CHAPTER 6

BAFFLE FISHWAYS

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1. PRINCIPLE

The first baffle fishways (or "Denil" fishways) were developed in Belgium by the civil engineer, Denil, to allow salmon to pass the Angleur dam on the river Ourthe (DENIL, 1909). The principle aim of such fishways is to reduce the mean velocity of the flow by placing a series of baffles on the floor and/or walls of a straight channel, which has a rectangular cross-section and a relatively steep slope.

These baffles, in shapes of varying complexity, cause secondary helical currents to form which ensure an extremely efficient dissipation of energy in the flow through intense transfer of the momentum.

Experiments on hydraulic models were first initiated by DENIL (DENIL, 1936-1938). They were later repeated and expanded upon by others. The aim of these experiments was to simplify the shape of the original baffles which were very sophisticated, whilst still retaining equivalent hydraulic efficiency. MCLEOD and NEMENYI (1940) in the USA, WHITE and NEMENYI (1942) in Great Britain, and more recently LARINIER (1978, 1983), LARINIER and MIRALLES (1981) in France, LONNEBJERG (1980) in Denmark, RAJARATNAM and KATOPODIS (1984, 1990) RAJARATNAM *et al.* (1985, 1987) in Canada, have all contributed to developments.

2. CHARACTERISTICS AND OPERATION

There are numerous types of baffles that have been studied on hydraulic models but not assessed in the field from a "biological" point of view. The following only deals with those that have been tested in practice and proven their efficiency, and on which there is sufficient feedback.

There are three different types of baffle fishways:

- Fishways in which the baffles are fitted only on the floor of a horizontal channel. Wide fishways may be built by juxtaposing the "unit" pattern of the baffle several times. While these fishways are very versatile in this respect, thus offering a very wide range of discharge, nevertheless they have the disadvantage of only withstanding a modest variation in the upstream water level, because velocity increases rapidly with depth,

- Fishways in which the baffles are located both on the floor and on the sides. These have the advantage of withstanding greater variations in the upstream water level. However, as the size of the migrator generally limits the dimensions and consequently the width of the baffles and the channel, the flow is limited and may not exceed several hundreds of litres per second,

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- Fishways in which the baffles are placed on the sides only (LARINIER and MIRALLES, 1981). These have the advantage of withstanding major variations in the upstream water level and are capable of conveying significant flows. They are also very efficient. Their major disadvantage is that they are likely to become blocked by water-borne debris very easily, especially tree branches, and therefore to require excessive maintenance. This is why they are rarely used.

The geometric characteristics of the baffles are given in a dimensionless form*:* all dimensions are related to one reference dimension (width of the channel or height of the baffle). It is essential not to change the given geometric characteristics since any modification, whether in the shape of the baffle or in baffle spacing, can result in a significant alteration in the structure of the flow which can be very detrimental to the efficiency of the fishway.

Both an “hydraulic” and a “biological” operating range can be specified for any baffle fishway*:*

- **“Hydraulic” operating range**: a minimum flow is necessary for helical currents to form. Below this flow the fishway acts as a mini-pool pass. Above a certain flow, depending on the slope of the channel and the type and the size of the baffles, waves begin to occur which sweep the fishway from upstream to downstream. The helical currents only form occasionally, the flow progressively becomes supercritical, and the baffles do not fulfil their energy-dissipating role.

- **“Biological” operating range**: baffle fishways are suitable for certain species and certain sizes of fish. The operating range for each baffle-type fish pass (channel slope, baffle dimensions, flow discharge in the fishway) for any given migratory species can only be acquired from experience gained from monitored fishways.

Whilst the “hydraulic” operating range of a fishway can be determined quickly and easily in the laboratory by a study on a hydraulic model, the “biological” operating range takes much longer to assess. It can only be accomplished after careful monitoring of fishways, *i.e.* by trapping fish and by recording both the prevailing hydraulic (particularly the upstream head) and temperature conditions during each trapping period.

A certain amount of flexibility in the choice of dimensions of the baffles is possible by varying the width of the channel and the baffles proportionately. However, the following points must be noted:

- An increase in the size of the baffles, if the slope of the channel remains constant, results in an increase in the size of the helical currents and a simultaneous increase in the water velocities. If the size of these eddies becomes too large compared to that of the fish, then it may have an adverse effect on the efficiency of the pass. The fish would tend to orientate themselves in relation to local components of the velocity, and to bump into the baffles.

- A reduction in the size of the baffles has its disadvantages, because the hydraulic operating range of the pass, in respect of acceptable variation in upstream head, is reduced since it is also proportional to baffle, and therefore channel, dimensions.

In practice, it is generally advisable to use the smallest baffles possible, whilst remaining within their hydraulic operating range. This will maximise the size range of individuals able to utilise the pass.

Generally, any constriction of the channel cross-section that could cause an increase of velocity upstream of the first baffle, and therefore delay “charging” of the pass,

should be avoided. In particular, the invert of the floor of the pass upstream from the first baffle should always be situated well below the crest of this baffle ("point of discharge") so that the control section occurs at the first baffle and not somewhere further upstream. It is also an advantage for the upstream entrance to have rounded walls, to encourage a smooth and laminar flow that will not delay charging of the pass.

The downstream entrance of the fishway (*i.e.* entrance for the fish) must be submerged to a depth sufficient to prevent any local acceleration in flow, or any drop to form, which could have a detrimental effect on the passage of the fish. Fish must swim to enter a baffle fishway, without having to jump, to avoid any risk of injury. The most downstream baffle must be submerged, even during low water conditions, to at least the same depth as the head on the most upstream baffle.

3. LENGTH OF FLIGHTS AND RESTING POOLS

There is no resting zone for fish in a baffle fishway and the fish must pass in one attempt. Also, when the total drop (and as a consequence the length of the pass) becomes too great, fish must make an intensive effort for a period which may exceed the limits of its endurance. One or several **resting pools** should therefore be provided.

In practice a resting pool is installed for every 1.8 to 2.5 metres of drop for sea trout and salmon, and the length of the flights between resting pools is limited to 10 to 12 metres. It is clear that if one only took the larger fish (> 60cm) into account then it would be possible to use much longer flights. However this would have the effect of excluding smaller fish which do not have the endurance to pass the longer flight

Resting pools should be provided for every 1.20-1.50 metres of drop for small fish such as brown trout, and the length of the flights should not exceed 6 to 8 metres.

Any one flight of baffle fishway must be rectilinear (*i.e.* forms a straight line), and any change in direction should be made only at a resting pool. The resting pool must be long enough to prevent the flow from the upstream flight meeting the opposite wall with too much power (particularly where there is a 180° change in direction), or from disturbing the flow (*i.e.* inhibiting the formation of helical currents) in the next flight downstream.

A minimum acceptable length for a resting pool is about 10 d**,** d being the smallest dimension of the jet entering the resting pool, *i.e.* the smallest value of either the clear width of the baffles (side baffles) or the water depth over the baffles (floor baffles). A minimum depth of about 0.50 m below the invert of the floor is required. The same criteria for maximum volumetric dissipated power as used for pool fish passes can be applied to ensure that fish can rest.

4. USE AND LIMITS OF BAFFLE FISHWAYS

The flow in baffle fishways is characterised by significant velocity, turbulence and aeration. This type of pass is used for diadromous species such as salmon, sea and lake trout, marine lamprey (which use this type of fishway easily), and some large rheophilic potamodrous species such as barbel. Generally, baffle fishways are used for fish larger than around 30 cm. They may be used for smaller species such as brown trout, provided that the size of the baffles and the length of the flights are reduced significantly.

Generally small fish do not have enough endurance to use baffle fishways. The effort which traditionally-sized baffle fishways require of them is in the range of their burst

speed which they can only maintain for a few seconds. Consequently the length of the flights must be limited to a few metres, and this generally makes the use of this type of fish pass impractical. It is possible to adapt the hydraulic characteristics of the fishway (velocities, size of the helical currents) to smaller fish by using smaller baffles, in order to bring velocities within the range of the sustained speeds, which the fish can then maintain for several tens of seconds. However, this leads to very small fishways with all the resultant disadvantages: very limited operational flow discharge (several tens of litres/second), reduced attractivity, increased likelihood of blockages, and inability to withstand any significant variation in the upstream water level.

Having said that it is not an ideal proposition, it should be noted that small fish have been observed passing through baffle fishways in some circumstances. For example, small fish have been observed using baffle fishways as mini-pool passes, resting themselves in the space between baffles, when the head in the pass was extremely low and insufficient to generate the helical currents which occur in normal operation (CSP, 1989). In other cases, where passes were operating normally, it was observed that some fish managed to exploit the relatively calmer zones between baffles to progress step by step through the fishway (SCHWALME and MCKAY, 1985).

5. PLANE BAFFLE OR DENIL FISHWAY

This is the most common type of baffle fishway. Its main feature is the simplicity of construction of the baffles, which are in one plane, and placed at an angle of 45° to the floor of the channel. Its width (L) may vary between approximately 0.60 and 1.00 metre, and the channel slope (S) between 0.12 and 0.20 (12% and 20%).

The baffles are generally made of steel (8 mm to 10 mm thick), wood or concrete (maximum thickness L/20, where L is the width of the channel).

They have been widely used in Europe (France, Great Britain, Ireland, Sweden) for Atlantic salmon and sea trout. They are used on the East Coast of the USA for Atlantic salmon and Alewife.

Figure 1 shows the geometric characteristics.

Figure 2 shows the relationship between the flow $\mathbf{Q}^* = \mathbf{Q}/\left(\sqrt{\mathbf{g}}\mathbf{L}^{2.5}\right)$, the upstream head (ha/L), the mean depth of water (h/L) and the discharge velocity $\mathbf{V}^* = \mathbf{V}/\sqrt{\mathbf{gL}}$ for several channel slopes (S) in dimensionless form.

The operating head (ha) is the elevation of the upstream water surface relative to the vertex of the notch (the lower point) of the upstream baffle. The operating head (ha) should not be confused with the total head (hr), which is the elevation of the upstream water surface relative to the channel floor at the base of the upstream first baffle. This leads to the following relationship:

$$hr = ha + 0.236\ L \sin(45° + \text{arctg}\ S).$$

When the channel slope is changed from 10% to 20% (S = 0.1 to 0.2), hr changes from (ha + 0.183 L) to (ha + 0.196 L).

The mean depth of water (h) is the mean height of water in the fishway above the channel floor.

For **large salmonids,** a maximum gradient of 20% is generally used, and the internal width of the fishway (L) is generally between 0.80 and 1.00 metre. The width (L) can be greater in some fishways (1.20-1.30 m). However, there is little advantage in selecting such large baffles as it means that the channel slope must be reduced (in order to maintain acceptable velocity, aeration and turbulence levels). It also penalises the smaller fish (by increasing the size of helical currents, the distance between baffles and the length of the flights).

For passes specifically designed for **trout**, smaller baffles and shorter flights must be used. A channel width (L) between 0.50 and 0.70 metres is suggested, with a maximum channel slope of 20%.

The **lower operating limit** of a plane baffle fishway is dictated by two factors. These are the minimum head on the upstream baffle (ha) that allows the helical currents to generate (*i.e.* the pass to charge), and the minimum depth of water (h) in the pass that provides sufficient depth for the fish to swim. The ratio h/L = 0.5 can be taken as a limit, which corresponds to the minimum depth of water available above the crest of the baffle for the passage of the fish of 0.33 L.

The **upper operating limit** of the plane baffle fishway is much more difficult to define as it depends on the swimming ability of the fish. A maximum ratio of h/L 1.0 to 1.1 is reasonable.

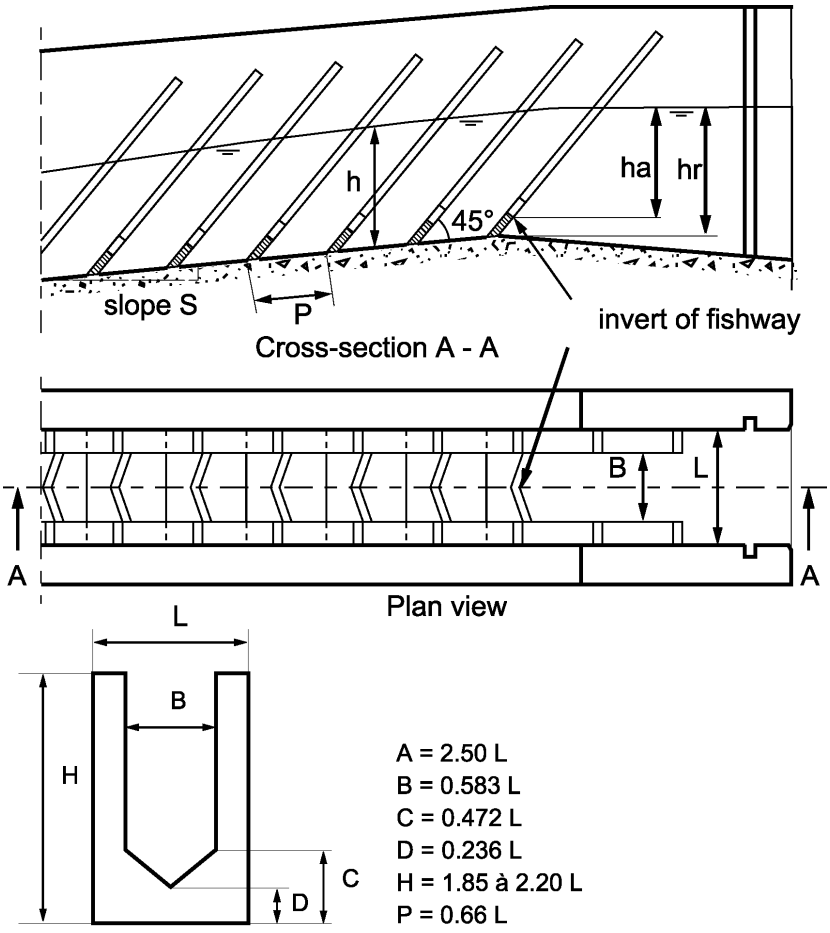


Figure 1: Characteristic parameters of a fishway with plane baffles.

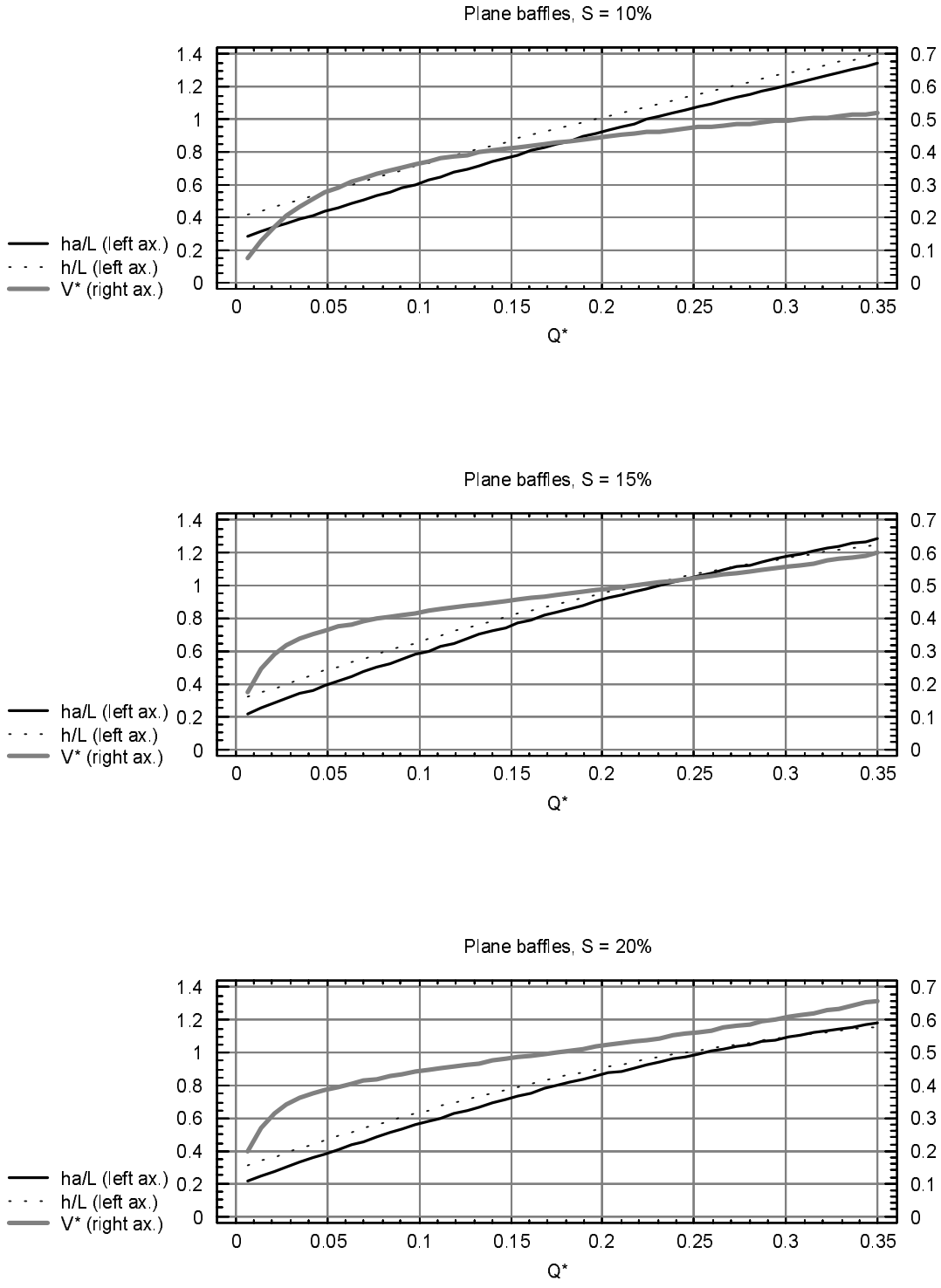


Figure 2: Relationship between flow discharge, upstream head, mean depth and average water velocity for a plane baffle fishway.

Figures 3 and 4 show the relationship between the flow (Q), the upstream head (ha), the mean depth of water (h) and the average water velocity (V) for a salmon pass 0.90 m in width and a trout pass 0.60 m in width, with a channel slope of 20%.

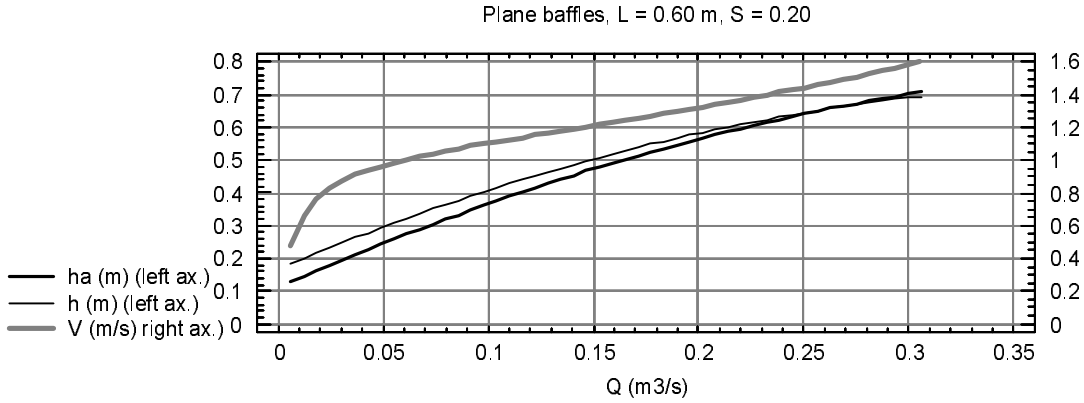


Figure 3: Relationship between flow, upstream head, mean depth and average water velocity for 0.60 m wide plane baffle fishways with a 20% gradient.

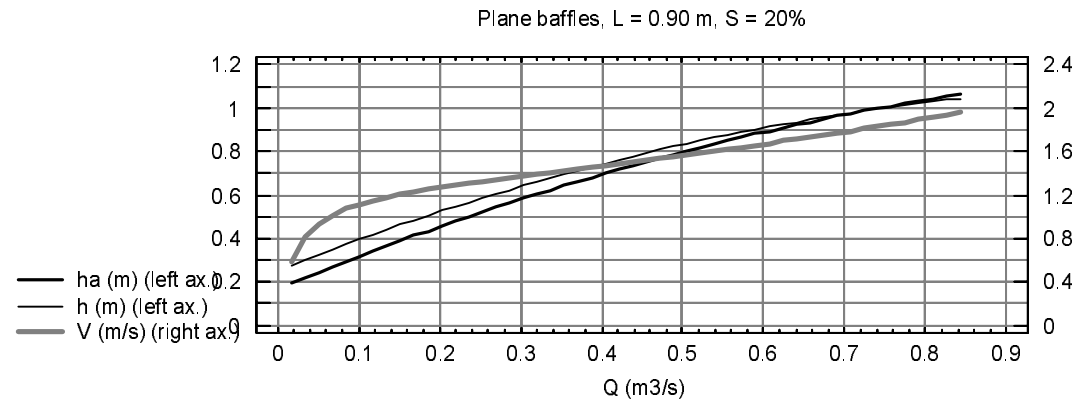


Figure 4: Relationship between flow, upstream head, mean depth and average water velocity for 0.90 m wide plane baffle fishways with a 20% gradient.

6. FATOU FISHWAYS

The Fatou fishway was directly inspired by the prototype developed by Denil (DENIL, 1909). This model is very efficient from a hydraulic point of view. However, it has two major drawbacks. It is not easily constructed because of the shape of the baffles, and branches and other floating debris can easily block it. Furthermore, the very high hydraulic efficiency of the baffles limits the kinetic energy of the jet at the entrance of the pass, resulting in a weak attraction at the entrance to the fishway. Insofar as its field of application is very similar to that of the plane baffle fishway, the latter is generally to be preferred.

Figure 5 shows the geometric characteristics of a Fatou fishway.

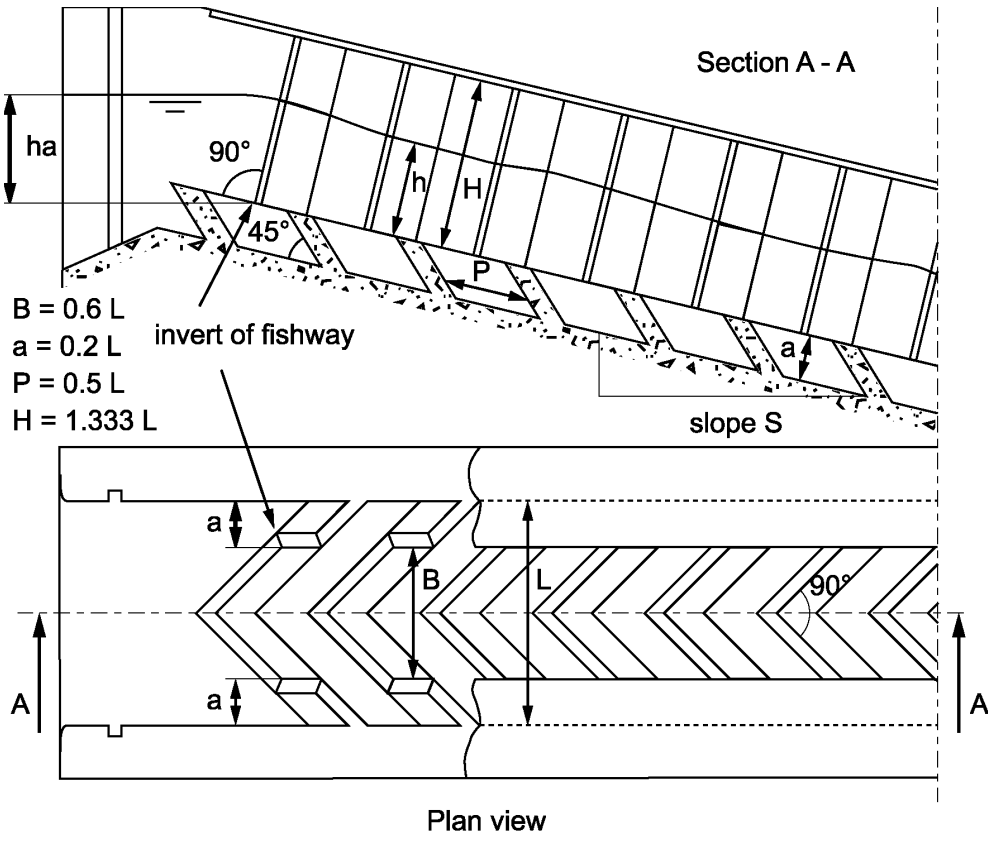


Figure 5: Characteristic parameters of the a fishway with Fatou baffles.

Figure 6 shows the relationship between the flow $\mathbf{Q}^* = \mathbf{Q}/\left(\sqrt{\mathbf{g}}\mathbf{L}^{2.5}\right)$ the upstream head (ha/L), the mean depth (h/L) and the average flow velocity $\mathbf{V}^* = \mathbf{V}/\sqrt{\mathbf{gL}}$, for several channel slopes (S) in dimensionless form.

The conditions of use are identical to those for plane baffle fishways.

The operating range is characterised by a minimum h/L ratio of approximately 0.4, to allow both the helical currents to “charge” the fishway and sufficient depth for the fish to swim, and a maximum h/L ratio of approximately 1.

Figures 7 and 8 show the relationship between the flow (Q), the upstream head (ha), the average depth of water (h) and the average water velocity (V), for a salmon pass 0.90 m wide and a trout pass 0.60 m wide, for a 20% gradient.

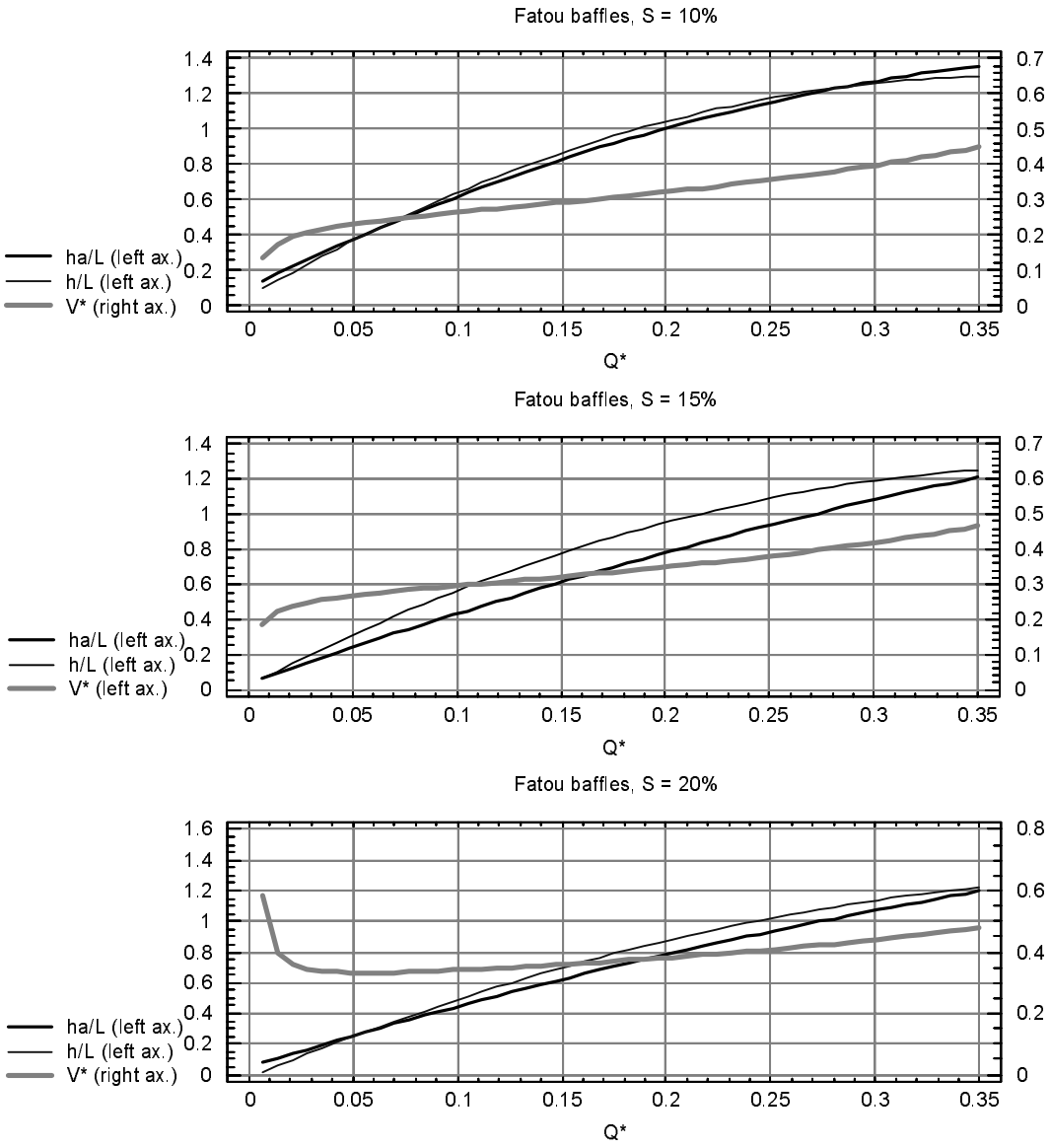


Figure 6: Relationship between flow, upstream head, mean depth and average water velocity for a fishway with Fatou baffles.

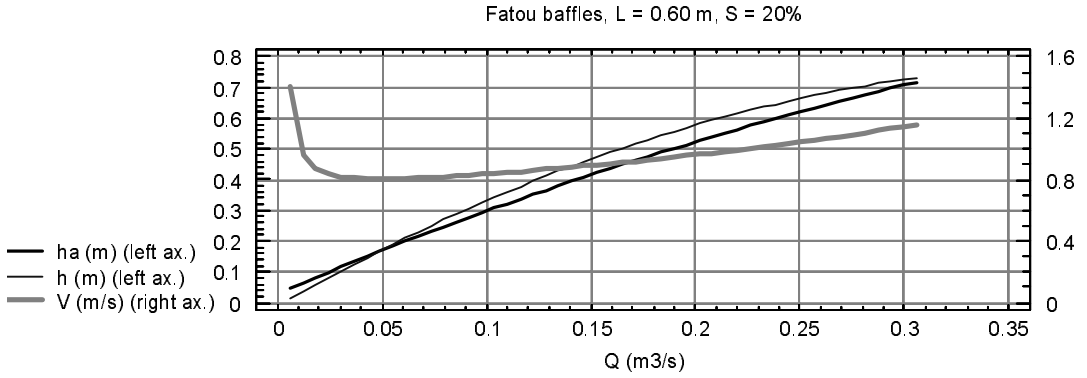


Figure 7: Relationship between flow, upstream head, mean depth and average water velocity for 0.60 m wide Fatou baffle fishways with a 20% gradient.

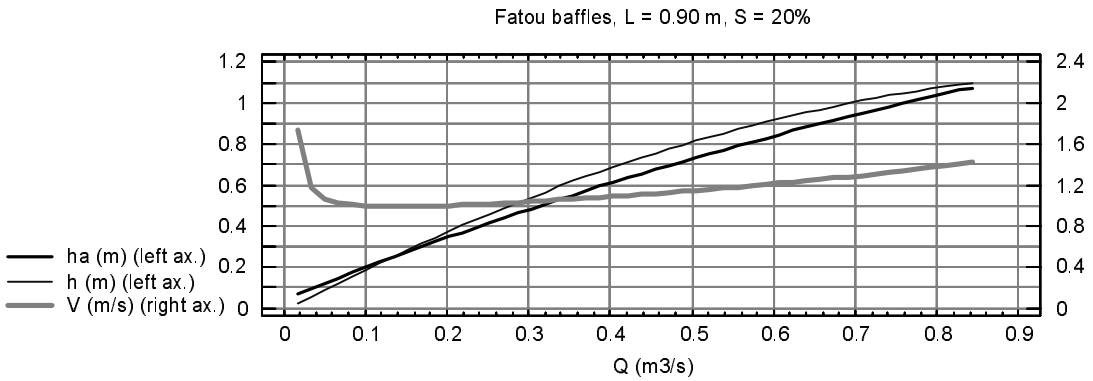


Figure 8: Relationship between flow, upstream head, mean depth and average water velocity for 0.90 m wide Fatou baffle fishways with a 20% gradient.

7. SUPER-ACTIVE TYPE BOTTOM BAFFLE FISHWAY

This type of fishway consists of a herringbone pattern of thin baffles that are placed on the bottom of the channel only. An advantage of this design is that many units can be juxtaposed enabling large attraction flows to be achieved. A longitudinal strip of the same height as the baffles must separate the baffle rows, in order to stabilise the flow. This type of baffle was developed on hydraulic models (LARINIER and MIRALLES, 1981) inspired by the RIRO model (DENIL, 1936-1938; LARINIER, 1977) which was used at the Roermond dam on the Meuse in the Netherlands. It has mainly been used in France, but has recently become quite widespread in Great Britain. The baffles are fabricated from steel (8-10 mm thick), and their height generally varies between 0.08 m and 0.20 m.

Figure 9 shows the geometric characteristics.

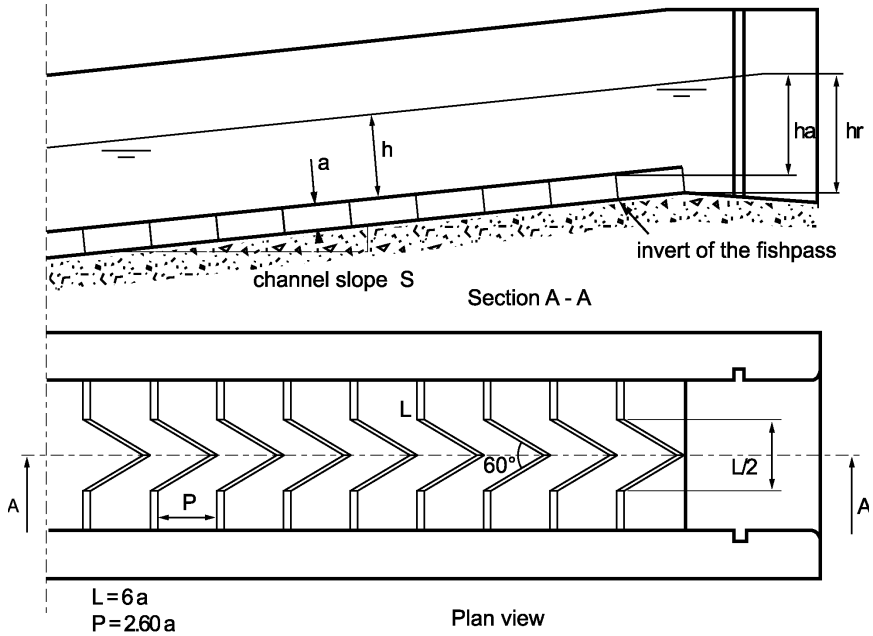


Figure 9: Characteristic parameters of a fishway with super-active-type bottom baffles.

Figure 10 shows the relationship between the unitary flow $q* = q / \sqrt{2g} \cdot a^{1.5}$, the upstream head (ha/a), the mean depth of water (h/a) above the baffles, and the average water velocity **V* = aq*/h** for several channel slopes (S), in dimensionless form.

(a) is the height of the baffles in metres.

The upstream head (ha) is the elevation of the upstream water surface relative to the lower point of the most upstream baffle (corresponding to the elevation of the upstream water surface before acceleration into the fishway begins). The relationship between the operating head (ha) and the total head (hr) relative to the invert of the bottom of the channel at the upstream end of the first baffle is as follows:

$$hr = ha + a - 2.6\ a\ S$$

The mean depth of water (h) is the average depth of water in the fishway above the baffles.

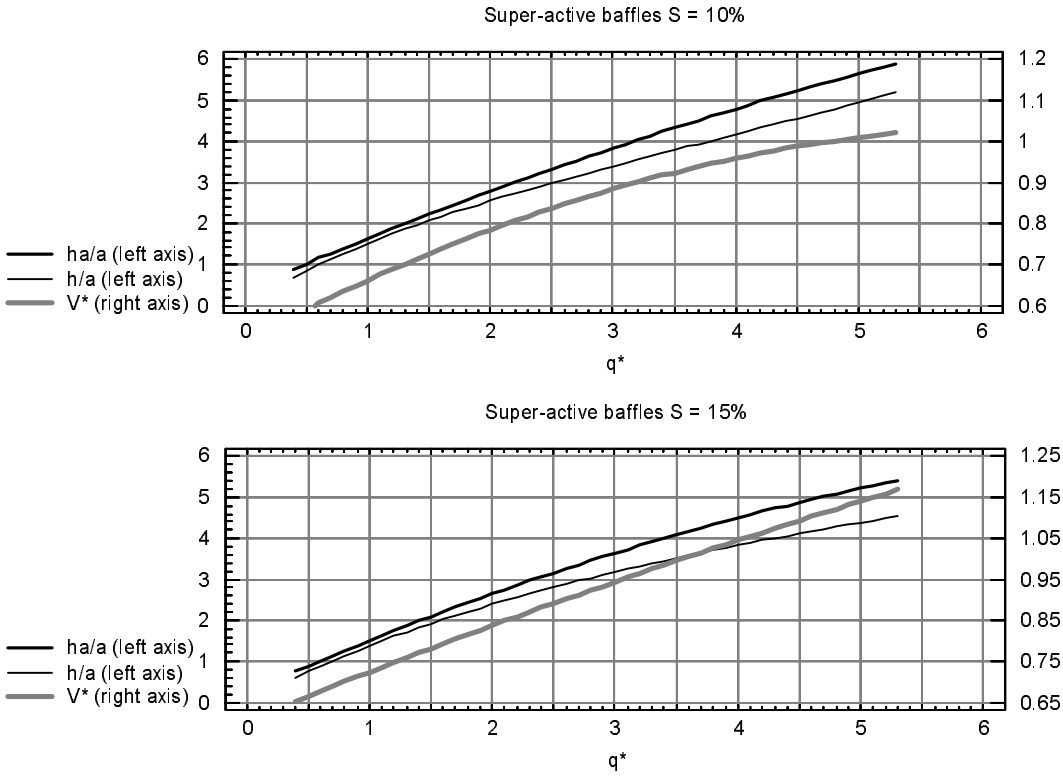


Figure 10: Relationship between the flow, upstream head, mean depth and average water velocity for a fishway with superactive-type bottom baffles.

Since the width of the fishway may vary considerably, the graphs give the relationship between ha and q, the unitary flow discharge (*i.e.* flow discharge per metre of width). The total flow Q (m^3/s) in a fishway consisting of a number N of juxtaposed units, of height (a) can easily be calculated from the unitary flow (q) using the following formula (where 6 a N is the width of the pass in metres):

$$Q = 6\ a\ N\ q$$

For large migratory salmonids, the height of the baffles (a) is generally taken to be between 0.10 m and 0.20 m, and the maximum channel slope to be 15-16%.

For fishways designed specifically for trout, the dimensions of the baffles and the length of the flights will both be reduced. Baffle heights between 0.08 and 0.10 m are recommended, again with a maximum gradient of 15-16%.

The **lower operating limit** is characterised by a minimum head on the upstream baffles (ha) (or a minimum depth of water above the baffles (h)) which allows the formation of the helical currents and sufficient depth for the fish to swim. The limit may be taken as h/a = 1.15. The minimum depth of water (h) to be used depends on the size of the fish. A minimum depth of 15-20 cm should be taken for large migratory salmonids and around 10 cm for trout.

The **upper operating limit** of the fishway is much more difficult to define, as it depends on the swimming ability of the fish.

Figures 11 and 12 show the relationship between the unitary flow (q), the upstream head (ha), the mean depth (h) and the average water velocity (V), for a salmon fishway with baffles 0.15 m high, and for a trout pass with baffles 0.10 m high, both for gradients of 15%. The operating range for the fishway for large salmonids, expressed as a unitary flow, should be between 250 l/s/m and 1400 l/s/m (*i.e.* corresponding to a range of around 50 to 60 cm in upstream water surface levels, ha between 0.23 m and 0.82 m). The operating range for the fishway for trout must be between 150 l/s/m and 500 l/s/m (corresponding to a difference of less than 30 cm in the upstream water surface levels, with ha between 0.18 m and 0.42 m).

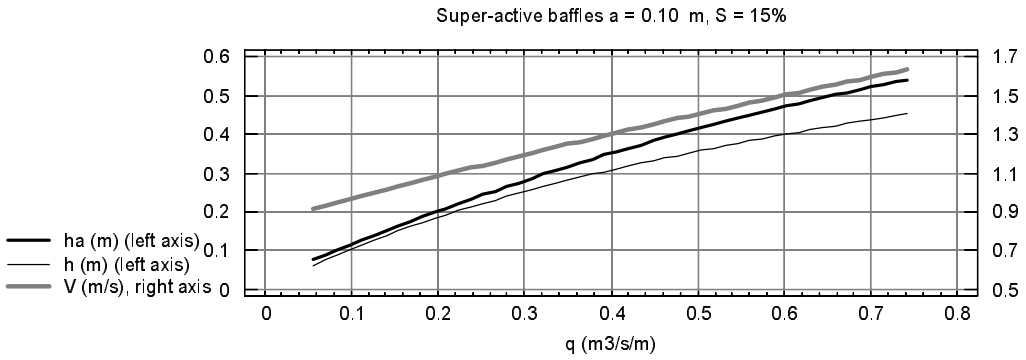


Figure 11: Relationship between flow, upstream head, mean depth and average water velocity for 0.10 m high superactive-type bottom baffle fishways with a 15% slope.

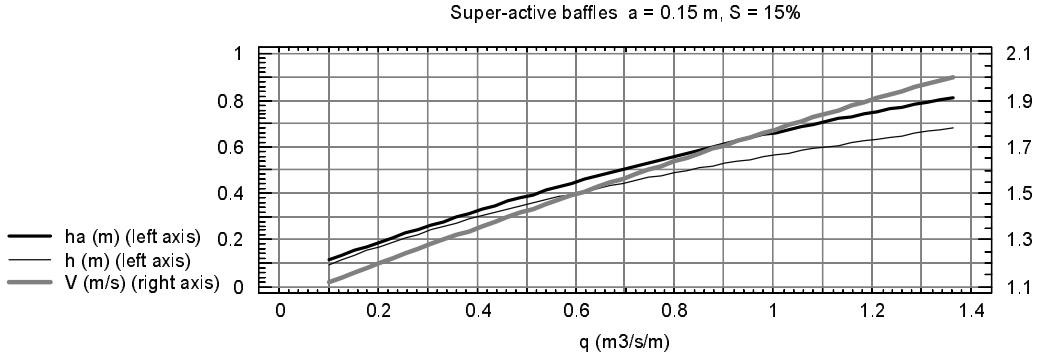


Figure 12: Relationship between flow, upstream head, mean depth and average water velocity for 0.15 m high superactive-type bottom baffle fishways with a 15% slope.

8. CHEVRON-TYPE BAFFLE FACILITIES FOR BOTH FISH AND CANOES-KAYAKS

It seemed, *a priori*, that fishways with bottom baffles should be able to allow canoes and kayaks to pass providing that some modifications were made. At some small-scale power plants, it was possible to envisage the construction of a single facility that could be used to accommodate both fish passage upstream and canoe passage downstream.

Further tests were carried out on models of baffle designs previously tested for fish passage, and these enabled the fishway to be adapted to accommodate boat passage (LARINIER, 1984).

For boats thick baffles (made of wood) are preferable to thin baffles (made of steel), because the latter are potentially too dangerous. The baffles with the simplest shape are best, *i.e.* the chevron-shaped baffles square in section, with the opening forming a right angle. The baffles have a square section, between 8 and 15 cm in size, usually 10-12 cm. Several chevron units can be juxtaposed in order to make the pass sufficiently wide to allow boats to pass (generally between 1.40 to 2.10 metres). The maximum permissible gradient is approximately 15-16%.

Longitudinal strips were added to the original model in order to reduce the aggressiveness of the baffles for canoes and kayaks. Since these longitudinal strips have the effect of increasing the discharge, their width should be restricted as much as possible.

The main disadvantage of this facility for fish passage is that it is less efficient hydraulically than the fishway with superactive baffles, and it must be remembered that, following the modelling tests, this type of baffle had originally been abandoned for fish pass use in favour of the former. The 'biological' operating range, which depends on the swimming ability of the fish, is thus reduced and limits the species for which the pass is useful.

This type of fishway is used only for large migratory salmonids (greater than 40 cm in length), and then only on condition that the upstream water level does not vary significantly. The operating range for passes for large salmonids, expressed in terms of unitary flow discharge, is between 250 l/s/m and 800-900 l/s/m (which corresponds to a variation in the upstream water level of approximately 30-40 cm). The operating range for trout is very low (around 10 cm), which considerably restricts the attraction of using such a fishway for this species.

Figure 13 shows the geometric characteristics. A minimum of two rows of chevron shapes is placed across the width of the fishway. The orientation of the chevrons shown on the figure is more suitable for the passage of fish because the low velocity zones that the migrators prefer to use are located on each side of the fishway. When the facility is to be used only for fish it is possible to exclude all the longitudinal strips except for the central one along the axis of the pass, which is required to stabilise the flow pattern. For boat passage the arrangement of the chevrons is reversed, so that the centre of the passage facility corresponds to the upstream point of the V, and the latter facilitates boat passage by guiding them to the centre of the pass. All the longitudinal strips must remain in place.

Figure 14 shows the relationship between the unitary flow $\mathbf{q}^* = \mathbf{q} / \sqrt{2\mathbf{g}} \cdot \mathbf{a}^{1.5}$ the upstream head (ha/a), the mean water depth (h/a) and the average water velocity **V* = aq*/h** for several channel slopes (S) in dimensionless form.

The upstream head (ha) is the elevation of the upstream water surface relative to the lower point of the most upstream baffle (corresponding to the elevation of the upstream water surface before acceleration into the fishway begins). The relationship between the operating head (ha) and the total head (hr) relative to the invert of the bottom of the channel at the upstream end of the first baffle is expressed as follows:

$$hr = ha + a - 3\,a\,S$$

The mean depth (h) is the average depth of water in the fishway above the baffles.

The flow Q (m^3/s) in the fishway is easily calculated by multiplying the unitary flow (q) obtained using ha by the width (L) of the fishway.

Figure 15 shows the relationship between the unit flow (q), the upstream head (ha), the mean depth (h) and the average water velocity (V) for a salmon fishway with baffles 0.10 m high.

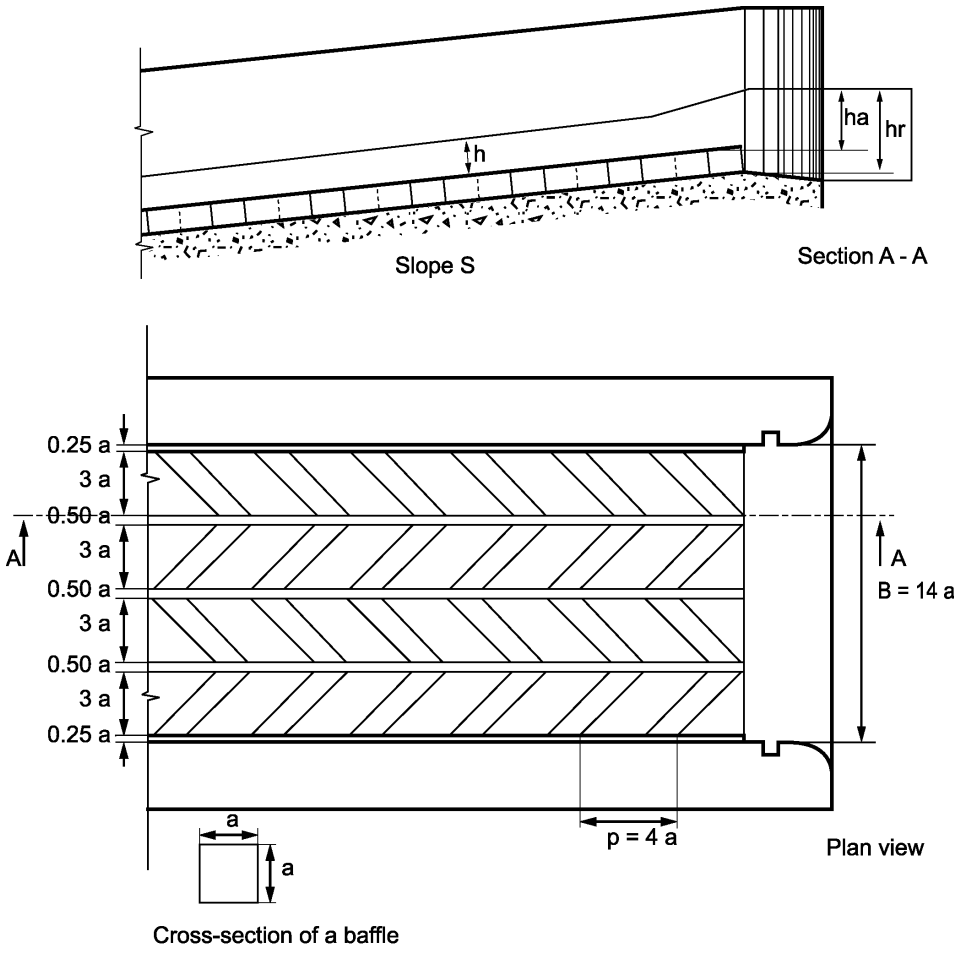


Figure 13: Characteristic parameters of a chevron baffle fishway.

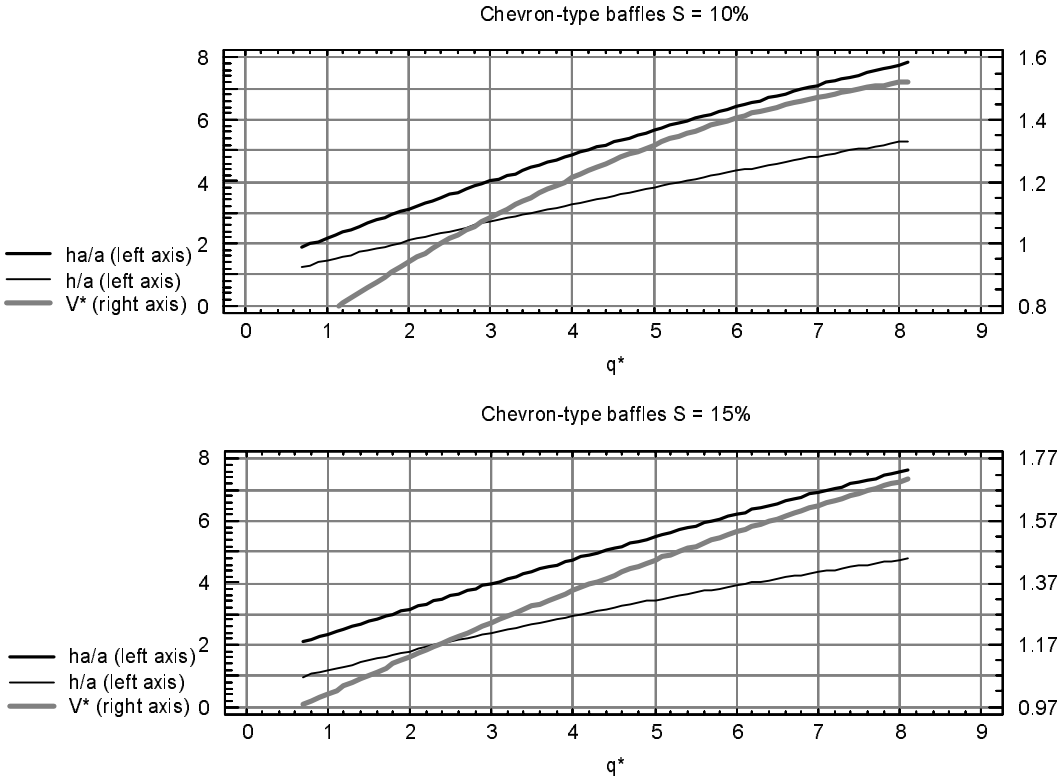


Figure 14: Relationship between flow, upstream head, mean depth and water velocity for a chevron baffle fishway.

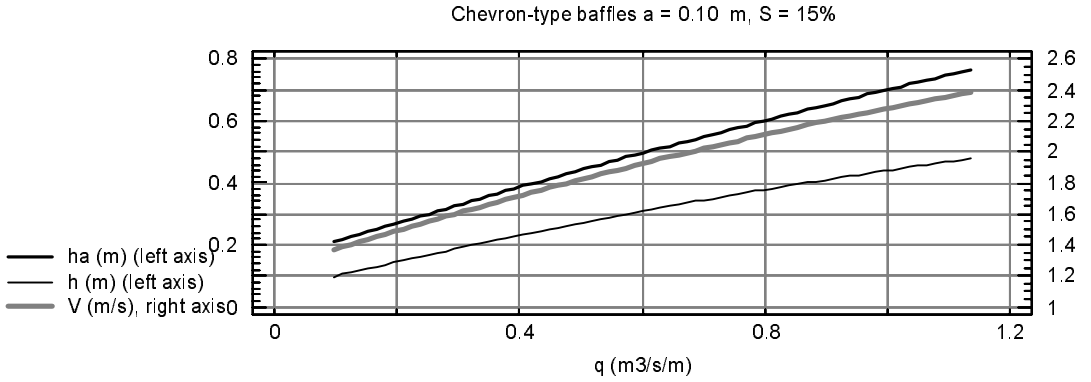


Figure 15: Relationship between flow, upstream head, mean depth and average water velocity for a chevron baffle fishway (a = 0.10 m, gradient 15%).

9. ALASKAN STEEPPASS

This type of fishway was developed during the 1960's in Alaska for Pacific salmon (ZIEMER, 1962) from a prototype tested in model form by MCLEOD and NEMENYI (1940). Several variants have been developed which differ in the height and angle of the side baffles. The standard Alaskan Steeppass (Figure 16) is narrow (0.56 m wide, 0.70 m high, clear interior width b 0.35 m), which allows steep slopes (25-33%) to be used.

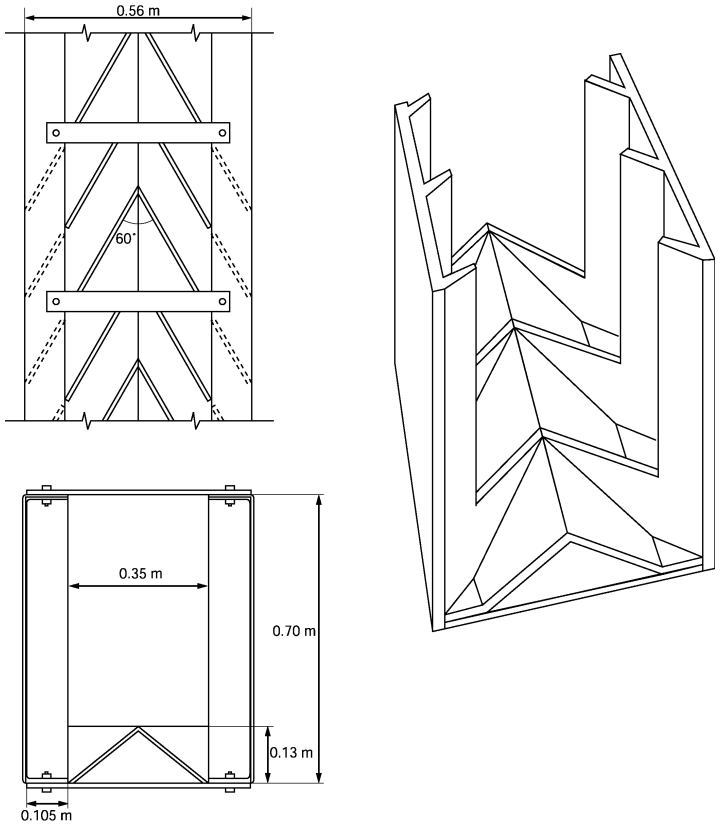


Figure 16: Characteristic parameters of the Alaskan Steeppass.

The discharge in the pass is given by (RAJARATNAM and KATOPODIS, 1991):

$$Q = 0.36 (S\ g)^{0.5}\ h^{1.55}$$

where:

Q is the fishway flow (m^3/s)
h is the depth above the floor baffles
S is the fishway slope
g is the acceleration due to gravity (9.81 m/s^2)

The fishway is prefabricated in sheet aluminium (6 mm thick) in 3-metre sections which weigh approximately 240 kg. It can be transported by helicopter and bolted together on site. It was developed with the specific aim of equipping natural waterfalls in Alaska which were situated in poorly accessible places, where cost-effective construction of concrete fishways was impossible.

The main disadvantage of this fishway is its limited flow and its limited ability to withstand variations in the upstream water level. The solution is usually to inject an auxiliary flow near the entrance to fishway in order to increase its attraction. Because of its restricted width it is very likely to become clogged with branches or other floating debris.

The use of this type of pass is of little interest in a country such as France where most of the obstructions are accessible, and where suitable installations at existing obstructions clearly require major civil engineering works.

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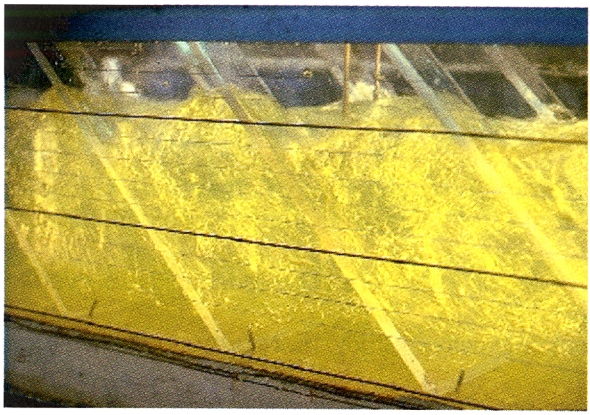


Photo 1: Flow in a reduced-scale model of a plane baffle fishway.



Photo 2: Experimental model of a fishway with super-active baffles.

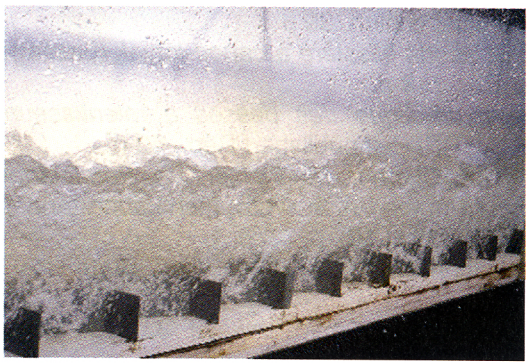


Photo 3: Flow in a reduced-scale model of a fishway with super-active baffles.



Photo 4: Trout travelling upstream through a model fishway with super-active baffles.



Photo 5: Flow in a reduced-scale model of a fishway with broad chevron-type baffles.

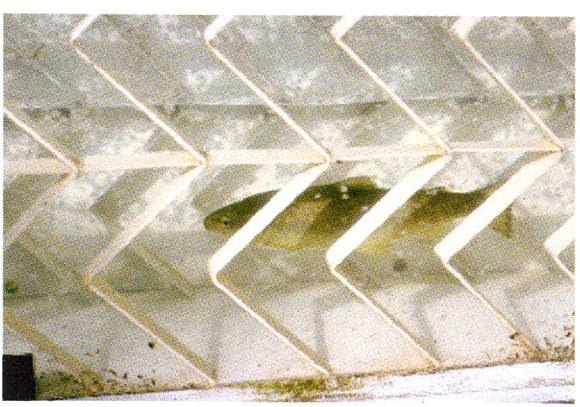


Photo 6: Trout travelling upstream through a scale-model fishway with side baffles.



Photo 7: Plane baffle fish pass at Cascadec weir (Isole river, Britanny).



Photo 8 : Fatou- type baffle fish pass on the Elle river (Britanny).



Photo 9: Superactive baffle fish pass in Normandy.



Photo 10: Fish pass with two flights of plane baffles on the Dore river (Puy-de-Dôme).



Photo 11: Chevron-type baffle fish pass used as a canoe pass at Brimeux on the Canche river (Pas de Calais).

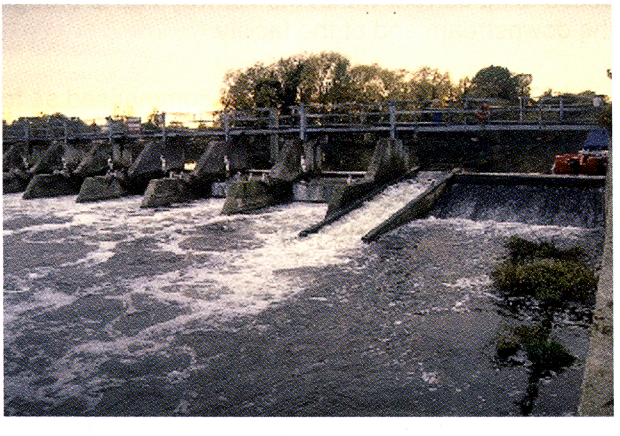


Photo 12: Super-active baffle fishway on the river Thames (England).