

CHAPTER 3

BIOLOGICAL FACTORS TO BE TAKEN INTO ACCOUNT IN THE DESIGN OF FISHWAYS, THE CONCEPT OF OBSTRUCTIONS TO UPSTREAM MIGRATION

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1. SWIMMING PERFORMANCE OF FISH, AND WATER VELOCITY AT FISH PASSAGE FACILITIES

1.1 The different levels of swimming activity

In fish one can generally distinguish several different levels of swimming activity which use different types of muscles (BLAXTER, 1969; BELL, 1986; WEBB, 1975).

- **Cruising activity**, which may be maintained for hours without causing any major physiological changes in the organism, using aerobic muscular activity ("red" muscles).

- **Burst activity**, requiring sustained and intense effort that cannot be maintained for very long (from a few seconds to tens of seconds, depending on the length of the fish, and the water temperature). This level of activity is associated with extreme acceleration ("darting", "fast-start activity") and leaping, *i.e.* violent activity of short duration. Practically all the muscular power used is provided by anaerobic mechanisms (in the "white" muscles) involving transformation of muscular glycogen to form lactic acid. Although the anaerobic reactions allow considerable muscle power to be generated very quickly they also produce a limited supply of energy, since the reserves of muscle glycogen are limited and, above a certain level, the concentration of lactic acid tends to inhibit muscular contraction.

- **Sustained activity**, which can be maintained for several minutes, but which tires the fish. This swimming activity uses the aerobic and anaerobic mechanisms in variable proportions, and the greater the effort, the more anaerobic mechanisms are required.

1.2 Swimming speed and endurance

One of the main factors to be taken into account in the design of fish passage facilities is the swimming capacity of the migrators concerned, which is expressed in terms of swimming speed and endurance, *i.e.* the length of time during which the fish can maintain this swimming speed.

The undulation of the body and the caudal fin are the source of propulsion in most species during migratory activity (particularly when passing obstructions).

Experiments have shown that the distance travelled (A) by the fish at each undulation of the body may vary between 0.6 and 0.8 times its length (L) (WARDLE, 1975). Swimming speed can therefore be expressed as follows:

$$V = A f$$

where f is the frequency of undulation of the body and the caudal fin (number of undulations per second).

The maximum swimming speed is therefore a function of the maximum beating frequency of the caudal fin. This maximum frequency is limited by the minimum time (t) between two contractions of the paravertebral muscles which ensure the fish's propulsion. This is expressed as follows by WARDLE (1975), who took 0.7 as a mean value for A :

$$V = 0.7 L/2t$$

Experiments have shown (WARDLE, 1975) that the time separating two successive muscular contractions is shorter in small fish. On the other hand, the contraction of "white" anaerobic muscles is very sensitive to temperature, the minimum time separating two muscular contractions decreasing with increasing temperature.

The maximum swimming speed therefore depends especially on the **length of the fish** and the **temperature**.

Endurance depends on the reserve of glycogen stored in the muscles. This reserve is used as soon as the fish exceeds its cruising speed, and the rate of depletion is a function of the swimming speed and the temperature. Endurance also depends on the length of the fish, its morphology (length-weight relationship, percentage of muscle mass) and temperature.

Experimental studies carried out in Great Britain (WARDLE, 1980; ZHOU, 1982; BEACH, 1984) allowed a number of empirical expressions to be obtained, which define the relationship between swimming speed, endurance, temperature, size and morphology of the fish.

From these equations the maximum swimming speeds and the endurance at any one speed for different temperatures and lengths can be derived. These are shown in figures 1 and 2 (after BEACH, 1984). Figure 3 shows the relationship between swimming speed and endurance for various sizes of fish at several temperatures.

These clearly provide good evidence of the importance of temperature and fish length on the maximum swimming speed, and particularly the fundamental role of the length of the fish on endurance. The maximum swimming speeds may vary in the ratio 1:2 for the same fish, depending on the temperature.

These results appear to be in perfect agreement with the data put forward by different authors (BELL, 1986) on the maximum swimming speeds possible under favourable temperature conditions. Maximum values are around 6 m/s to more than 8 m/s for salmon, 3 m/s to 4 m/s for trout, 4 m/s to 5 m/s for shad.

VIDELER (1993) proposed an equation based on a compilation of experimental results (obtained for fish length < 0.50 m) giving the maximum swimming speed (m/s) in relation to body length L (m):

$$V_{\max} = 0.4 + 7.4 L$$

It should be noted that for a fish of any given length, an increase in temperature results in a significant decrease in endurance. This reduction is due to the fact that a higher temperature corresponds to a higher maximum speed with a faster rate of depletion of the glycogen reserves of the muscles, and therefore lower endurance.

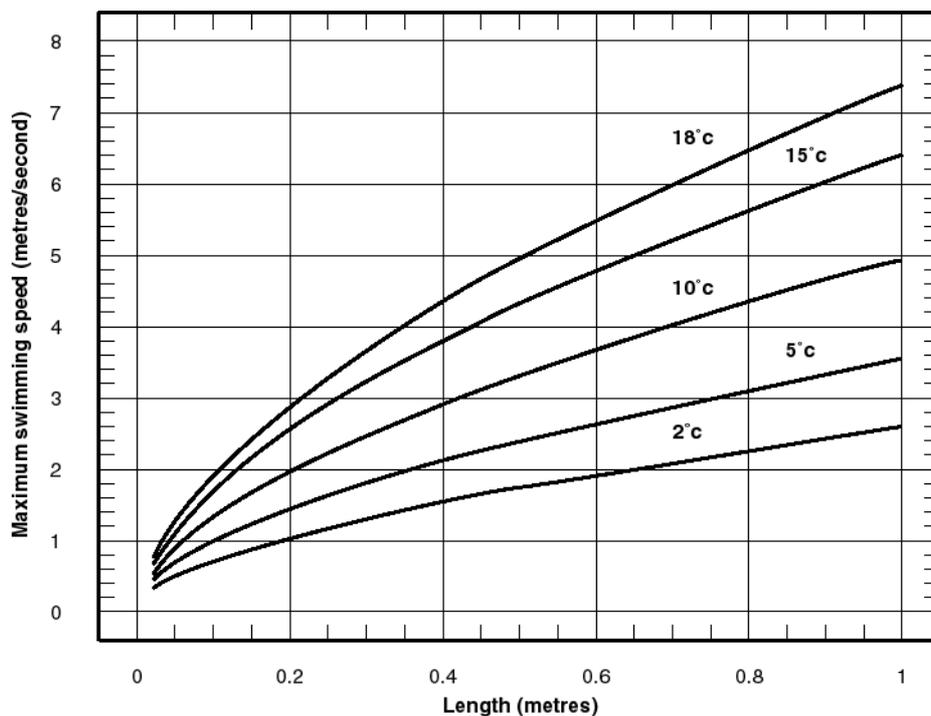


Figure 1: Maximum swimming speed vs. fish length and temperature for salmonids (after BEACH, 1984).

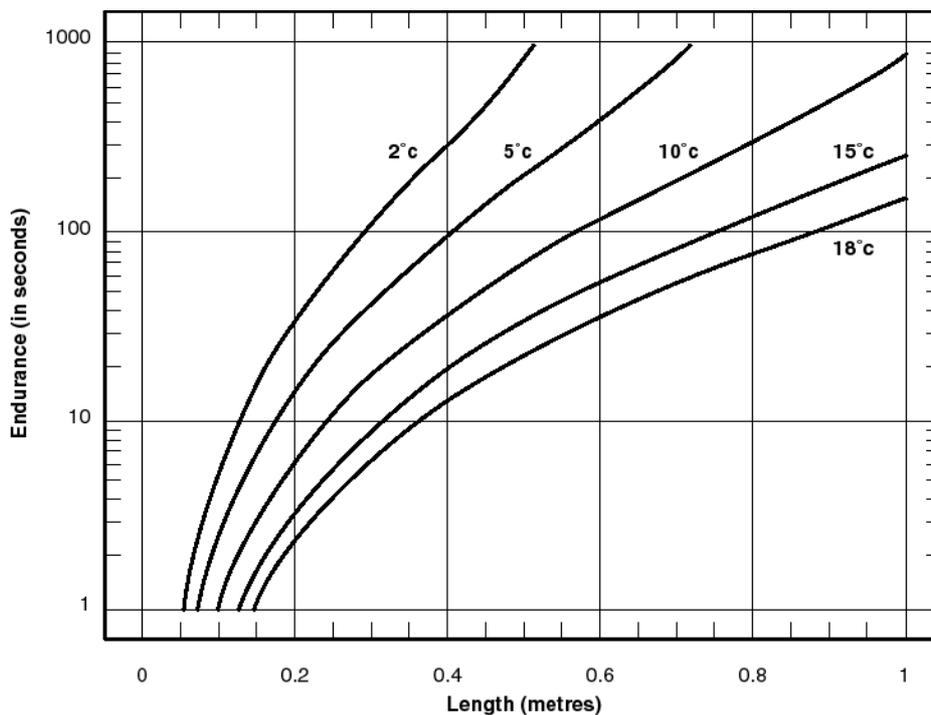


Figure 2: Endurance at maximum speeds vs. fish length and temperature for salmonids (after BEACH, 1984)

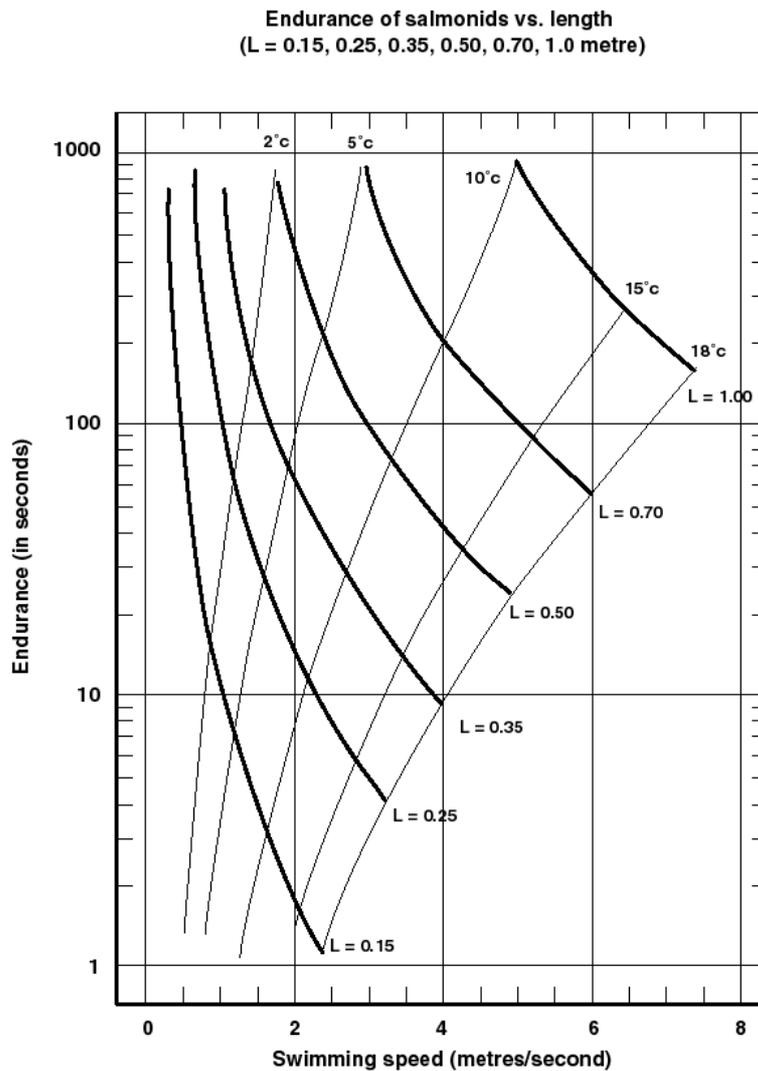


Figure 3: Swimming speed and endurance vs. fish length and temperature for salmonids.

Maximum cruising speed (the maximum speed at which fish can swim continuously without showing any signs of fatigue) increases rapidly with the size of the fish. VIDELER (1993) proposed an equation based on a compilation of experimental results (obtained for fish length < 0.55 m) giving the maximum cruising speed (m/s) in relation to body length L (m):

$$V_{cr} = 0.15 + 2.4 L$$

The same experimental results can also be described by the following equation:

$$V_{cr} = 2.3 L^{0.8}$$

The maximum cruising speed is around 1.7 to 2.5 m/s for salmon, 0.60 to 1.3 m/s for brown trout depending on the length of the individual; and around 0.50-0.60 m/s for Atlantic salmon smolts 0.15-0.20 cm long.

1.3 Maximum distances which can be covered at a given water velocity

From the preceding empirically derived relationships (BEACH, 1984) the maximum distance D , which can be covered by a fish in a flow of given velocity, U , may be determined.

This distance is expressed as:

$$D = (V-U) T$$

where T is the endurance (expressed in seconds) of the individual fish swimming at speed V .

This expression can be used to estimate the maximum distances that may be covered by salmonids of a given length and express them graphically. For example, Figure 4 shows the maximum distances which may be covered by salmonids of 0.35 m and 0.25 m in length.

These curves are relatively close to the semi-empirical curves proposed by ZIEMER (1961) and EVANS and JOHNSTON (1980) shown in Figure 5, except that the latter do not take temperature into account.

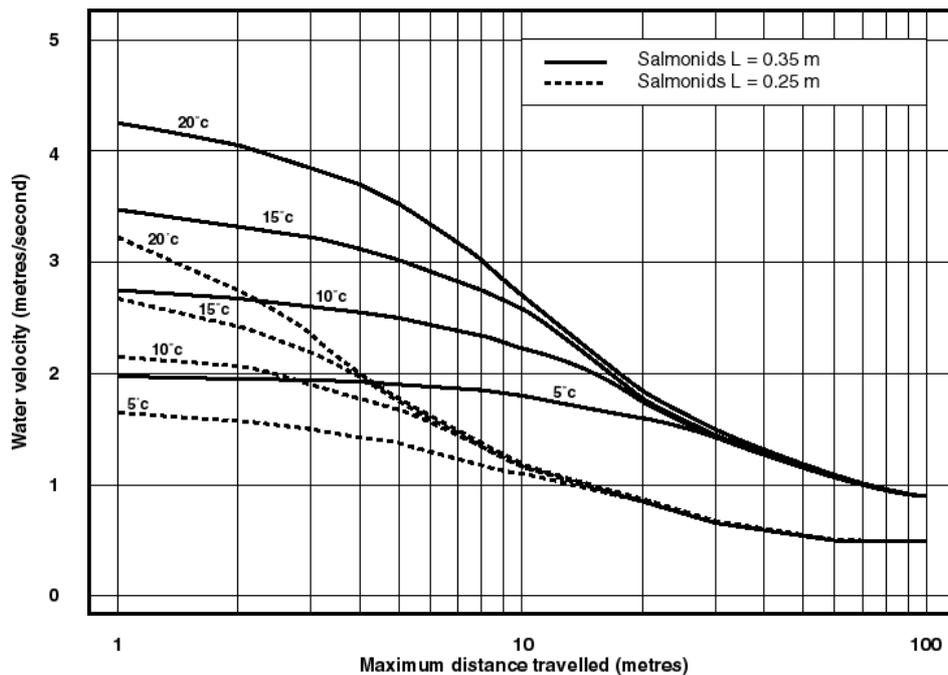


Figure 4: Maximum swimming distance vs. water velocity and temperature for 2 lengths of salmonid.

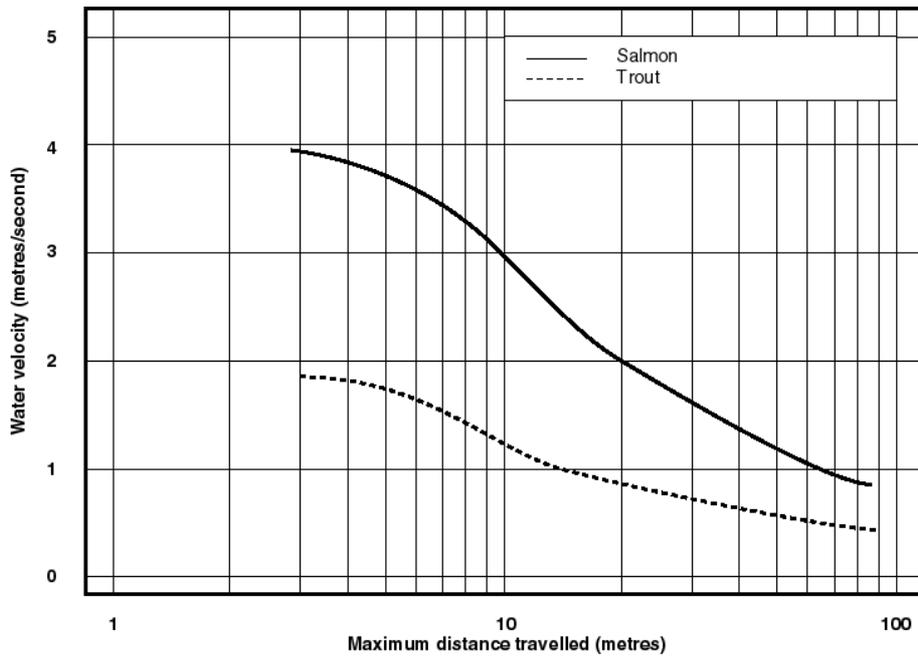


Figure 5: Swimming capacity of migrating salmon and trout (after ZIEMER, 1961 and EVANS and JOHNSTON, 1980).

1.4 Capacity to leap

Certain species, particularly salmonids, are capable of leaping over an obstruction provided that they find, at the foot of the obstacle, conditions that enable them to use this skill.

The movement of a leaping fish may be compared to the trajectory of a projectile. The equation for a trajectory may be expressed in the form:

$$X = (V_0 \cos \alpha) t \quad Y = (V_0 \sin \alpha) t - 0.5 g t^2$$

where X and Y are the horizontal and vertical distances covered by the projectile (in this case the fish) V_0 the initial speed, α the angle of incidence to the horizontal plane, and g the acceleration due to the gravity (9.81 m/s^2). The trajectory of the fish is parabolic, the maximum height reached by the fish depends on its initial speed and the angle of the leap from the water:

$$Y_{\max} = (V_0 \sin \alpha)^2 / 2g$$

The horizontal distance corresponding to the maximum height X_{\max} is given by the expression:

$$X_{\max} = V_0^2 \cos \alpha \sin \alpha / g$$

Figure 6 shows the theoretical leaping curves for salmon as a function of the angle of leap from the water surface and temperature. It clearly demonstrates the dominant role which temperature plays on the height of the obstacle which can be leapt over.

However, it should be noted (POWERS and OSBORN, 1985) that for greater accuracy it may be advisable to add a height corresponding to a large fraction of the length of the fish to the height Y_{max} . This is because the fish uses its propulsive force until its caudal fin leaves the surface of the water. On the other hand, the preceding equation does not take account of the increasing component of the existing water velocity at the foot of the fall from which the fish can benefit. The values for leaping from the above formula are therefore conservative.

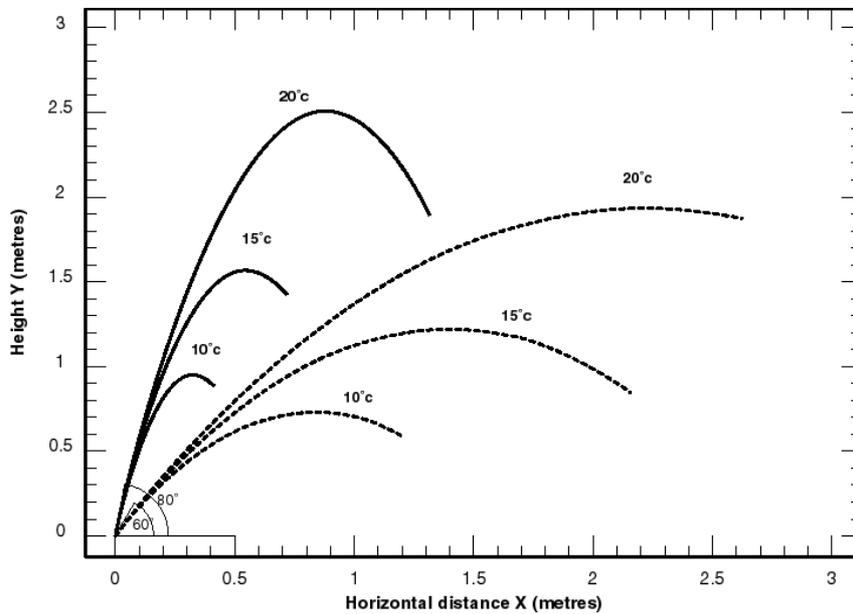


Figure 6: Theoretical leaping curves vs. temperature and angle of the leap from the water surface for salmon (length 0.80 m).

1.5 Swimming capacity and fishways

The maximum speeds proposed above relate to fish in excellent physical condition (no injuries, short time of residence in fresh water by large migrators, etc.). Furthermore, endurance must be considered to be the period of maximum effort resulting in total exhaustion of the fish. In practice, it is advisable to stay well within these limits when deciding or estimating the effort that is required of migrants at a fish passage facility.

The use of the mean water velocity (discharge divided by the cross-sectional area normal to the direction of the flow) as the sole criteria for passability of an obstacle or for the sizing of a fishway, is not a straightforward matter:

- Firstly, the fish are capable of perceiving very slight variations in water velocity and generally exploit the most favourable zones to help them make progress. For example they might use the lower velocity of the boundary layer in the vicinity of a surface (wall or floor) to progress, or they might use a recirculating flow (such as an eddy downstream of an obstacle) to rest.

- On the other hand, when major spatial or temporal fluctuations occur in the water velocity, (e.g. in a very turbulent flow for example), **the energy which the fish needs to travel a certain distance may increase considerably**. That is when it is compared to that required to cover the same distance in a more regular flow with parallel streamlines having

the same average velocity. This can be particularly critical in circumstances when the maximum velocity of the flow comes close to the burst speed of the fish.

This applies particularly to the Denil fishways, which are characterised by very aerated, three-dimensional flow patterns, with relatively moderate mean flow velocities associated with very high turbulence intensities.

The figures given above demonstrate that the smaller species have a limited burst speed, and that often they can only sustain these speeds or slightly lower speeds for a very brief period (a few seconds).

Only natural bypass channels and pool fish passes are suitable for these species. In pool fish passes, the fish only has to make an effort to pass the notch, slot, or orifice over a distance of no more than several decimetres. The fish may also avoid zones of maximum velocity in the jets between pools by using the lower velocities of the boundary layer or of the recirculation regions on each side of the jet.

Bottom-baffle fishways, in which local water velocity in the best cases is still in the neighbourhood of 1 m/s (pass with small flow, hydraulically efficient baffles), and which are very sensitive to variations in the level upstream, may only be used for large fish (salmon, sea trout).

Plane, FATOU or Alaskan baffle fishways, in which the velocity may be as low as 0.7-0.8 m/s, are likely to ensure passage for small species or individuals. This is on condition that the length of the flights be less than 6-8 m, and that the size of the baffles be reduced in keeping with the size of the fish.

2. LIGHTING AT FISH PASSAGE FACILITIES

If a pass has to be covered, or else passage has to take place in some form of culvert, then the question arises as to whether or not to light the fishway.

A number of observations made on salmonids (AITKEN *et al.*, 1966; ROGERS and CANE, 1979) show that the fish can use a very long pass or tunnel without any lighting being required.

According to BELL (1986), the progress of the migrators is not slowed down by darkness.

Experiments carried out on the west coast of the USA (LONG, 1959) showed that while a migrator (steelhead trout) delayed longer before entering a darkened pass, once it had done so, it would pass it more quickly than when the same pass was lit. Whereas it took two minutes per pool in the darkened fish pass, it took more than eight minutes per pool in the illuminated pass.

Experiments were carried out with a view to using lighting to encourage migrators to use the fishways at night. All the trials were inconclusive. At The Dalles dam (West Coast USA), less than 10% of the migrators used the pass between 20.00 hrs and 04.00 hrs, irrespective of whether or not the pass was lit. At the McNary dam, the trials showed that the fish did not enter the pass at night, no matter what the lighting conditions. In contrast, the light allowed the fish which did enter the pass before nightfall to complete their passage (FIELDS, 1966).

Observations on some plants (Grand Sault, Madeleine River, Quebec) showed that Atlantic salmon did not enter the underground section of a pool pass when the transition from light to darkness was sudden. The pass did not function correctly unless it was lit.

At the Tuilières plant on the Dordogne, the exit from the fish lift consists of nine underground pools. The fish trapped in the lift tank are released into the downstream pool of a covered pass. The artificial lighting in this fishway has proved to be essential to enable the shad to pass through successfully, since they would otherwise tend to remain stuck in the naturally lit pools at the downstream end of the facility (DARTIGUELONGUE *et al.*, 1992).

Conversely, lighting in a fish passage facility may prevent nocturnal migration of some lucifugous species (*e.g.* eels), some or even all of which may be deterred.

Experiments have been carried out to attempt to determine the influence of lighting on the passage of various species of Pacific salmon and trout in pipes with a diameter of 0.6 and 0.9 metres (SLATICK, 1970). The results showed that all the species could pass through the pipes without lighting. Of the four species tested (chinook, coho, sockeye salmon and steelhead trout), only steelhead trout seemed to benefit significantly (in terms of the percentage completing the passage) from the lighting in the pipes. However, the speed of passage seemed to be faster for steelhead trout and sockeye and coho salmon when the pipe was lit, whilst the opposite was true with chinook salmon.

In conclusion, it would appear preferable, if a pass has to be covered or buried, to avoid any sudden transition between the intensity of outside light and that inside the pass or pipe, through some form of lighting in the first section (artificial light, windows, widening the entrance). Some authors (METSKER, 1968) recommend the use of vegetation at the entrance and exit of the pass (in the case of culverts) in order to provide a gradient in the lighting conditions.

If from experience, lighting throughout a pass does not appear to be an essential requirement for most species to use it (except perhaps for some species such as shad), it can always be retained as a safety factor when designing a fish pass.

3. THE CONCEPT OF AN OBSTRUCTION TO MIGRATION

There is often a tendency to associate the concept of an obstruction to migration with the height of the fall. The reality is much more complex. Whether an obstacle can be passed or not depends on the hydrodynamic conditions at the foot of the obstacle (velocity, depth of the water, configuration of the jets, aeration, turbulence, etc.) in relation to the swimming and leaping capacities of the species concerned.

The hydrodynamic conditions depend both on the geometry of the obstruction (height and configuration, slope, length, etc) and the discharge passing it, which is related to the hydrological conditions at the time of migration as well as the operation of any plant.

Figure 7 shows several configurations of obstacles with the same head drop across them. If the swimming ability of the fish allows it, obstacle (a) is passable. In (b), the depth of water is inadequate on the downstream face, preventing the fish from swimming. In (c), the presence of a shallow apron at the foot of the dam and the absence of a suitable depth of water make it impossible for the fish to pass, no matter what its swimming capacity. In (d), the presence of a sill to enhance the head stops the fish at the point where it causes an abrupt change in the water profile.

It has been seen that the swimming and leaping capacities depend on the species and size of the individuals, their physiological condition and the ambient temperature conditions. The difficulty of passage at an obstruction is therefore linked to its geometry, to the species concerned and the hydrological and temperature conditions during the migrating season. For all these reasons, most authors consider that a head difference of even less than 0.50-0.60 metre may be impassable to large migratory salmonids, and perhaps even lower for other species with a lower swimming capacity, such as the eel.

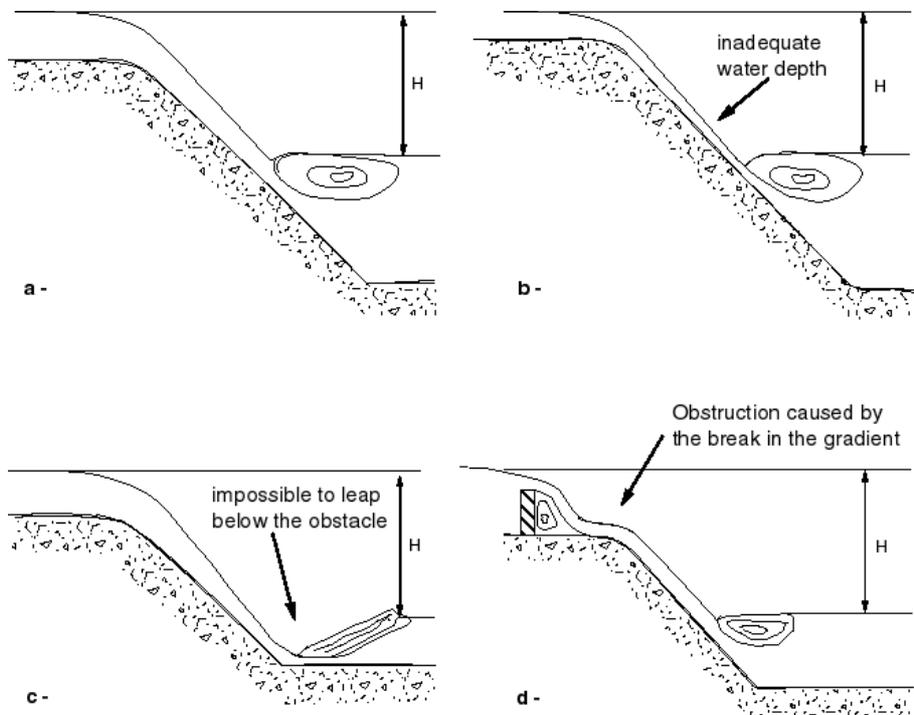


Figure 7: Schematic plan illustrating the influence of the profile of a weir on difficulty for fish passage.

The passability of an obstruction must be considered for each migratory **species** present in the watercourse. For any given species, an obstruction on a watercourse may be **total**, *i.e.* permanently impassable for **all individuals**. It may be **partial**, *i.e.* impassable for certain individuals. It may be **temporary**, *i.e.* completely impassable at certain times of the year (under certain hydrological or temperature). It is frequently the case that low obstacles are impassable during low flows because the depth of water on the apron is too shallow to permit fish to swim. Some low weirs may be impassable at low temperature, the fish having insufficient swimming capacity to pass at this time.

The negative impact on fish caused by temporary obstacles which delay them during migration and may cause them to stay in unsuitable zones in the lower part of the watercourse, or cause injury as a result of repeated, fruitless attempts to pass, must not be underestimated.

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