c

# Assessment of passability during upstream migration

# Fixed elements of weirs and dams

## Configurations frequently encountered

The hydraulic conditions for the fixed elements of obstacles depend on the type of structure, its geometry (height, profile, slope and distance that must be overcome), the constituent materials (concrete, riprap, etc.) and the discharges flowing over or through the obstacle.

Depending on the configuration of the downstream face (see Figure 53), a number of different situations may exist.

### ■ Vertical or subvertical falls that fish can clear exclusively by jumping

For weirs with vertical or subvertical downstream faces, flows over the weir generally form a waterfall with a plunging jet that fish cannot overcome by swimming (except in special cases where the head-drop is very low and a skimming flow forms).

A majority of behavioural studies and observations have shown that when the slope of a glacis exceeds approximately 60°, all attempts to clear the obstacle occur by jumping. But for a 40° slope, fish try to swim over the obstacle approximately half the time (Lauritzen *et al*. 2010). Consequently, **a weir is considered vertical or subvertical when the slope of the downstream face is greater than 150% (56°)[2].**

NB Only a limited number of species (sea trout, Atlantic salmon, brown trout, mullets and grayling) are truly capable of jumping over an obstacle and only if the fish find suitable conditions at the foot of the obstacle enabling them to prepare the jump.

### ■ Inclined faces that fish can overcome by swimming

The passability of an inclined weir depends on the flow characteristics on the glacis (water depth, velocity) and the distance to be covered (a direct function of the slope of the glacis and the height of the weir) that must be compared with the swimming capabilities (swimming speed $U_{max}$ and the endurance at that speed) and the morphological characteristics (body depth) of the given species.

### ■ Complex configurations comprising a succession of inclined sections and other, more or less vertical sections (steps)

A step is a break in the downstream face constituting a rupture in the long profile of the weir. The presence of one or more steps (stepped weirs, sills on the weir crest, etc.), particularly during periods of low discharge, can significantly reduce the passability of the weir. The type of flow caused by the step(s) determines the impact on passability.

*2. In the framework of the ICE protocol, reference is regularly made to the slope of structures or parts of structures. The slope, i.e. the inclination of the structure, is generally expressed as a percentage. Angles expressed in decimal degrees are also frequently used, even if they do not in fact measure a slope, but rather an elevation angle. To facilitate use of both systems, readers will find below a simple method to convert between percentages and decimal degrees.*

$\alpha = \arctan(p/100)$

$p = \tan(\alpha) \times 100$

*where* $\alpha$ *= elevation angle expressed in decimal degrees and p = slope expressed in percentage.*

In general, the fixed elements (spillway, glacis) of weirs and dams are now built of reinforced concrete, whereas structures prior to 1900 were built of masonry. However, these differences in construction materials do not significantly influence the flow conditions (water depth and flow velocity).

**Caution.** Hydraulic analysis of rock weirs is much more complicated than analysis of "standard" weirs. This difficulty is due to the variability in the organisation of the weir, as well as the shapes and sizes of the rocks, particularly in light of the fact that their positioning during the construction process is never very precise. That is why special criteria were developed for this type of obstacle in the ICE protocol.

**Figure 53**


*a © Larinier - Ecohydraulic centre, b © Burgun - Onema, c © Chanseau - Onema*
*d © Chanseau - Onema, e © Onema, f © Voegtlé - Ecogea*

*Examples of obstacle configurations often encountered. (a) Vertical weir with a plunging jet, (b) complex weir with an upstream step, a glacis and a downstream waterfall, (c) inclined weir with a step at the top, (d) inclined weir, (e) rock weir, (f) rock weir with a steep slope under low-flow conditions.*

The geometric and hydraulic parameters used to determine the passability of structures (the most simple configurations) are the following:

- **vertical or subvertical fall:** the difference between the elevations in the upstream and downstream water lines, the height of the obstacle (difference between the elevations of the weir crest and of the downstream water line), the depth of the plunge pool, the unit discharge (the discharge per meter width) and the geometry of the crest which influences the initial velocity of the flow prior to the fall;
- **inclined downstream face:** the difference between the elevations in the upstream and downstream water lines, the height of the obstacle (difference between the elevations of the weir crest and of the downstream water line), the depth of the plunge pool, the slope and roughness of the glacis, the unit discharge which determines the water depth and velocity on the glacis.

NB In stepped weirs, i.e. weirs made up of several vertical steps separated by more or less long horizontal or inclined sections, the flow configuration and its description are more complex and passage of fish is generally more difficult. In addition, the description and assessment of passability can be more difficult if the structure does not have the same profile over the entire width.

The degree of passability is generally the result of the cumulative effects of these parameters and often the limiting impact of a single parameter.

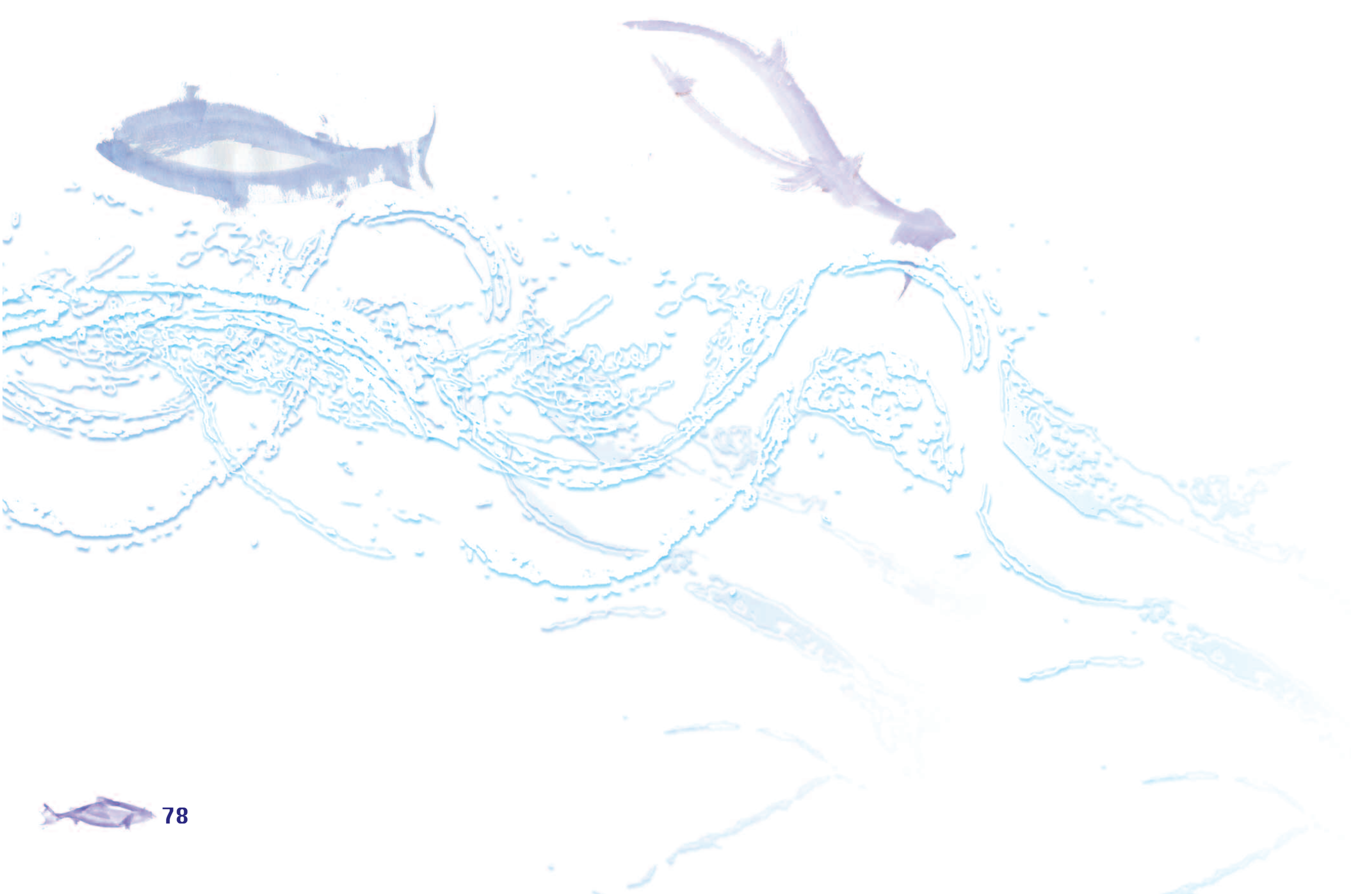
In this chapter, the method used to determine the passability class is presented for:

- **weirs with vertical or subvertical falls (slope >150% (56°));**
- **weirs with inclined downstream faces (slope ≤150%);**
- **rock weirs, a special type of inclined weir which, due to the construction method, generally creates highly heterogeneous flows.**

**Passage over gates (notably spillway gates) is comparable to weirs with vertical or subvertical falls.**

**Finally, there is a special section for eels given their special passage capabilities.**

**Note that there is also a special section for the assessment of weirs and dams equipped with fish passes.**



# Vertical and subvertical obstacles

## (slope >150% (56°))

### Passability criteria for jumping species

As noted in the section on the passage capabilities of fish, when the overflow height and the depth of the plunge pool are sufficient, jumping fish are capable of clearing maximum heights approximately equal to $Lp/2 + (U_{max} \sin\beta)^2 / 2g$ (see Table 2, Chapter A).

#### ■ Definition of passability classes

Using Table 4 (previous chapter), which indicates the maximum theoretical jumping heights determined for the size class selected for a stage/species, the classification below was established, on the condition of sufficient overflow height and plunge-pool depth.

If the head-drop DH is less than the theoretical jumping height of the minimum size of fish $Lp_{min}$ in the given species ($DH_{min}$), the obstacle is considered a **low-impact passable barrier (ICE class = 1)**.

If the head-drop DH is between the theoretical jumping height of the minimum size of fish $Lp_{min}$ ($DH_{min}$) and the average size of fish $Lp_{avg}$ ($DH_{avg}$) in the given species, the obstacle is considered a **medium-impact partial barrier (ICE class = 0.66)**.

If the head-drop DH is between the theoretical jumping height of the average size of fish $Lp_{avg}$ ($DH_{avg}$) and the maximum size of fish $Lp_{max}$ ($DH_{max}$) in the given species, the obstacle is considered a **high-impact partial barrier (ICE class = 0.33)**.

Finally, if the head-drop DH is greater than the theoretical jumping height of the maximum size of fish $Lp_{max}$ in the given species ($DH_{max}$), the obstacle is considered a **total barrier (ICE class = 0)**.

#### ■ Extreme head-drop $DH_{extreme}$

In order to reduce the time spent in the field and avoid taking unnecessary measurements, it was decided that when the head-drop is greater than $DH_{max}$, the maximum theoretical head-drop that can be cleared by fish of size $Lp_{max}$, plus approximately 50 cm, the obstacle is necessarily impossible to overcome and there is no need to study the site any further. This type of head-drop is labelled $DH_{extreme}$.

## Non-jumping species

Vertical and subvertical obstacles generally cause waterfalls that species can overcome only by jumping.

However, non-jumping species can nonetheless overcome vertical falls when flow conditions meet several criteria (see Figure 54), namely:

- the water level is sufficient to create a "skimming flow". This type of flow generally occurs when the head-drop DH is less than half the overflow height H at the weir. A virtual skimming flow (0.5 H < DH < H) is sufficient to ensure some passage, but does not offer optimum conditions;
- the depth of water must be sufficient to enable the fish to swim. This condition is seen as fulfilled if the overflow height H is greater than or equal to $H_{min}$, a criterion defined in the section on the passage capabilities of fish;
- the depth of the plunge pool Hf at the foot of the weir must be sufficient and generally meet the criterion ($Hf \geq Hf_{min}$) defined in the section on the passage capabilities of fish;
- the flow velocity V must be compatible with the swimming capabilities of the given species.

The classification below was established, on the strict and prior condition that the other criteria (skimming flow, depth of plunge pool and sufficient overflow height) are met in full:

- when the flow velocity in the jet created by the head-drop DH is less than the maximum speed $U_{max}$ assigned to the minimum fish size ($Lp_{min}$) for the given species, the obstacle may be considered a **low-impact passable barrier (ICE class = 1)**;
- when the flow velocity in the jet created by the head-drop DH is between the maximum speeds $U_{max}$ assigned to the minimum fish size ($Lp_{min}$) and the average fish size ($Lp_{avg}$) for the given species, the obstacle may be considered a **medium-impact partial barrier (ICE class = 0.66)**;
- when the flow velocity in the jet created by the head-drop DH is between the maximum speeds $U_{max}$ assigned to the average fish size ($Lp_{avg}$) and the maximum fish size ($Lp_{max}$) for the given species, the obstacle may be considered a **high-impact partial barrier (ICE class = 0.33)**;
- when the flow velocity in the jet created by the head-drop DH is greater than the maximum speed $U_{max}$ assigned to the maximum fish size ($Lp_{max}$) for the given species, the obstacle may be considered a **total barrier (ICE class = 0)**.

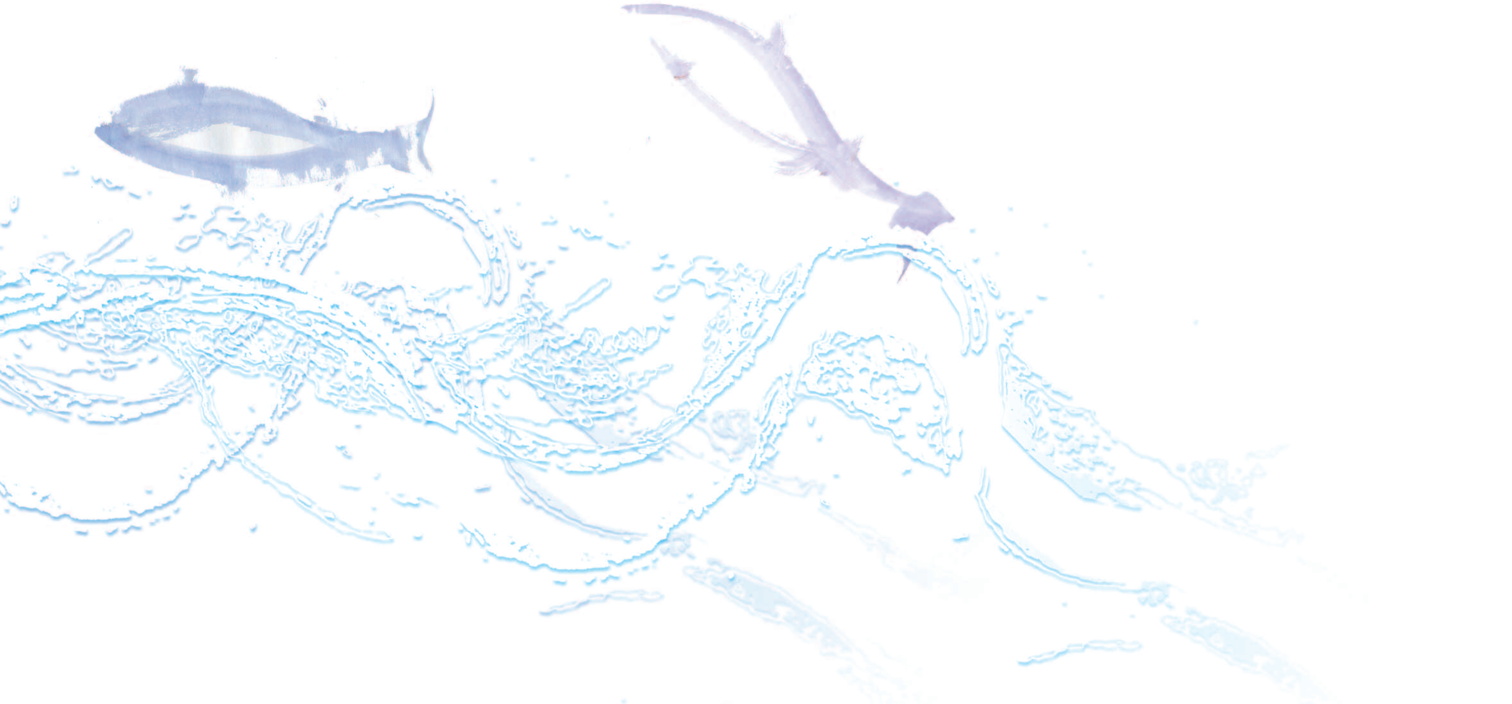
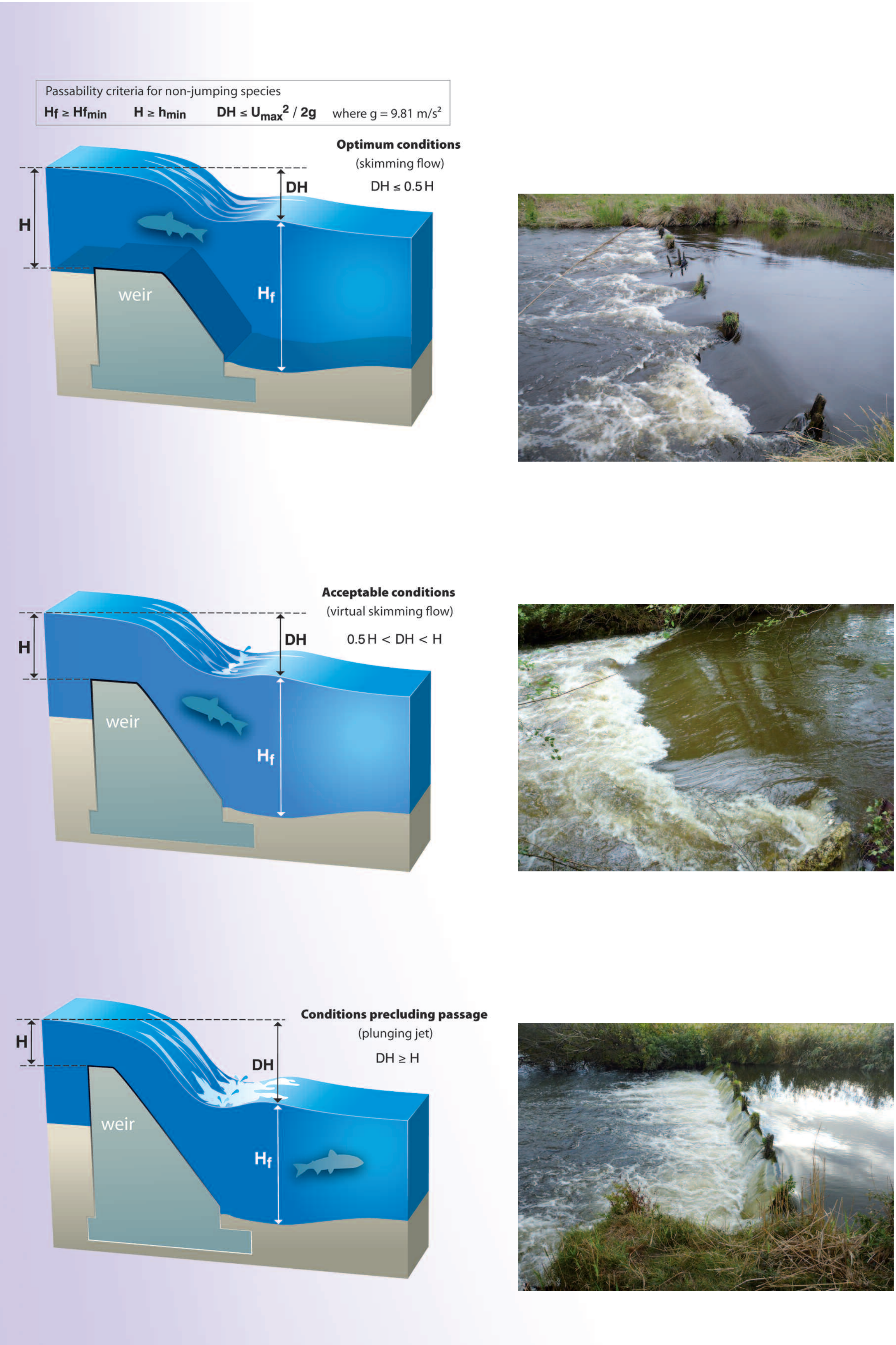


**Figure 54**




*a, b, c © Voegtlé - Ecogea*

*Types of jets and passage conditions for non-jumping species confronting a vertical or subvertical obstacle (slope >150% (56°)). (a) Skimming flow, (b) virtual skimming flow, (c) plunging jet (waterfall).*

# Determining passability classes

## ■ Threshold values used for the decision tree

Table 7 on the next page lists the various threshold values used to determine the passability of a vertical or subvertical weir (slope >150% (56°)).

Table 8 below shows approximate values for the necessary minimum depths of plunge pools $Hf_{min}$ as a function of the head-drop and the angle of incidence of the jet (or slope of the weir).

These tables are accompanied by a decision tree (see Figure 55) that can be used to determine the ICE passability class.

**Tableau 8** *Approximate minimum depth $Hf_{min}$ of a plunge pool required for fish to overcome a vertical or subvertical obstacle (>150%).*

| Head-drop DH (m) | Minimum depth of plunge pool ($Hf_{min}$) at foot of vertical or subvertical weir (>150%) |
|---|---|
| ≤ 0.25 | 0.30 m |
| ]0.25 - 0.50] | 0.45 m |
| ]0.50 - 0.75] | 0.70 m |
| ]0.75 - 1.00] | 0.85 m |
| ]1.00 - 1.50] | 1.00 m |
| ]1.50 - 2.00] | 1.20 m |
| > 2.00 | 1.40 m |

**Tableau 7** *Summary of the basic criteria (behaviour, overflow height, head-drop) used to determine the ICE passability classes for vertical and subvertical weirs (slope >150%) using the decision tree in Figure 55.*

| ICE species group | Species | Jumping species | Minimum overflow height ($H_{min}$) | Theshold values for head-drops in assessing weirs with vertical downstream faces >150% (m) | | | | $DH_{extreme}$ |
|---|---|---|---|---|---|---|---|---|
| | | | | ICE passability class | | | | |
| | | | | 1 | 0.66 | 0.33 | 0 | |
| 1 | Atlantic salmon (*Salmo salar*)<br>Brown or sea trout [50-100] (*Salmo trutta*) | Yes | 0.20 m | ≤ 1.00 | ]1.00 - 1.50] | ]1.50 - 2.50] | > 2.50 | 3.00 m |
| 2 | Mullets (*Chelon labrosus, Liza ramada*) | Yes | 0.10 m | ≤ 0.80 | ]0.80 - 1.10] | ]1.10 - 1.80] | > 1.80 | 2.50 m |
| 3a | Allis shad (*Alosa alosa*) | No | 0.15 m | ≤ 0.60 | ]0.60 - 1.00] | ]1.00 - 1.40] | > 1.40 | 2.00 m |
| 3b | Twaite shad (*Alosa fallax fallax*) | | 0.10 m | | | | | |
| 3c | Sea lamprey (*Petromyzon marinus*) | | | | | | | |
| 4a | Brown or sea trout [25-55] (*Salmo trutta*) | Yes | 0.10 m | ≤ 0.50 | ]0.50 - 0.90] | ]0.90 - 1.40] | > 1.40 | 2.00 m |
| 4b | Brown trout [15-30] (*Salmo trutta*) | | 0.05 m | ≤ 0.30 | ]0.30 - 0.50] | ]0.50 - 0.80] | > 0.80 | 1.50 m |
| 5 | Asp (*Aspius aspius*)<br>Pike (*Esox lucius*) | No | 0.15 m | ≤ 0.60 | ]0.60 - 1.00] | ]1.00 - 1.40] | > 1.40 | 2.00 m |
| 6 | Grayling (*Thymallus thymallus*) | Yes | 0.10 m | ≤ 0.40 | ]0.40 - 0.75] | ]0.75 - 1.20] | > 1.20 | 1.50 m |
| 7a | Barbel (*Barbus barbus*)<br>Chub (*Squalius cephalus*)<br>Nase (*Chondrostoma nasus*) | No | 0.10 m | ≤ 0.30 | ]0.30 - 0.60] | ]0.60 - 0.90] | > 0.90 | 1.50 m |
| 7b | River lamprey (*Lampetra fluviatilis*) | | 0.05 m | | | | | |
| 8a | Common carp (*Cyprinus carpio*) | No | 0.25 m | ≤ 0.20 | ]0.20 - 0.50] | ]0.50 - 0.70] | > 0.70 | 1.50 m |
| 8b | Common bream (*Abramis brama*)<br>Pikeperch (*Sander lucioperca*) | | 0.15 m | | | | | |
| 8c | White bream (*Blicca bjoerkna*)<br>Ide (*Leuciscus idus*)<br>Burbot (*Lota lota*)<br>Perch (*Perca fluviatilis*)<br>Tench (*Tinca tinca*) | | 0.10 m | | | | | |
| 8d | Daces (*Leuciscus spp.* except *Idus*) | | 0.05 m | | | | | |
| 9a | Bleak (*Alburnus alburnus*)<br>Schneider (*Alburnoides bipunctatus*)<br>Mediterranean barbel (*Barbus meridionalis*)<br>Blageon (*Telestes souffia*)<br>Crucian carp (*Carassius carassius*)<br>Prussian carp (*Carassius gibelio*)<br>Roach (*Rutilus rutilus*)<br>Rudd (*Scardinius erythrophthalmus*)<br>SW European nase (*Parachondrostoma toxostoma*) | No | 0.05 m | ≤ 0.15 | ]0.15 - 0.35] | ]0.35 - 0.50] | > 0.50 | 1.00 m |
| 9b | Streber (*Zingel asper*)<br>Bullheads (*Cottus spp.*)<br>Gudgeons (*Gobio spp.*)<br>Ruffe (*Gymnocephalus cernuus*)<br>Brook lamprey (*Lampetra planeri*)<br>Stone loach ( *Barbatula barbatula*)<br>Spined loach (*Cobitis taenia*) | | | | | | | |
| 10 | Sunbleak (*Leucaspius delineatus*)<br>Bitterling (*Rhodeus amarus*)<br>Threespine stickleback (*Gasterosteus gymnurus*)<br>Smoothtail ninespine stickleback (*Pungitius laevis*)<br>Minnows (*Phoxinus spp.*) | No | 0.05 m | ≤ 0.10 | ]0.10 - 0.20] | ]0.20 - 0.30] | > 0.30 | 1.00 m |
| 11a | European eel [yellow eel] *(Anguilla anguilla)* | No | 0.02 m | ≤ 0.20 | ]0.20 - 0.35] | ]0.35 - 0.50] | > 0.50 | 1.00 m |
| 11b | European eel [glass eel] *(Anguilla anguilla)* | | - | - | - | - | - | |

*(*) The values indicated for eels correspond to the passability classes set when the analysis takes into account only the swimming capabilities of the species. In cases where the obstacle includes a crawling zone, the assessment must also use the special tables for crawling (see the section on eels).*

## ■ Decision tree

The various steps in determining the ICE passability class of a vertical obstacle (see Figure 55) are presented below.

***1. Comparison of head-drop DH with $DH_{extreme}$ (see Table 7 on previous page)***

If the total head-drop DH ≥ $DH_{extreme}$, stop the assessment. The obstacle cannot be overcome by the given species or group of species (ICE class = 0).

If DH < $DH_{extreme}$, take all the measurements on the structure (long profiles, overflow height, depth of plunge pool), then go to Step 2.

***2. Analysis of the overflow height at the obstacle***

If the overflow height H ≥ $H_{min}$ (see Table 7), go to Step 3 because the overflow height is sufficient.

If H < $H_{min}$, under the given hydrological conditions the obstacle may be considered a total barrier in the sense of the ICE protocol (ICE class = 0). However, the analysis should be pursued (go to Step 3) in order to determine the passability class in the event other hydrological conditions provide enough overflow height. Depending on the score of the subsequent analysis, it will be possible to decide whether or not to return to the obstacle for measurements under other hydrological conditions.

**Caution.** For jumping species and small head-drops, the horizontal distance jumped by the fish is generally sufficient to land directly in the upstream reach. In this fairly deep zone, flow velocities are generally low and compatible with efforts of fish to recommence swimming. The narrower the crest of the weir, the easier it is for the fish to reach the upstream reach. In cases where the head-drop DH ≤ $DH_{min}$ (see the head-drop for ICE class 1 in Table 7) and the thickness of the weir crest is less than the average size $Lp_{avg}$ of the fish, the minimum overflow height $H_{min}$ criterion may be neglected and the user may proceed directly to Step 3.

***3. Analysis of the plunge pool at the foot of the obstacle***

If the depth of the plunge pool at the foot of the obstacle Hf ≥ $Hf_{min}$ (see Table 8), then conditions are sufficient. Go to Step 4.

If Hf < $Hf_{min}$, the obstacle may be considered a total barrier in the sense of the ICE protocol (ICE class = 0).

***4. Jumping species***

If the species or group of species is capable of jumping (see Table 7), go to Step 6. If not, go to Step 5.

***5. Skimming flows***

If DH ≤ 0.5 H, the flow may be considered a skimming flow. Go to Step 6.

If 0.5 H < DH ≤ H, the flow may be considered a virtual skimming flow. However, the structure will in all cases impact the species in question. The ICE class may not exceed 0.66. In Step 6, select the ICE class indicated in Table 7 if it is less than or equal to 0.66, otherwise the ICE class is set to 0.66.

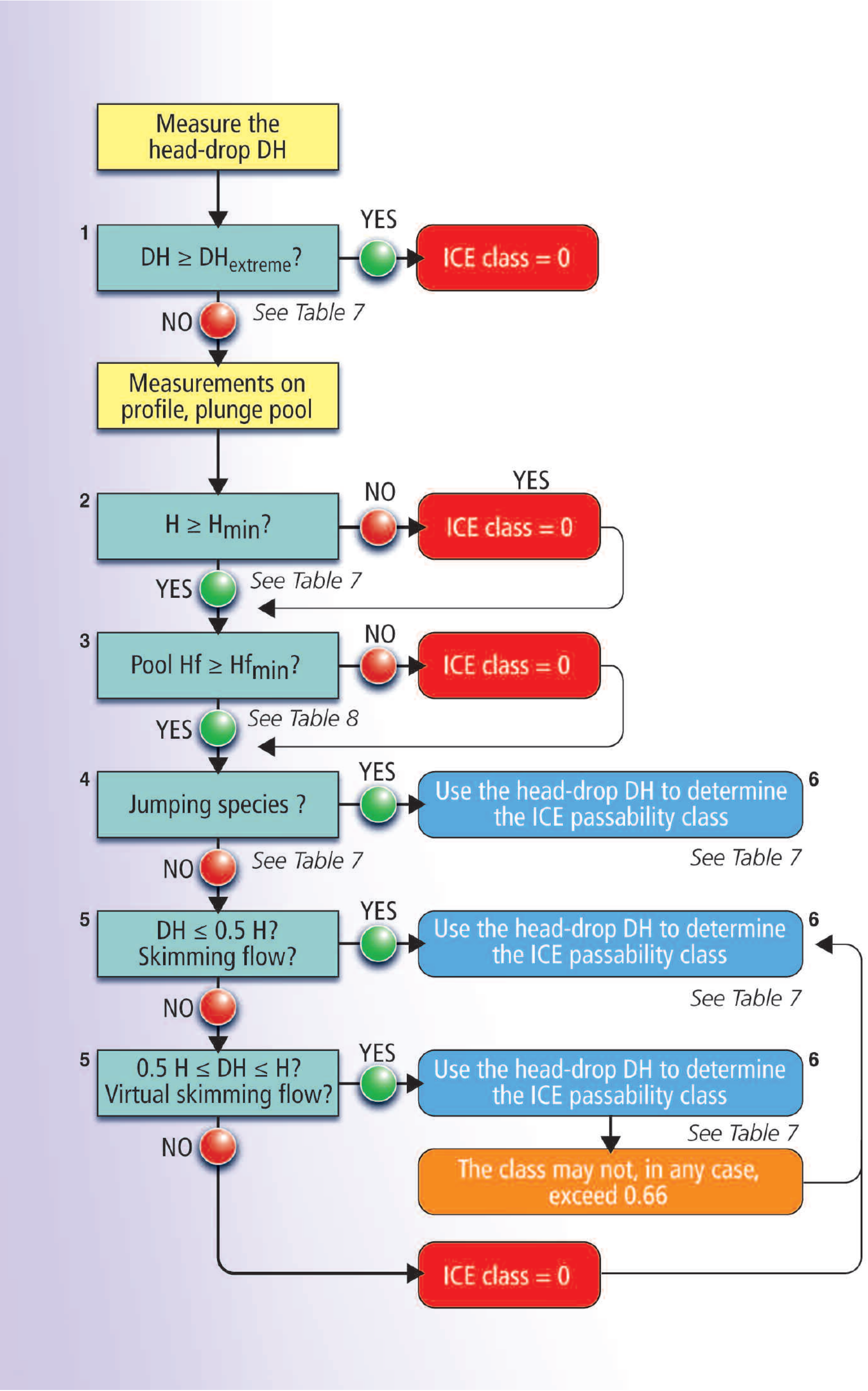
If DH > H, the flow is a plunging jet and the obstacle may be considered a total barrier in the sense of the ICE protocol (ICE class = 0).

NB If the flow is near the transition point between a plunging jet and a skimming flow, it may be worthwhile to continue the assessment and, in Step 6, to roughly determine the passability class under more favourable hydrological conditions (shift to a skimming flow if the downstream water level rises). Depending on the results, it may be decided whether or not to return to the site when different hydrological conditions prevail.

***6. Analysis of the head-drop***

On the basis of the head-drop DH, use Table 7 to determine the ICE passability class of the structure.

**Figure 55**




*Decision tree to determine ICE passability classes for vertical and subvertical obstacles (slope >150% (56°)).*

# Weirs with inclined downstream faces (slope ≤150%)

Weirs having an inclined glacis may enable fish to overcome the obstacle by swimming. Passability depends on the flow characteristics on the glacis (water depth, velocities) and the distance that the fish must cover. These characteristics must be analysed in conjunction with the swimming capabilities and the morphology of the given species (maximum swimming speed $U_{max}$, endurance at $U_{max}$ and body depth of the fish).

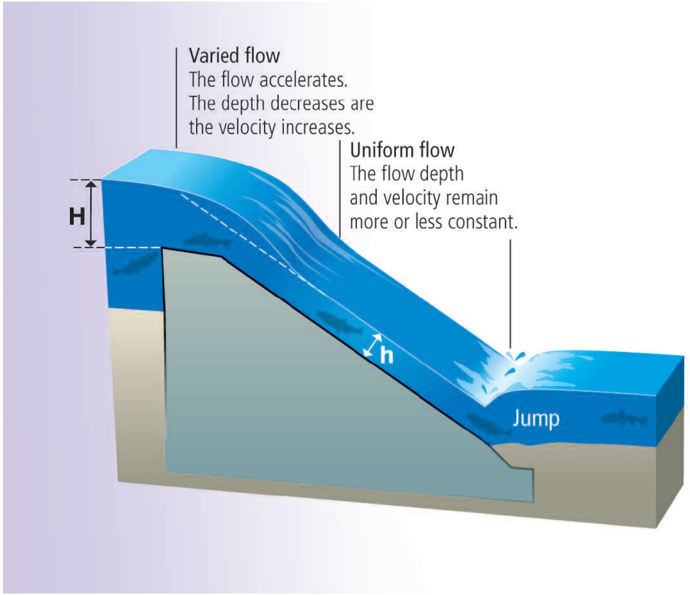
## Passability criteria on a uniform inclined glacis

### ■ Flow conditions

The parameters determining the flow characteristics (velocity V and depth h) on a glacis are the slope $\alpha$, unit discharge q, i.e. the discharge per meter width, and the roughness of the glacis surface.

The flow velocity on a glacis increases during the descent until the flow becomes uniform, at which point the depth remains more or less constant (see Figure 56). The distance required for the flow to become uniform increases with the unit discharge (discharge per meter width) and decreases with the roughness of the underlying surface.

Figure 56




*Changes in flow conditions along an inclined glacis.*

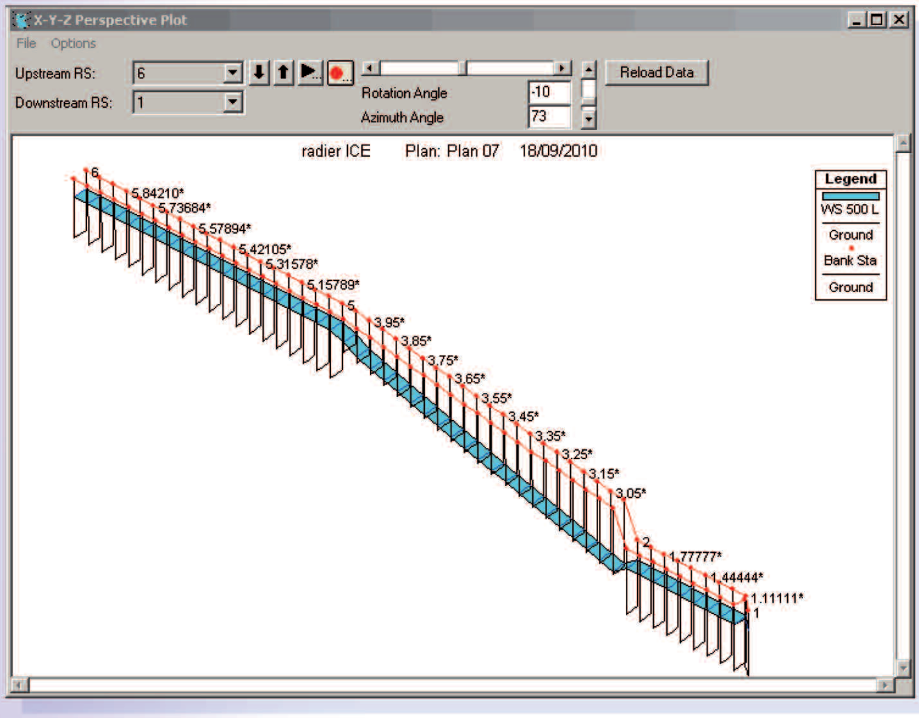
To analyse the changes in the flow conditions for a very simple case, i.e. a weir with a straightforward glacis (regular slope, no breaks or steps), hydraulic modelling was carried out using the HEC-RAS software developed by the U.S. Army Corps of Engineers.

The modelling was carried out for a weir with a total head-drop of five metres (see Figure 57), by varying the different physical and hydraulic parameters influencing the flow conditions, namely:

- the slope of the glacis. A total of seven slopes were tested, 3% (1.7°), 6% (3.4°), 12% (6.8°), 25% (14°), 50% (26.6°), 100% (45°) and 150% (56°);
- the length of the glacis. The length was simply adjusted to the slope to produce the set 5-metre head-drop;

■ the roughness of the glacis. To model the effects of roughness, seven Manning-Strikler (n) coefficients were tested, 0.01 (very smooth substrate equivalent to floated concrete); 0.015, 0.02, 0.03, 0.04, 0.05 and 0.06 (very rough, equivalent to coarse masonry);
■ unit discharge (the discharge per meter width). Seven unit discharges were tested, 125, 250, 500, 750, 1000, 1500 and 2000 L/s/m.

**Figure 57**




*Graphic presentation of hydraulic modelling using the HEC RAS software.*

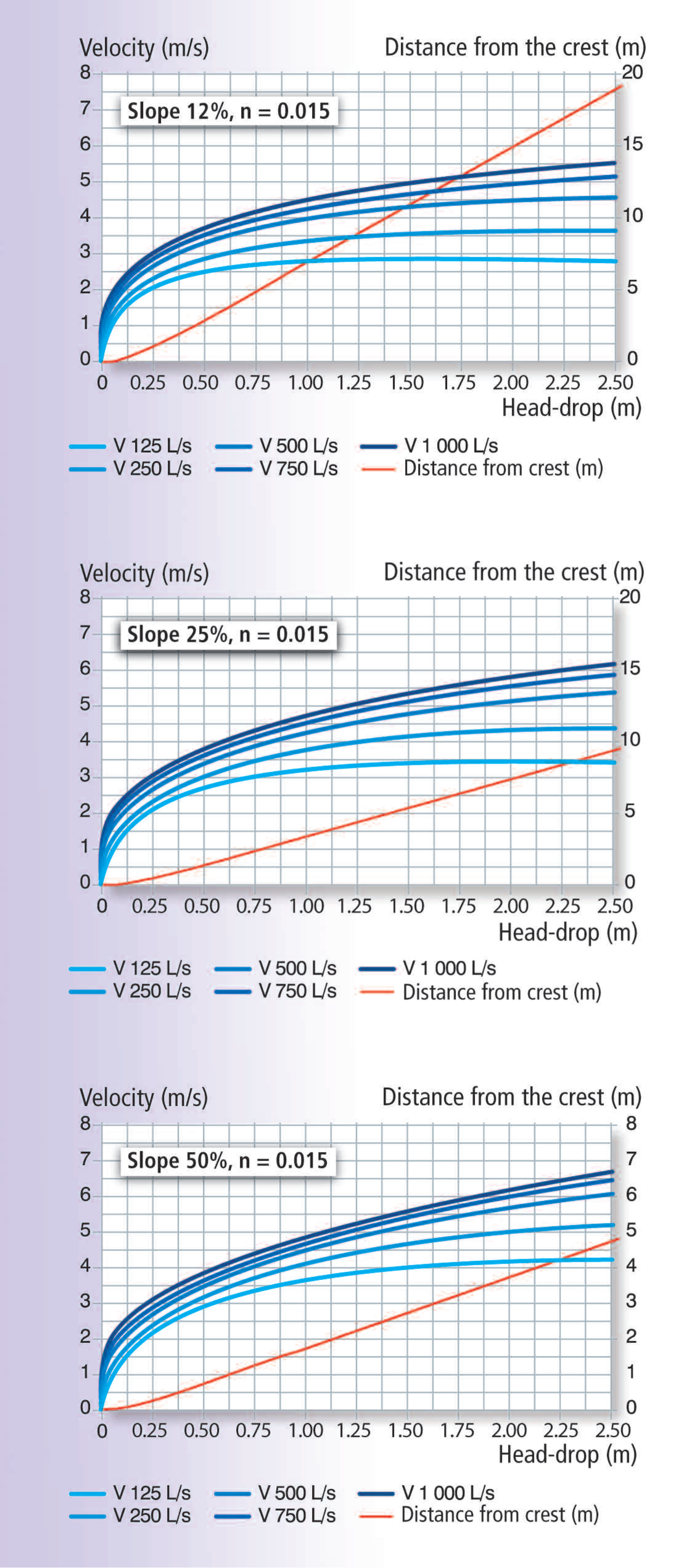
The changes in flow velocities along the glacis, calculated for the various unit discharges as a function of the various slope and roughness pairs, were extracted from the hydraulic model and plotted graphically, indicating the distance from the crest (or the fall).

At the end of the hydraulic modelling, approximately 50 graphs had been produced (see Figure 58).

The graphs reveal:
■ an acceleration in the velocity starting at the crest until a certain distance at which the flow becomes uniform (constant velocity and depth);
■ that velocities increase with the unit discharge;
■ the distance at which the flow becomes uniform increases with the unit discharge and decreases with the roughness.

Taking for example the first graph in Figure 58, for a 12% slope with a Manning coefficient of 0.015 and a unit discharge of 125 L/s/m, the velocity gradually increases and then stabilises at approximately 2.8 m/s at approximately 7 metres from the weir crest. For a greater unit discharge of 500 L/s/m, the flow does not become uniform until it has reached a distance of 11 metres from the crest. At that point, the velocity becomes constant at approximately 4.5 m/s.

**Figure 58**




*Graphs showing the relation between flow velocity, head-drop and distance from the weir crest as a function of the unit discharge (125 L/s/m to 1000 L/s/m), the slope (12%, 25% and 50%) and the roughness of the glacis surface (Manning n =0.015).*

## ■ Modelling fish passability

Swimming capability is expressed in terms of the maximum swimming speed $U_{max}$ and endurance t at maximum speed.

The time (dt) required for a fish, swimming at $U_{max}$ and located at a distance x from the crest of the obstacle where the flow velocity is V(x), to cover distance dx is:

$$d_t = \frac{d_x}{(U_{max} - V_{(x)})}$$

The endurance t(D) required to overcome a distance D from the crest can be expressed as:

$$t(D) = \int_0^D \frac{d_x}{(U_{max} - V_{(x)})}$$

For a given distance from the crest, the above equation indicates the time required for a fish swimming at its $U_{max}$ speed to reach the weir crest or, an equivalent result, the distance that can be overcome by a fish capable of swimming at a given maximum speed $U_{max}$ and possessing a given endurance t.

In this manner, on the basis of the hydraulic conditions obtained by modelling a given weir and for a given unit discharge, it is possible to calculate the distance that can be overcome by a fish endowed with a maximum swimming speed $U_{max}$ and an endurance t.

The results are presented as graphs indicating the head-drops and the distances that can be overcome by fish having maximum swimming speeds between 2 m/s and 7 m/s, as a function of their endurance at $U_{max}$.

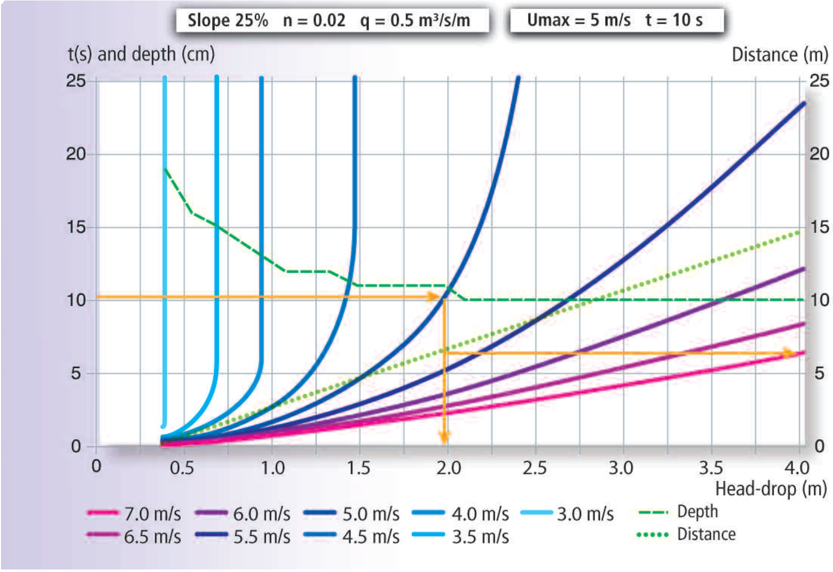
Graphs were produced for six slopes (3% to 100%), seven unit discharges (0.125 m³/s/m to 2 m³/s/m), seven roughness values (Manning n 0.01 to 0.06), representing a total of approximately 300 graphs similar to that in Figure 59 and 3 000 endurance/head-drop combinations that fish can overcome.

Of course, the minimum water depth $h_{min}$ required for swimming must be available for the fish to cover the distances indicated by the graphs. The graphs also indicate the depth of water on the glacis as a function of the head-drop (or of the distance from the crest). It is necessary to check that the water depth is sufficient for the given fish.

The graph shown in Figure 59 presents the results for a 25% slope, a roughness coefficient n=0.02 and a unit discharge q = 0.5 m³/s/m (m²/s).

This particular graph indicates that, for a fish having a maximum speed $U_{max}$ = 5 m/s and an endurance t = 10 s, the passable head-drop is slightly less than 2 metres and the passable distance is approximately 6.5 metres. The water depth on the glacis (dashed line labelled "Depth" on the graph) varies from approximately 20 cm to 10 cm as a function of the distance from the crest and stabilises at approximately 7 metres from the crest.

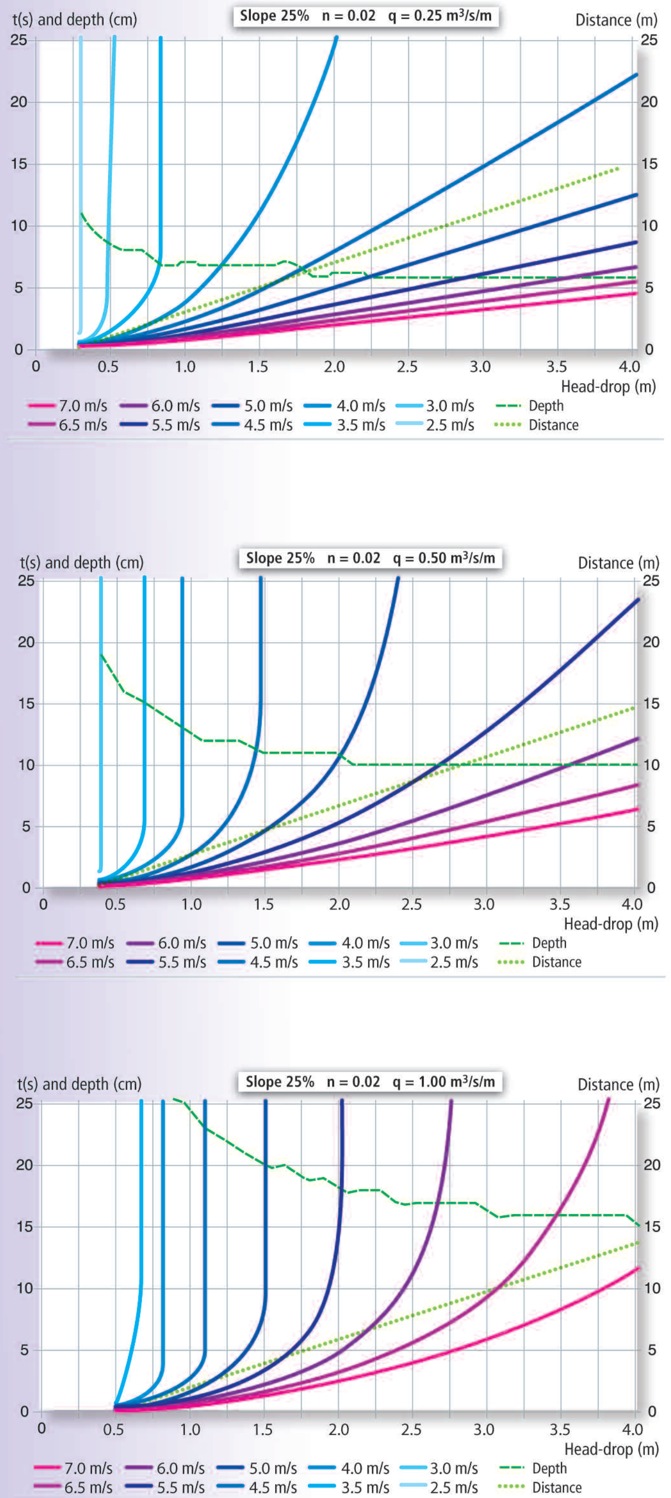
**Figure 59**




*Relation between the passable head-drop, maximum swimming speed and endurance, given a slope of 25%, roughness n = 0.02 and unit discharge q = 0.5 m³/s/m (m²/s).*

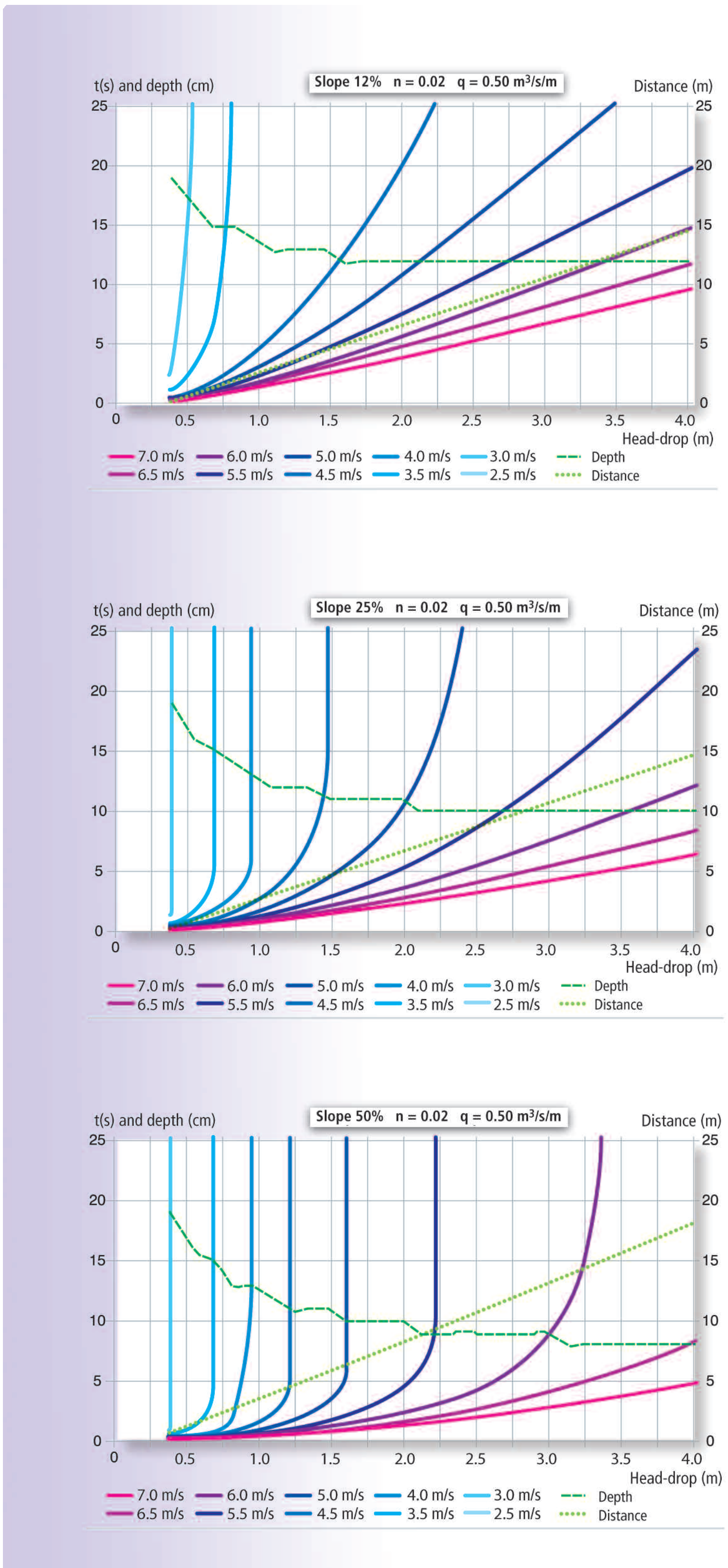
The graphs shown in Figures 60, 61 and 62 show the influence of the unit discharge as well as that of the slope and roughness of the glacis.

**Figure 60**



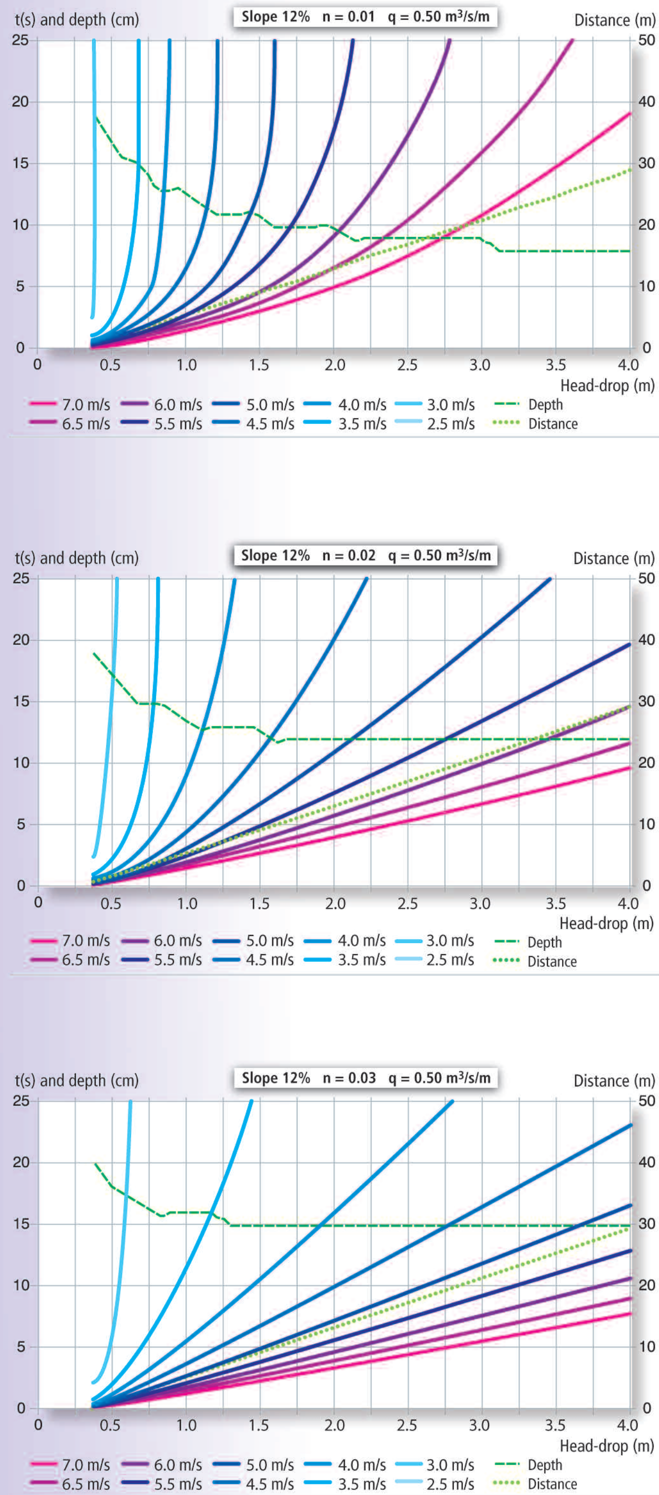

*Passable head-drop as a function of the maximum swimming speed $U_{max}$ and the endurance t on a glacis having a slope of 25% and roughness n = 0.02. The three graphs correspond to three different unit discharges (q = 0.25 m³/s/m, 0.5 m³/s/m and 1.0 m³/s/m).*

Figure 61




*Passable head-drop as a function of the maximum swimming speed $U_{max}$ and the endurance t on a glacis where the unit discharge $q = 0.5\ m^3/s/m$. The three graphs correspond to three different slopes (12%, 25% and 50%) having a constant roughness $n = 0.02$.*

Figure 62




*Passable head-drop as a function of the maximum swimming speed $U_{max}$ and the endurance t on a glacis where the unit discharge q = 0.5 m³/s/m and the slope (12%) are constant. The three graphs correspond to three different roughness values (n = 0.01, n = 0.02 and n = 0.03).*

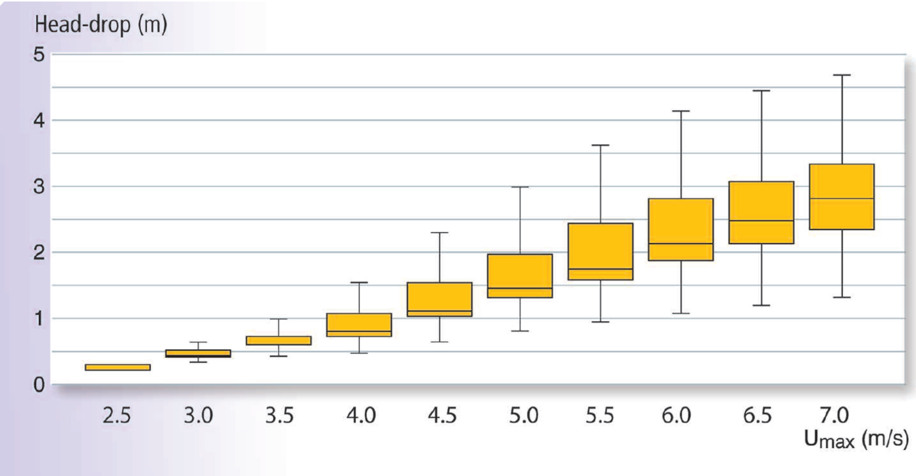
## ■ Statistical analysis of results

Using all the above results, an assessment of the passable head-drops for each species group was carried out as a function of the maximum swimming speeds $U_{max}$, the slope $\alpha$, the roughness n, the unit discharges q and the necessary water depths $h_{min}$. For the assessment, endurance values between 10 and 20 seconds were used, values that are generally associated with the $U_{max}$ values of fish of all species.

Figures 60 to 62 make clear that the passable head-drop is largely determined by the maximum swimming speed $U_{max}$ of the fish (where the endurance is between 10 and 20 seconds). The other parameters such as the unit discharge, roughness and particularly the slope have much less impact.

The graph in Figure 63 uses boxplots to show the passable head-drops as a function of the maximum swimming speed $U_{max}$ (where the endurance is between 10 and 20 seconds), taking into account all the other tested parameters (slope, unit discharge, roughness).

Figure 63




*Passable head-drops as a function of the maximum swimming speed $U_{max}$ (where the endurance is between 10 and 20 seconds), whatever the values of the other tested parameters (slope, unit discharge, roughness).*

## ■ Definition of passability classes

By comparing the hydraulic conditions (average velocities and water depths as a function of the unit discharges and slope) on a glacis and the swimming capabilities of the various migratory species or groups of species (swimming speeds for the selected size classes $Lp_{min}$, $Lp_{avg}$ and $Lp_{max}$), it is possible to determine, for each species or group of species, the ICE passability class for a weir with an inclined downstream face as a function of its head-drop, which is the difference between the water levels upstream and downstream of the weir.

For a given species, it is then possible to set a maximum passable head-drop for each of the three sizes selected ($Lp_{min}$, $Lp_{avg}$ and $Lp_{max}$).

Using the same method as that selected for vertical weirs (slope >150%) and the maximum passable head-drop values, it was decided to adopt the following classification system (on the condition of sufficient water depth on the glacis and in the plunge pool):

- if the head-drop DH is passable for fish of minimum size $Lp_{min}$ in the given species, the obstacle is considered a low-impact passable barrier **(ICE class = 1)**;
- if the head-drop DH is between the passable heights for fish of minimum $Lp_{min}$ and average $Lp_{avg}$ sizes in the given species, the obstacle is considered a medium-impact partial barrier **(ICE class = 0.66)**;
- if the head-drop DH is between the passable heights for fish of average $Lp_{avg}$ and maximum $Lp_{max}$ sizes in the given species, the obstacle is considered a high-impact partial barrier **(ICE class = 0.33)**;
- if the head-drop DH is not passable for fish of maximum size $Lp_{max}$ in the given species, the obstacle is considered a total barrier **(ICE class = 0)**.

The threshold values for head-drops between ICE classes are similar to those obtained for weirs having vertical or subvertical downstream faces.

## Steps in the weir profile

A step is a break in the downstream face constituting a rupture in the long profile of the weir. Examples are stepped weirs or sills on the crest of the weir (see Figure 64).

The presence of one or more steps in a weir, particularly during periods of low discharge, can make it much more difficult for fish to overcome the weir. The type of flow caused by the step(s) determines the impact on passability.

Figure 64


a, b © Burgun - Onema

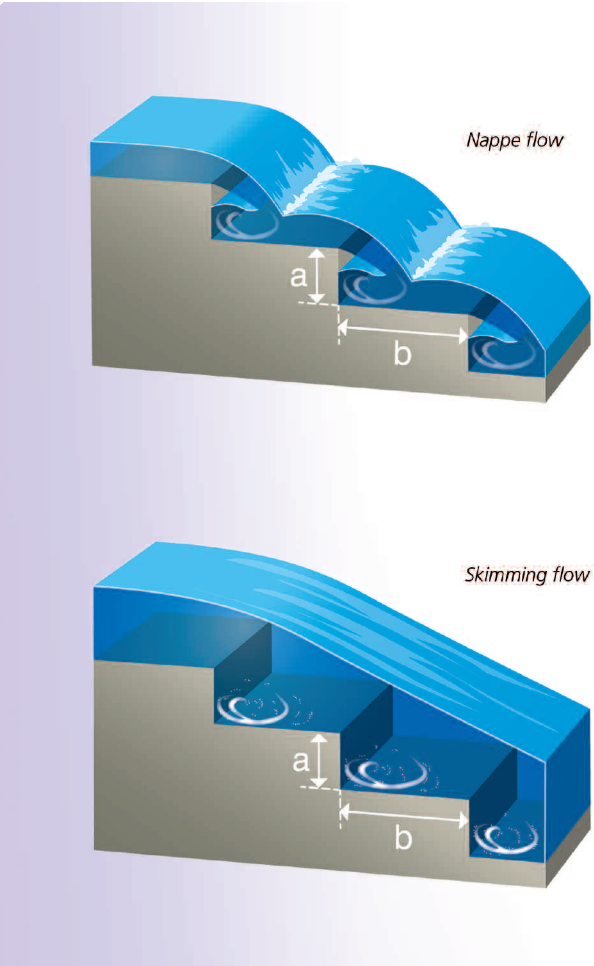
*Examples of steps in inclined downstream faces. (a) A stepped weir, (b) a sill on the crest of the weir.*

A step can cause two types of flow (see Figure 65):
- nappe flow, where the sheet of water falls over the crest of the step, resulting in a hydraulic jump
- skimming flow, where the discharge is sufficient to "erase" the step.

The main step characteristics are its height (a) and its horizontal or subhorizontal length (b).

Shifts between the two types of flow depend on the geometric characteristics of the step (height a and length b) and the unit discharge q. The higher the step (a), the greater the discharge required to transition from a nappe to a skimming flow.

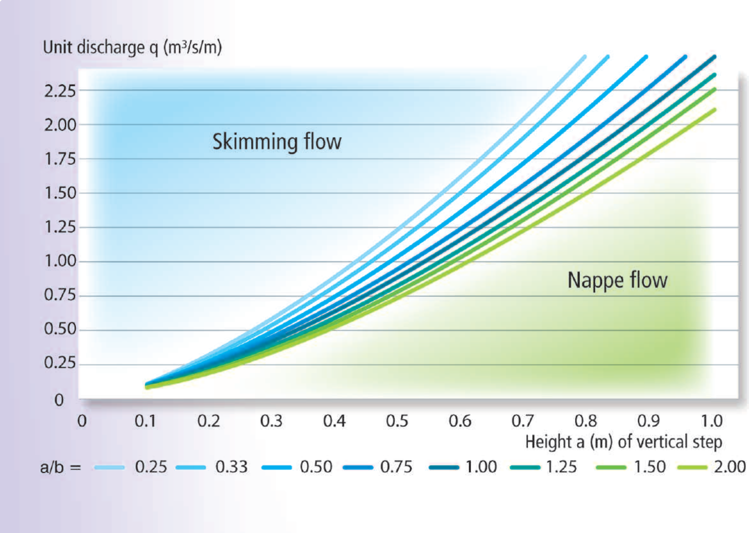
Figure 65




*Nappe flow (with hydraulic jump) and skimming flow over steps.*

Figure 66 presents the unit discharges at which transition occurs for step heights between 0.1 and 1 metre and for a/b ratios from 0.25 to 2.

Figure 66




*Transition between a nappe flow (with hydraulic jump) to a skimming flow as a function of the unit discharge and step characteristics.*

Fish can clear a step only by swimming, i.e. when the step has been "erased" by a skimming flow.

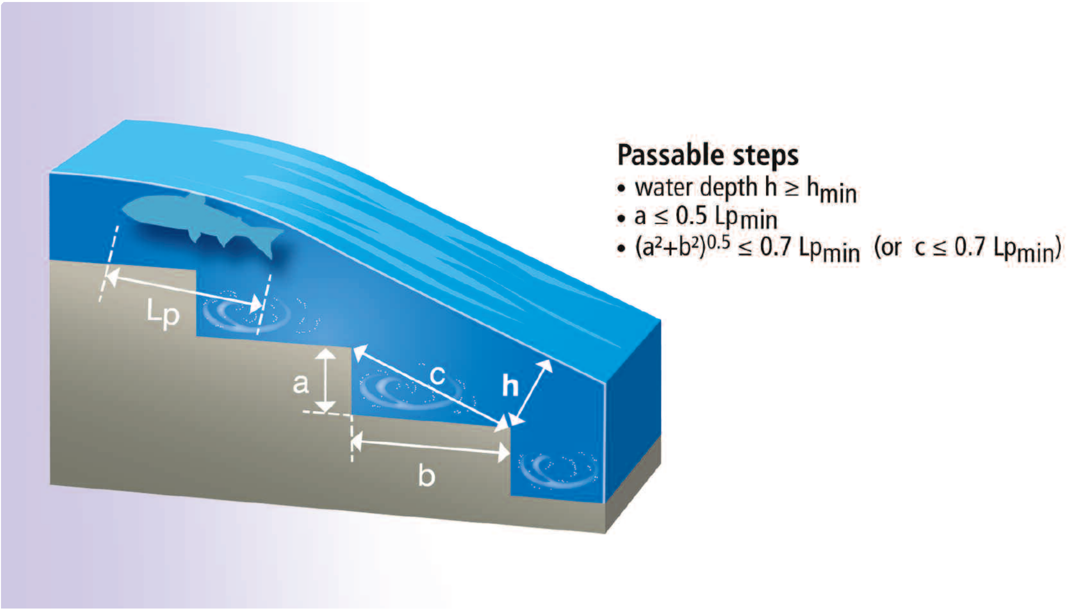
Consequently, it is thought that fish can clear a step only if the following conditions are met (see Figure 67):

- a skimming flow exists;
- the fish is long enough ($Lp_{min}$ of the species) compared to the size of the step. It is necessary to check that the following conditions prevail:

  $a \leq 0.5\ Lp_{min}$ and $(a^2+b^2)^{0.5} \leq 0.7\ Lp_{min}$ or in other terms $c \leq 0.7\ Lp_{min}$

Practically speaking, the second condition is sufficient because the first (skimming flow) is implicitly more or less fulfilled when the depth of water on the glacis is sufficient for the given species to swim, i.e. $h \geq h_{min}$.

Figure 67




*Necessary conditions for fish to overcome a step.*

NB The position of the step on the glacis can influence passage in different manners, depending on the hydrological conditions in the river. A step toward the top of the weir may have greater impact than a step located at a lower point because the latter may be submerged during periods of high discharge.

**Caution.** For the ICE protocol, a weir is considered to have a step in each case where the slope of a part of the glacis is greater than 150%, followed downstream by a section with a slope less than the first and less than 150%. **In cases where the water depth over the step is greater than twice the height of the step ($h \geq 2a$), the step may be considered negligible and need not be taken into account in the passability calculations.**

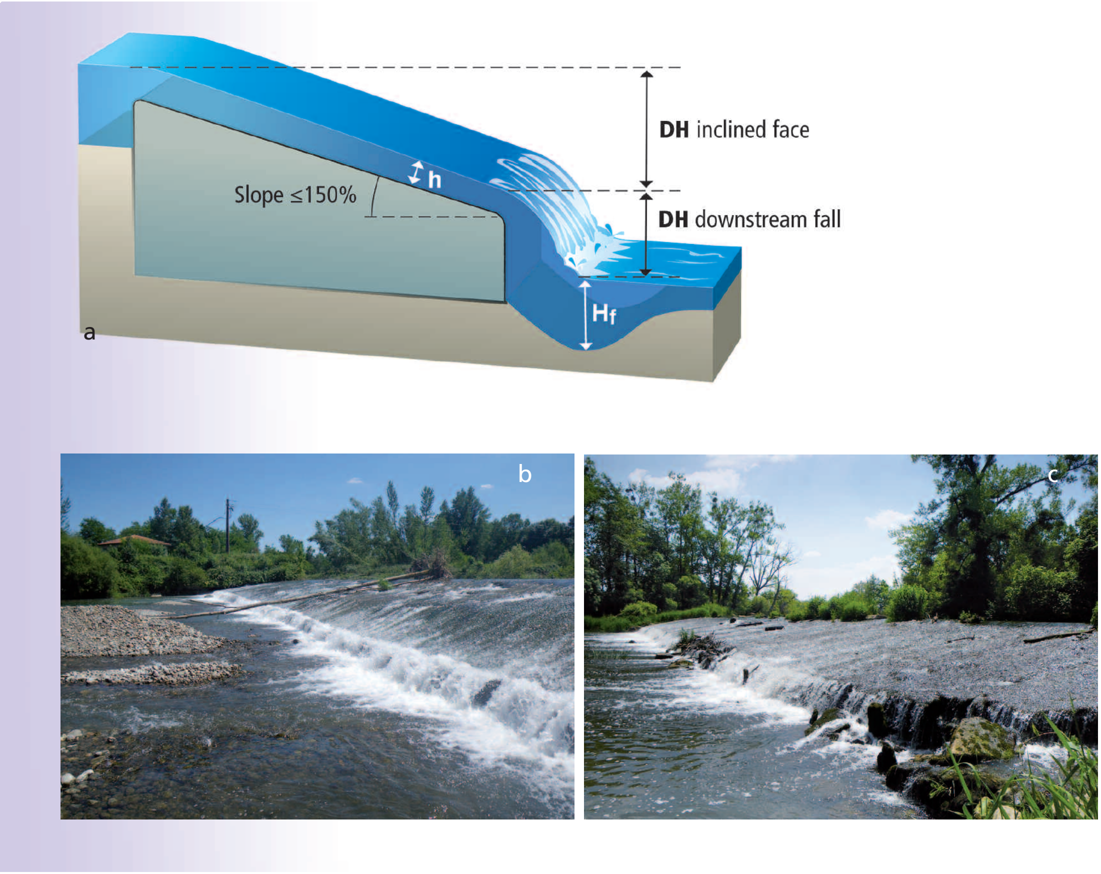
## Downstream fall

Weirs with inclined downstream faces often have a waterfall at the downstream end that can reduce the passability of the structure (see Figure 68).

The downstream fall must be analysed in the same manner as a vertical weir (slope >150%).

The overall passability of the structure is determined on the basis of the combined passability of the inclined section and that of the downstream fall as shown in Table 9, using the same method as that developed for complex or mixed structures (see the section on complex structures).

**Figure 68**




a © Chanseau - Onema
b © Burgun - Onema

*Examples of flows. (a) Diagram showing an inclined weir with a downstream fall, (b, c) flows over an inclined downstream face with a downstream fall.*

**Tableau 9**

*Table showing the ICE class for inclined weirs having a downstream fall.*

| ICE class of the inclined section | ICE class of the downstream fall | | | |
|---|---|---|---|---|
| | 0 | 0.33 | 0.66 | 1 |
| 0 | 0 | 0 | 0 | 0 |
| 0.33 | 0 | 0 | 0.33 | 0.33 |
| 0.66 | 0 | 0.33 | 0.33 | 0.66 |
| 1 | 0 | 0.33 | 0.66 | 1 |
| NC | 0 | NC (≤ 0.33) | NC (≤ 0.66) | NC |

## Determining passability classes

### ■ Threshold values used for the decision tree

Table 10 on the next page lists the step dimensions and the head-drops corresponding to the various passability classes. Table 11 below shows the necessary minimum depths of plunge pools $Hf_{min}$ as a function of the head-drop and the angle of incidence of the jet (or slope of the glacis).

These tables are accompanied by a decision tree (see Figure 69) that can be used to determine the ICE passability class.

**Tableau 11** *Approximate minimum depth $Hf_{min}$ of a plunge pool required for fish to overcome an inclined weir (≤150%).*

| Head-drop DH (m) | Angle of incidence of the jet (or slope of the glacis) | | | |
|---|---|---|---|---|
| | ≤ 25% | ]25% - 50%] | ]50% - 100%] | ]100% - 150%] |
| ≤ 0.25 | 0.10 m | 0.15 m | 0.20 m | 0.30 m |
| ]0.25 - 0.50] | 0.10 m | 0.20 m | 0.30 m | 0.40 m |
| ]0.50 - 1.00] | 0.15 m | 0.35 m | 0.50 m | 0.65 m |
| ]1.00 - 1.50] | 0.20 m | 0.50 m | 0.70 m | 0.90 m |
| ]1.50 - 2.00] | 0.25 m | 0.60 m | 0.85 m | 1.10 m |
| > 2.00 | 0.30 m | 0.70 m | 0.95 m | 1.25 m |

NB The values calculated for the depths of the plunge pool are absolute minimum values required for the passage of obstacles. That is why much higher values are systematically used when designing fish passes.

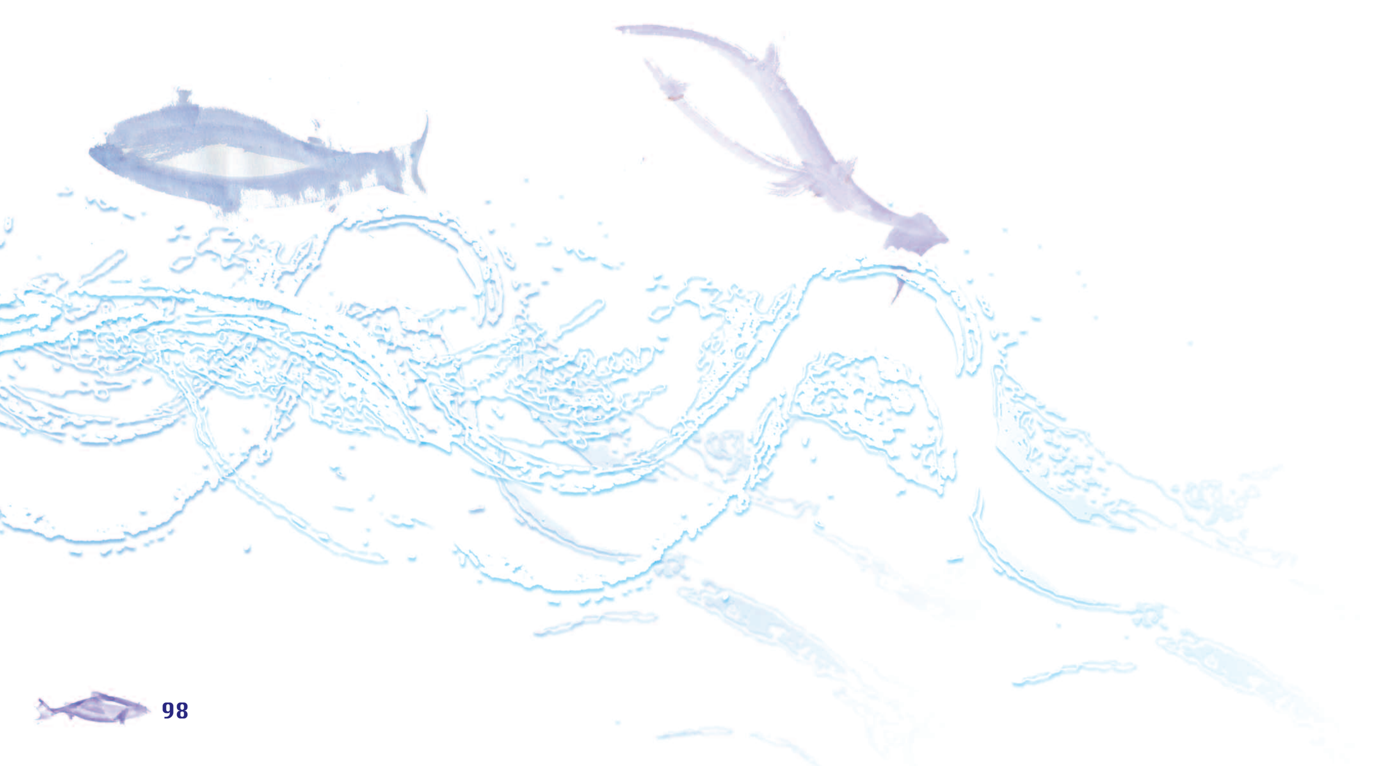


**Tableau 10** *Summary of the basic criteria (water depth, step dimensions, head-drop) used to determine the ICE passability classes for inclined weirs (slope ≤150%) using the decision tree in Figure 69.*

| ICE species group | Species | Minimum water depth $h_{min}$ required for swimming | Maximum step dimensions | | Threshold values for head-drops in assessing inclined weirs ≤ 150% (m) | | | | $DH_{extreme}$ |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | ICE passability class | | | | |
| | | | $a_{max}$ | $c_{max}$ | 1 | 0.66 | 0.33 | 0 | |
| 1 | Atlantic salmon (*Salmo salar*)<br>Brown or sea trout [50-100] (*Salmo trutta*) | 0.20 m | 0.35 m | 0.50 m | ≤ 1.0 | ]1.0 - 1.5] | ]1.5 - 2.5] | > 2.5 | 3.0 m |
| 2 | Mullets (*Chelon labrosus, Liza ramada*) | 0.10 m | 0.20 m | 0.30 m | ≤ 0.8 | ]0.8 - 1.1] | ]1.1 - 1.8] | > 1.8 | 2.5 m |
| 3a | Allis shad (*Alosa alosa*) | 0.15 m | 0.25 m | 0.40 m | ≤ 0.6 | ]0.6 - 1.0] | ]1.0 - 1.4] | > 1.4 | 2.0 m |
| 3b | Twaite shad (*Alosa fallax fallax*) | 0.10 m | 0.20 m | 0.30 m | | | | | |
| 3c | Sea lamprey (*Petromyzon marinus*) | | 0.35 m | 0.50 m | | | | | |
| 4a | Brown or sea trout [25-55] (*Salmo trutta*) | 0.10 m | 0.20 m | 0.30 m | ≤ 0.5 | ]0.5 - 0.9] | ]0.9 - 1.4] | > 1.4 | 2.0 m |
| 4b | Brown trout [15-30] (*Salmo trutta*) | 0.05 m | 0.10 m | 0.15 m | ≤ 0.3 | ]0.3 - 0.5] | ]0.5 - 0.8] | > 0.8 | 1.5 m |
| 5 | Asp (*Aspius aspius*)<br>Pike (*Esox lucius*) | 0.15 m | 0.30 m | 0.40 m | ≤ 0.6 | ]0.6 - 1.0] | ]1.0 - 1.4] | > 1.4 | 2.0 m |
| 6 | Grayling (*Thymallus thymallus*) | 0.10 m | 0.15 m | 0.25 m | ≤ 0.4 | ]0.4 - 0.75] | ]0.75 - 1.2] | > 1.2 | 1.5 m |
| 7a | Barbel (*Barbus barbus*)<br>Chub (*Squalius cephalus*)<br>Nase (*Chondrostoma nasus*) | 0.10 m | 0.15 m | 0.20 m | ≤ 0.3 | ]0.3 - 0.6] | ]0.6 - 0.9] | > 0.9 | 1.5 m |
| 7b | River lamprey (*Lampetra fluviatilis*) | 0.05 m | 0.15 m | 0.25 m | | | | | |
| 8a | Common carp (*Cyprinus carpio*) | 0.25 m | 0.25 m | 0.40 m | ≤ 0.2 | ]0.2 - 0.5] | ]0.5 - 0.7] | > 0.7 | 1.5 m |
| 8b | Common bream (*Abramis brama*)<br>Pikeperch (*Sander lucioperca*) | 0.15 m | 0.20 m | 0.25 m | | | | | |
| 8c | White bream (*Blicca bjoerkna*)<br>Ide (*Leuciscus idus*)<br>Burbot (*Lota lota*)<br>Perch (*Perca fluviatilis*)<br>Tench (*Tinca tinca*) | 0.10 m | 0.15 m | 0.20 m | | | | | |
| 8d | Daces (*Leuciscus spp.* except *Idus*) | 0.05 m | 0.10 m | 0.15 m | | | | | |
| 9a | Bleak (*Alburnus alburnus*)<br>Schneider (*Alburnoides bipunctatus*)<br>Mediterranean barbel (*Barbus meridionalis*)<br>Blageon (*Telestes souffia*)<br>Crucian carp (*Carassius carassius*)<br>Prussian carp (*Carassius gibelio*)<br>Roach (*Rutilus rutilus*)<br>Rudd (*Scardinius erythrophthalmus*)<br>SW European nase (*Parachondrostoma toxostoma*) | 0.05 m | 0.05 m | 0.10 m | ≤ 0.15 | ]0.15 - 0.35] | ]0.35 - 0.5] | > 0.5 | 1.0 m |
| 9b | Streber (*Zingel asper*)<br>Bullheads (*Cottus spp.*)<br>Gudgeons (*Gobio spp.*)<br>Ruffe (*Gymnocephalus cernuus*)<br>Brook lamprey (*Lampetra planeri*)<br>Stone loach ( *Barbatula barbatula*)<br>Spined loach (*Cobitis taenia*) | | | | | | | | |
| 10 | Sunbleak (*Leucaspius delineatus*)<br>Bitterling (*Rhodeus amarus*)<br>Threespine stickleback (*Gasterosteus gymnurus*)<br>Smoothtail ninespine stickleback (*Pungitius laevis*)<br>Minnows (*Phoxinus spp.*) | 0.05 m | 0.05 m | 0.05 m | ≤ 0.1 | ]0.1 - 0.2] | ]0.2 - 0.3] | > 0.3 | 1.0 m |
| 11a | European eel [yellow eel] *(Anguilla anguilla)* | 0.02 m | 0.10 m | 0.15 m | ≤ 0.20 | ]0.20 - 0.35] | ]0.35 - 0.5] | > 0.5 | 1.0 m |
| 11b | European eel [glass eel] *(Anguilla anguilla)* | - | - | - | - | - | - | - | |

*(*) The values indicated for eels correspond to the passability classes set when the analysis takes into account only the swimming capabilities of the species. In cases where the obstacle includes a crawling zone, the assessment must also use the special tables for crawling (see the section on eels).*

## ■ Decision tree

The steps below should be followed to determine the ICE passability class of an obstacle (see Figure 69).

### *1. Comparison of head-drop DH with $DH_{extreme}$*

If the total head-drop DH ≥ $DH_{extreme}$ (see Table 10), the obstacle cannot be overcome by the given species or group of species (ICE class = 0).

If DH < $DH_{extreme}$, take all the measurements on the structure (long profiles, water depth, depth of plunge pool). Go to Step 2.

### *2. Analysis of the downstream fall, if it exists*

If a fall exists (slope >150%) at the downstream end of the glacis, it is necessary to determine the passability of the fall using the procedure presented in the section on vertical and subvertical obstacles (start at Step 4 *Jumping species* in the decision tree in Figure 55).

If the fall cannot be overcome by the given species or group of species, then the entire obstacle is considered a total barrier (ICE class = 0).

If the downstream fall can be overcome, but is the dominant factor in the overall head-drop (DH downstream fall > DH inclined face), go to Step 3a.

Otherwise, go to Step 3b.

### *3. Analysis of the plunge pool at the foot of the obstacle*

a) If there is a downstream fall and it is the dominant factor in the overall head-drop (DH downstream fall > DH inclined face), the depth of the plunge pool at the foot of the obstacle should be checked. It must be sufficient as per the procedure for vertical falls >150% (Step 3), taking into account the head-drop created by the downstream fall (DH downstream fall). If Hf ≥ $Hf_{min}$ (see Table 8), the depth is sufficient. Go to Step 4.

b) If there is not a downstream fall or if it is not the dominant factor in the overall head-drop (DH downstream fall < DH inclined face), it is necessary to check the depth of the plunge pool at the foot of the obstacle using Table 11 and taking into account the total head-drop of the obstacle DH = DH inclined face + DH downstream fall) and the slope of the glacis. If Hf ≥ $Hf_{min}$ (see Table 11), the depth is sufficient. Go to Step 4.

If Hf < $Hf_{min}$, the obstacle may be considered a total barrier (ICE class = 0).

### *4. Analysis of the water depth on the glacis*

If h ≥ $h_{min}$ (see Table 10), the depth is sufficient. Go to Step 5.

If h < $h_{min}$, under the given hydrological conditions the obstacle may be considered a total barrier in the sense of the ICE protocol (ICE class = 0). However, the analysis should be pursued (go to Step 5) in order to determine the passability class in the event other hydrological conditions provide enough water depth. Depending on the score of the subsequent analysis, it will be possible to decide whether or not to return to the obstacle for measurements under other hydrological conditions.

### *5. Analysis of steps on the inclined downstream face*

If there are no steps or if the steps are negligible (h ≥ 2a), go directly to Step 6.

If the dimensions (a and c) of a single step exceed the maximum values $a_{max}$ and $c_{max}$ listed in Table 10, the obstacle may be considered a total barrier (ICE class = 0).

If the dimensions (a and c) of all steps are lower than the threshold values, go to Step 6.

### *6. Analysis of the head-drop DH of the inclined downstream face*

On the basis of the head-drop DH of the inclined downstream face (DH inclined face or simply DH if there is no downstream fall), use Table 10 to determine the ICE passability class of the downstream face.

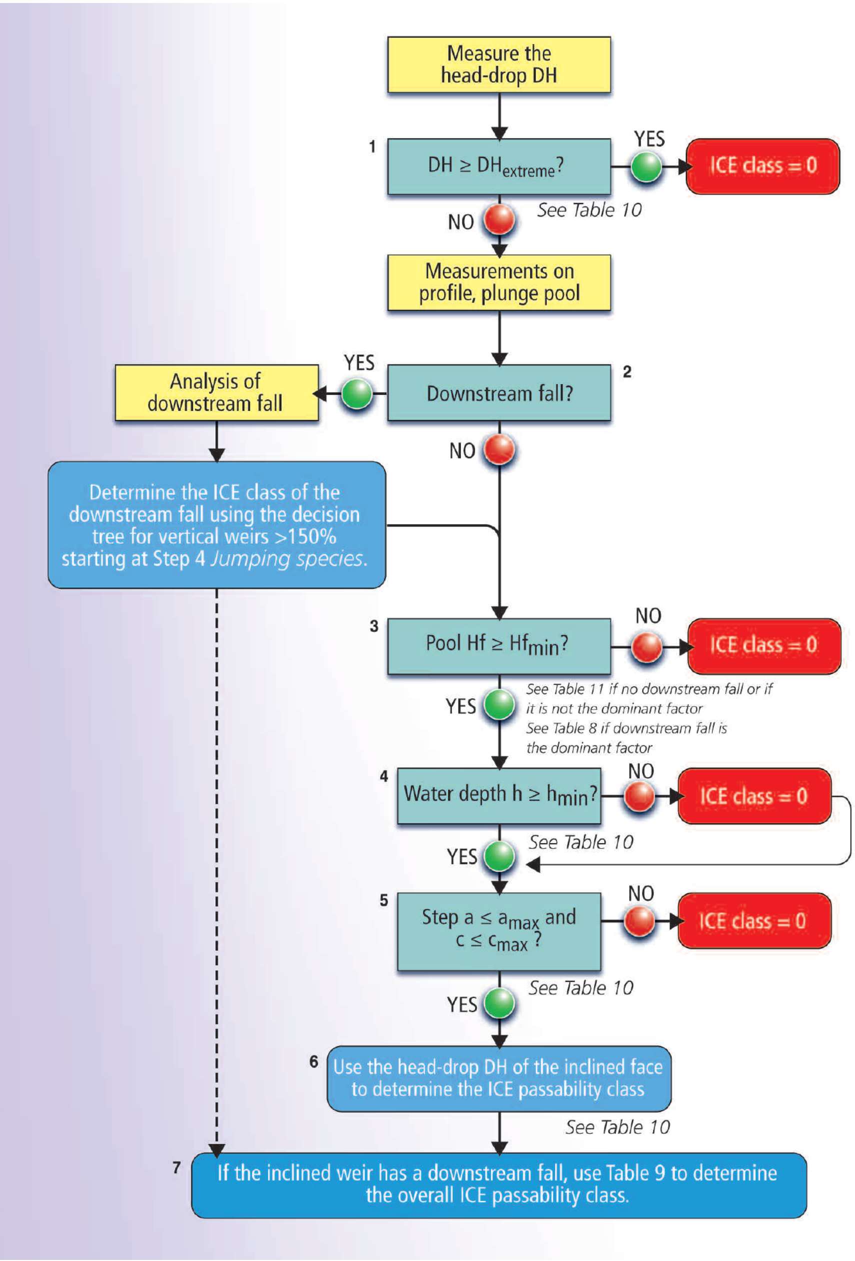
Then go to Step 7.

### *7. Analysis of the overall passability of the structure*

If the inclined weir has a downstream fall, use Table 9 to determine the overall ICE passability class.

If the inclined weir does not have a downstream fall, the overall ICE passability class is that resulting from Step 6.

**Figure 69**




*Decision tree to determine ICE passability classes for inclined weirs (slope ≤150% (56°)).*

# Rock weirs, a special case

## General

Massive extractions of alluvial matter from riverbeds in France during the 1960s and 1970s produced a considerable impact on rivers, including drops in bed levels, bank erosion, destruction of bank-protection systems, downcutting of structure foundations and drops in groundwater levels. A large number of rock weirs were created to limit downcutting in rivers by stabilising the upstream riverbed or to protect existing infrastructure (see Figure 70).

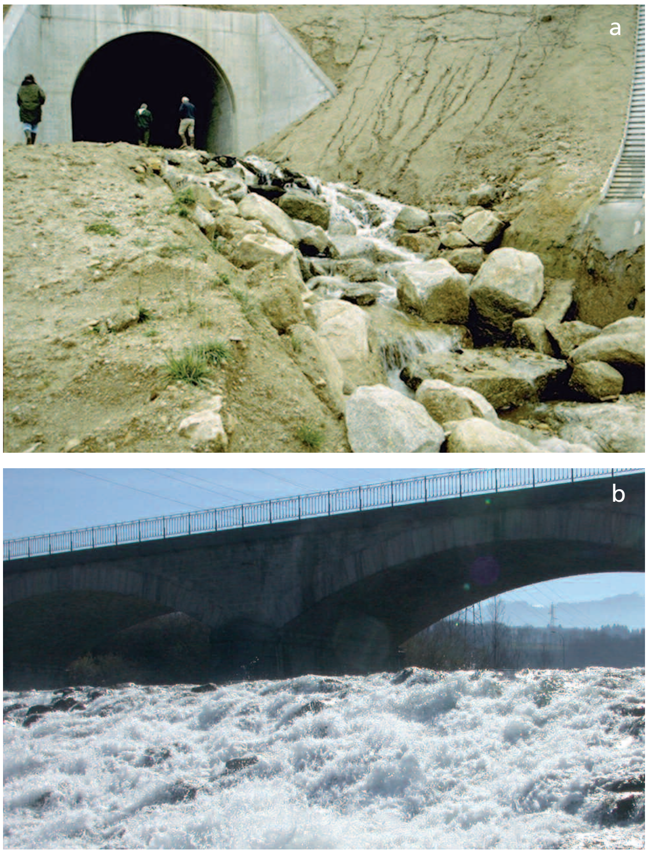
Rock weirs were also created to replace partially removed weirs where it was deemed necessary to maintain the long profile of the river in order to safeguard social conditions and/or economic activities located upstream.

Similar to "standard" weirs, numerous configurations of rock weirs may be observed with head-drops ranging from less than 1 metre to over 10 metres.

The dimensions of the rocks can vary significantly from one site to another and even for a given weir, from a few dozen kilograms to several tons. The rocks generally touch each other and form a glacis with a more or less steep slope ranging from 5% to over 30%.

Depending on the physical and hydraulic configuration of each site, the rocks may be positioned according to different types of layout (see Figure 71 on the next page). The weir may consist of one or more layers of rocks positioned more or less closely to each other. In some cases, notably when the passage of fish was taken into account during the design of the weir, the slope of the glacis was reduced and large rocks were positioned more or less uniformly to reduce flow velocities and provide fish with rest areas.

Figure 70




a, b © Larinier - Ecohydraulic centre

*Examples of rock weirs.*

*(a) (b) Examples of rock weirs installed to stabilise the long profile of the riverbed near infrastructure.*

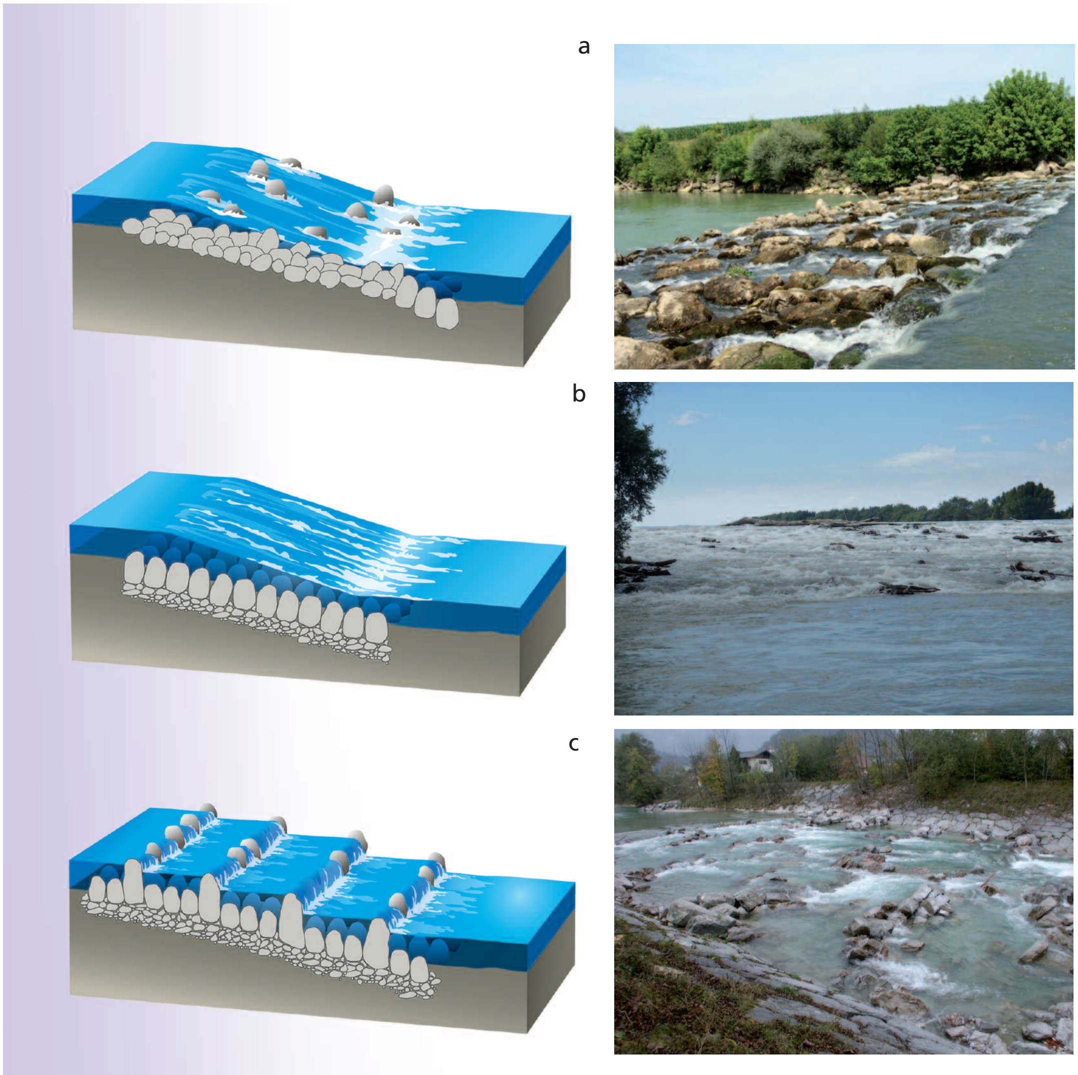
c, d © Voegtlé - Ecogea

*(c) (d) Examples of riprap used to protect the foundation of a weir from erosion.*

e © Voegtlé - Ecogea
f © Larinier - Ecohydraulic centre

*e) (f) Examples of stabilisation weirs for the riverbed of the Gave de Pau River, designed to avoid downcutting.*

Figure 71




a, b, © Chanseau - Onema
c © Larinier - Ecohydraulic centre

*Examples of various rock-weir layouts.*

Depending on the situation, the rocks may be free standing or joined using concrete or tar (see Figure 72). For free-standing rocks, if there is sufficient coarse bedload, the voids least exposed to flow may be filled in over time.

72

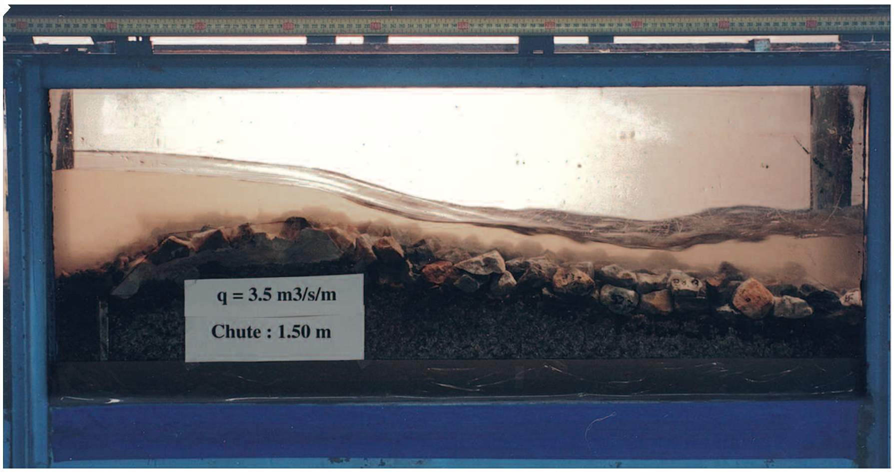

a © Voegtle - Ecogea
b © Larinier - Ecohydraulic centre

*Examples of (a) free-standing rocks and (b) joined rocks.*

## Fish and hydraulic problems

Similar to an inclined weir (see the section on weirs with inclined downstream faces (slope ≤150%)), the flow velocity increases progressively from the crest downstream until the flow becomes uniform, at which point the average water depth remains approximately constant along the rest of the glacis (see Figure 73). The rougher the surface and the lower the unit discharge, the shorter the distance to create uniform conditions. The distance is approximately 3 to 4 metres for unit discharges of 1 to 2 $m^3/s/m$.

**Figure 73**




*© drawn from Larinier et al. (2006)*

*Flow over joined rocks with a slope of 10% (model to 1:22 scale).*

Because the rocks provide high energy dissipation along the entire glacis, the hydraulic jump at the foot of the weir is much less pronounced than in standard weirs.

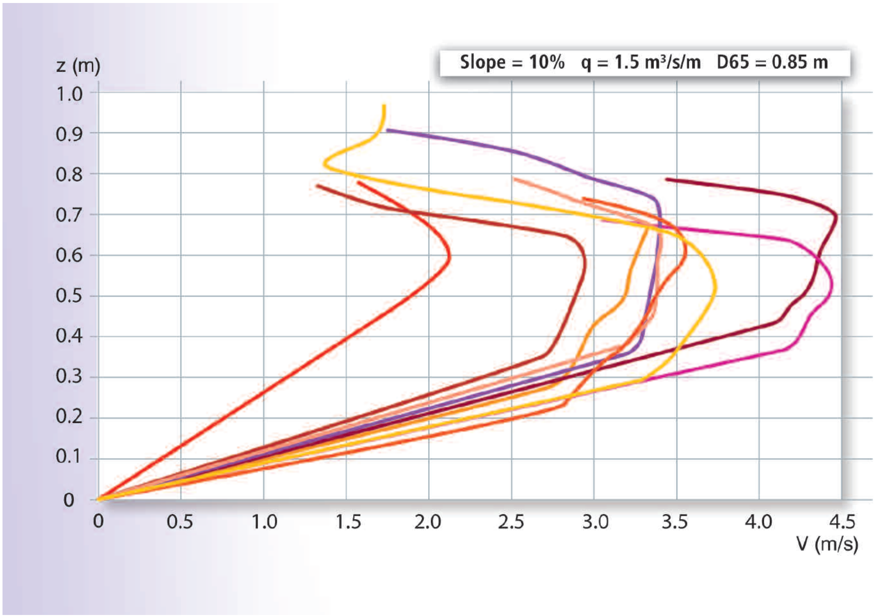
The flow conditions (water depth, velocity, type of flow) are determined by the slope of the glacis, the length of the glacis (or the head-drop), the unit discharge and the surface roughness, which itself depends on the size and shape of the rocks, their layout and whether or not they are joined.

Hydraulic analysis of rock weirs is much more difficult than for "standard" weirs due to the variability in the organisation of the weir, as well as the shapes and sizes of the rocks, particularly in light of the fact that their positioning during the construction process is never very precise.

In addition, contrary to "standard" weirs (see the section on weirs with inclined downstream faces (slope ≤150%)), given the size of the rocks, hydraulic modelling of the flow conditions is not possible. This is because the rocks constitute irregularities of approximately the same size as the flow depth (or greater), particularly under the hydrological conditions prevalent during the migratory periods of fish.

Figure 74 illustrates this by showing the velocity profiles measured for a 1.5 $m^3/s/m$ unit discharge on a rock chute (slope 10%) where the size of the rocks was D65 = 0.85 m. The measurements for several points in the water column in uniform sections reveal the high spatial variability of the velocity profiles (maximum values ranging from 2.1 m/s to 3.7 m/s) and a very strong velocity gradient in the column.

Figure 74




© drawn from Larinier et al. (2006)

*Example of velocity profiles on a rock chute made up of joined rocks (D65 = 0.85 m) with a slope of 10%.*

The passability of a rock weir depends on the flow velocities, water depths (between and/or above the rocks) taking into account the size of the given species, the "quality" of the sheet of water (no hydraulic jumps, no air gaps, etc.) and the distance that the fish must cover (see Figures 75 and 76).

Two factors limit passability:

- for a low unit discharge, the sheet of water is generally disrupted, the water depth is insufficient to allow swimming and the water can even infiltrate between the rocks;
- for higher unit discharges, the sheet of water is less disrupted, however the flow velocities can rapidly exceed the swimming capabilities of most species.

The range of unit discharges for which the chute remains passable decreases as the slope increases, for all species and groups of species.

Often, rock weirs do not provide large fish with rest areas, which means they must be cleared in a single shot. The largest rocks breaking the water surface may offer rest areas for the smallest species if the agitation and turbulence are not excessive (see Figures 75 and 76).

Figure 75


a © Voegtlé - Ecogea
b © Chanseau - Onema

*Examples of flows over rock weirs.*

Figure 76


a © Voegtlé - Ecogea
b © Larinier - Onema

*Flows over rock weirs vary in quality.*

## A difficult assessment

Assessing the passability of rock weirs is much more difficult than "standard" weirs due to the complexity and variability of flows (three-dimensional flows).

As noted above, **mathematical modelling is not an option**. Empirical hydraulic laws are not applicable and it is difficult to establish average values for parameters such as water velocities and depth.

**Physical modelling in a laboratory** may be possible, but is generally very complex given the difficulty of creating an accurate scale model due to the great differences in structures. In addition, physical modelling is not widely applicable because the parameters for one site (size of rocks, slope, unit discharges, head-drop, etc.) do not necessarily correspond to those of another site. Finally, physical modelling requires major financial and human resources that are simply not available for the type of approach promoted by the ICE protocol.

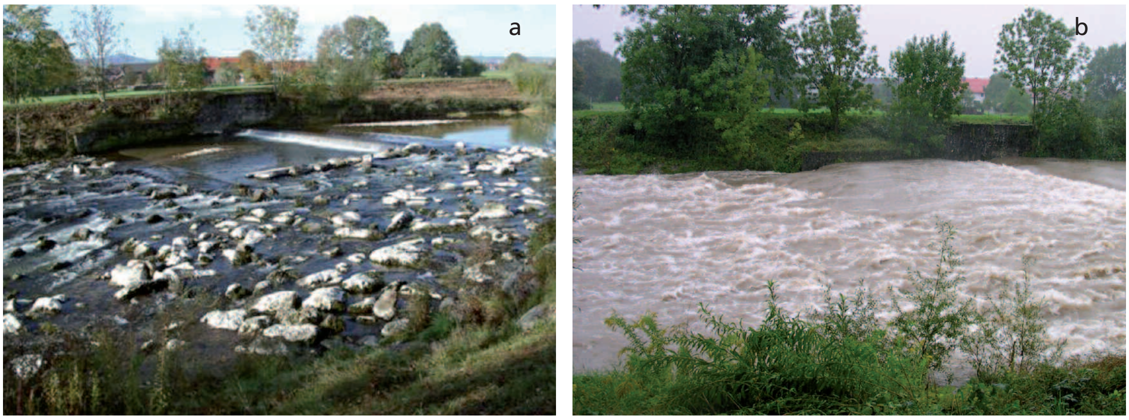
Similarly, **in situ biological assessments using capture-mark-recapture (CMR) or telemetric techniques are complex, require extensive resources** and are limited to a few species (generally large in size). It is also difficult to transfer them to other sites.

**Finally, measurements in the field are possible in some cases, but take a great deal of time and may be risky for the persons involved. In addition, it is generally not possible to carry out measurements under medium- and high-flow conditions.**

For example, Wang and Hartlieb (2011) attempted to analyse the possible passageways for fish (brown trout and small species) at a weir on the Schwaig River in Baveria, equipped with a "natural" rock pass (length = 35 m; width = 20 m; slope = 4%). The analysis consisted of measuring a number of parameters on the rock pass, namely the flow velocities using a current meter, water depths and the widths of potential migratory corridors (see Figure 77).

The measurements revealed isolated elements in the passageways, but required, under low-flow conditions, significant human resources (four people for two days) and could not be carried out under medium- and high-flow conditions for safety reasons (see Figure 77).

Figure 77




© Wang

*Field measurements were carried out at a weir on the Schwaig River to assess passageways. (a) Low-flow conditions at the weir on the Schwaig River, (b) High-flow conditions at the same weir.*

## Passability criteria and classes

Given the technical impossibility of carrying out precise measurements on this type of structure and of creating hydraulic and physical models, it is difficult to propose passability criteria.

**For the ICE protocol, it is suggested first to check that a potential passageway exists for fish and then to assess passability on the basis of two criteria that are simple to measure or estimate, i.e. the head-drop DH and the average slope of the glacis.**

Passability criteria have been extrapolated, notably from the results of the physical modelling in a laboratory of "passable by design" weirs (Larinier *et al.*, 1995) and, more recently, from experiments on natural fish passes and from project feedback accumulated in France and abroad.

### ■ Passageway with sufficient water depth ($h_{min\ rock}$)

Similar to "standard" weirs, a fish must find itself in water of sufficient depth such that it can actively propel its way forward by undulating its body and using its tail fins.

For a "standard" weir, the minimum water depth $h_{min}$ required to enable a fish to swim was set at approximately 1.5 times the average body depth $hp_{avg}$ of fish in the given species and at the given development stage.

Given the significantly greater heterogeneity of flows over rock weirs, the first step is to check that a potential passageway exists for fish. **The entire passageway must provide a sufficient and minimum water depth** $h_{min\ rock}$ enabling the given species to swim without encountering barriers (hydraulic jumps or steep waterfalls).

The greater the average slope of the glacis, the greater the necessary unit discharge q to ensure a "consistent" flow capable of "erasing" the succession of jumps caused by the rocks. Given the size of the rocks, it is difficult, when discharges are low, to speak of a "sheet of water" over the weir. The flow is rather a series of cascades comparable to a stepped weir. In this case, the fish can progress from one station to another (from one rock to another) only if the height and layout of the rocks do not create local waterfalls that the fish cannot overcome.

To take this aspect into account, a solution is to select **a minimum water depth that is proportional to the slope**. For this type of structure where access is often difficult and the heterogeneity of flows is greater, it will often be difficult to determine the water depth other than visually or through a limited number of measurements in accessible zones.

The absolute minimum values for water depth over rock weirs $h_{min\ rock}$ are indicated in Table 12.

For example, the minimum water depth for an Atlantic salmon is 20 cm for slopes up to 9% ($h_{min}$ value in Table 10), but increases to 25 cm, 30 cm and 40 cm for slopes of 10%, 12% and 14% respectively.

**Tableau 12** *Absolute minimum water depths $h_{min\ rock}$ established as a function of the slope to enable the passage of rock weirs.*

| ≤ 5% | ]5% - 7%] | ]7% - 9%] | ]9% - 11%] | ]11% - 13%] | ]13% - 15%] |
|---|---|---|---|---|---|
| 10 cm | 15 cm | 20 cm | 25 cm | 30 cm | 40 cm |

*The $h_{min}$ value for the given species (see Table 10) applies if it is greater.*

**The values calculated for water depths are absolute minimum values required for passage. That is why much higher values (3 to 4 times body depth) are systematically used when designing fish passes and particularly "passable by design" rock weirs and rock passes.**

For example, Larinier *et al.* (1995) recommend for "passable by design" weirs made of joined rocks minimum water depths of 30 cm for large migratory salmonids and sea lampreys, 40 cm for shad and 20 cm for brown trout, rheophilic cyprinids and small species. These values correspond roughly to 2 to 3 times the minimum water depths $h_{min}$ selected for "standard" weirs, i.e. 3 to 4 times the body depth of the fish, depending on the species.

### ■ Determining passability for species groups as a function of the weir slope

Contrary to "standard" weirs, rock weirs often have slight slopes, but lengths can often reach several dozen metres.

Given the need for a "consistent" flow on the glacis, i.e. a flow having a water depth sufficient to avoid the formation of jumps that fish cannot overcome, the maximum passable distance for a given species depends essentially on the flow velocity (a function of the surface roughness, the slope and the discharge) and on the swimming speed of the species.

Using the equation of Rice *et al.* (1998), the average flow velocity Vm can be roughly calculated as a function of the slope of the rock weir and the water depth:

$$\sqrt{\frac{8}{\lambda}} = \frac{v_m}{\sqrt{g.h_m.I}} = 2.21.ln\left(\frac{h_m}{d_{84}}\right) + 6.00$$

where:

Vm: average flow velocity (m/s)

hm: water depth (m)

d84: diameter of the rocks making up the weir that is not exceeded by 84% of the rocks (m)

I: slope of the weir (m/m)

A rough passability assessment of a rock weir can be carried out in a manner similar to that for inclined weirs (see the section on weirs with inclined downstream faces (slope ≤150%)) or for road/rail structures (see the section on this type of structure), i.e. by analysing the distance that a fish can cover against a flow having a given average velocity.

By comparing flow velocities V and the distance that a fish can cover against a flow having a given velocity (see the section on the assessment of road/rail structures), it is possible to assign a passability class (0, 0.33, 0.66, 1) to each species or group of species as a function of the weir slope and the head-drop DH that the fish must overcome.

The values produced by this method are comparable to the criteria established by Larinier *et al.* (1995; 2006) for sizing "passable by design" weirs and/or "natural" fish passes made of joined rocks.

However, similar to the values selected for minimum water depths required for passage, the threshold values between passability classes (and particularly the value determining whether the obstacle can be considered a low-impact passable barrier (ICE class = 1)) differ widely from the "conservative" criteria established for "passable by design" weirs and "natural" fish passes, which are sized to ensure the passage of all fish of a given species.

## Steps

In most cases, a step exists at the crest of the weir as part of a scour-protection system (concrete, sheet piles).

Similar to "standard" weirs, a step along the entire width of a rock weir can substantially degrade the passage conditions for fish, particularly under low-flow conditions (see Figure 78).

Figure 78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*Examples of rock weirs with steps.*

It is possible to use the same criteria as those for "standard" weirs concerning the relative dimensions (a and c) of the the step with respect to the average size ($Lp_{avg}$) of the species or group of species.

NB Some obstacles may be seen either as rock weirs with a large step at the crest, or as vertical weirs with rock protection at the foot. The type of assessment (for a "standard" weir or for a rock weir) is not particularly important because the final result on the passability class should be similar. For this type of mixed structure, see also the section on complex structures.

## Plunge pool

Except under flood conditions and contrary to "standard" weirs, the energy is progressively dissipated along the weir due to the rocks.

A hydraulic jump is virtually non-existent downstream of the weir. In that the slope is often slight, it was deemed that **a deep plunge pool is not indispensable** for the protocol..

## Determining passability classes

### ■ Threshold values used for the decision tree

Table 13 (next page) provides the necessary minimum water depths ($h_{min\ rock}$) that must be checked. It also indicates the maximum heights and lengths of steps if they exist.

Tables 14 and 15 (next pages) indicate the head-drop threshold values for the passability classes of a rock weir as a function of the average slope of the weir. To enhance legibility, the data were divided into two tables, i.e. the data for average slopes ≤9% are shown in Table 14 and those for average slopes >9% are shown in Table 15.

These tables are accompanied by a decision tree (see Figure 79) showing how the ICE passability classes are determined.

**Tableau 13** *Minimum water depths ($h_{min\ rock}$) required for a viable passageway over a rock weir and maximum step dimensions ($a_{max}$ and $c_{max}$).*

| ICE species group | Species | Maximum step dimensions | | Minimum water depths ($h_{min\ rock}$) for assessments of rock weirs | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $a_{max}$ | $c_{max}$ | Slope ≤ 5% | 5% < Slope ≤ 7% | 7% < Slope ≤ 9% | 9% < Slope ≤ 11% | 11% < Slope ≤ 13% | 13% < Slope ≤ 15% | Slope > 15% |
| 1 | Atlantic salmon (*Salmo salar*)<br>Brown or sea trout [50-100] (*Salmo trutta*) | 0.35 m | 0.50 m | 0.20 m | 0.20 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 2 | Mullets (*Chelon labrosus, Liza ramada*) | 0.20 m | 0.30 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 3a | Allis shad (*Alosa alosa*) | 0.25 m | 0.40 m | 0.15 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 3b | Twaite shad (*Alosa fallax fallax*) | 0.20 m | 0.30 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 3c | Sea lamprey (*Petromyzon marinus*) | 0.35 m | 0.50 m | | | | | | | |
| 4a | Brown or sea trout [25-55] (*Salmo trutta*) | 0.20 m | 0.30 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 4b | Brown trout [15-30] (*Salmo trutta*) | 0.10 m | 0.15 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 5 | Asp (*Aspius aspius*)<br>Pike (*Esox lucius*) | 0.30 m | 0.40 m | 0.15 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 6 | Grayling (*Thymallus thymallus*) | 0.15 m | 0.25 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 7a | Barbel (*Barbus barbus*)<br>Chub (*Squalius cephalus*)<br>Nase (*Chondrostoma nasus*) | 0.15 m | 0.20 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 7b | River lamprey (*Lampetra fluviatilis*) | 0.15 m | 0.25 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 8a | Common carp (*Cyprinus carpio*) | 0.25 m | 0.40 m | 0.25 m | 0.25 m | 0.25 m | 0.25 m | 0.30 m | 0.40 m | - |
| 8b | Common bream (*Abramis brama*)<br>Pikeperch (*Sander lucioperca*) | 0.20 m | 0.25 m | 0.15 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 8c | White bream (*Blicca bjoerkna*)<br>Ide (*Leuciscus idus*)<br>Burbot (*Lota lota*)<br>Perch (*Perca fluviatilis*)<br>Tench (*Tinca tinca*) | 0.15 m | 0.20 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 8d | Daces (*Leuciscus spp.* except *Idus*) | 0.10 m | 0.15 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 9a | Bleak (*Alburnus alburnus*)<br>Schneider (*Alburnoides bipunctatus*)<br>Mediterranean barbel (*Barbus meridionalis*)<br>Blageon (*Telestes souffia*)<br>Crucian carp (*Carassius carassius*)<br>Prussian carp (*Carassius gibelio*)<br>Roach (*Rutilus rutilus*)<br>Rudd (*Scardinius erythrophthalmus*)<br>SW European nase (*Parachondrostoma toxostoma*) | 0.05 m | 0.10 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 9b | Streber (*Zingel asper*)<br>Bullheads (*Cottus spp.*)<br>Gudgeons (*Gobio spp.*)<br>Ruffe (*Gymnocephalus cernuus*)<br>Brook lamprey (*Lampetra planeri*)<br>Stone loach ( *Barbatula barbatula*)<br>Spined loach (*Cobitis taenia*) | | | | | | | | | |
| 10 | Sunbleak (*Leucaspius delineatus*)<br>Bitterling (*Rhodeus amarus*)<br>Threespine stickleback (*Gasterosteus gymnurus*)<br>Smoothtail ninespine stickleback (*Pungitius laevis*)<br>Minnows (*Phoxinus spp.*) | 0.05 m | 0.05 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 11a | European eel [yellow eel] *(Anguilla anguilla)* | 0.10 m | 0.15 m | 0.10 m | 0.15 m | 0.20 m | 0.25 m | 0.30 m | 0.40 m | - |
| 11b | European eel [glass eel] *(Anguilla anguilla)* | - | - | - | - | - | - | - | - | |

*(*) The values indicated for eels correspond to the passability classes set when the analysis takes into account only the swimming capabilities of the species. In cases where the obstacle includes a crawling zone, the assessment must also use the special tables for crawling (see the section on eels).*

**Tableau 14** *Head-drop threshold values used to determine the ICE passability classes for rock weirs (slope ≤9%) using the decision tree in Figure 79.*

| ICE species group | Species | Head-drop (DH) threshold values (m) for assessing rock weirs | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Slope ≤ 5% | | | 5% < Slope ≤ 7% | | | | 7% < Slope ≤ 9% | | | |
| | | ICE passability class | | | ICE passability class | | | | ICE passability class | | | |
| | | 1 | 0.66 | 0.33 | 1 | 0.66 | 0.33 | 0 | 1 | 0.66 | 0.33 | 0 |
| 1 | Atlantic salmon (*Salmo salar*)<br>Brown or sea trout [50-100] (*Salmo trutta*) | - | - | - | - | - | - | - | - | - | - | - |
| 2 | Mullets (*Chelon labrosus, Liza ramada*) | - | - | - | - | - | - | - | ≤ 6.4 | > 6.4 | - | - |
| 3a | Allis shad (*Alosa alosa*) | - | - | - | - | - | - | - | ≤ 3.2 | ]3.2-8.0] | > 8.0 | - |
| 3b | Twaite shad (*Alosa fallax fallax*) | - | - | - | - | - | - | - | ≤ 1.8 | ]1.8-4.4] | > 4.4 | - |
| 3c | Sea lamprey (*Petromyzon marinus*) | | | | | | | | | | | |
| 4a | Brown or sea trout [25-55] (*Salmo trutta*) | - | - | - | - | - | - | - | ≤ 1.8 | ]1.8-6.4] | > 6.4 | - |
| 4b | Brown trout [15-30] (*Salmo trutta*) | - | - | - | ≤ 3.0 | > 3.0 | - | - | ≤ 1.0 | ]1.0-1.8] | ]1.8-3.2] | > 3.2 |
| 5 | Asp (*Aspius aspius*)<br>Pike (*Esox lucius*) | - | - | - | - | - | - | - | ≤ 3.2 | ]3.2-8.0] | > 8.0 | - |
| 6 | Grayling (*Thymallus thymallus*) | - | - | - | - | - | - | - | ≤ 1.8 | ]1.8-4.4] | > 4.4 | - |
| 7a | Barbel (*Barbus barbus*)<br>Chub (*Squalius cephalus*)<br>Nase (*Chondrostoma nasus*) | - | - | - | ≤ 3.0 | > 3.0 | - | - | ≤ 1.0 | ]1.0-1.9] | ]1.9-6.4] | > 6.4 |
| 7b | River lamprey (*Lampetra fluviatilis*) | - | - | - | ≤ 3.0 | > 3.0 | - | - | ≤ 1.0 | ]1.0-1.9] | ]1.9-6.4] | > 6.4 |
| 8a | Common carp (*Cyprinus carpio*) | ≤ 0.3 | ]0.3-0.9] | ]0.9-2.4] | ≤ 0.3 | ]0.3-0.8] | ]0.8-1.8] | > 1.8 | ≤ 0.2 | ]0.2-0.8] | ]0.8-1.8] | > 1.8 |
| 8b | Common bream (*Abramis brama*)<br>Pikeperch (*Sander lucioperca*) | ≤ 1.6 | >1.6 | - | ≤ 1.0 | ]1.0-6.0] | > 6.0 | - | ≤ 0.5 | ]0.5-1.5] | ]1.5-3.2] | > 3.2 |
| 8c | White bream (*Blicca bjoerkna*)<br>Ide (*Leuciscus idus*)<br>Burbot (*Lota lota*)<br>Perch (*Perca fluviatilis*)<br>Tench (*Tinca tinca*) | - | - | - | ≤ 1.0 | ]1.0-6.0] | > 6.0 | - | ≤ 0.5 | ]0.5-1.5] | ]1.5-3.2] | > 3.2 |
| 8d | Daces (*Leuciscus spp.* except *Idus*) | - | - | - | ≤ 1.0 | ]1.0-6.0] | > 6.0 | - | ≤ 0.5 | ]0.5-1.5] | ]1.5-3.2] | > 3.2 |
| 9a | Bleak (*Alburnus alburnus*)<br>Schneider (*Alburnoides bipunctatus*)<br>Mediterranean barbel (*Barbus meridionalis*)<br>Blageon (*Telestes souffia*)<br>Crucian carp (*Carassius carassius*)<br>Prussian carp (*Carassius gibelio*)<br>Roach (*Rutilus rutilus*)<br>Rudd (*Scardinius erythrophthalmus*)<br>SW European nase (*Parachondrostoma toxostoma*) | - | - | - | ≤ 0.4 | ]0.4-1.5] | > 1.5 | - | - | ≤ 0.7 | ]0.7-1.8] | > 1.8 |
| 9b | Streber (*Zingel asper*)<br>Bullheads (*Cottus spp.*)<br>Gudgeons (*Gobio spp.*)<br>Ruffe (*Gymnocephalus cernuus*)<br>Brook lamprey (*Lampetra planeri*)<br>Stone loach ( *Barbatula barbatula*)<br>Spined loach (*Cobitis taenia*) | | | | | | | | | | | |
| 10 | Sunbleak (*Leucaspius delineatus*)<br>Bitterling (*Rhodeus amarus*)<br>Threespine stickleback (*Gasterosteus gymnurus*)<br>Smoothtail ninespine stickleback (*Pungitius laevis*)<br>Minnows (*Phoxinus spp.*) | ≤ 0.4 | >0.4 | - | - | ≤ 0.4 | ]0.4-1.0] | > 1.0 | - | - | ≤ 0.5 | > 0.5 |
| 11a | European eel [yellow eel] (*Anguilla anguilla*) | - | - | - | ≤ 0.4 | ]0.4-1.5] | > 1.5 | - | - | ≤ 0.7 | ]0.7-1.8] | > 1.8 |
| 11b | European eel [glass eel] (*Anguilla anguilla*) | - | - | - | - | - | - | - | - | - | - | - |

*(*) The values indicated for eels correspond to the passability classes set when the analysis takes into account only the swimming capabilities of the species. In cases where the obstacle includes a crawling zone, the assessment must also use the special tables for crawling (see the section on eels).*

**Tableau 15** *Head-drop threshold values used to determine the ICE passability classes for rock weirs (slope >9%) using the decision tree in Figure 79.*

| ICE species group | Species | Head-drop (DH) threshold values (m) for assessing rock weirs | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 9% < Slope ≤ 11% | | | | 11% < Slope ≤ 13% | | | | 13% < Slope ≤ 15% | | | | Slope > 15% |
| | | ICE passability class | | | | ICE passability class | | | | ICE passability class | | | | ICE passability class |
| | | 1 | 0.66 | 0.33 | 0 | 1 | 0.66 | 0.33 | 0 | 1 | 0.66 | 0.33 | 0 | 0 |
| 1 | Atlantic salmon (*Salmo salar*)<br>Brown or sea trout [50-100] (*Salmo trutta*) | ≤ 4.0 | ]4.0-9.0] | > 9.0 | - | ≤ 2.4 | ]2.4-4.8] | ]4.8-6.6] | > 6.6 | ≤ 0.9 | ]0.9-2.6] | ]2.6-4.2] | > 4.2 | > 0.0 |
| 2 | Mullets (*Chelon labrosus, Liza ramada*) | ≤ 2.6 | ]2.6-5.0] | ]5.0-9.0] | > 9.0 | ≤ 1.8 | ]1.8-2.8] | ]2.8-4.8] | > 4.8 | ≤ 0.2 | ]0.2-1.2] | ]1.2-2.6] | > 2.6 | > 0.0 |
| 3a | Allis shad (*Alosa alosa*) | ≤ 1.8 | ]1.8-3.2] | ]3.2-6.0] | > 6.0 | ≤ 1.1 | ]1.1-2.2] | ]2.2-3.6] | > 3.6 | - | ≤ 0.6 | ]0.6-1.5] | > 1.5 | > 0.0 |
| 3b<br>3c | Twaite shad (*Alosa fallax fallax*)<br>Sea lamprey (*Petromyzon marinus*) | ≤ 1.0 | ]1.0-2.1] | ]2.1-4.0] | > 4.0 | ≤ 0.5 | ]0.5-1.5] | ]1.5-2.4] | > 2.4 | - | - | ≤ 0.9 | > 0.9 | > 0.0 |
| 4a | Brown or sea trout [25-55] (*Salmo trutta*) | ≤ 1.0 | ]1.0-2.6] | ]2.6-6.0] | > 6.0 | ≤ 0.4 | ]0.4-1.5] | ]1.5-3.0] | > 3.0 | - | - | ≤ 1.0 | > 1.0 | > 0.0 |
| 4b | Brown trout [15-30] (*Salmo trutta*) | ≤ 0.5 | ]0.5-1.0] | ]1.0-1.8] | > 1.8 | - | ≤ 0.4 | ]0.4-0.9] | > 0.9 | - | - | - | > 0.0 | > 0.0 |
| 5 | Asp (*Aspius aspius*)<br>Pike (*Esox lucius*) | ≤ 1.8 | ]1.8-3.2] | ]3.2-6.0] | > 6.0 | | ≤ 1.1 | ]1.1-2.2] | ]2.2-3.6] | > 3.6 | - | ≤ 0.6 | ]0.6-1.5] | > 1.5 |
| 6 | Grayling (*Thymallus thymallus*) | ≤ 1.0 | ]1.0-2.1] | ]2.1-4.0] | > 4.0 | ≤ 0.5 | ]0.5-1.5] | ]1.5-2.4] | > 2.4 | - | - | ≤ 0.9 | > 0.9 | > 0.0 |
| 7a | Barbel (*Barbus barbus*)<br>Chub (*Squalius cephalus*)<br>Nase (*Chondrostoma nasus*) | ≤ 0.5 | ]0.5-1.4] | ]1.4-2.6] | > 2.6 | - | ≤ 0.6 | ]0.6-1.5] | > 1.5 | - | - | - | > 0.0 | > 0.0 |
| 7b | River lamprey (*Lampetra fluviatilis*) | ≤ 0.5 | ]0.5-1.4] | ]1.4-2.6] | > 2.6 | - | ≤ 0.6 | ]0.6-1.5] | > 1.5 | - | - | - | > 0.0 | > 0.0 |
| 8a | Common carp (*Cyprinus carpio*) | - | ≤ 0.8 | ]0.8-1.8] | > 1.8 | - | ≤ 0.2 | ]0.2-0.9] | > 0.9 | - | - | - | > 0.0 | > 0.0 |
| 8b | Common bream (*Abramis brama*)<br>Pikeperch (*Sander lucioperca*) | - | ≤ 0.8 | ]0.8-1.8] | > 1.8 | - | ≤ 0.2 | ]0.2-0.9] | > 0.9 | - | - | - | > 0.0 | > 0.0 |
| 8c | White bream (*Blicca bjoerkna*)<br>Ide (*Leuciscus idus*)<br>Burbot (*Lota lota*)<br>Perch (*Perca fluviatilis*)<br>Tench (*Tinca tinca*) | - | ≤ 0.8 | ]0.8-1.8] | > 1.8 | - | ≤ 0.2 | ]0.2-0.9] | > 0.9 | - | - | - | > 0.0 | > 0.0 |
| 8d | Daces (*Leuciscus spp.* except *Idus*) | - | ≤ 0.8 | ]0.8-1.8] | > 1.8 | - | ≤ 0.2 | ]0.2-0.9] | > 0.9 | - | - | - | > 0.0 | > 0.0 |
| 9a | Bleak (*Alburnus alburnus*)<br>Schneider (*Alburnoides bipunctatus*)<br>Mediterranean barbel (*Barbus meridionalis*)<br>Blageon (*Telestes souffia*)<br>Crucian carp (*Carassius carassius*)<br>Prussian carp (*Carassius gibelio*)<br>Roach (*Rutilus rutilus*)<br>Rudd (*Scardinius erythrophthalmus*)<br>SW European nase (*Parachondrostoma toxostoma*) | - | ≤ 0.3 | ]0.3-1.0] | > 1.0 | - | - | ≤ 0.4 | > 0.4 | - | - | - | > 0.0 | > 0.0 |
| 9b | Streber (*Zingel asper*)<br>Bullheads (*Cottus spp.*)<br>Gudgeons (*Gobio spp.*)<br>Ruffe (*Gymnocephalus cernuus*)<br>Brook lamprey (*Lampetra planeri*)<br>Stone loach ( *Barbatula barbatula*)<br>Spined loach (*Cobitis taenia*) | | | | | | | | | | | | | |
| 10 | Sunbleak (*Leucaspius delineatus*)<br>Bitterling (*Rhodeus amarus*)<br>Threespine stickleback (*Gasterosteus gymnurus*)<br>Smoothtail ninespine stickleback (*Pungitius laevis*)<br>Minnows (*Phoxinus spp.*) | - | - | - | > 0.0 | - | - | - | > 0.0 | - | - | - | > 0.0 | > 0.0 |
| 11a | European eel [yellow eel] *(Anguilla anguilla)* | - | ≤ 0.3 | ]0.3-1.0] | > 1.0 | - | - | ≤ 0.4 | > 0.4 | - | - | - | > 0.0 | > 0.0 |
| 11b | European eel [glass eel] *(Anguilla anguilla)* | - | - | - | - | - | - | - | - | - | - | - | - | |

*(*) The values indicated for eels correspond to the passability classes set when the analysis takes into account only the swimming capabilities of the species. In cases where the obstacle includes a crawling zone, the assessment must also use the special tables for crawling (see the section on eels).*

## ■ Decision tree

The steps below should be followed to determine the ICE passability class of an obstacle (see Figure 79).

### *1. Analysis of the minimum water depth in the passageway*

If $h < h_{min\ rock}$, under the given hydrological conditions the obstacle may be considered a total barrier in the sense of the ICE protocol (ICE class = 0). However, the analysis should be pursued (go to Step 2) in order to determine the passability class in the event other hydrological conditions provide enough water depth. Depending on the score of the subsequent analysis, it will be possible to decide whether or not to return to the obstacle for measurements under other hydrological conditions.

### *2. Analysis of steps*

If there are no steps or if the steps are negligible ($h \geq 2a$), go directly to Step 3.

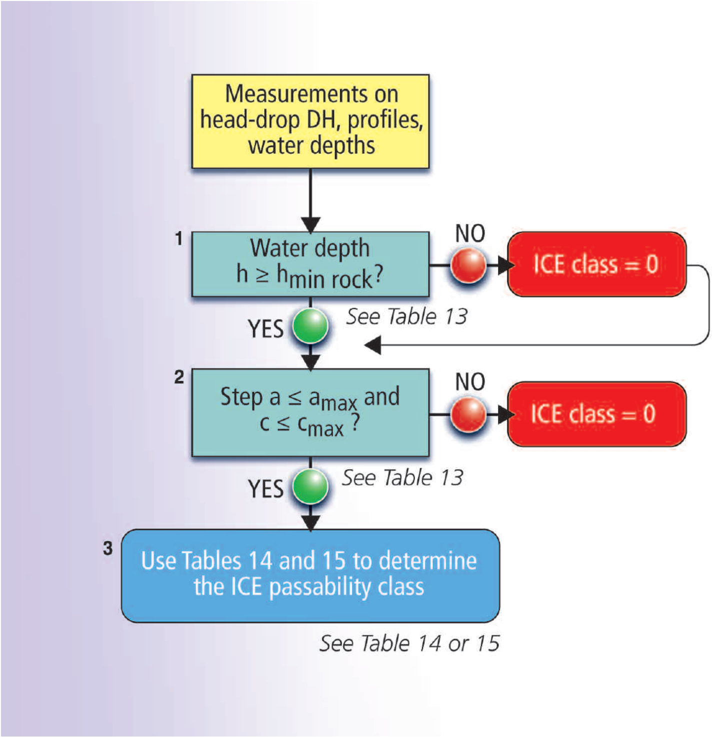
If the dimensions (a and c) of a single step exceed the maximum values $a_{max}$ and $c_{max}$ listed in Table 13, the obstacle may be considered a total barrier (ICE class = 0).

If the dimensions (a and c) of all steps are lower than the threshold values, go to Step 3.

### *3. Analysis of the head-drop DH as a function of the slope*

On the basis of the head-drop DH and of the slope, use Table 14 or 15 to determine the ICE passability class of the structure.

Figure 79




*Decision tree to determine ICE passability classes for rock weirs.*

# Moving parts of an obstacle

## Overflows

The difficulty of passing gates or spillway gates (see Figure 80) is not significantly different than that of passing vertical obstacles.

**That is why obstacles where overflows exist should be assessed in the same manner as vertical obstacles** (see the section on vertical and subvertical obstacles (slope >150%)).

In order to accurately determine the passability of the structure, in-depth knowledge on gate management is required.

Figure 80


a © Burgun - Onema
b © Richard - Onema

*Flows over the moving parts (gates) of weirs. (a) Weir with spillway gates. (b) Weir comprising a series of lift gates.*

# Underflows

## Passability criteria

At some obstacles, notably weirs and dams equipped with gates (vertical or inclined lift gates, radial gates, etc.), the water may flow in part or in whole under the gates. These flows may represent potential passageways for fish.

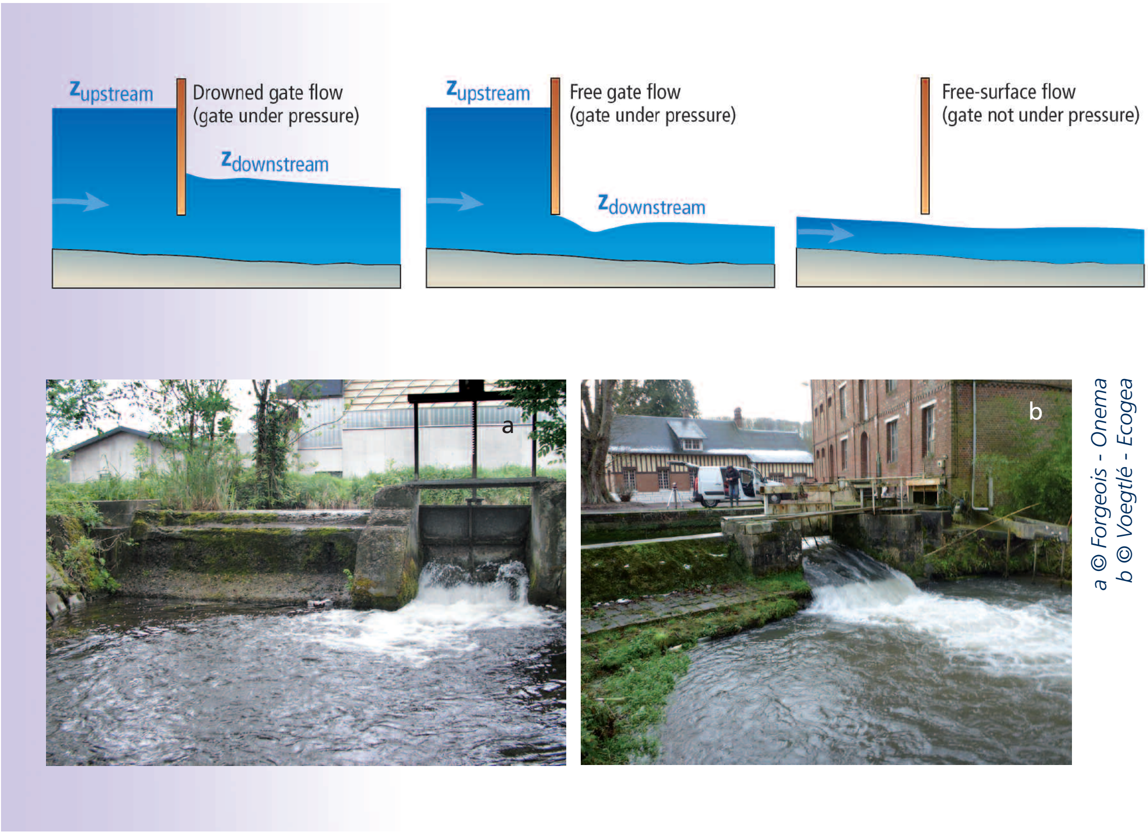
Even though the flow velocities are very often far greater than the swimming capabilities of fish, it is nonetheless worthwhile to acquire the data required to determine the passability of these gates by the various groups of species. This information is even more important when a structure is made up primarily of gates.

### ■ The different types of flows under gates

**If the gate is under pressure,** the flow is similar to that through an orifice, i.e. the opening is completely filled (see Figure 81a).

**If the gate is not under pressure** (see Figure 81b), i.e. the water level upstream of the gate ($Z_{upstream}$) is lower than the underside of the gate, the flow is not accelerated and contracted as is the case for a gate under pressure. **The result is a free-surface flow and the passability assessment is identical to that for an inclined weir.**

Figure 81




*Diagrams and examples of gates under pressure and not under pressure. (a) Photo of a gate under pressure, (b) Photo of a free-surface flow (gate not under pressure).*

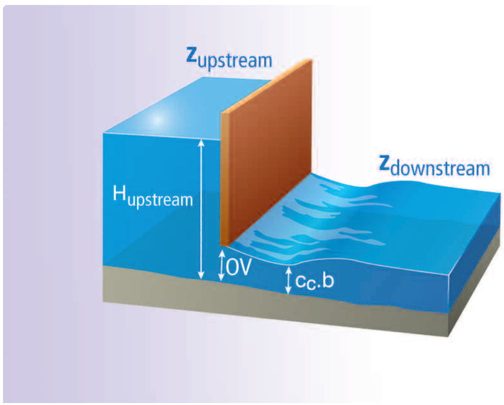
## ■ Drowned and free gate flows

### *Free gate flow*

Generally speaking, for a free gate flow (see Figure 82), the water level downstream of the gate is, on the whole, lower than the underside of the gate. The jet created by the flow passing through the orifice with a cross-sectional area S is accelerated until it reaches a contracted cross-sectional area Sc, where the flow velocity is at its maximum and may be roughly calculated as:

$$V_{max} = \sqrt{2 \, . \, g \, . \, H_{upstream}}$$

Figure 82




Where
$H_{upstream}$ : height of water upstream of the gate
**OV** : gate opening
$c_c$ : contraction coefficient

*Parameters used to calculate a free gate flow.*

For the ICE protocol, the maximum velocity of the jet must be determined in order to compare it to the swimming capabilities of the given species or group of species.

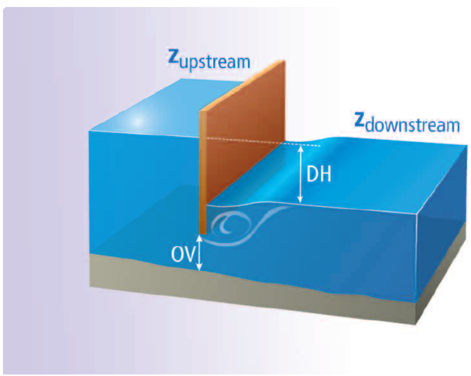
### *Drowned gate flow*

On the other hand, for a drowned gate flow (see Figure 83), the water level downstream of the gate is higher than the underside of the gate. In this case, the downstream level influences the upstream flow and the upstream and downstream water levels (or more precisely the difference in the water levels upstream and downstream of the gate) must be taken into account when assessing the flow conditions at the gate.

The average velocity of the flow at the opening may be roughly calculated as:

$$V_{max} = \sqrt{2 \, . \, g \, . \, DH}$$

Figure 83




Where
$DH = Z_{upstream} - Z_{downstream}$ : difference in the water levels upstream and downstream of the gate
**OV** : gate opening

*Parameters used to calculate a drowned gate flow.*

### ■ Definition of passability classes

By comparing the flow velocities $V_{max}$ with the swimming capabilities of the various species or groups of species (maximum swimming speeds $U_{max}$ for the selected size class $Lp_{min}$, $Lp_{avg}$ et $Lp_{max}$), it is possible to determine the passability class for passage under gates or through orifices, as a function of the head-drop DH (drowned gate) or the height of the water behind the gate $H_{upstream}$ (free gate flow).

However, the above is a simplified approach because even if the parameters (DH and $H_{upstream}$) selected to gauge the passability of a structure are the main factors determining the hydraulic conditions under a gate, other factors such as the thickness of the gate, its shape and the roughness of the glacis can also influence the conditions.

As long as the depth of water in the contracted section and the gate opening are sufficient, passability is determined as follows:

- if the head-drop DH (or $H_{upstream}$ for free gate flow) results in flow velocities V less than the maximum speed $U_{max}$ assigned to the minimum fish size $Lp_{min}$ for the given species, the obstacle may be considered a **low-impact passable barrier (ICE class = 1)**;
- if the head-drop DH (or $H_{upstream}$ for free gate flow) results in flow velocities V that are between the maximum speeds $U_{max}$ assigned to the minimum $Lp_{min}$ and average $Lp_{avg}$ fish sizes for the given species, the obstacle may be considered a **medium-impact partial barrier (ICE class = 0.66)**;
- if the head-drop DH (or $H_{upstream}$ for free gate flow) results in flow velocities V that are between the maximum speeds $U_{max}$ assigned to the average $Lp_{avg}$ and maximum $Lp_{max}$ fish sizes for the given species, the obstacle may be considered a **high-impact partial barrier (ICE class = 0.33)**;
- if the head-drop DH (or $H_{upstream}$ for free gate flow) results in flow velocities V greater than the maximum speed $U_{max}$ assigned to the maximum fish size $Lp_{max}$ for the given species, the obstacle may be considered a **total barrier (ICE class = 0).**

## Size of opening

The flow depth and the minimum height of the opening enabling fish to use their full swimming capabilities and ensuring passage under a gate depend directly on the size of the fish and its morphology (form factor).

For a "standard" weir, the minimum water depth $h_{min}$ required to enable a fish to swim was set at approximately 1.5 times the average body depth of fish in the given species (see the discussion on minimum water depths in the section on the passage capabilities of fish).

However, it is often difficult to measure water depths at the point of contraction given the high water velocities generally observed there. To take into account the contraction in the water level, the proposed solution is to set a minimum water depth and a **minimum height of the gate opening ($OV_{min}$) corresponding to approximately two times the water depths and fish body depths calculated for the various species.**

For example, the minimum gate opening $OV_{min}$ is approximately 40 cm for large, migratory salmonids and approximately 10 cm for small brown trout (Lp < 30 cm).

## Determining passability classes

### ■ Threshold values used for the decision tree

Table 16 lists the various threshold values used to determine passability under a gate or through an orifice.

The table is accompanied by a decision tree (see Figure 84) that can be used to determine the ICE passability class.

### ■ Decision tree

Proceed step by step (see Figure 84) to determine the passability class.

***1. Compare the head-drop DH (for a drowned gate) or $H_{upstream}$ (for free gate flow) with $DH_{extreme}$***

If $DH \geq DH_{extreme}$ (for a drowned gate) or if $H_{upstream} \geq DH_{extreme}$ (for free gate flow) (see Table 16), the obstacle may be considered a total barrier in the sense of the ICE protocol (ICE class = 0).

If $DH < DH_{extreme}$, go to Step 2.

***2. Analysis of the gate opening***

If the gate opening or the height of the orifice $OV \geq OV_{min}$ (see Table 16), the height of the passage under the gate and the depth at the point of contraction are sufficient. Go to Step 3.

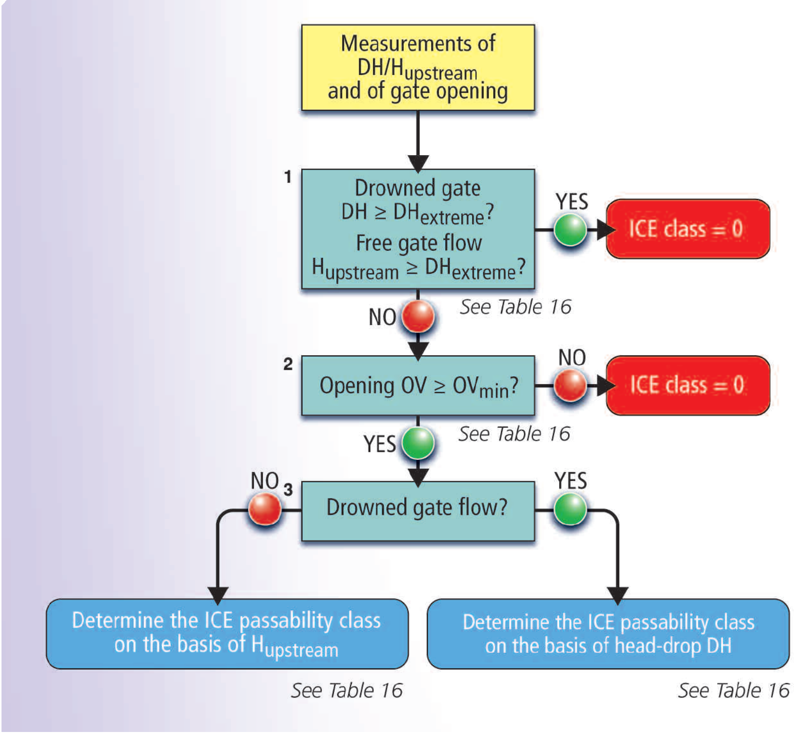
If $OV < OV_{min}$, the obstacle may be considered a total barrier under the current configuration and the current hydrological conditions (ICE class = 0).

***3. Analysis of the head-drop (drowned gate) or of $H_{upstream}$ (free gate flow)***

For a drowned gate, determine the passability class as a function of the head-drop DH (see Table 16).

For a free gate flow, determine the passability class as a function of $H_{upstream}$ (see Table 16).

Figure 84




*Decision tree to determine ICE passability classes for passage under gates or through bottom orifices.*

**Tableau 16** *Summary of the basic criteria required to determine ICE passability classes for passage under gates or through bottom orifices using the decision tree in Figure 84.*

| ICE species group | Species | Minimum water depth ($h_{min}$) required for swimming | Minimum gate opening ($Ov_{min}$) | Threshold values for passage under gates, for head-drop DH (drowned flow) or for $H_{upstream}$ (free gate flow) (m) — ICE passability class 1 | 0.66 | 0.33 | 0 | DH extreme |
|---|---|---|---|---|---|---|---|---|
| 1 | Atlantic salmon (*Salmo salar*)<br>Brown or sea trout [50-100] (*Salmo trutta*) | 0.20 m | 0.40 m | ≤ 1.00 | ]1.00 - 1.50] | ]1.50 - 2.20] | >2.20 | 3.00 m |
| 2 | Mullets (*Chelon labrosus, Liza ramada*) | 0.10 m | 0.20 m | ≤ 0.80 | ]0.80 - 1.10] | ]1.10 - 1.50] | >1.50 | 2.50 m |
| 3a | Allis shad (*Alosa alosa*) | 0.15 m | 0.30 m | ≤ 0.60 | ]0.60 - 0.90] | ]0.90 - 1.30] | >1.30 | 2.00 m |
| 3b | Twaite shad (*Alosa fallax fallax*) | 0.10 m | 0.20 m | | | | | |
| 3c | Sea lamprey (*Petromyzon marinus*) | | | | | | | |
| 4a | Brown or sea trout [25-55] (*Salmo trutta*) | 0.10 m | 0.20 m | ≤ 0.45 | ]0.45 - 0.80] | ]0.80 - 1.30] | >1.30 | 2.00 m |
| 4b | Brown trout [15-30] (*Salmo trutta*) | 0.05 m | 0.10 m | ≤ 0.30 | ]0.30 - 0.50] | ]0.50 - 0.60] | >0.60 | 1.50 m |
| 5 | Asp (*Aspius aspius*)<br>Pike (*Esox lucius*) | 0.15 m | 0.30 m | ≤ 0.60 | ]0.60 - 0.90] | ]0.90 - 1.30] | >1.30 | 2.00 m |
| 6 | Grayling (*Thymallus thymallus*) | 0.10 m | 0.20 m | ≤ 0.45 | ]0.45 - 0.70] | ]0.70 - 1.00] | >1.00 | 1.50 m |
| 7a | Barbel (*Barbus barbus*)<br>Chub (*Squalius cephalus*)<br>Nase (*Chondrostoma nasus*) | 0.10 m | 0.20 m | ≤ 0.30 | ]0.30 - 0.50] | ]0.50 - 0.80] | >0.80 | 1.50 m |
| 7b | River lamprey (*Lampetra fluviatilis*) | 0.05 m | 0.10 m | | | | | |
| 8a | Common carp (*Cyprinus carpio*) | 0.25 m | 0.50 m | ≤ 0.20 | ]0.20 - 0.40] | ]0.40 - 0.60] | > 0.60 | 1.50 m |
| 8b | Common bream (*Abramis brama*)<br>Pikeperch (*Sander lucioperca*) | 0.15 m | 0.30 m | | | | | |
| 8c | White bream (*Blicca bjoerkna*)<br>Ide (*Leuciscus idus*)<br>Burbot (*Lota lota*)<br>Perch (*Perca fluviatilis*)<br>Tench (*Tinca tinca*) | 0.10 m | 0.20 m | | | | | |
| 8d | Daces (*Leuciscus spp.* except *Idus*) | 0.05 m | 0.10 m | | | | | |
| 9a | Bleak (*Alburnus alburnus*)<br>Schneider (*Alburnoides bipunctatus*)<br>Mediterranean barbel (*Barbus meridionalis*)<br>Blageon (*Telestes souffia*)<br>Crucian carp (*Carassius carassius*)<br>Prussian carp (*Carassius gibelio*)<br>Roach (*Rutilus rutilus*)<br>Rudd (*Scardinius erythrophthalmus*)<br>SW European nase (*Parachondrostoma toxostoma*) | 0.05 m | 0.10 m | ≤ 0.10 | ]0.10 - 0.25] | ]0.25 - 0.45] | > 0.45 | 1.00 m |
| 9b | Streber (*Zingel asper*)<br>Bullheads (*Cottus spp.*)<br>Gudgeons (*Gobio spp.*)<br>Ruffe (*Gymnocephalus cernuus*)<br>Brook lamprey (*Lampetra planeri*)<br>Stone loach ( *Barbatula barbatula*)<br>Spined loach (*Cobitis taenia*) | | | | | | | |
| 10 | Sunbleak (*Leucaspius delineatus*)<br>Bitterling (*Rhodeus amarus*)<br>Threespine stickleback (*Gasterosteus gymnurus*)<br>Smoothtail ninespine stickleback (*Pungitius laevis*)<br>Minnows (*Phoxinus spp.*) | 0.05 m | 0.10 m | ≤ 0.05 | ]0.05 - 0.10] | ]0.10 - 0.20] | > 0.20 | 1.00 m |
| 11a | European eel [yellow eel] *(Anguilla anguilla)* | 0.02 m | 0.04 m | ≤ 0.10 | ]0.10 - 0.25] | ]0.25 - 0.45] | > 0.45 | 1.00 m |
| 11b | European eel [glass eel] *(Anguilla anguilla)* | - | - | - | - | - | - | |

*(*) The values indicated for eels correspond to the passability classes set when the analysis takes into account only the swimming capabilities of the species. In cases where the obstacle includes a crawling zone, the assessment must also use the special tables for crawling (see the section on eels).*

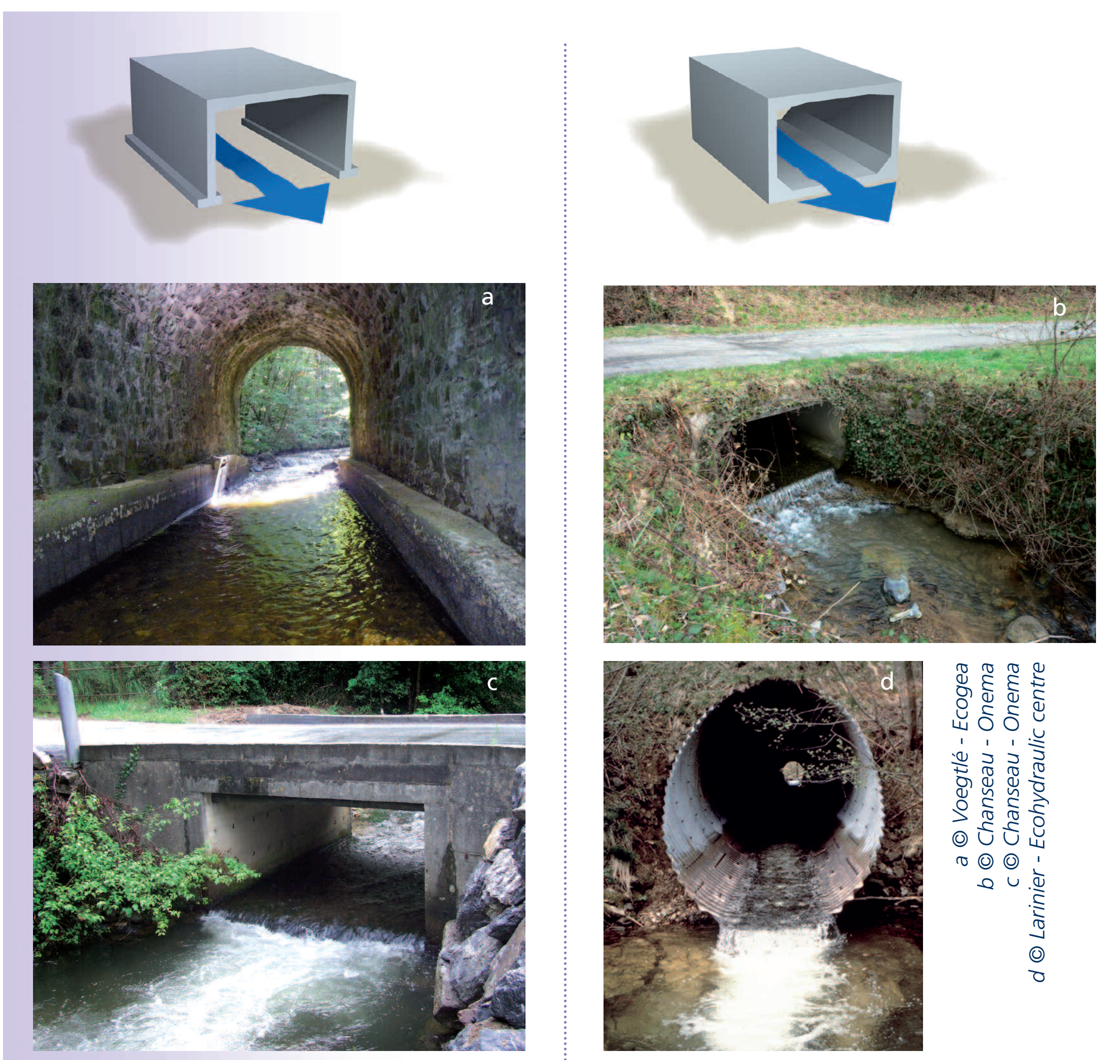
# Road/rail structures

## The different types of structures

This section deals with passability assessments on road, highway and rail structures (see Figure 85), namely open-bottom frames, closed-bottom frames, culverts, arches and certain types of similar structures (bridge aprons, fords, etc.).

Their existence in the natural environment generally modifies the substrate (notably the case for closed-bottom frames), lighting conditions and the flow regime.

**Figure 85**




a © Voegtlé - Ecogea
b © Chanseau - Onema
c © Chanseau - Onema
d © Larinier - Ecohydraulic centre

*Diagrams and photos of open-bottom and closed-bottom structures. (a, c) Open-bottom passages, (b, d) closed-bottom passages.*

# The main causes limiting passage

Structures under roads, highways and train lines may constitute major obstacles to the upstream migration of fish.

The main factors likely to limit the passage of fish are discussed below.

### ■ Excessive flow velocities inside structures

When the slope of the structure (culvert, crossing, etc.) is fairly high, the flow accelerates suddenly at the head of the structure. Given the low roughness of the structure surface, flows can rapidly reach high velocities, even to the point of becoming a torrent (see Figure 86).

The uniform water velocities preclude any rest zones, thus obliging the fish to clear the obstacle in a single shot. The necessary effort may significantly exceed the swimming capabilities of fish and particularly their endurance.

Figure 86


a © Voegtlé - Ecogea
b © Baudoin - Onema

*Examples of high flow velocities in culverts.*

### ■ Insufficient water depths

The smoothness of the structure and a pronounced slope can result in very low water depths, notably during low-flow periods, which can make swimming and further progress upstream very difficult or even impossible for fish (see Figure 87).

In a fairly rare number of cases, the structure may be oversized with respect to the width of the river at the transit point. If the bottom of the structure is flat, i.e. without a "talweg" or channel, the water depth may drop significantly, even outside of low-flow periods.

Figure 87


a © Voegtlé - Ecogea
b © Onema

*Examples of very low water depths on the aprons of road bridges.*

## ■ Falls or steps inside or at the downstream end of structures

Fish may also be blocked at the downstream end of structures by waterfalls (see Figure 88). This very frequent situation is generally due to incorrect installation of the structure with respect to the long profile of the river. It may, however, also be due to a drop in the downstream riverbed if no preventive measures (bed control devices) were taken to stabilise the bed.

The angle of incidence of the jet at the outlet is a function of the flow velocity inside the structure and can increase the difficulty of overcoming the downstream fall.

In a small number of cases, there may be a step inside the structure. This type of problem is often caused by poor adjustment of the various components making up the structure. The low water depths that are common make passage particularly difficult, even if the step is not particularly high.

**Figure 88**


a © Burgun - Onema
b, d © Chanseau - Onema
c © Voegtlé - Ecogea

*Examples of falls downstream of road structures.*

## ■ Poor positioning at the head of the structure

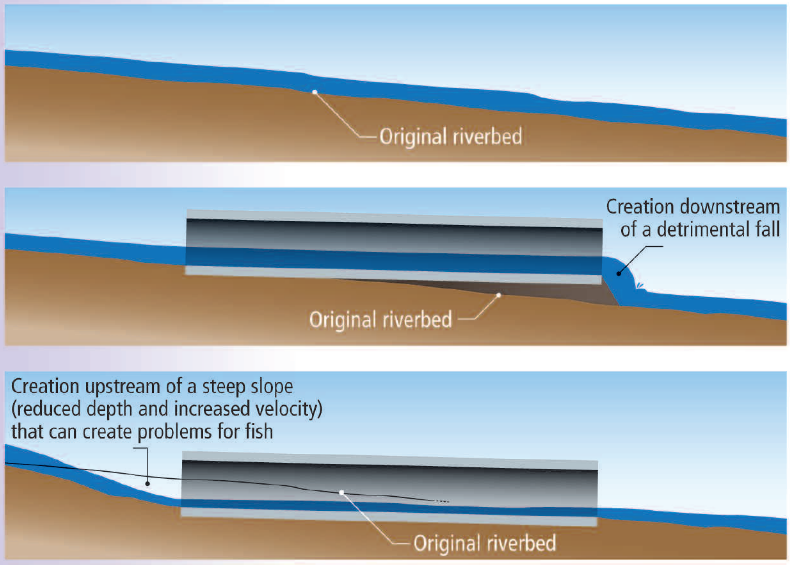
Poor positioning at the head of the structure may, in some cases, result in the creation just upstream in the riverbed of a zone characterised by high velocities and low depths that is difficult for fish to overcome (see Figures 89a and 89b).

**Figure 89a**

© Voegtlé - Ecogea

*Example of high flow velocities created upstream of culverts.*

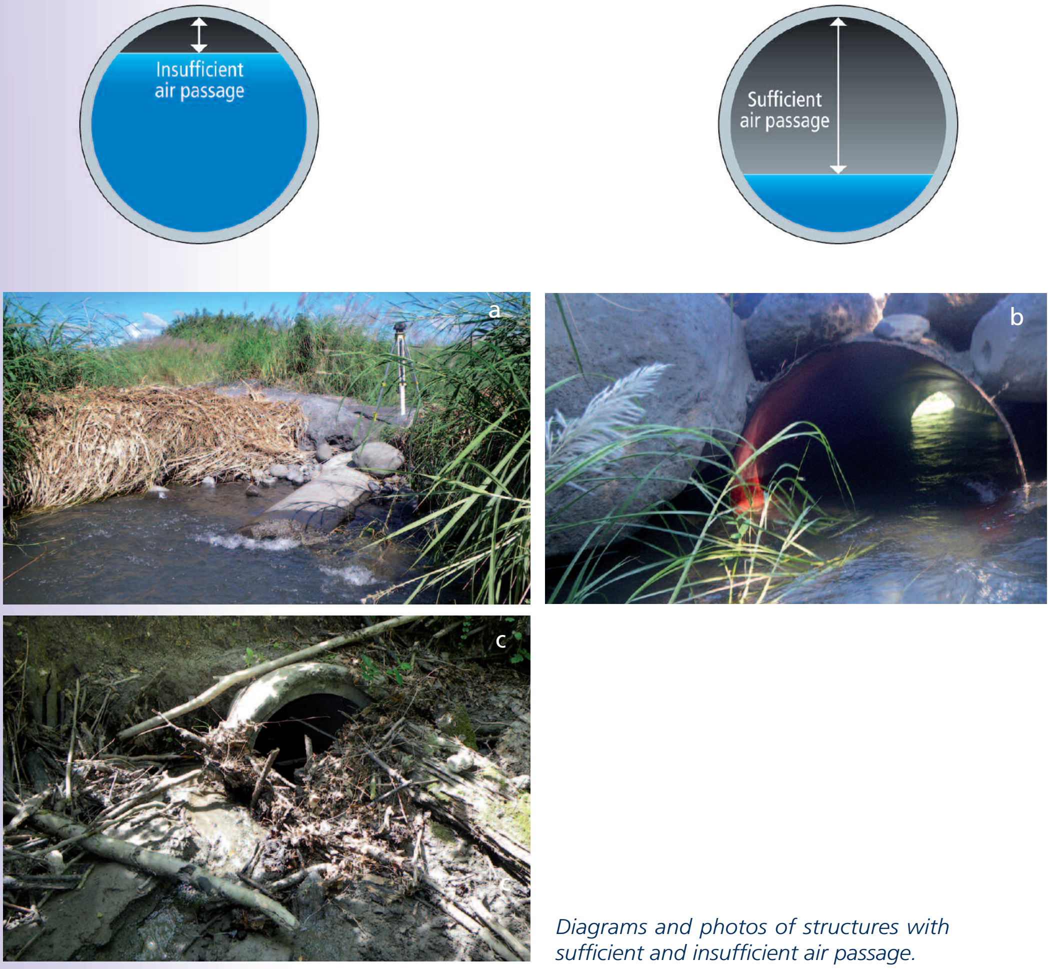
Figure 89 b




*Examples of the problems created by poor longitudinal positioning of a structure.*

■ **An accumulation of debris at the entry or inside the structure** is a further cause of obstacles for migratory fish. This often occurs when the structure is too small compared to the width of the river (resulting in a major reduction in the available passage width) and when the air passage (between the water line and the top of the structure) is not sufficient (see Figure 90ac).

Figure 90




a, b © Voegtle - Ecogea
c © Burgun - Onema

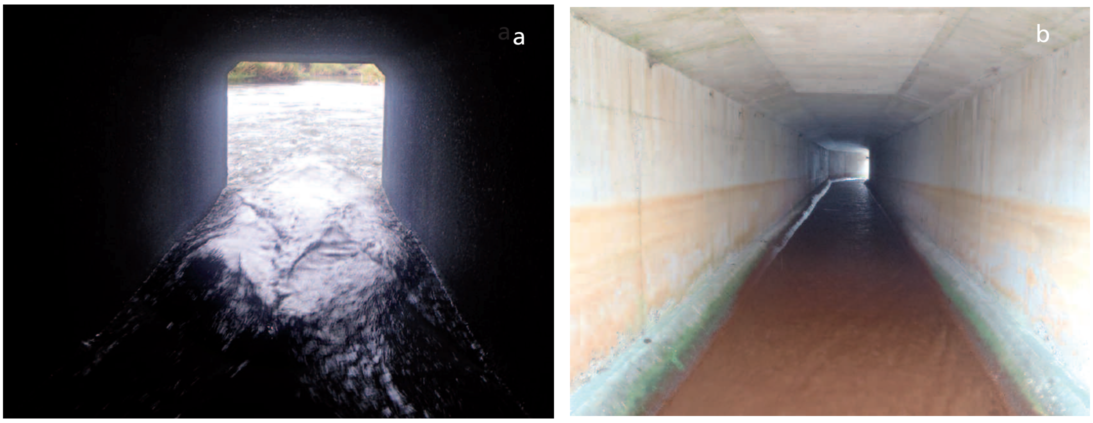
*Diagrams and photos of structures with sufficient and insufficient air passage.*

■ **Abrupt changes in light.** When there is an abrupt change in the intensity of light at the entry of a culvert (see Figure 91), some species, particularly those under way during the day, may hesitate to enter or to pursue their progression in the structure.

**However, given that the available knowledge on this topic is very incomplete, this type of disturbance is not taken into account in the ICE protocol.**

For more information, readers should consult the reports published by the Ecology ministry in 2007 and 2008 (Egis Environnement-Hydrosphère, 2007 and 2008).

Figure 91




a © Voegtlé - Ecogea
b © Chanseau - Onema

*(a) An abrupt change in luminosity can inhibit passage of the structure during the day, (b) in a structure with a larger cross-sectional area, the change in luminosity is more gradual.*

# Assessment procedure

The assessment of passability consists of identifying and determining the impact of the main factors likely to limit the movement of the various species or groups of species.

The most important factors are the velocity/distance parameter, followed by the water depth and the presence of falls/steps in or at the outlet of the structure.

## Assessing the distance a fish can cover against a given flow velocity

Contrary to weirs, the slopes of these structures are generally not steep (a few percent at most), however their length may be considerable.

The maximum distance that a given species can overcome is a function of the flow velocity in the structure, which itself depends directly on the structure shape, roughness, slope and the entering discharge.

The passability assessment is carried out in a manner similar to that for weirs with inclined downstream faces. The objective is to determine the maximum passable distance for a fish having a swimming speed U and the corresponding endurance $t_U$, confronted with an average flow velocity V.

In structures having a relatively steep slope (a few percent), fish, particularly small species, are obliged to use their maximum speed $U_{max}$.

When slopes are not as steep, fish may not be required to call on their maximum swimming speed in order to overcome the obstacle. On the condition that the flow velocity remains significantly less than the maximum speed, fish can swim more or less at their cruising speed. In this case, it is the length of the structure that may become the limiting factor.

### ■ Swimming rhythm of the fish (from cruising to maximum speed)

The maximum muscular power corresponding to anaerobic glycolysis ($P_{ana}$) produced by a fish is proportional to its maximum speed $U_{max}$:

$$P_{ana} = k\, U_{max}^3$$

The maximum muscular power corresponding to aerobic glycolysis ($P_{aer}$) is proportional to the upper limit of its cruising speed $U_{cr}$ prior to the shift to anaerobic conditions:

$$P_{aer} = k\, U_{cr}^3$$

According to Bell (1981), the muscular energy (power x time) under anaerobic conditions ($W_{ana}$) available during swimming at maximum speed is:

$$W_{ana} = P_{ana} \cdot t_{Umax} = k.U_{max}^3 \cdot t_{Umax}$$

During swimming at speed U under aerobic-anaerobic conditions, i.e. when U is between $U_{max}$ and $U_{cr}$, the muscular power expended is:

$$P = k\,U^3$$

The expended anaerobic power can therefore be written as:

$$P_{ana} = P - P_{aer} = k\,(U^3 - U_{cr}^3)$$

The maximum available anaerobic energy provided by the muscles during swimming at speed U can be written as:

$$W_{ana} = t_U\,k\,(U^3 - U_{cr}^3)$$

As a result:

$$W_{ana} = t_U\,k\,(U^3 - U_{cr}^{\ 3}) = k.U_{max}^3 \cdot t_{Umax}$$

And:

$$t_U = U_{max}^3 \cdot t_{Umax} / (U^3 - U_{cr}^3)$$

The maximum distance that the fish can cover while swimming at speed U against a flow with a velocity V is therefore:

$$D = (t_{Umax}\,U_{max}^3)(U-V)/(U^3 - U_{cr}^3)$$

According to Videler (1993), the cruising speed of a fish is roughly equivalent to one-third of its maximum speed ($U_{max} \approx 3\,U_{cr}$). The maximum distance D that the fish can cover while swimming at speed U can also be written as:

$$D = 27\,t_{Umax}\,U_{cr}\,(U/U_{cr} - V/U_{cr})/\,((U/U_{cr})^3 - 1)$$

The maximum distance is covered when $\delta D/\delta U = 0$, i.e. when:

$$U/U_{cr} = 1 + 1{,}913\,(V/U_{cr} - 1)^{0.72}$$

For a given flow velocity, the above equation calculates the swimming speed resulting in the greatest distance covered.

An initial maximum exists when $V < U_{cr}$ and $U = U_{cr}$, in which case distance D is obviously infinite.

If $V > 2/3\,U_{max}$, the optimum swimming speed is close to $U_{max}$ given that $U > 0.95\,U_{max}$.

**The best solution for a fish is therefore to swim at its cruising speed $U_{cr}$ as long as the flow velocity does not exceed the cruising speed.**

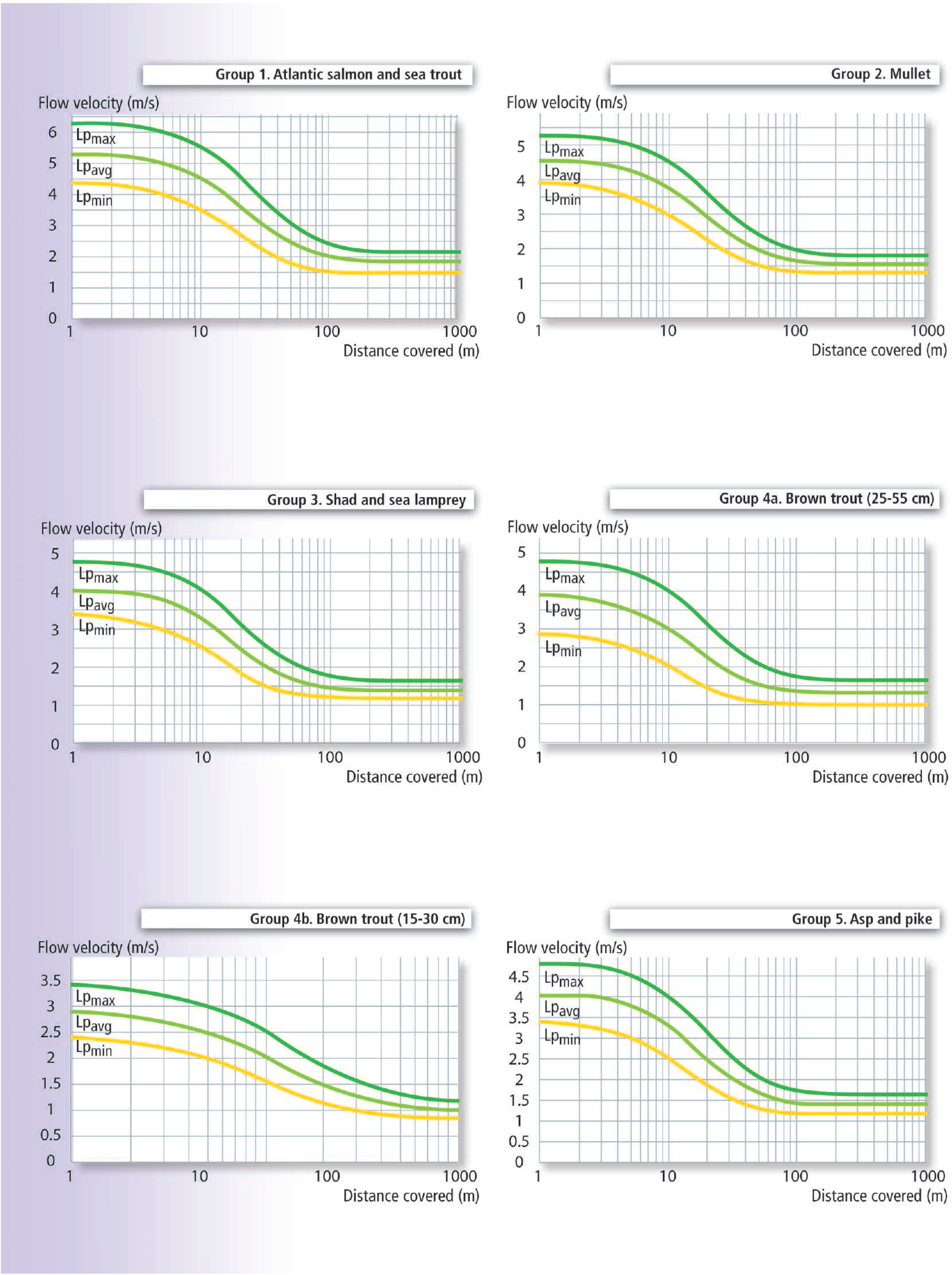
**When the flow velocity exceeds two-thirds of the maximum swimming speed, the distance covered is greatest when the fish swims at its maximum speed.**

## ■ Assessing the maximum distance a fish can cover against a given flow velocity

For the various species groups, the distances covered as a function of the flow velocity are shown on a semi-log plot, assuming that fish adjust their speed to the flow velocity in order to obtain optimum conditions (see Figures 92 and 93).

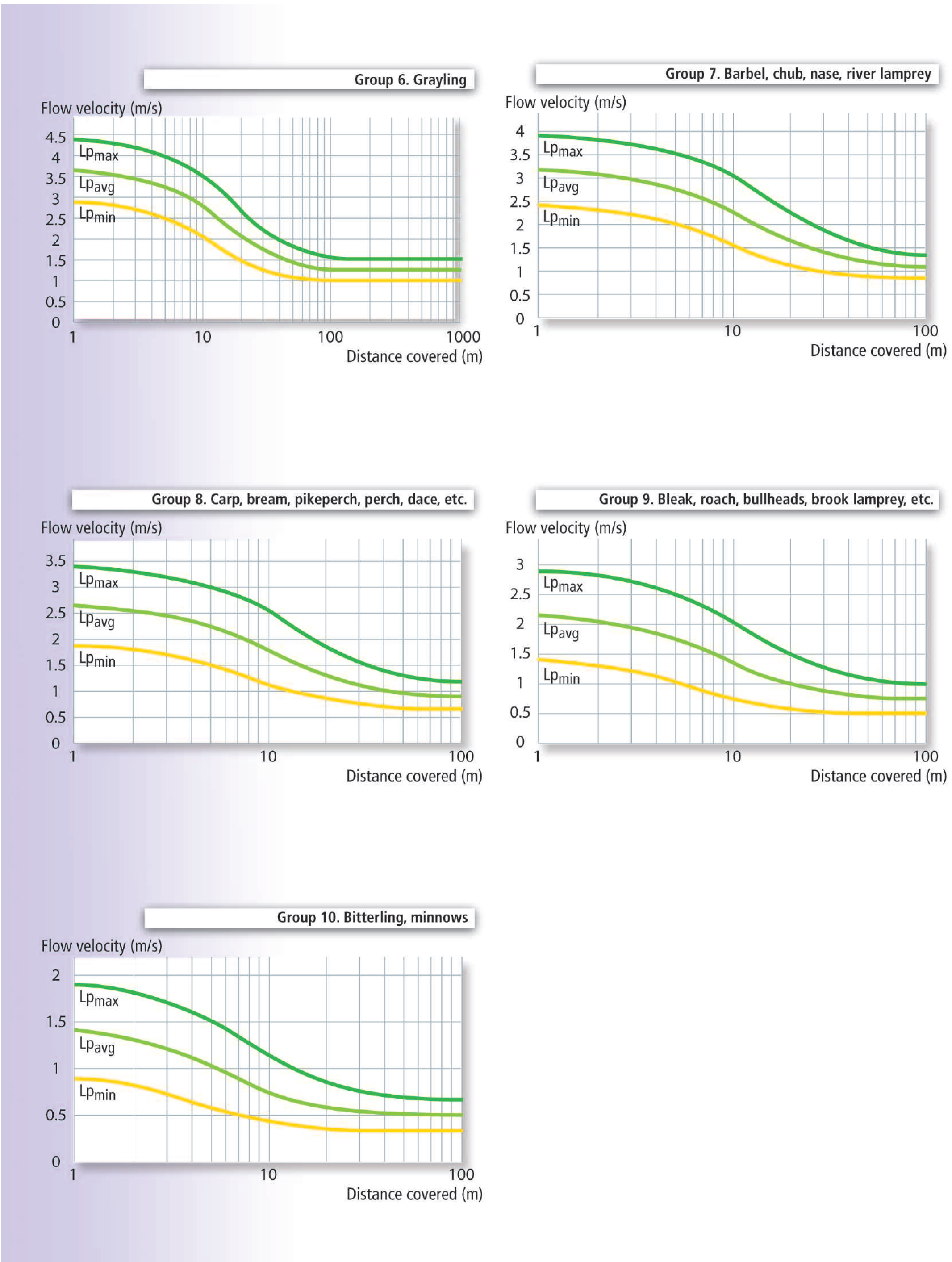
For each species or group of species, the dark green, light green and yellow lines correspond to the largest ($Lp_{max}$), average ($Lp_{avg}$) and smallest ($Lp_{min}$) fish, respectively.

**Figure 92**




*Distance covered as a function of the flow velocity for the species or groups of species number 1 to 5.*

Figure 93




*Distance covered as a function of the flow velocity for the species or groups of species number 6 to 10.*

## Definition of passability classes

For weirs with inclined downstream faces (see the section on weirs with inclined downstream faces (slope ≤150%)), it was possible to determine a passability class (0, 0.33, 0.66, 1) for each species or group of species as a function of the head-drop DH.

For road structures, hydraulic analysis has shown that beyond a certain steepness and a certain distance (the precise values depend on the species or group of species), all structures limit passage to some degree. However, up to those threshold values for the slope and length, it is impossible to determine the passability of a structure (ICE class = NC). In this case, it is necessary to determine the flow velocities in the structure, either using hydraulic modelling software (FishXing, Hec Ras or similar software) or simply by measuring the flow velocities. Measurements are not always easy to carry out, particularly if the structure is too small to enable entry.

The curves in Figures 92 and 93 set the limits between passability classes (0, 0.33, 0.66, 1). To determine the maximum passable slopes for a given length and for a species or group of species, the maximum flow velocities $V_{max}$ enabling passage of the structure were drawn from the graphs presented above.

The slopes producing the maximum flow velocities, taking into account standard roughness values (Manning n=0.01 to 0.03) and unit discharges between 0.05 and 2 $m^3/s/m$, were then calculated.

Statistical analysis was then carried out on the slopes, checking to make sure that the water depths were greater than the minimum depths required by the given species.

This analysis was run for structures having lengths L< 20 m, 20 m < L < 50 m and 50 m < L < 100 m.

## Downstream fall

A large number of culverts and road structures have a fall at their downstream end (see Figure 94) that can significantly block the passage of fish.

The downstream fall should be analysed to determine its passability using the same method as that for weirs having a vertical downstream face. An initial passability class for the fall can be determined using the decision tree and the corresponding table presented in the section on vertical and subvertical obstacles (slope >150%).

To take into account the effect of the fall, which can be considerable in certain cases, the same method as that for complex or mixed structures (see the section on complex structures) or for inclined weirs having a downstream fall (see the section on weirs with inclined downstream faces (slope ≤150%)) was adopted. Consequently, the overall ICE passability class determined for the structure should be downgraded or the ICE class for the most difficult part (downstream fall or culvert) should be adopted.

Figure 94

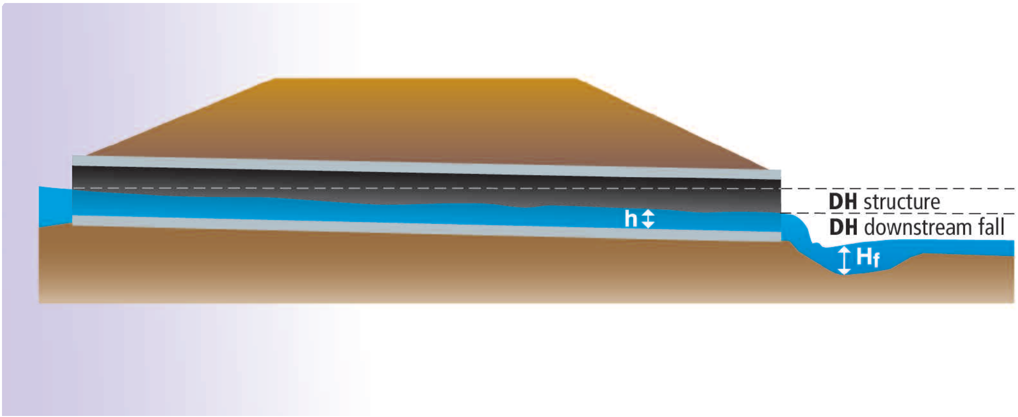



*Diagram showing a road structure with a downstream fall.*

Table 17 shows the passability class for the overall structure as a function of the classes for the two parts (road structure and downstream fall).

Tableau 17

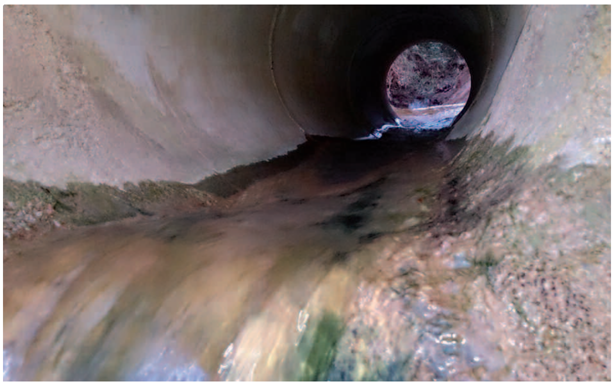
*Table to determine the overall ICE class for road structures having a downstream fall.*

| ICE class of the culvert | ICE class of the downstream fall | | | |
|---|---|---|---|---|
| | 0 | 0.33 | 0.66 | 1 |
| 0 | 0 | 0 | 0 | 0 |
| 0.33 | 0 | 0 | 0.33 | 0.33 |
| 0.66 | 0 | 0.33 | 0.33 | 0.66 |
| 1 | 0 | 0.33 | 0.66 | 1 |
| NC | 0 | NC (≤ 0.33) | NC (≤ 0.66) | NC |

## Step in the structure

Similar to weirs, a step in the structure can substantially degrade the passage conditions for fish, particularly under low-flow conditions. The type of flow caused by the step(s) determines the impact on passability. Generally, the step is caused by two parts of the structure (round or box culverts) becoming disjointed (see Figure 95).

Figure 95



© Baudoin - Onema

*Example of a poorly installed culvert in which the disjointed elements create steps.*

Fish can clear a step only by swimming, i.e. when the step has been "erased" by a skimming flow.

The same criteria as for "standard" weirs should be used. They deal notably with the relative dimensions of the step with respect to the average size $Lp_{avg}$ of the given species or group of species (see the section on steps in weirs with inclined downstream faces (slope ≤150%)).

## Structures submerged upstream and/or downstream

Depending on the size of the structure with respect to the discharge of the river, the inlet may find itself completely submerged by the upstream water level. In this case, the structure functions as a bottom orifice or a pipe, where the velocities at the upstream end are much higher than for an open-channel flow.

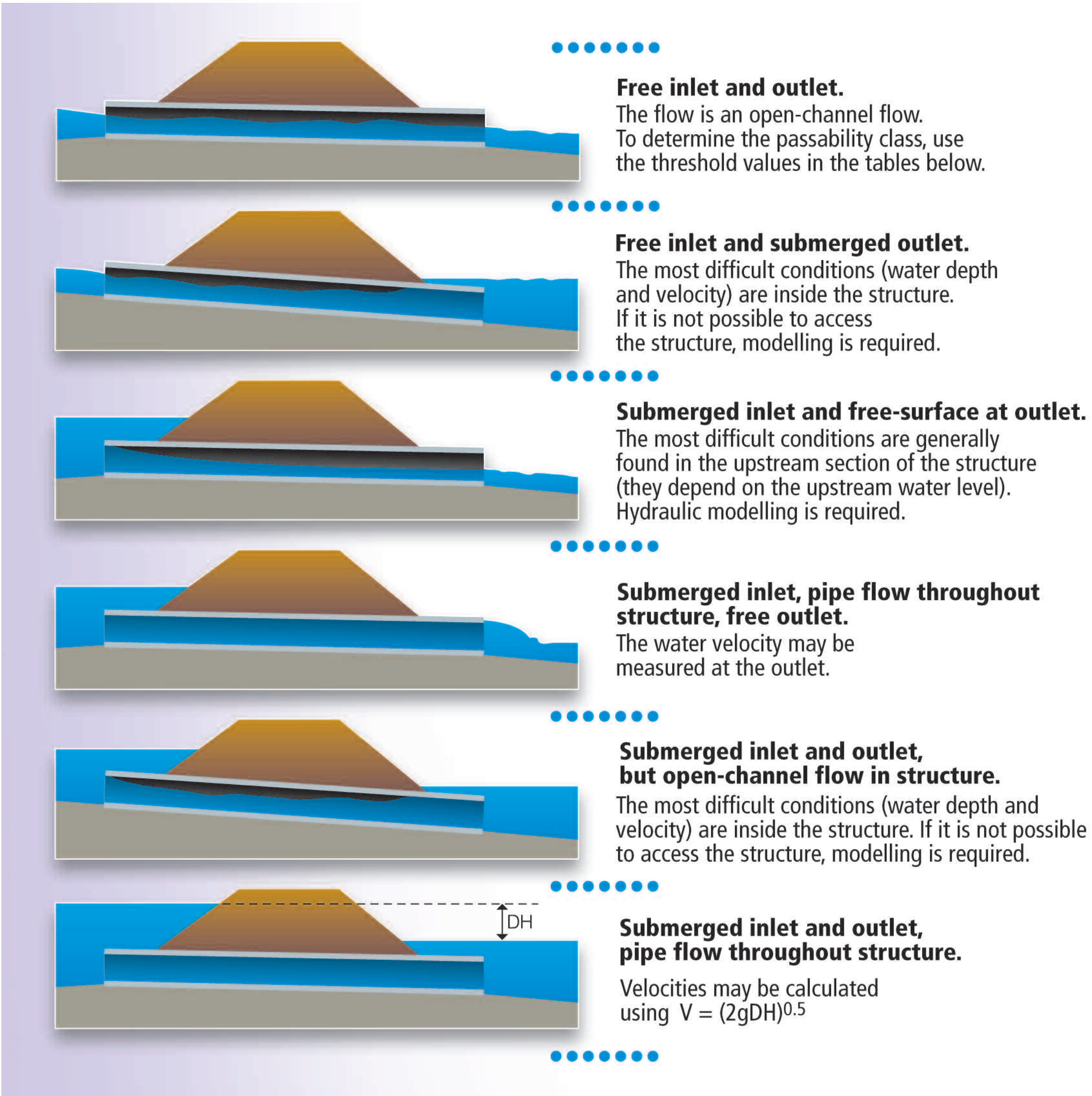
**When the structure is submerged upstream**, the hydraulic passageways are generally fairly small (round or box culvert) and it is difficult to measure the water velocities and depths. **Determination of structure passability will require an assessment of the maximum velocity using orifice calculations** (see the section on flows under gates) **or using hydraulic modelling software (FishXing, Hec Ras or similar software).**

**The downstream outlet of the structure may also be (partially) submerged.** In which case, measurements of water velocities and depths at the outlet are not representative of the flow conditions inside the structure. **If it is impossible to enter the structure to carry out velocity measurements, hydraulic modelling is required to determine the hydraulic conditions encountered by fish along the entire length of the structure.**

**However, even if hydraulic modelling is theoretically necessary, it is nonetheless often worthwhile to run the analysis using the decision tree and the corresponding tables** (see Tables 18 and 19). **The resulting passability class should be considered a maximum**, i.e. the ICE passability class of the structure should be less than or equal to the analysis result. **Depending on the passability class produced by the assessment, it will be possible to decide whether or not to undertake hydraulic modelling.**

Figure 96 shows various flow configurations through culverts and discusses the methods used to determine passability.

**Figure 96**




*Various flow configurations in culverts.*

# Determining passability classes

## ■ Threshold values used for the decision tree

Table 18 can be used to determine the passability class of a structure as a function of its length and slope.

**Tableau 18** *Summary of the basic criteria required to determine ICE passability classes for road structures and culverts, as a function of their length and slope, using the decision tree in Figure 97.*

| ICE species group | Species | Minimum water depth ($h_{min}$) required for swimming | Maximum step dimensions | | Slope threshold values for assessing road structures (%) | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Structure ≤ 20m | | | | Structure > 20m | | |
| | | | | | ICE passability class | | | | ICE passability class | | |
| | | | $a_{max}$ | $c_{max}$ | NC | 0.66 | 0.33 | 0 | NC | 0.33 | 0 |
| 1 | Atlantic salmon (*Salmo salar*) | 0.20 m | 0.35 m | 0.50 m | ≤4.00 | ]4.00 - 7.00] | ]7.00 - 12.00] | >12.00 | ≤4.00 | ]4.00- 7.00] | >7.00 |
| | Brown or sea trout [50-100] (*Salmo trutta*) | | | | | | | | | | |
| 2 | Mullets (*Chelon labrosus, Liza ramada*) | 0.10 m | 0.20 m | 0.30 m | ≤3.50 | ]3.50 - 6.00] | ]6.00 - 10.00] | >10.00 | ≤3.50 | ]3.50 - 6.00] | >6.00 |
| 3a | Allis shad (*Alosa alosa*) | 0.15 m | 0.25 m | 0.40 m | ≤3.00 | ]3.00 - 5.00] | ]5.00 - 8.00] | >8.00 | ≤3.00 | ]3.00 - 5.00] | >5.00 |
| 3b | Twaite shad (*Alosa fallax fallax*) | 0.10 m | 0.20 m | 0.30 m | | | | | | | |
| 3c | Sea lamprey (*Petromyzon marinus*) | | 0.35 m | 0.50 m | | | | | | | |
| 4a | Brown or sea trout [25-55] (*Salmo trutta*) | 0.10 m | 0.20 m | 0.30 m | ≤3.00 | ]3.00 - 5.00] | ]5.00 - 8.00] | >8.00 | ≤3.00 | ]3.00 - 5.00] | >5.00 |
| 4b | Brown trout [15-30] (*Salmo trutta*) | 0.05 m | 0.10 m | 0.15 m | ≤1.00 | ]1.00 - 2.00] | ]2.00 - 4.00] | >4.00 | ≤1.00 | ]1.00 - 2.00] | >2.00 |
| 5 | Asp (*Aspius aspius*) | 0.15 m | 0.30 m | 0.40 m | ≤3.00 | ]3.00 - 5.00] | ]5.00 - 8.00] | >8.00 | ≤3.00 | ]3.00 - 5.00] | >5.00 |
| | Pike (*Esox lucius*) | | | | | | | | | | |
| 6 | Grayling (*Thymallus thymallus*) | 0.10 m | 0.15 m | 0.25 m | ≤2.00 | ]2.00 - 3.00] | ]3.00 - 6.00] | >6.00 | ≤2.00 | ]2.00 - 3.00] | >3.00 |
| 7a | Barbel (*Barbus barbus*) | 0.10 m | 0.15 m | 0.20 m | ≤1.00 | ]1.00 - 2.00] | ]2.00 - 4.00] | >4.00 | ≤1.00 | ]1.00 - 2.00] | >2.00 |
| | Chub (*Squalius cephalus*) | | | | | | | | | | |
| | Nase (*Chondrostoma nasus*) | | | | | | | | | | |
| 7b | River lamprey (*Lampetra fluviatilis*) | 0.05 m | 0.15 m | 0.25 m | | | | | | | |
| 8a | Common carp (*Cyprinus carpio*) | 0.25 m | 0.25 m | 0.40 m | ≤0.75 | ]0.75 - 1.25] | ]1.25 - 2.00] | >2.00 | ≤0.75 | ]0.75 - 1.50] | >1.50 |
| 8b | Common bream (*Abramis brama*) | 0.15 m | 0.20 m | 0.25 m | | | | | | | |
| | Pikeperch (*Sander lucioperca*) | | | | | | | | | | |
| 8c | White bream (*Blicca bjoerkna*) | 0.10 m | 0.15 m | 0.20 m | | | | | | | |
| | Ide (*Leuciscus idus*) | | | | | | | | | | |
| | Burbot (*Lota lota*) | | | | | | | | | | |
| | Perch (*Perca fluviatilis*) | | | | | | | | | | |
| | Tench (*Tinca tinca*) | | | | | | | | | | |
| 8d | Daces (*Leuciscus spp.* except *Idus*) | 0.05 m | 0.10 m | 0.15 m | | | | | | | |
| 9a | Bleak (*Alburnus alburnus*) | 0.05 m | 0.05 m | 0.10 m | ≤0.75 | ]0.75 - 1.25] | ]1.25 - 2.00] | >2.00 | ≤0.75 | ]0.50 - 1.50] | >1.50 |
| | Schneider (*Alburnoides bipunctatus*) | | | | | | | | | | |
| | Mediterranean barbel (*Barbus meridionalis*) | | | | | | | | | | |
| | Blageon (*Telestes souffia*) | | | | | | | | | | |
| | Crucian carp (*Carassius carassius*) | | | | | | | | | | |
| | Prussian carp (*Carassius gibelio*) | | | | | | | | | | |
| | Roach (*Rutilus rutilus*) | | | | | | | | | | |
| | Rudd (*Scardinius erythrophthalmus*) | | | | | | | | | | |
| | SW European nase (*Parachondrostoma toxostoma*) | | | | | | | | | | |
| 9b | Streber (*Zingel asper*) | | | | | | | | | | |
| | Bullheads (*Cottus spp.*) | | | | | | | | | | |
| | Gudgeons (*Gobio spp.*) | | | | | | | | | | |
| | Ruffe (*Gymnocephalus cernuus*) | | | | | | | | | | |
| | Brook lamprey (*Lampetra planeri*) | | | | | | | | | | |
| | Stone loach ( *Barbatula barbatula*) | | | | | | | | | | |
| | Spined loach (*Cobitis taenia*) | | | | | | | | | | |
| 10 | Sunbleak (*Leucaspius delineatus*) | 0.05 m | 0.05 m | 0.05 m | ≤0.50 | ]0.50 - 1.00] | ]1.00 - 1.50] | >1.50 | ≤0.50 | ]0.50 - 1.00] | >1.00 |
| | Bitterling (*Rhodeus amarus*) | | | | | | | | | | |
| | Threespine stickleback (*Gasterosteus gymnurus*) | | | | | | | | | | |
| | Smoothtail ninespine stickleback (*Pungitius laevis*) | | | | | | | | | | |
| | Minnows (*Phoxinus spp.*) | | | | | | | | | | |
| 11a | European eel [yellow eel] (*Anguilla anguilla*) | 0.02 m | 0.10 m | 0.15 m | ≤0.75 | ]0.75 - 1.25] | ]1.25 - 2.00] | >2.00 | ≤0.75 | ]0.50 - 1.50] | >1.50 |
| 11b | European eel [glass eel] (*Anguilla anguilla*) | - | - | - | - | - | - | - | - | - | - |

*(*) The values indicated for eels correspond to the passability classes set when the analysis takes into account only the swimming capabilities of the species. In cases where the obstacle includes a crawling zone, the assessment must also use the special tables for crawling (see the section on eels).*

In certain cases, when the slope is very low, it is necessary to use the flow velocities. In such cases, use Table 19 to determine the passability class. The tables also list the necessary minimum water depths $h_{min}$ and the maximum step sizes ($a_{max}$ and $c_{max}$) used in analysing the passability of steps. These tables should be used with the decision tree (see Figure 97) to determine the ICE passability class.

**Tableau 19** *Summary of the basic criteria required to determine ICE passability classes for road structures and culverts, as a function of their length and the flow velocities, using the decision tree in Figure 97.*

| ICE species group | Species | Minimum water depth ($h_{min}$) required for swimming | Maximum step dimensions | | Velocity threshold values for assessing road structures (m/s) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Structure ≤ 20m | | | | 20m< Structure ≤ 50m | | | | Structure > 50m | | | |
| | | | | | ICE passability class | | | | ICE passability class | | | | ICE passability class | | | |
| | | | $a_{max}$ | $c_{max}$ | 1 | 0.66 | 0.33 | 0 | 1 | 0.66 | 0.33 | 0 | 1 | 0.66 | 0.33 | 0 |
| 1 | Atlantic salmon (*Salmo salar*)<br>Brown or sea trout [50-100] (*Salmo trutta*) | 0.20 m | 0.35 m | 0.50 m | ≤ 2.70 | ]2.70 - 3.60] | ]3.60 - 4.50] | >4.50 | ≤ 1.80 | ]1.80 - 2.40] | ]2.40 - 3.00] | >3.00 | ≤ 1.50 | ]1.50 - 2.00] | ]2.00 - 2.40] | >2.40 |
| 2 | Mullets (*Chelon labrosus, Liza ramada*) | 0.10 m | 0.20 m | 0.30 m | ≤ 2.25 | ]2.25 - 2.90] | ]2.90 - 3.60] | >3.60 | ≤ 1.60 | ]1.60 - 2.00] | ]2.00 - 2.40] | >2.40 | ≤ 1.35 | ]1.35 - 2.00] | ]2.00 - 2.40] | >2.40 |
| 3a | Allis shad (*Alosa alosa*) | 0.15 m | 0.25 m | 0.40 m | | | | | | | | | | | | |
| 3b | Twaite shad (*Alosa fallax fallax*) | 0.10 m | 0.20 m | 0.30 m | ≤ 1.85 | ]1.85 - 2.50] | ]2.50 - 3.10) | >3.10 | ≤ 1.35 | ]1.35 - 1.70] | ]1.70 - 2.15] | >2.15 | ≤ 1.20 | ]1.20 - 1.45] | ]1.45 - 1.75] | >1.75 |
| 3c | Sea lamprey (*Petromyzon marinus*) | | 0.35 m | 0.50 m | | | | | | | | | | | | |
| 4a | Brown or sea trout [25-55] (*Salmo trutta*) | 0.10 m | 0.20 m | 0.30 m | ≤ 1.85 | ]1.85 - 2.50] | ]2.50 - 3.10) | >3.10 | ≤ 1.35 | ]1.35 - 1.70] | ]1.70 - 2.15] | >2.15 | ≤ 1.20 | ]1.20 - 1.45] | ]1.45 - 1.75] | >1.75 |
| 4b | Brown trout [15-30] (*Salmo trutta*) | 0.05 m | 0.10 m | 0.15 m | ≤ 1.15 | ]1.15 - 1.70] | ]1.70 - 2.25] | >2.25 | ≤ 0.80 | ]0.80 - 1.20] | ]1.20 - 1.60] | >1.60 | ≤ 0.80 | ]0.80 - 1.15] | ]1.15 - 1.40] | >1.40 |
| 5 | Asp (*Aspius aspius*)<br>Pike (*Esox lucius*) | 0.15 m | 0.30 m | 0.40 m | ≤ 1.85 | ]1.85 - 2.50] | ]2.50 - 3.10] | >3.10 | ≤ 1.35 | ]1.35 - 1.70] | ]1.70 - 2.15] | >2.15 | ≤ 1.20 | ]1.20 - 1.45] | ]1.45 - 1.75] | >1.75 |
| 6 | Grayling (*Thymallus thymallus*) | 0.10 m | 0.15 m | 0.25 m | ≤ 1.50 | ]1.50 - 2.05] | ]2.05 - 2.75] | >2.75 | ≤ 1.10 | ]1.10 - 1.45] | ]1.45 - 1.80] | >1.80 | ≤ 1.10 | ]1.10 - 1.30] | ]1.30 - 1.55] | >1.55 |
| 7a | Barbel (*Barbus barbus*)<br>Chub (*Squalius cephalus*)<br>Nase (*Chondrostoma nasus*) | 0.10 m | 0.15 m | 0.20 m | ≤ 1.20 | ]1.20 - 1.70] | ]1.70 - 2.25] | >2.25 | ≤ 0.80 | ]0.80 - 1.20] | ]1.20 - 1.60] | >1.60 | ≤ 0.80 | ]0.80 - 1.15] | ]1.15 - 1.40] | >1.40 |
| 7b | River lamprey (*Lampetra fluviatilis*) | 0.05 m | 0.15 m | 0.25 m | | | | | | | | | | | | |
| 8a | Common carp (*Cyprinus carpio*) | 0.25 m | 0.25 m | 0.40 m | | | | | | | | | | | | |
| 8b | Common bream (*Abramis brama*)<br>Pikeperch (*Sander lucioperca*) | 0.15 m | 0.20 m | 0.25 m | | | | | | | | | | | | |
| 8c | White bream (*Blicca bjoerkna*)<br>Ide (*Leuciscus idus*)<br>Burbot (*Lota lota*)<br>Perch (*Perca fluviatilis*)<br>Tench (*Tinca tinca*) | 0.10 m | 0.15 m | 0.20 m | ≤ 0.85 | ]0.85 - 1.15] | ]1.15 - 1.60] | >1.60 | ≤ 0.70 | ]0.70 -1.00] | ]1.00 - 1.35] | >1.35 | ≤ 0.70 | ]0.70 - 0.95] | ]0.95 - 1.20] | >1.20 |
| 8d | Daces (*Leuciscus spp.* except *Idus*) | 0.05 m | 0.10 m | 0.15 m | | | | | | | | | | | | |
| 9a | Bleak (*Alburnus alburnus*)<br>Schneider (*Alburnoides bipunctatus*)<br>Mediterranean barbel (*Barbus meridionalis*)<br>Blageon (*Telestes souffia*)<br>Crucian carp (*Carassius carassius*)<br>Prussian carp (*Carassius gibelio*)<br>Roach (*Rutilus rutilus*)<br>Rudd (*Scardinius erythrophthalmus*)<br>SW European nase (*Parachondrostoma toxostoma*) | 0.05 m | 0.05 m | 0.10 m | ≤ 0.85 | ]0.85 - 1.15] | ]1.15 - 1.60] | >1.60 | ≤ 0.70 | ]0.70 - 1.00] | ]1.00 - 1.35] | >1.35 | ≤ 0.70 | ]0.70 - 0.95] | ]0.95 - 1.20] | >1.20 |
| 9b | Streber (*Zingel asper*)<br>Bullheads (*Cottus spp.*)<br>Gudgeons (*Gobio spp.*)<br>Ruffe (*Gymnocephalus cernuus*)<br>Brook lamprey (*Lampetra planeri*)<br>Stone loach ( *Barbatula barbatula*)<br>Spined loach (*Cobitis taenia*) | | | | | | | | | | | | | | | |
| 10 | Sunbleak (*Leucaspius delineatus*)<br>Bitterling (*Rhodeus amarus*)<br>Threespine stickleback (*Gasterosteus gymnurus*)<br>Smoothtail ninespine stickleback (*Pungitius laevis*)<br>Minnows (*Phoxinus spp.*) | 0.05 m | 0.05 m | 0.05 m | ≤ 0.55 | ]0.55 - 0.75] | ]0.75 - 1.00] | >1.00 | ≤ 0.55 | ]0.55 - 0.75] | ]0.75 - 1.00] | >1.00 | ≤ 0.55 | ]0.55 - 0.75] | ]0.75 - 1.00] | >1.00 |
| 11a | European eel [yellow eel] (*Anguilla anguilla*) | 0.02 m | 0.10 m | 0.15 m | ≤ 0.85 | ]0.85 - 1.15] | ]1.15 - 1.60] | >1.60 | ≤ 0.70 | ]0.70 - 1.00] | ]1.00 - 1.35] | >1.35 | ≤ 0.70 | ]0.70 - 0.95] | ]0.95 - 1.20] | >1.20 |
| 11b | European eel [glass eel] (*Anguilla anguilla*) | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |

*(*) The values indicated for eels correspond to the passability classes set when the analysis takes into account only the swimming capabilities of the species. In cases where the obstacle includes a crawling zone, the assessment must also use the special tables for crawling (see the section on eels).*

■ **Decision tree**

To determine the passability class of a road structure or culvert having a free inlet and outlet (see the first diagram in Figure 96), use the decision tree presented below (see Figure 97).

*1. Analysis of the downstream fall, if it exists*

If a fall exists at the downstream end of the structure, passability should be determined using the method for vertical weirs (start the assessment at Step 3 in the decision tree in the section on vertical and subvertical weirs (slope >150%)). If the fall cannot be overcome by the given species or group of species, then the entire obstacle is considered a total barrier (ICE class = 0). If the obstacle is not a total barrier (ICE class > 0), then go on to Step 2.

If a fall does not exist, go to Step 6.

*2. Analysis of the water depth in the structure*

If the depth is greater than the minimum, i.e. $h \geq h_{min}$ (see Table 18), the depth is sufficient. Go to Step 3.

If $h < h_{min}$, under the given hydrological conditions the obstacle may be considered a total barrier in the sense of the ICE protocol (ICE class = 0). However, the analysis should be pursued (go to Step 3) in order to determine the passability class in the event other hydrological conditions provide enough water depth. Depending on the score of the subsequent analysis, it will be possible to decide whether or not to return to the obstacle for measurements under other hydrological conditions.

*3. Analysis of steps in the structure*

If there are no steps or if the steps are negligible ($h \geq 2a$), go directly to Step 4.
If the dimensions (a and c) of a single step exceed the maximum values $a_{max}$ and $c_{max}$ listed in Table 18, the obstacle may be considered a total barrier (ICE class = 0). If the dimensions (a and c) of all steps are lower than the threshold values, go to Step 4.

*4. Analysis of the slope*

On the basis of the length of the structure (L < 20 m or L > 20 m) and its slope, use Table 18 to determine the ICE passability class of the structure.
If the ICE passability class is NC, go to Step 5.
If the ICE passability class is not NC, go to Step 9.

*5. Analysis of flow velocities*

On the basis of the length of the structure (L < 20 m, 20 m < L < 50 m or L > 50 m) and the measured or estimated flow velocities, use Table 19 to determine the ICE passability class of the structure. Go to Step 9.
If the flow velocities cannot be measured or estimated, the passability class cannot be determined (ICE class = NC). Go to Step 9.

*6. Analysis of structure positioning with respect to the natural riverbed*

Check whether the entire structure is positioned lower than the natural riverbed.
If the structure is lower than the natural riverbed, go to Step 8.
If not, go to Step 7.

### *7. Analysis of whether the structure lies under the downstream water level*

Check whether the structure lies entirely below the downstream water level.
If the entire structure lies below the downstream water level, go to Step 8.
If not, go to Step 2.

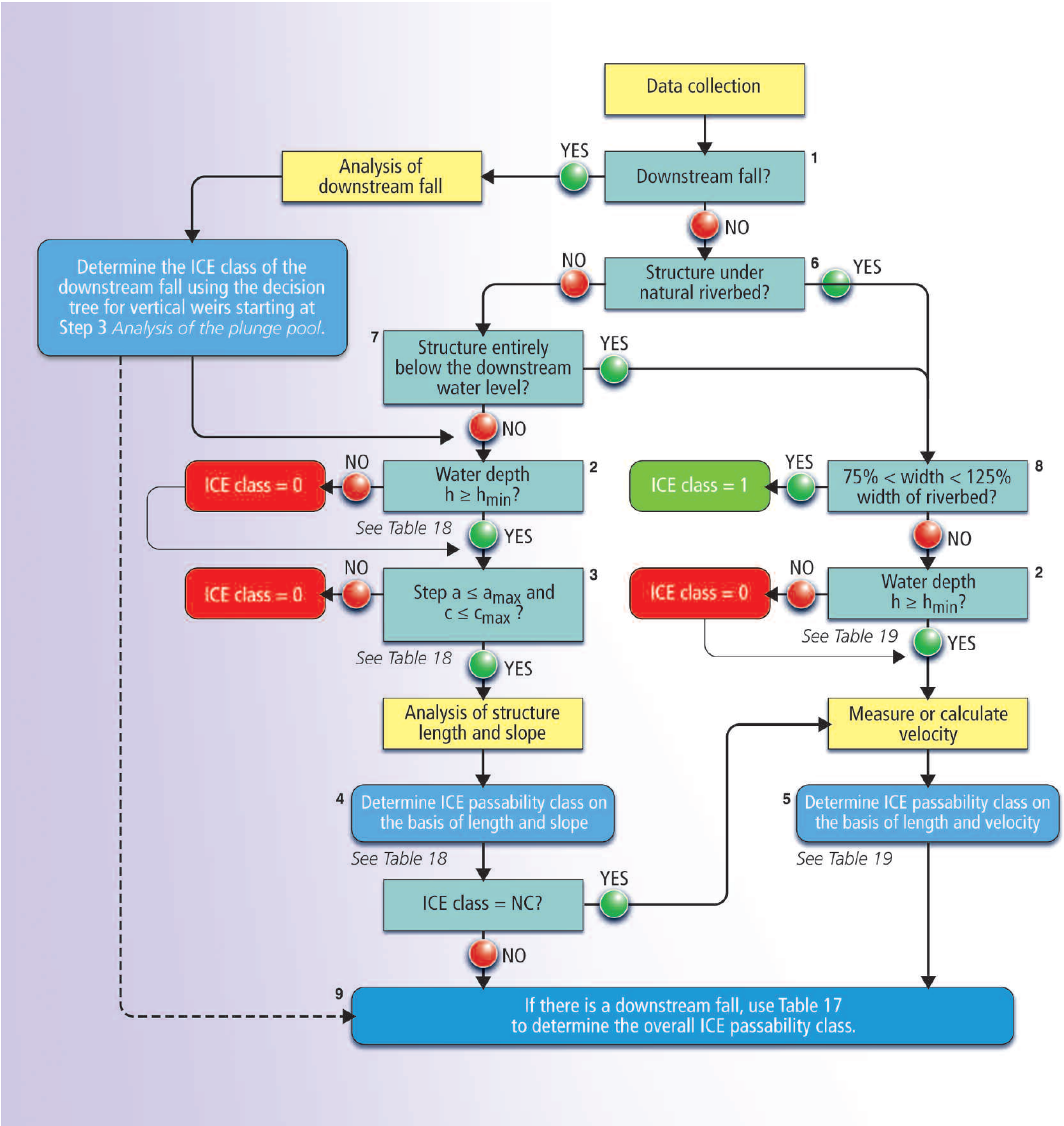
### *8. Analysis of the structure width*

Calculate the cumulative width of the structure (e.g. the combined width of several box culverts) and compare it to the **wetted riverbed**.
If the structure width is between 75% and 125% of the riverbed width, the structure is not considered an obstacle to passage (ICE class = 1) and the assessment can be terminated.
If not, check that $h \geq h_{min}$ (see Step 2 and Tables 18 and 19), then go to Step 5.

### *9. Analysis of structure passability*

If there is a downstream fall, use Table 17 to determine the overall ICE passability class. If there is not a downstream fall, the overall ICE passability class is that resulting from Step 4 or 5.

**Figure 97**




*Decision tree to determine ICE passability classes for road structures or culverts.*

# Tidal structures

## General

This type of structure is established in the lower sections of river basins exposed to tidal conditions. They control the access to rivers and marshes, and are often the first obstacles encountered by fish, notably diadromous fish when they migrate from the sea to fresh waters.

The purpose of these obstacles is generally to limit entry of salt water from downstream, while facilitating exit of water coming from upstream.

They often comprise gates that close partially or totally at high tide to limit the entry of sea water. Following the high tide, the gates open to let out the water stored during the period leading up to the high tide (see Figure 98). When there is a particular need to protect the upstream area, pumps may also be installed to accelerate the evacuation of the water. Where this is the case, fish mortalities may occur if the structures are not equipped with the necessary systems to avoid passage of the fish through the pumps.

Figure 98


a, b © Voegtlé - Ecogea

*Example of tide gates on the Jalle de la Maréchale River in the Médoc region (near Bordeaux), (a) at low tide, (b) at high tide.*

**In some cases, estuarine structures may function in reverse, i.e. let the water enter at high tide and block its exit at low tide** (see Figure 99). The purpose is often to maintain the water level in a port or basin for boating and/or tourism activities. In terms of fish passage, this type of structure is much less troublesome in that upstream migration generally occurs during high tide.

**Figure 99**


a, b © Voegtlé - Ecogea

*Example of the Lac Marin (on the Courant de Soustons River in the Landes region, SW France). (a) High tide, the sea water flows over the obstacle into the lake upstream, (b) at low tide, a weir maintains the water level in the lake.*

## The different types of structures

There are generally three types of devices installed in protection structures.

- **Tide gates.** They are secured to vertical uprights and generally block the entire width of the riverbed. The gates are often very large, thus ensuring rapid evacuation of the water accumulated upstream during the high tide or during floods (see Figure 100).

**Figure 100**


a © Voegtlé - Ecogea
b © Chanseau - Onema

*Examples of tide gates. (a) Tide gates at the outlet of the Arcins marshes in the Gironde department, SW France. (b) Tide gates on the Livenne River.*

- **Gate systems.** These installations generally consist of lift or radial gates (see Figure 101).

**Figure 101**

a © Voegtlé - Ecogea

*Example of a gate system.*
*A lift gate on the Courant de Soustons River in the Landes region, SW France.*

■ **Flap gates.** Flap gates are generally smaller than tide gates and are often positioned in the lower section of a structure (see Figure 102). The most common shapes are square or rectangular and the flaps open from the bottom (fixtures at the top).

In certain cases, notably for estuarine structures subjected to strong swells and waves, the flaps may be installed on the upstream end of culverts.

The culverts (or covered canals) are occasionally very long. That is the case, for example, on many coastal rivers along the Albâtre coast in Normandy, where the estuarine culverts are generally several metres long and the outlets are located below the highly mobile pebble beaches.

**Figure 102**


a, b, d, e, f © Voegtlé - Ecogea
c © Verdeyroux - Onema

*Examples of flap gates on tidal structures. (a) and (b) Flaps on the Médoc River, (c) "Stalin's organs" on the Arroudet stream, (d) structure comprising tide gates and flap gates in the lower section, on the Jale de Castelnau River, (e and f) estuarine structure on the Yères River, comprising a flap gate upstream (photo on left) and a long culvert downstream (photo on right).*

A majority of structures are equipped with "passive" systems operating according to the basic rules of hydraulics. These systems are generally made up of tide gates and flaps that close when the downstream water level is higher than the upstream level.
In some cases, however, the systems can be automated. These structures generally consist of lift gates and flap gates.

## Assessment of passability

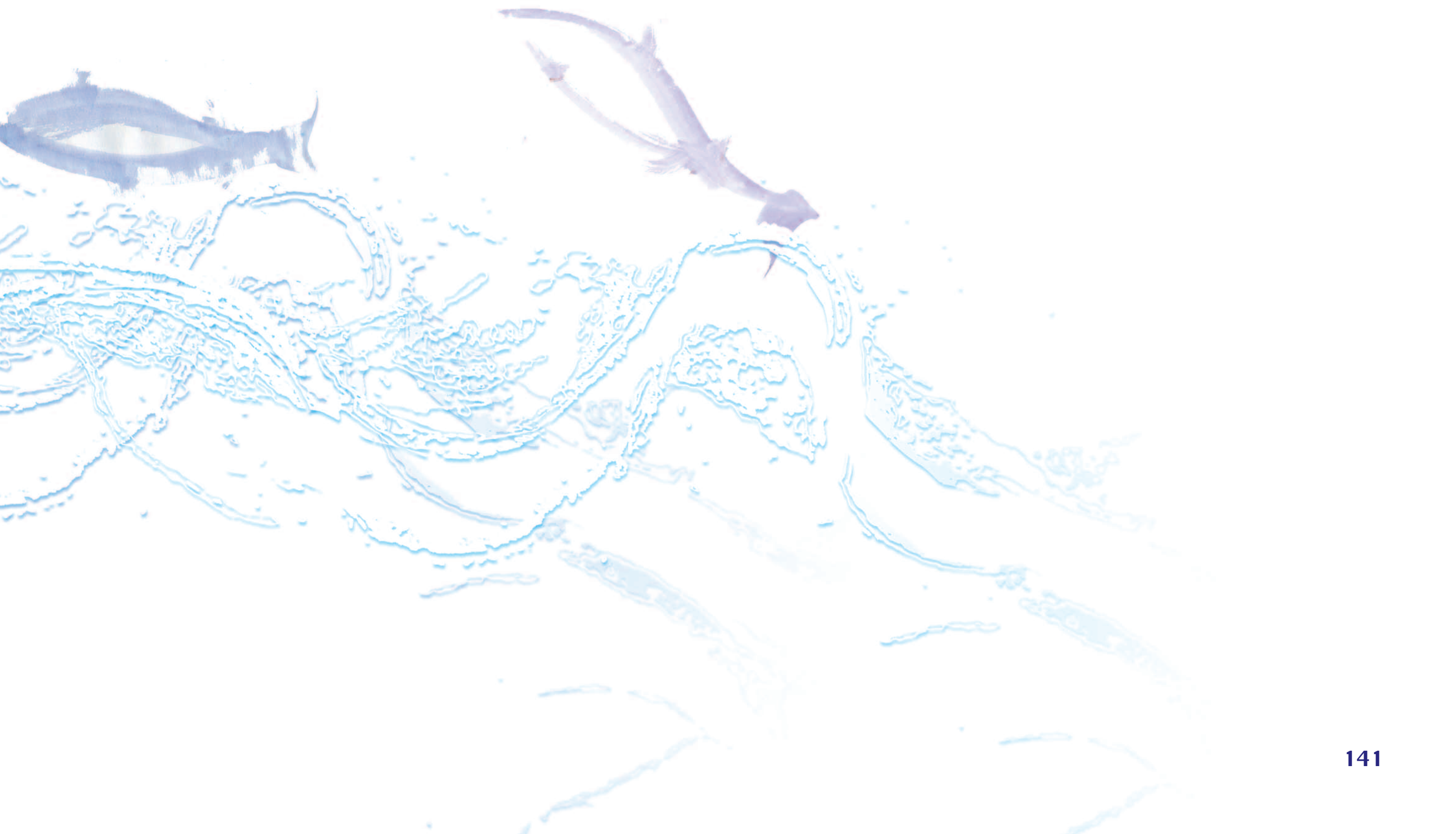
Knowledge on the behaviour of fish at tidal structures and on the influence of tides is still very limited, due notably to the complexity of the necessary experiments. It is nonetheless possible to say that a majority of the concerned species take advantage of the high tides to colonise the areas upstream of the structures.

However, it is also clear that in most cases, particularly when estuarine structures are designed to avoid or limit the entry of water further upstream, they create major problems for the passage of the fish species that use the tidal currents to travel upstream. By closing when the tide rises and stopping the tidal waters, in general they also put a complete stop to the migration of fish. In addition, the flow velocities in structures (culverts and/or in flap gates) are often too high at low tide and when the tide starts coming in, thus reducing the possibilities for fish to pass the structures at that time in the tidal sequence.

When estuarine structures function in reverse, i.e. let the water enter at high tide and block its exit at low tide, there are generally far fewer problems.

For the above reasons, it would appear **difficult to propose simple criteria for a passability assessment of tidal structures**. In most cases, an analysis of the local hydraulic conditions, as a function of the **wider hydrological and maritime conditions**, must be carried out. The assessment must necessarily call on in-depth knowledge of the management systems employed for the given structures and on the opening conditions of the gates as a function of the upstream and downstream water levels (tidal coefficients, high tides, low tides, etc.).

However, if there are no possible passageways upstream at low tide (directly via the structure or via a fish pass) or at high tide (no water can enter the upstream area), the structure may be considered a total or virtually total barrier (ICE class = 0), for all species and groups of species.



# Complex and mixed structures

Complex or mixed obstacles are structures made up of different materials along the longitudinal axis (e.g. a concrete vertical or inclined weir followed downstream by a rock weir) or a series of successive obstacles that, administratively speaking, constitute a single structure (e.g. a mill dam with a pre-barrage or a succession of two weirs, etc.).

It was decided to break these complex structures down into a series of "simple" structures (see Figure 103), then to determine the passability of each part separately and finally to calculate a passability class for the structure as a whole, according to the rules presented below.

The approach is comparable in terms of its rationale to that used for inclined weirs or road/rail structures having a downstream fall (see the sections on these types of structures).

## Breaking the structure into a series of "simple" structures along the longitudinal axis

Each part of the obstacle must be assigned to one of the following obstacle types:

- vertical or subvertical obstacle (slope > 150%);
- weir with inclined downstream face (slope ≤150%);
- rock weir;
- structure comprising gates or where underflows occur;
- road/rail structure.

Figure 103


a © Onema
b © Voegtlé - Ecogea

*Examples of complex structures than can be broken down into "simple" structures. (a) Example of a complex or mixed structure that can be broken down into a weir with an inclined downstream face and a downstream rock weir, (b) example of a structure that can be broken down into a weir with an inclined downstream face and a vertical fall (pre-barrage).*

**However, this breakdown is valid only if the hydraulic conditions for each part of the overall structure are not overly influenced by the presence of the other parts** (see Figure 104).

This approach can theoretically be used for an unlimited number of successive parts. However, if there are more than three or four parts, the hydraulic conditions are probably fairly complex and cannot be broken down in a simple manner.

**In this case, an assessment will realistically require more in-depth analysis** calling on hydraulic modelling to describe the flow conditions throughout the structures as a function of the hydrological conditions. The hydraulic model will require the development and calibration of a digital application based on the physical (precise geometry of the structure, roughness of surfaces) and hydraulic (discharges, conditions at the furthest upstream and downstream points as a function of the discharges, etc.) data points. **Initially, however, it is certainly worthwhile to use the assessment method for complex structures. The resulting passability class should be considered a maximum,** i.e. the ICE passability class of the structure should be less than or equal to the assessment result. **Depending on the passability class produced by the assessment, it will be possible to decide whether or not to undertake hydraulic modelling.**

Figure 104


a © Voegtlé Ecogea
b © Richard - Onema

*Examples of structures than cannot be broken down into "simple" structures.*
*(a) Two "simple" structures. Due to the gate configuration, the initial velocity at the head of the inclined face is much higher than for a normal inclined weir on which the velocity increases progressively. Hydraulic modelling would be of no use in this case because passage under the gate is not possible. The overall structure may be considered a total barrier (ICE class = 0).*
*(b) In this case, the structure cannot be broken down into three simple structures (downstream fall, inclined weir and passage under the gate. Due to the gate configuration, the initial velocity at the head of the inclined face is much higher than for a normal inclined weir on which the velocity increases progressively.*

## Determining the passability class for each part of a structure

The passability classes for each separate part of the structure are determined using the methods for each type of obstacle presented in the previous sections.

## Determining the passability class for the structure as a whole

In order to take into account the cumulative impact of obstacles, the proposed solution is to downgrade the overall passability class by one or two levels, depending on the configuration of the overall structure.

Table 20 presents the results for a structure made up of two separate obstacles.

**Tableau 20** *Table to determine the overall ICE class for a complex structure comprising two parts.*

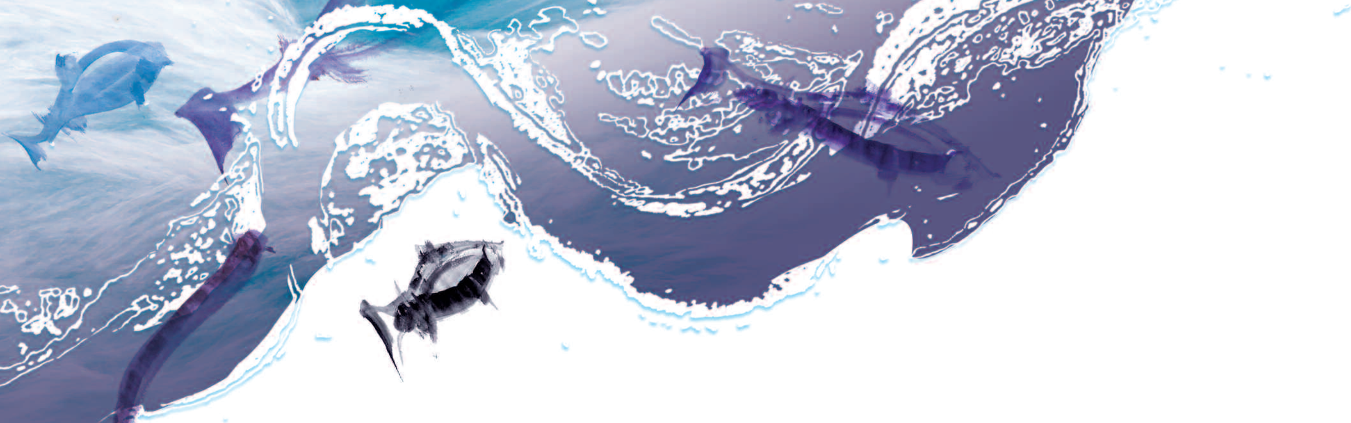
| ICE class of the upstream obstacle | ICE class of the downstream fall | | | |
|---|---|---|---|---|
| | **0** | **0.33** | **0.66** | **1** |
| 0 | 0 | 0 | 0 | 0 |
| 0.33 | 0 | 0 | 0.33 | 0.33 |
| 0.66 | 0 | 0.33 | 0.33 | 0.66 |
| 1 | 0 | 0.33 | 0.66 | 1 |
| NC | 0 | NC (≤ 0.33) | NC (≤ 0.66) | NC |

For a set of "x" simple structures, it was decided that the overall passability class corresponds to the lowest class among the simple structures minus one class, when there are at least three simple structures having an ICE class of less than 1.

If only two of the "x" simple structures have an ICE class of less than 1, Table 20 should be used.

Below are a number of examples.

- For a set of "x" simple structures each having an ICE class = 0.66, the overall structure may be considered a high-impact partial barrier (ICE class = 0.33 using Table 20 if x = 2 or one class lower than the worst simple structure if x ≥ 3).
- For a set of "x" simple structures each having an ICE class = 0.33, the overall structure may be considered a total barrier (ICE class = 0 using Table 20 if x = 2 or one class lower than the worst simple structure if x ≥ 3).
- For a set of four simple structures having ICE classes = 0.33, 0.66, 0.66 and 1, the overall structure may be considered a total barrier (ICE class = 0 by downgrading to one class lower than the worst simple structure).
- For a set of four simple structures having ICE classes = 0.33, 0.66, 1 and 1, the overall structure may be considered a high-impact partial barrier (ICE class = 0.33 using Table 20).



# Eels, a special case

## Specific approach

### ■ General

During their upstream migration, eels are capable of overcoming obstacles in two ways:

- by swimming at low speeds against the current (speeds are less than 0.5 m/s for glass eels and between 1 and 1.5 m/s for elvers and yellow eels);
- by crawling up rough, inclined surfaces over which a very thin sheet of water flows.

Assessment of obstacle passability for eels during upstream migration was tested as early as 2006 in the Loire-Bretagne basin (Steinbach, 2006). A general outline of the approach will be presented below.

### ■ Size of eels

The ICE protocol takes into account eels likely to migrate over large distances (corresponding to the continental range of the species), i.e. very young fish between 60 and 120 mm long (glass eels) and larger fish up to 400 mm long (elvers and yellow eels).

Very small eels can climb up vertical walls. They would appear to use the surface tension created by the contact between their bodies and the wet wall to counteract the force of gravity (Legault, 1986 and 1987). However, in growing, the weight to surface tension ratio increases, which explains why only the smallest eels (less than 120 mm in length) can use this technique.

Older fish, namely elvers and yellow eels, have greater swimming capabilities than glass eels. They can swim over some obstacles having low head-drops when crawling is not possible.

To take into account the specific aspects of each age, two distinct groups were created:

- the glass-eel and young-elver group, corresponding to fish between 60 and 120 mm long;
- the elver and yellow-eel group, corresponding to fish longer than 120 mm.

### ■ Passability criteria and integration of crawling capabilities

Given their swimming capabilities, any structure comprising a fall represents a major obstacle for the glass-eel and young-elver group if they must overcome the obstacle by swimming. For the elver and yellow-eel group, threshold values for the passability classes are presented in the tables used with the various decision trees depending on the type of obstacle, similar to the other species (see the previous sections addressing each type of obstacle).

However, the assessment of structure passability for eels must take into account the special crawling capabilities of the species (and the "climbing" capabilities of very small eels). That is why it appeared necessary to formulate specific passability criteria for the crawling technique.

The proposed solution is first to check that a potential crawl way exists for the fish and then to assess passability on the basis of two criteria that are simple to measure or estimate, i.e. the distance the fish must cover and the average slope of the crawl way. The assessment procedure is presented below.

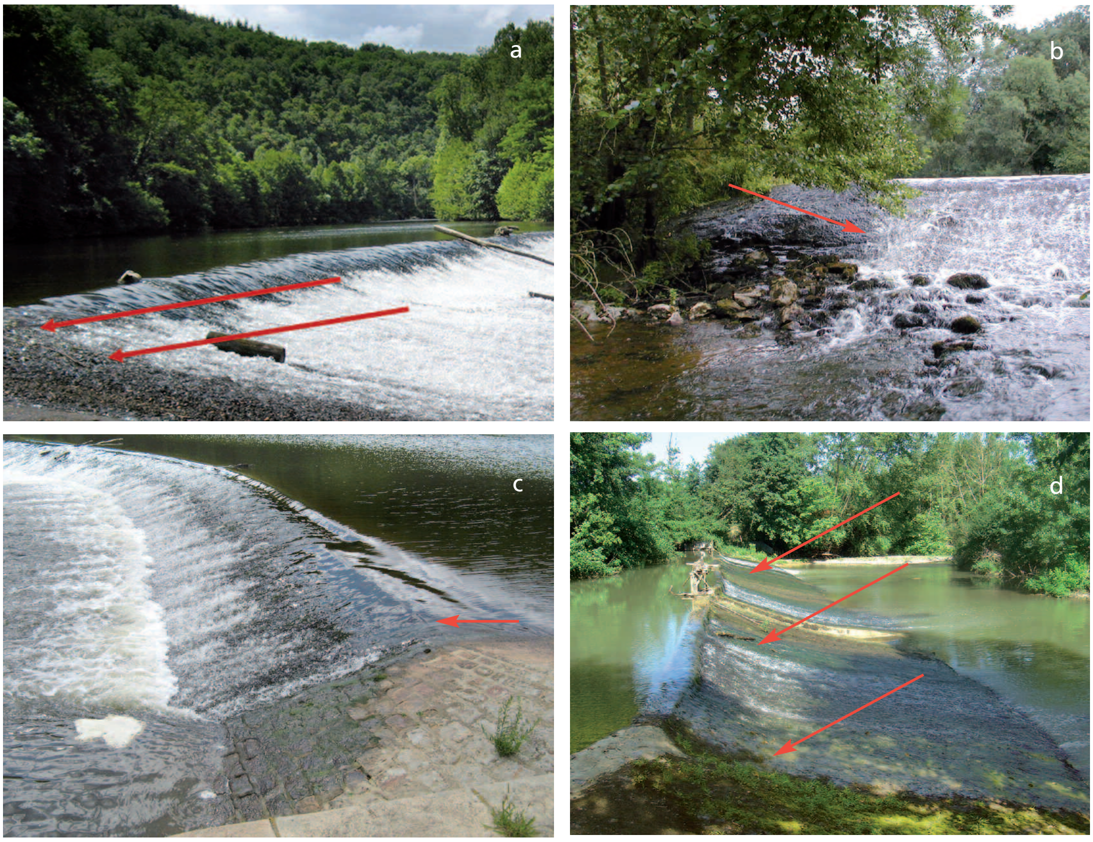
### *Does a crawl way exist?*

A rough surface can help eels in their progression, particularly on steep slopes. The effectiveness of the rough components depends on their size in several dimensions and on the spacing in different directions. The multiple combinations of these various elements and their variability make it very difficult to characterise and measure this criterion precisely.

The proposed solution is to integrate roughness via a single qualitative parameter, i.e. the existence or absence of a usable crawl way, spanning either the entire structure or a given transverse section.

A usable crawl way is characterised by a continuous section where the water depth is very low, less than 10 mm for glass eels and less than 20 mm for elvers (see Figure 105).

**Figure 105**




a, b, c © Steinbach - Onema
d © Chanseau - Onema

*Examples of crawl ways.*

If a crawl way does not exist for the structure, eels must count solely on their swimming capabilities to overcome the obstacle. In this case, the decision trees presented in the previous sections for each type of obstacle may be used for elvers.

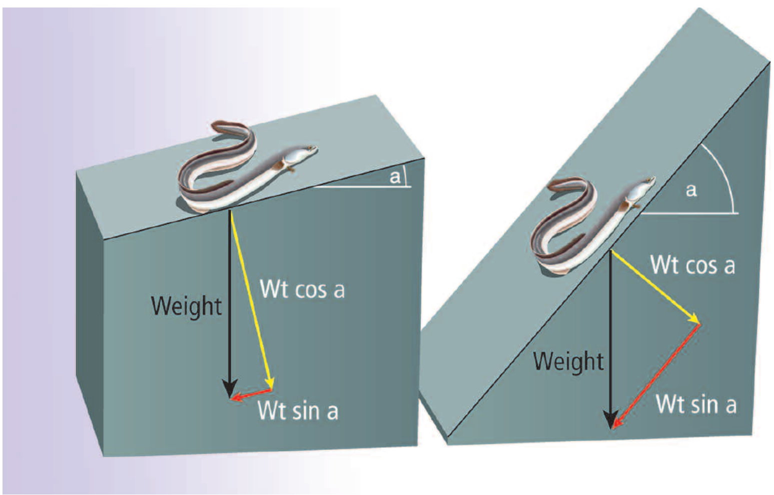
For glass eels, which have no real swimming capability, the obstacle may be considered a total barrier (ICE class = 0).

### *Slope*

On the basis notably of experiments carried out on test installations (Legault, 1989; Voegtlé and Larinier, 2000), the slope of a crawl way was deemed the main parameter in characterising the passability of an obstacle.

The weight of a fish can be broken down into a normal component (Wt cos a) and a tangential component (Wt sin a) (see Figure 106). The part of its weight that an eel must overcome when crawling is proportional to sin a. The part of its weight that adds to the surface tension, thus maintaining the eel in place, is proportional to cos a, where a is the slope of the surface expressed as an elevation angel (degrees).

**Figure 106**




*Breakdown of weight into two components (one favourable to maintaining the eel in place and the other unfavourable).*

For the slightest slopes, less than or equal to 20 to 30% (reference value = 15°, Voegtlé and Larinier, 2000), eels are less sensitive to breaks in roughness or to increases in the hydraulic load. They must overcome only a small fraction of their weight. Over 90% of their weight helps them maintain their position on the rough surface and they do not need to call on the surface tension (see Table 21). Such slight slopes also correspond to a sheet of water where eels may progress more rapidly by swimming, if the hydraulic load permits.

**Tableau 21** *Breakdown of weight into two components.*

| | Slope (% and degree) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 14% 8° | 32% 18° | 48% 26° | 100% 45° | 130% 53° | 173% 60° | 230% 66° | 300% 72° | 500% 79° | ∝ 90° |
| cosα | 0.99 | 0.95 | 0.90 | 0.70 | 0.60 | 0.50 | 0.40 | 0.31 | 0.20 | 0.00 |
| sinα | 0.14 | 0.31 | 0.43 | 0.70 | 0.80 | 0.87 | 0.91 | 0.95 | 0.98 | 1.00 |

Starting with slopes in the 100 to 175% (45 to 60°) range, eels must make a much greater effort given that they must drive most of their weight forward (70 to 90%) while at the same time having lost 30 to 45% of the weight component that pressed them down on the rough surface. The surface tension is now indispensable in helping them maintain their position on the surface. These conditions favour the smallest eels. Any roughness in the crawl way can help them progress. The effectiveness of the rough components depends on their size in several dimensions and on the spacing in different directions, in conjunction with the size of the eels.

A reduction in the slope increases the tolerance of eels to two other limiting factors, i.e. the roughness of the crawl way and the hydraulic load, neither of which can be precisely measured.

***Distance to be overcome***

In light of current knowledge and in a pragmatic approach, it was judged that the greater the distance to be overcome, the greater the probability that an eel will encounter excessive flow velocities, unsuitable water depths, excessively smooth sections and/or breaks in the slope that are not compatible with its crawling capabilities. In addition, the greater the slope, the faster the fish will tire. The proposed solution is to determine the passability of structures by combining two factors, the length and the slope of the potential crawl way (see the tables below). If the crawl way is made up of different sections (different slopes), each section should be assessed separately.

## Determining passability classes

### ■ Threshold values used for the decision tree

Tables 22 and 23 below indicate the applicable passability class as a function of the slope and the distance to be covered. These tables are accompanied by a decision tree (see Figure 107) that can be used to determine the ICE passability class of a given structure.

NB The ICE protocol is primarily intended for man-made structures. However, it is worthwhile to note that the heterogeneity of surfaces and flows in a natural obstacle (waterfall, etc.) can help eels and notably glass eels in overcoming the obstacle, compared to a man-made structure. Under these very special conditions, an ICE assessment may significantly underestimate passability, particularly when rest zones exist in the natural obstacle. For glass eels, this type of obstacle should not be considered a single obstacle, but a succession of obstacles.

**Tableau 22** *Table to determine the ICE passability class of structures having a crawl way for glass eels (60 to 120 mm), as a function of the slope and length of the crawl way, using the decision tree in Figure 107.*

| Slope in % (P) | Distance to be overcome (L in metres) | | | | | | |
|---|---|---|---|---|---|---|---|
| | L ≤ 0.5 | 0.5 < L ≤ 1 | 1 < L ≤ 2 | 2 < L ≤ 5 | 5 < L ≤ 10 | 10 < L ≤ 20 | L > 20 |
| P ≤ 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5 < P ≤ 12.5 | 1 | 1 | 1 | 1 | 0.66 | 0.66 | 0.66 |
| 12.5 < P ≤ 25 | 1 | 1 | 1 | 1 | 0.66 | 0.66 | 0.66 |
| 25 < P ≤ 50 | 1 | 1 | 1 | 0.66 | 0.66 | 0.66 | 0.33 |
| 50 < P ≤ 75 | 1 | 1 | 1 | 0.66 | 0.66 | 0.33 | 0.33 |
| 75 < P ≤ 100 | 1 | 1 | 0.66 | 0.66 | 0.33 | 0.33 | 0.33 |
| 100 < P ≤ 150 | 1 | 1 | 0.66 | 0.66 | 0.33 | 0.33 | 0 |
| 150 < P ≤ 300 | 1 | 0.66 | 0.66 | 0.33 | 0.33 | 0 | 0 |
| P > 300 | 0.66 | 0.66 | 0.66 | 0.33 | 0 | 0 | 0 |

**Tableau 23** *Table to determine the ICE passability class of structures having a crawl way for elvers (120 to 400 mm), as a function of the slope and length of the crawl way, using the decision tree in Figure 107.*

| Slope in % (P) | Distance to be overcome (L in metres) | | | | | | |
|---|---|---|---|---|---|---|---|
| | L ≤0.5 | 0.5 < L ≤ 1 | 1 < L ≤ 2 | 2 < L ≤ 5 | 5 < L ≤ 10 | 10 < L ≤ 20 | L > 20 |
| P ≤ 5 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5 < P ≤ 12.5 | 1 | 1 | 1 | 1 | 1 | 0.66 | 0.66 |
| 12.5 < P ≤ 25 | 1 | 1 | 1 | 1 | 0.66 | 0.66 | 0.33 |
| 25 < P ≤ 50 | 1 | 1 | 1 | 0.66 | 0.66 | 0.33 | 0.33 |
| 50 < P ≤ 75 | 1 | 1 | 0.66 | 0.66 | 0.33 | 0.33 | 0 |
| 75 < P ≤ 100 | 1 | 0.66 | 0.66 | 0.33 | 0.33 | 0 | 0 |
| 100 < P ≤ 150 | 1 | 0.66 | 0.33 | 0.33 | 0 | 0 | 0 |
| 150 < P ≤ 300 | 0.66 | 0.33 | 0.33 | 0 | 0 | 0 | 0 |
| P > 300 | 0.66 | 0.33 | 0 | 0 | 0 | 0 | 0 |

**■ Decision tree**

The various steps in determining the ICE passability class are presented below.

***1. Does a crawl way exist?***

If a continuous passageway exists with a very low flow depth (< 20 mm for elvers and < 10 mm for glass eels), then draft the long profile of the potential crawl way and go to Step 3.

If not, eels are required to use their swimming capabilities. Go to Step 2.

However, if a crawl way is not manifest, it may nonetheless be worthwhile to determine the passability class for more favourable hydrological conditions under which a crawl way may appear. Depending on the score of the subsequent analysis (Step 3), it will be possible to decide whether or not to return to the obstacle for measurements under other discharge conditions.

***2. Determining the overall passability class of the obstacle if a crawl way does not exist***

For elvers, use the various tables for the different types of structures in the same manner as for the other fish species.

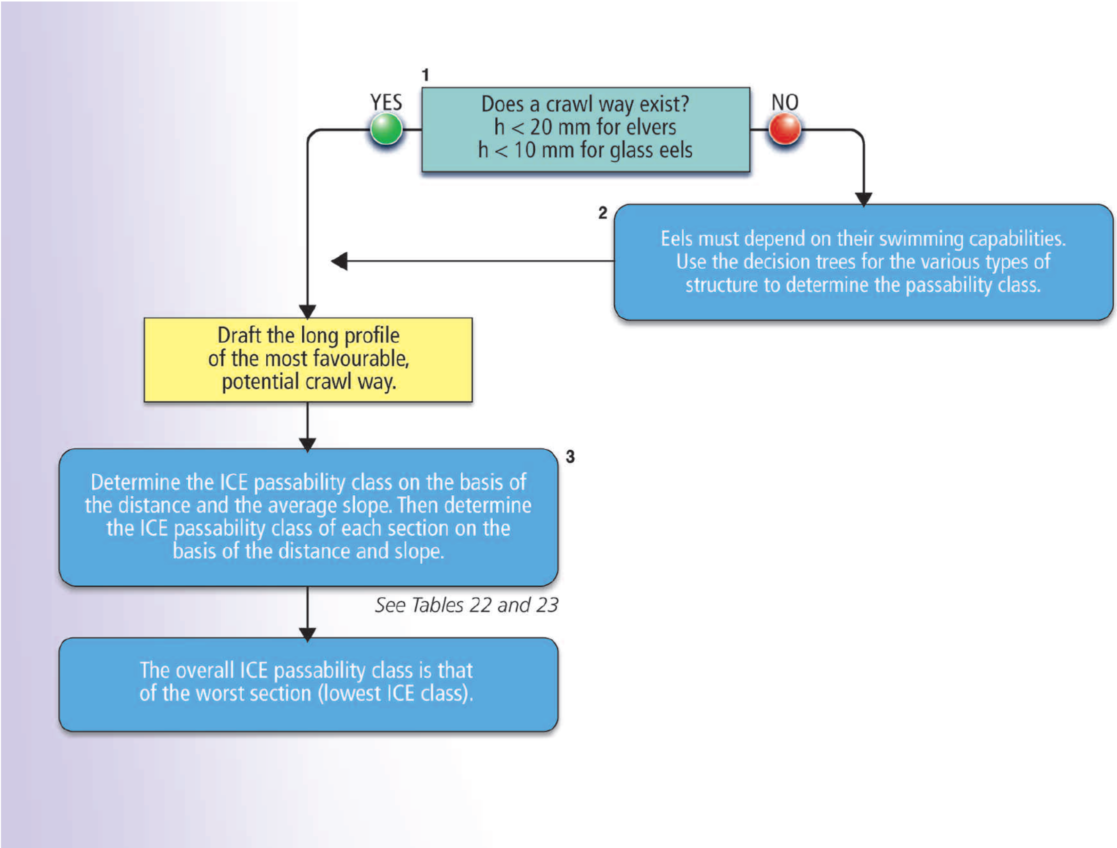
For glass eels, the obstacle may be considered a total barrier (ICE class = 0).

***3. Determining the overall passability class of the obstacle if a crawl way does exist***

Determine the ICE passability class using Tables 22 and 23, taking into account the total distance and the average slope of the crawl way.

If the crawl way was broken down into different sections, determine the passability class of each section using the same tables. If one or more of the sections are assigned a passability class lower than the class for the crawl way as a whole, the lowest class determines the result for the entire crawl way.

**Figure 107**




*Decision tree to determine ICE passability classes for eels.*