged orifice (d x c)	0.25 x 0.30 m	useless

Figure 6: Characteristics of a pool type fishway used in Germany for coarse fish and trout (from JENS, 1982).

The recommended maximum differences in level between pools are 0.30 m in fishways for trout, and 0.25 m in fishways for coarse fish species. The minimum depths recommended are 0.60 m and 0.80 m, and minimum lengths of the pool 0.80 m and 2.0 m respectively. The flow in this type of pass is less than 200 litres/second. While the author gives the minimum dimensions of the pools, gaps and orifices, he does not provide any other criteria that allow the dimensions of the pools to be determined as a function of the characteristics selected for the notches.

The author recommends that blocks, with a diameter of 15 to 20 cm, be positioned on the floor of the pass in order to increase its roughness, and thus to provide resting areas for smaller species.

This type of fishway is very calm and is suitable for most species, even small ones. However, it may prove to be less attractive and more difficult for the fish to locate on a large river because of its low discharge. In addition, it can only withstand small variations in upstream water level.

10.4 Vertical slot fishway

This type of fishway (Figure 7) was developed, following several studies on models, to allow salmon to pass the Hell's Gate rapids on the Fraser River in Canada (CLAY, 1961). The original model consisted of a series of huge pools 5.5 m long and 6.1 m wide, with two vertical slots 60 cm wide. The flow from the slots converged and met in the central section resulting in efficient energy dissipation, and creating calm zones on each side of the pool immediately downstream from the walls. Numerous fishways based on the same principal but consisting usually of only one slot, have been constructed all over the world (CLAY, 1961; ANDREW, 1990).

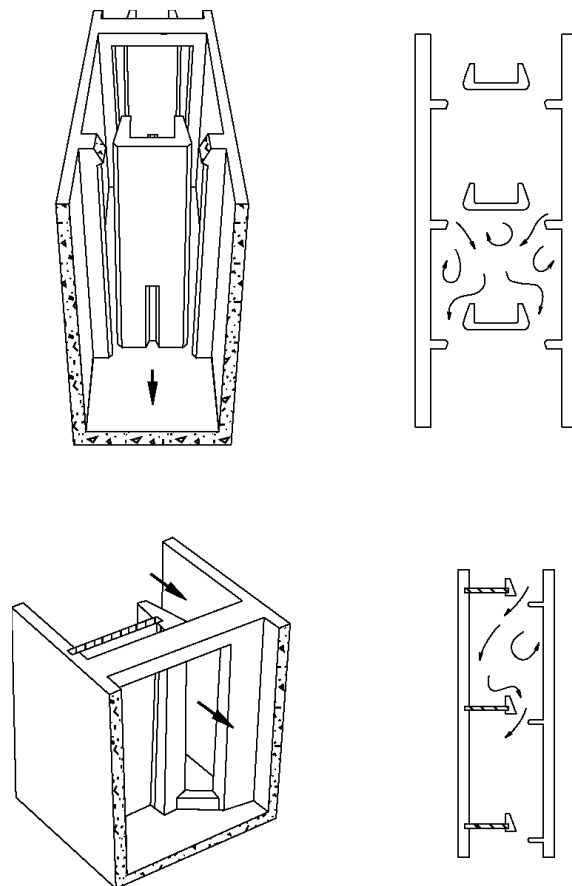


Figure 7: Single and paired vertical slot fishway.

Generally, a sill of at least 20 cm in height is installed at the base of the slot. This sill has two purposes: better guidance and stabilisation of the diagonal jet to prevent short-circuiting (or by-passing of the dissipation pool), and limiting the flow in the fishway.

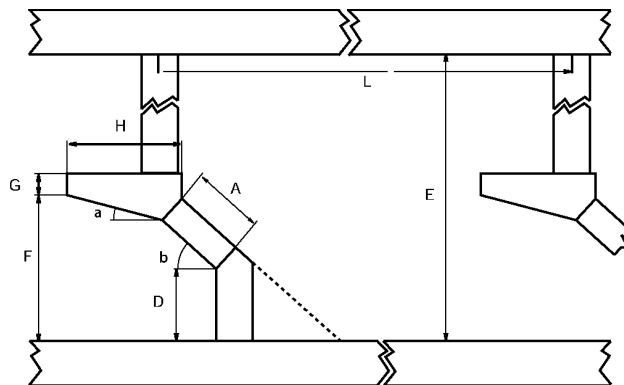
The flow at the exit from the slot tends to be directed perpendicularly to the crest of the sill. It is generally oriented at 30°-45° to the direction of the flow of the pool. The angle must be larger the smaller the height of the sill, in order to prevent short-circuiting. On the other hand, the angle must be reduced when the height of the sill is significant to prevent the flow hitting the opposite wall of the pool with too much force, which could risk disturbing the behaviour of the migrator. The optimum angle is therefore a function of the dimensions of the pools, *i.e.* the ratio of length to width.

The coefficient of discharge is affected by the geometry of the slot. Whether the crests are sharp or rounded to a greater or lesser extent, the height of the sill, and the water level at the slot, all influence the coefficient of discharge (PERKINS, 1973; RAJARATNAM *et al.*, 1984; LENNE, 1990), which may vary from 0.65 to more than 0.85 (CLAY, 1961).

The coefficients of discharge of fishways with vertical slots studied on scale models in France are around 0.65-0.70. These relatively low values are explained by the fact that the profile of the slots is characterised by sharp crests, whilst those used in the USA are generally rounded (RIZZO, 1986).

The drop between the pools is generally around 30 cm for large migratory salmonids. The geometry of the slots and the shape of the pools may vary significantly from one fishway to another.

Figure 8 shows the geometric characteristics of some vertical slot fishways constructed in France, most of which have been the subject of study in scale models (I.M.F.T., 1982, 1983, 1986, 1988; LENNE, 1990).



	Bazacle	Ramier	Belleville (2 slots)	Bergerac (2 slots)	Mauzac	Clais de Vire	Vichy
a (°)	15	15	20	17	19	18	15
b (°)	45	45	45	45	45	45	45
A(m)	0.40	0.50	0.60	0.55	0.45	0.30	0.50
D(m)	0.40	0.375	0.40	0.45	0.485	0.40	0.42
E(m)	2.50	2.50	5.00	6.00	2.80	2.50	2.50
F(m)	0.86	0.93	1.10	1.15	1.064	0.80	1.00
G(m)	0.15	0.13	0.20	0.22	0.20	0.12	0.15
H(m)	0.80	0.90	1.08	1.20	1.00	0.65	1.00
L(m) between cross walls axis	3.70	4.50	4.40	4.50	3.80	3.30	4.50

Figure 8: Geometric characteristics of a vertical slot fishway.

The ratio of the length of the pools in relation to the width of the slot varies from 8 to 10. The width of the pools in single vertical slot fishways varies from 6 to 8 times the width of the slot and becomes around 9 to 10 times the width of the slot in a paired vertical slot fishway.

Tests were carried out on a model (LENNE, 1990) with a view to simplifying the geometry of the baffles and of the cross walls, and to propose a standard design of which the characteristics are expressed as a function of the width of the slot (Figure 9).

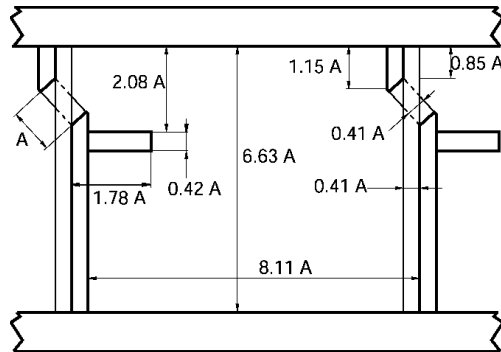


Figure 9: Characteristics of a simplified vertical slot fishway.

The great advantage of the vertical slot fishway is that it can accommodate significant variations in the upstream water level, provided that the level downstream is subjected to similar variations.

The conditions of velocity and turbulence remain very stable, whatever the water levels in the fishway, and the fish can pass through the fishway, swimming at its preferred depth.

10.5 Triangular weir-type pool fishways

The design of triangular weir-type pool fishways (or “pool and chute-type” fishways) was developed on the West Coast of the USA (BATES, 1990). It was developed in order to obtain fish passage facilities that operate over a large range of flows and upstream water levels, without the requirement for either an auxiliary flow in the downstream section, or any control device regulating the flow upstream. At low water level, the fishway behaves like a classic fishway with a plunging flow, the energy being dissipated in each pool. At high water, plunging flow and good fish passage conditions can be maintained on the edges of the pools whilst a high velocity streaming flow forms in the central section of the fishway. The pool and chute fishway therefore acts as a pool pass at low flow and a rough channel at high flow. There is no point in rationalising design in terms of maximum volumetric dissipated power in a pool. Figure 10 gives the characteristics of the fishway in the dam at Town on the River Yakima. The gradient is close to 10% and it can pass a discharge of around 10 m³/s. The sloping shoulder weirs have been designed with 1/4 to 1/3 slopes.

This type of fishway is very good at passing debris since its open design encourages debris to wash over the weirs and out of the fishway and it is substantially submerged at highest flow. Pool and chute fishways should not be used where the total drop exceeds 2 metres until the concept has been more thoroughly tested (BATES, 1997).

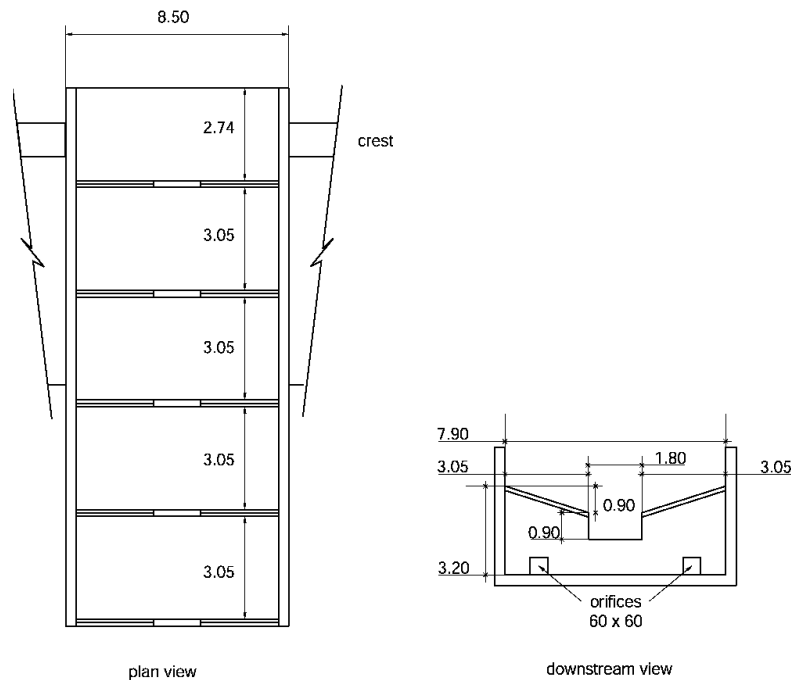


Figure 10: Pool and chute fishway (from BATES, 1990).

Following tests carried out on different scale models at the Institute of Hydraulic Engineering in Toulouse, France, triangular weir-type pool fishways have been constructed in the south-west of France (on the Adour, Salat, Neste and Lot rivers). The main difference in relation to the “pool and chute” fishway concept is that the energy is actually dissipated satisfactorily within each pool for all upstream water level conditions which may occur during the target species’ migration period. The length of the pools is equivalent to 12 times the maximum head in the centre of the V-notch.

Design criteria for such fishways have not yet been developed, mainly due to the difficulty of defining the hydraulic conditions in the facility in simple terms. In practice, triangular weir type fishways are only used for moderate drops for which the upstream water level fluctuations during the migration period are themselves moderate. Such fish passes have been built on obstructions in order to allow both fish and canoes and kayaks to pass.

11. PRE-BARRAGES

Pre-barrages often present an attractive solution to the problem of passing low obstacles. They consist of several weirs forming wide pools downstream of the obstruction, which break up the drop to be passed. These weirs are generally constructed near to one of the banks in order to facilitate maintenance. On small watercourses they can be easily constructed across the full width of the channel. Figure 11 shows various configurations of pre-barrages.

The main advantage of such structures is their attractiveness for fish, because of the very high percentage of the discharge of the watercourse that is likely to pass through the facility. This attractiveness is generally to the detriment of the “comfort” of the fish because in order to limit the number of pools relatively high head drops are frequently used for pre-barrages. If the head differences between pools for large salmonids are usually of the order of 0.30 m to 0.45 m in pool passes, then head drops at pre-barrages may be of the order of 0.45 m to 0.60 m.

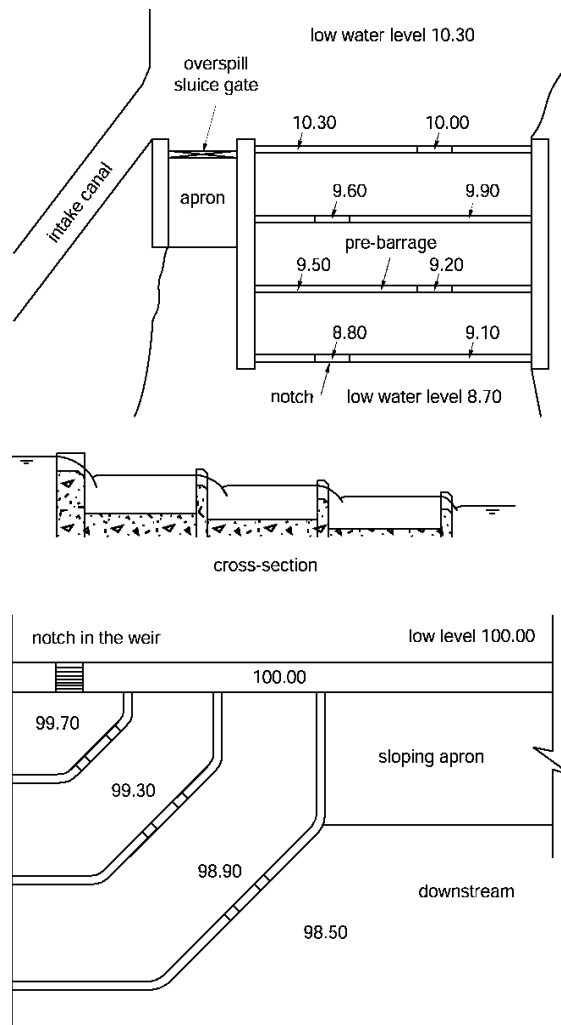


Figure 11: Schematic plans illustrating successive pre-barrages used to form fishways extending over a part or all of the width of the stream.

When designing pre-barrages, it is advisable to:

- Ensure that, irrespective of the flow in the watercourse, there is a sufficient head over the traverses to allow the fish to pass. During low water, the flow must generally be concentrated in a notch, with a minimum head of around 0.20-0.30 m.

- Maintain more or less constant drops from one pool to another as the water level upstream rises. When the pre-barrage is built adjacent to one of the banks, the facility will need to absorb successive increases in flow from the upstream pools to the downstream pool. This should be taken into account in determining both the elevation of the walls and the lengths of the different overflow weirs.

- Provide an appropriate profiled shape to the weirs so that the fish can pass from one pool to another without any difficulty. The walls should generally be around 0.20-0.30 m thick, or even more, to ensure both stability and solidity of the structure. If they are made rectangular, for reasons of simplicity, they will act as broad-crested weirs and will be difficult for the fish to pass. It is advisable to provide an adherent nappe by using a smooth, rounded shape or at least bevelling them to make them easier for the fish to pass. The

same should be done to all the walls that the fish are likely to need to pass. Particular attention should be paid to the most upstream notch, which is generally cut into the existing weir. It will generally form a much broader weir than the others and may pose particular problems for passage. For this reason it is sometimes necessary to reduce the first head difference at the upstream end to around 30 cm. On the other hand, the first drop at the downstream end can sometimes be increased for very low flow discharge conditions, especially if migration predominantly takes place during periods of medium to high water. The downstream water level generally rises more rapidly than the water level upstream of the obstruction as the flow discharge increase and thus tends to submerge the downstream drop very quickly.

- Ensure the durability of the fish passage facility and also prevent erosion, either by protecting the floor of the pools (with concrete or large blocks) or by sinking the walls deep enough below the bed.

- Make the pools sufficiently deep. The depth should be more than twice the drop wherever possible.

As is the case with pool passes, the minimum volume of the pools is a function of the flow and the drop. The flow and, consequently, the volumetric power dissipation in the pools generally increases very rapidly as the water level upstream rises.

If the fish only has to pass through a few pools, the criteria adopted for the maximum volumetric dissipated power may be higher than that adopted for pool passes. While the pre-barrages should be designed with volumetric dissipated power of the order of 50 watts/m³ or even less for low water conditions, a level close to 500 watts/m³ can be accepted as the maximum limit for operation of large pre-barrages passing several cubic metres/second.

Pre-barrage weirs are generally used for rivers with salmonid populations. This type of facility is to be avoided for most riverine species and shad since the flow in most cases is "plunging".

12. NATURAL BYPASS CHANNELS

The artificial river, or "natural bypass channel", is a shallow sloping channel mimicking a natural watercourse and linking the forebay and tailbay. The velocity in the channel is reduced and the energy is dissipated by the roughness of the bottom, the banks, and by a series of constrictions and expansions of the flow created by blocks, groynes and weirs positioned more or less regularly throughout the channel.

Provided that a number of criteria are taken into account at the design stage, this type of installation can be multi-purpose. It may form a fish passage facility for migratory fish and a white-water course for canoes, kayaks or rafts.

Currently there are few natural bypass channels for fish passage in France compared to the more conventional fish passes such as pool or baffled fish passes, but it is anticipated that the use of this type of environmentally-friendly passage will increase over the next few years. However, the low gradient (a few per cent, from less than 2% to a maximum of 5%) of such passes means that they are very long and this will prevent their widespread use.

As with any other fishway, it is recommended that the entrance to the bypass channel (*i.e.* the downstream entrance for the fish) should be located as far upstream as possible and very close to the obstruction. Because of the low slope required in this type of

fishway, it is sometimes difficult to position the entrance immediately below the obstruction, and it has to be located well downstream of the latter. This will restrict their efficiency, and consequently makes them of limited use on large rivers. On the other hand, this disadvantage can be overcome on smaller waterways by passing a large proportion of the total flow through the facility.

Velocities, drops and turbulence in the fish passage facility can be adapted to the swimming capacity and behaviour of the particular species found in the river.

In principle there are two types of natural bypass channels:

- Those in which the power dissipation is concentrated at local drops formed by regularly spaced, more or less "porous" weirs. These weirs create a series of pools of a sufficient length to adequately dissipate energy and to control excessive turbulence, so that there is no carry-over of velocity and turbulence to pools downstream. This type of diversion channel can be designed using the same criteria as those used for more traditional pool fish passes.

- Those in which the power dissipation is less localised and occurs more or less regularly along the facility. This is achieved by using posts, groynes, large blocks, etc. It is advisable to use an hydraulic model to define the geometry of such a channel, unless proceeding empirically on the site, in order to avoid any risk of creating point difficulties (local drops, high velocities, hydraulic jumps...) which might impede fish.

The discharge in such fish facilities depends on the slope and the width of the channel. The unit discharge per metre of width can be increased when the slope of the facility is reduced. As a rule discharge per metre of width varies from less than $0.1 \text{ m}^3/\text{s}/\text{m}$ to more than $0.5 \text{ m}^3/\text{s}/\text{m}$ depending on the slope.

In France a frequent limitation to the use of bypass channels is the necessity to pass both fish and canoes through the same structure. This has led to the use of submerged obstacles such as rock weirs or groynes instead of the hydraulically much more efficient rows of emergent stone-blocks. The resulting decrease in rugosity has made it necessary to reduce the slope of the facility. The channel is therefore unable to accommodate significant upstream water level variation without special regulating devices (gates). These control structures may themselves cause local head differences or velocities that the fish cannot pass. Therefore the installation of a small conventional fish pass, bypassing the control device, is necessary to allow the fish to leave the facility.

Fishways consisting of a series of pools with small head differences, separated by shallow V-shaped weirs constructed from sheet-piles with wooden capping, have been used on the river Meuse and its tributaries in the Netherlands (BOITEN, 1990). Their very low gradient (3.33%) makes them closer to bypass channel than traditional pool-fish passes.

The length of the pools is equivalent to $14 H_1$, H_1 being the head in the centre of the V-notch. The energy is actually dissipated satisfactorily within a length of 12 times the design head H_1 .

Figure 12 shows the characteristics of the pools for several design flows Q , given that the fishway operates with a flow of between $0.5Q$ and Q (*i.e.* an upstream head of between $0.75 H_1$ and H_1). The operating range of such a facility is very limited. It is around 10 cm for a pass suitable for $2 \text{ m}^3/\text{s}$, and remains below 20 cm for a pass suitable for $5 \text{ m}^3/\text{s}$. The volumetric power dissipation in the facility remains less than $100 \text{ Watts}/\text{m}^3$.

The design criteria proposed by the author stem directly from laws of similarity of hydraulic models. These fishways were first modelled to produce an optimised design for a particular slope (3.3%) and discharge. Extrapolations were then made using different geometrical scales to determine pass dimensions for different operating flows. The limit of this approach is that the head drop between pools increases in proportion to the operating flow: the drop varies from 0.20 m for $Q = 1.15 \text{ m}^3/\text{s}$ to 0.375 m for $Q = 5.5 \text{ m}^3/\text{s}$. From a practical point of view, the drop should only be selected as a function of the target species, and absolutely not as a function of the design flow.

On more recent fish passes, the V-shaped weirs are constructed of boulders or stone-filled gabions injected with concrete.

This type of pass is suitable mainly for obstructions installed on rivers with a very low gradient, and for obstructions where the upstream water level remains virtually constant.

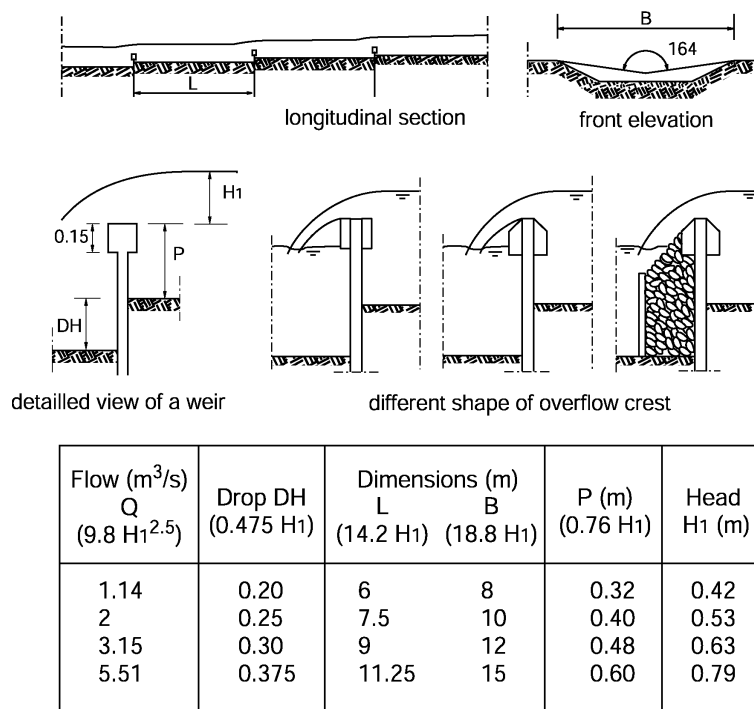


Figure 12: Layout of the V-shaped pool fishway used in the Netherlands (from BOITEN, 1990).

Figure 13 shows the characteristics of a bypass channel on the river Adour consisting of pools 8 m in length separated by triangular shallow V rock weirs. The gradient is 5%, which may be considered as the upper limit for the slope of this type of facility. The flow varies from 900 litres/second to almost $3 \text{ m}^3/\text{s}$ for a variation of around 30 cm in the upstream head. The volumetric power dissipation therefore varies from 90 watts/ m^3 to 250 watts/ m^3 . The drops between the pools are 0.40 m. This type of pass is mainly reserved for salmonids and fast water cyprinids.

The bypass channels described above are channels where the energy dissipation is concentrated at more or less regularly positioned overflow weirs.

In the natural bypass channel recently built at the Lac des Gaves (I.M.F.T., 1991) on the Gave de Pau, the power is partly dissipated by local drops, and partly by the rugosity of large cobbles and blocks on the bed and the banks. The facility consists of a series of trapezoidal reaches (maximum width 1.20 to 2.80 m) some 43 m in length. It has a 0.3% gradient and an approximate depth of 0.80 m. Between each reach a 5 m long stilling pool is used to dissipate a 0.30 m head drop. The stilling basin also can act as a resting pool for the fish. The overall gradient of the facility is around 0.9%, and the flow varies from 1.5 m³/s at the upstream end, to 4 m³/s at the downstream end after an auxiliary flow has been added. The materials used in the channel are selected from the coarsest granulometric part of the alluvium of the Gave de Pau (gravel and cobbles). The flow velocities in the river increase very rapidly with the flow discharge, which has made it necessary to install a sluice at the upstream end of the facility in order to maintain a relatively constant flow. A small pool type fish pass with submerged orifices allows fish to pass the obstacle created by the partial closure of the sluice during high river flows.

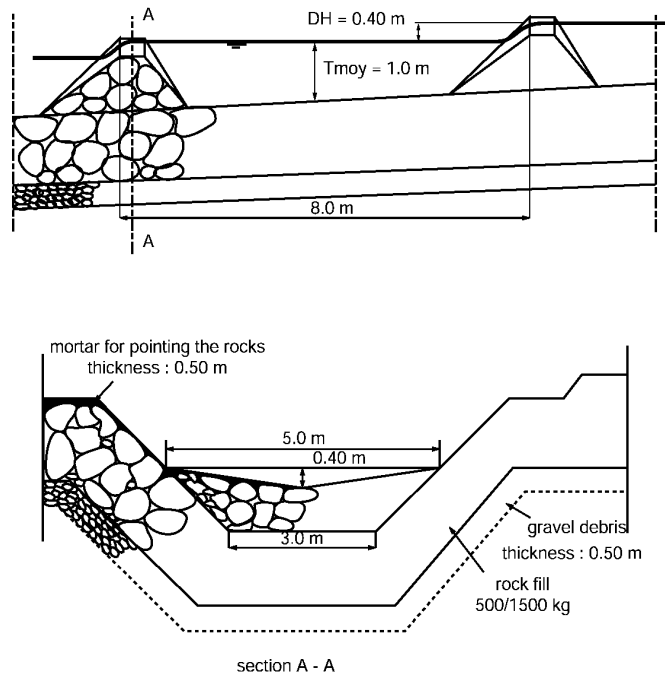


Figure 13: Bypass channel with rock-fill weirs.

A similar type of bypass channel, where the gradient is generally between 1 and 1.5%, is used in Denmark (LONNEBJERG, 1990). The facility at Holstebro is 655 m in length and allows the fish to pass a total drop of 5 m. The section is trapezoidal (2.5 m maximum width), and the base and walls are covered with blocks of 15 cm to 20 cm. Larger blocks (50 cm) are positioned on the bottom and at the sides at regular intervals (every 2 m), in order to increase the roughness of the bed while also creating individual rest zones for the fish. The flow is regulated during the season and is between 0.4 m³/s and 1 m³/s during migration periods. The facility has 6 regularly spaced rest pools. Most of the power in this fishway is expended by the rugosity of the bed and walls.

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Photo 1: Ice Harbor type fishway at the Vernon dam (Connecticut River, USA), looking upstream.

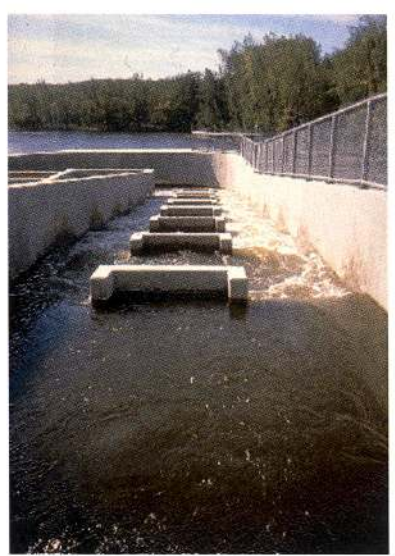


Photo 2: Ice Harbor type fishway at the Vernon dam (Connecticut River, USA), looking downstream.



Photo 3: Submerged orifice type fishway at Clunie Dam (Scotland).



Photo 4: Small "plunging flow" salmonid fish pass at Cau dam (Gave d'Ossau, Atlantic Pyrenees).



Photo 5: Semi-circular notch fishpass at the Hom dam, on the river Orne (Normandy).



Photo 6: Deep lateral side notch and submerged orifice fish pass (Vézère river).

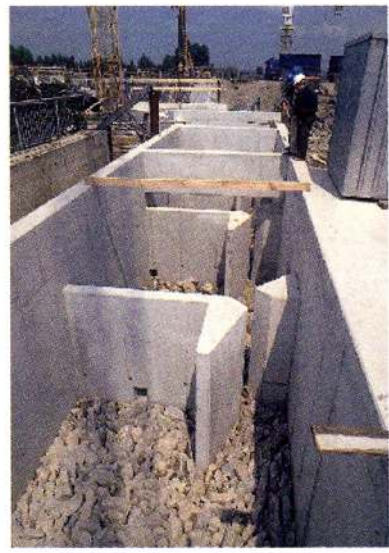


Photo 7: Vertical slot fish pass at Iffezheim power plant (river Rhin). Note the blocks on the floor to make small species passage easier.



Photo 8: Vertical slot fishway at Mauzac power plant on the river Dordogne.



Photo 9: Vertical slot fish pass at a small weir on the river Gardon.



Photo 10: Chamfered angles in a change of direction pool in a large paired vertical slot fishway (Puyoo weir, river Gave de Pau).



Photo11: V-shaped weir fishway at Sambeck dam on the river Meuse (Netherlands).



Photo 12: Detail of flow above the V-shaped weir at Sambeck fishway on the river Meuse (Netherlands).



Photo 13: Detail of the V-shaped weir at the fishway at Sambeck dam on the river Meuse (Netherlands).



Photo 14: General view of the natural bypass channel at Chatillon sur Lison weir (river Loue).

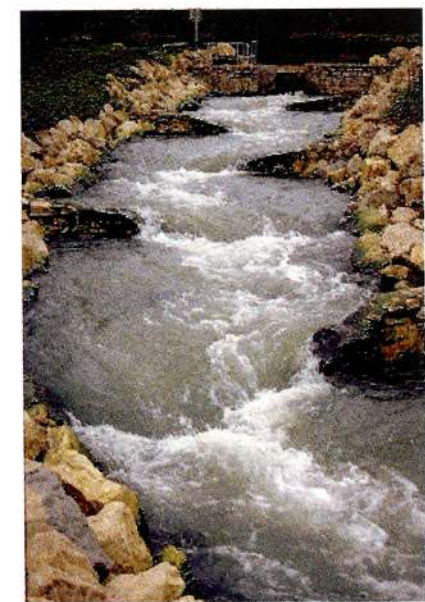


Photo 15: Natural bypass channel for salmonids on the river Loue (Chatillon sur Lison weir).

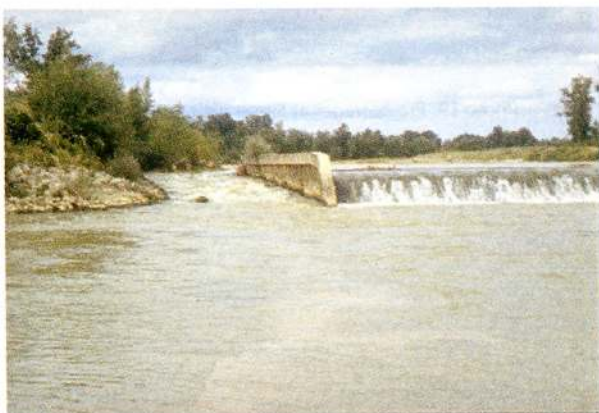


Photo 16: Natural bypass channel for shad on the Adour river (Toulouze weir).



Photo 17: Triangular weir fishway at Sarrancolin dam on the river Neste.



Photo 18: Natural bypass channel on the river Bröl (Germany).



Photo 19: Pre-barrages at Sinsat weir (Ariège river).



Photo 21: Natural bypass channel at Biron small-scale power plant on the Gave de Pau river.



Photo 20 : Pre-barrages at Lestelle weir on the Gave de Pau river