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CHAPTER 13

DOWNSTREAM MIGRATION: PROBLEMS AND FACILITIES

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1. OVERVIEW

Downstream fish passage technology is much less advanced than it is for upstream fish passage facilities. This is simply due to the fact that efforts to re-establish free movement for migrating fish began with the construction of upstream fish passage facilities, and that downstream migration problems have only been recognised and addressed more recently. It is also because it is much more difficult and complex to develop effective facilities for downstream migration. This situation is not restricted to France, since as yet, no country has found satisfactory solutions for downstream migration problems, especially where large installations are involved (EPRI, 1994).

2. SPECIES AND STAGES INVOLVED IN DOWNSTREAM MIGRATION

Downstream migration, *i.e.* migration descending a river towards the sea or a lake, concerns fish at different stages of development, depending on the species. The diadromous and potadromous species which are legally recognised and listed as protected migratory species in France, and the particular development stages involved in downstream migration, are as follows:

- Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta trutta*): juveniles (smolts) migrating to the sea to reach their feeding grounds, and adults (kelts) after spawning. With respect to kelts it should be noted that the provision of downstream passage facilities for adult sea trout is much more important than for salmon because multiple spawning is much more frequent in trout than in salmon.

- Allis shad (*Alosa alosa*): mainly juveniles (since most adults die after spawning).

- Twaite shad (*Alosa fallax*): both juveniles and adults.

- Eels (*Anguilla anguilla*): adults only, during migration to their marine spawning grounds.

- Sea lamprey (*Petromyzon marinus*) and River lamprey (*Lampetra fluviatilis*): juveniles of both, and also adults in the case of river lamprey.

- Brown trout (*Salmo trutta fario*) and Grayling (*Thymallus thymallus*): juveniles migrating to downstream feeding grounds, and adults after spawning.

- Pike (*Esox lucius*): both adults and juveniles.

Although not specifically listed and thus protected by legislation many riverine species (cyprinids, piscivorous species) move significant distances both upstream and downstream during their life cycle. This may involve movements in annual, seasonal or even daily cycles for purposes including spawning, dispersion, feeding, shelter and colonisation.

Migration occurs at specific times according to the species and stage of development.

3. PROBLEMS ARISING IN HARNESSED RIVERS WITH DOWNSTREAM MIGRANTS

The installation of a dam on a river can cause many problems for downstream migration. These can include:

- the delay, or even the total prevention of downstream migration in still water zones in the impoundments;

- damage to fish when passing over spillways or through turbines;

- mortalities as a result of predation by fish or birds either in the impoundment or else at the outlet of turbines;

- mortalities due to changes in water quality (deficit in oxygen content in the impoundment, super saturation of atmospheric gases downstream of turbines or spillways).

Only specific problems related to hydroelectric plants will be considered further here (*i.e.* those related to water quality will be left aside).

As a general rule, all these problems have been thoroughly studied with respect to anadromous species, and more particularly to salmonids, but comparatively little information is available on other migratory species. The following comments apply to migrating juvenile salmonids unless specified otherwise.

3.1 Passage through spillways

Passage through spillways may be either a direct cause of injury or mortality, or else an indirect cause resulting from the increased susceptibility of disorientated or stunned fish to predation and disease. Studies carried out at various sites abroad (USA, Canada, etc.) have shown that the direct mortality rate varies greatly from one location to another. Relatively low mortality rates between 0% and 4% have been recorded for the Bonneville, McNary and John Day dams on the Columbia River, which all have spillways about 30 m high. In contrast, on the Elwha river, mortality rates at the Glines dam (60 m high spillway) and Lower Elwha dam (30 m high spillway) were much higher at 8% and 37% respectively (BELL and DELACY, 1972; RUGGLES, 1980; RUGGLES and MURRAY, 1983).

It appears that the manner in which energy is dissipated in the spillway can have a profound effect on fish mortality rates. The mortalities can be due to several causes including shearing effects, abrasion against spillway surfaces, turbulence in the stilling basin at the base of the dam, sudden variations in velocity and pressure as the fish hit the water, and physical shock or damage from collisions with aprons or baffles.

When passing over a spillway then entering the pool, fish can fall in one of two ways, either in free-fall (*i.e.* free from the water column), or else contained within the column of falling water.

When a fish is falling in free-fall conditions it reaches a terminal velocity that is related to its length. This terminal velocity is about 12 m/s (after a 25-30 m fall) for fish from 10 to 13 cm in length, 15-16 m/s (after a 30-40 m fall) for fish from 15 to 18 cm, and more than 58 m/s (after a fall of more than 200 m) for fish of 60 cm. Experiments have shown that, whatever the size of fish, significant damage occurs (injuries to the gills, eyes and internal organs) when the impact velocity on the water surface exceeds 15-16 m/s (BELL and DELACY, 1972). This critical velocity is reached after a free fall of around 30-40 m for fish of 15-16 cm in length, but only 13 m for fish longer than 60 cm.

Free-falling fish with a length of less than 10-13 cm, whose terminal velocity remains below critical velocity, do not suffer any harm whatever the height of the fall. Larger fish do not suffer damage, provided that the impact velocity remains below the critical velocity of 15-16 m/s. The latter corresponds to a fall varying from 12 metres in height for large individuals (length > 60 cm) to 30 metres for fish which are 18 cm long.

The expectancy of survival for a fish passing over a spillway and entering a pool while contained in the column of water, provided that it decelerates in a jet without undue deflection, will be the same as under the best free-fall conditions, with the same impact velocity of the jet on the surface of the water (BELL and DELACY, 1972). A column of water reaches the critical velocity for fish (16 m/s) after a drop of 13 m. For heights greater than this, there is a risk of significant injury and mortality will increase rapidly in proportion to the drop (100% mortality for a drop of 50-60 m).

In short, passage through a spillway under free-fall conditions is always less hazardous for small fish (under 15-18 cm in length) because they never reach a terminal velocity that is more than the critical velocity. For larger fish the hazards are identical whether they pass under free-fall conditions, or whether they are contained in the column of water.

In all cases, the less the turbulence at the base of the dam, and the smaller the physical strike (which relies on sufficient volume of water and the absence of dangerous structures such as energy dissipaters) then the greater the chances of survival for fish.

Provided that there is a pool of a sufficient volume at its base “ski jump” spillways, where the column of water falls free into the pool below, are preferable to other types of spillway, because the abrasion on the spillway face is eliminated (RUGGLES and MURRAY, 1983). This is particularly the case for small fish, and all the more so if it enables fish to fall freely outside the water column.

In France spillways are rarely a problem for fish, particularly those on rivers used by amphibiotic species where dams are generally of moderate height (less than 10 metres). Provided that they are able to fall safely on the downstream side, with sufficient depth at the base of the dam and no over-aggressive baffles (pre-cast blocks, rip-rap, etc.), then spillways are usually considered to be the safest way for fish to pass a dam.

3.2 Passage through hydraulic turbines

Fish passing through turbines are subjected to various forms of stress that are likely to cause high mortality. These stresses include strike from moving or stationary parts of the turbine (guide vanes, vanes or blades on the wheel), sudden acceleration or deceleration (from 3-5 m/s at the entrance of the turbine to 10-30 m/s within the wheel), shear, very sudden variations in pressure, and cavitation.

Numerous experiments have been conducted in several countries (USA, Canada, Sweden, Switzerland, Germany and France), ***mainly on juvenile salmonids***, but also on clupeidae and eels, to determine their mortality rate when passing through the main types of turbine. These are summarised in BELL, 1981; MONTREAL ENGINEERING COMPANY, 1981; MONTEN, 1985; EPRI, 1987; LARINIER and DARTIGUELONGUE, 1989; EPRI, 1992).

The mortality rate in Pelton turbines is 100%. Fortunately, these turbines are only used for very high heads and are not installed on rivers used by amphibiotic species.

The mortality rate for ***salmonids*** (juvenile salmon and trout) in Francis and Kaplan turbines varies greatly, depending on the properties of the runner (diameter, speed of rotation, etc.), their mode of operation, the head, and the size of the fish concerned. The rate varies from under 5% to over 90% in Francis turbines. On average, it is lower in Kaplan turbines, from under 5% to approximately 20%. However, the difference between these two types of turbines is simply due to the fact that Francis turbines are generally installed with higher heads. When both types of turbine are installed with the same head and discharge then the damage caused is similar. Low values of mortality rates (around 5%) have been recorded in the large low-head Francis turbines of the Mauzac power plant on the Dordogne river (LARINIER and DARTIGUELONGUE, 1989).

The mortality rate varies between fish species. In physostomes (salmonids, clupeidae and cyprinids) the pressure in the swim bladder can be regulated relatively quickly through the air canal and the mouth, and these species can resist sudden variations in pressure quite well. On the other hand, in physoclists (perch and pike perch), the pressure is regulated much more slowly by gaseous exchange through the blood vessels in the wall of the swim bladder. The risk of rupturing the swim bladder following a sudden drop in pressure is thus much greater, and these species are thus much more susceptible to variations in pressure.

Generally, the mortality rate in ***adult eels*** is generally high because of their length. It may be 4 to 5 times higher than that in juvenile salmonids. Typical values are between 15% and 30% in large low-head Kaplan turbines, and even 50% to 100% in the smaller turbines used in most small-scale hydropower plants (MONTEN, 1985; LARINIER and DARTIGUELONGUE, 1989; DESROCHERS, 1984; HADDERINGH and BAKKER, 1998). The lowest values, around 6%, have been recorded in low-head, three-blade, Kaplan turbines (HADDERINGH and BAKKER, 1998).

Until recently, it was thought that ***juvenile shad*** were more susceptible to turbine mortality than salmonids. Comparative recorded mortality rates were between 65% and 80% in turbines where the salmonid mortality rate was around 10% to 15% (TAYLOR and KYNARD, 1985). However more recent experiments using new methods (individual balloon tags which inflate once they have passed through the turbine to bring the fish up to the surface) suggest that the mortality rates are actually similar to those observed in salmonids (RUGGLES, 1992; HEISEY *et al.*, 1993). Mortality rates for shad had been over-estimated because of the experimental protocols and recovery techniques used.

Various formulae for predicting the mortality rate have been suggested. In a study carried out in France (LARINIER and DARTIGUELONGUE, 1989) formulae were developed, based on the properties of the turbine and the size of the fish, to predict the mortality rate of juvenile salmonids and eels in Francis and Kaplan turbines.

In the case of **Francis turbines**, the regression formula which best expresses the mortality rate for juvenile salmonids is as follows:

$$P = [\mathrm{SIN}(-4.21 + 1.25\,V1^{0.821} + 2.28\,N^{0.19}\,(TL/esp)^{0.84}\,W1^{0.71})]^2 \qquad (R = 0.87)$$

where P is the mortality rate (between 0 and 1), V1 (in m/s) and W1 (in m/s) are the absolute and relative velocities at the entrance to the runner, N (rpm) is its speed of rotation, TL (in m) is the length of the fish, and esp (in m) is the distance between the vanes, measured at mid-height.

The drawback with this formula is that the geometry and mode of operation of the runner must be known in order to evaluate the characteristics of the entrance velocity triangle. A simpler alternative formula with parameters that are more easily avalaible may be used:

$$P = [SIN(6.54 + 0.218\ H + 118\ TL - 3.88\ D1m + 0.0078\ N)]^2 \qquad (R = 0.85)$$

where H is the net head (in m), D1m the entrance diameter of the wheel measured at mid-height (in m), N (in rpm) is the speed of rotation, and TL (in m) is the length of the fish.

The only factors that have a significant effect on the mortality in **Kaplan turbines** are the length of the fish (TL in m), and the distance esp (in m) between the blades (number Np) at mid-blade (esp = 3.14 D1m/Np).

For juvenile salmonids:

$$P = [SIN(13.4 + 42.8(TL/esp))]^2 \qquad (R = 0.59)$$

For eels:

$$P = [SIN(28.6 + 48.7(TL/esp))]^2 \qquad (R = 0.85)$$

In most cases these formulae give a rough estimate of mortality rates, and serve to identify those installations that are likely to cause substantial damage. However they generally tend to overestimate damage caused by large low-head Kaplan-type turbines, where mortality rates are generally less than 5% for juvenile salmonids. This over-estimation can be explained by the angular transformation (arcsine) used for mortality rates in statistical computations. While this transformation is recommended in statistics when working on proportions or percentages, it is not as good at the extreme ends of the range of possible values (*i.e.* near 0 and 1) as it is elsewhere. It would be advisable to do a new analysis without using this transformation while accepting the risk of predicting negative mortality rates for some of the very largest turbines.

3.3 Predation

The installation of hydropower plants tends to increase mortality rates amongst migrating species by making them more vulnerable to both piscivorous birds and to piscivorous fish in the vicinity of the installation. Impoundments may provide a habitat that can support very considerable populations of piscivorous species. They can also cause accumulations of migrating fish above a dam, which are more easily exploited by predators. After crossing through a plant fish may be damaged, stunned, stressed, disoriented or become trapped in turbulence or recirculating eddies at the base of the dam. All of these situations increase the vulnerability of the migrator to predators. Although little data is available to demonstrate it, predation may have a significant impact on overall mortality rates. Mortality rates of up to 32 % have been reported for smolts released immediately downstream from the spillway of two dams of the Snake River (RUGGLES and MURRAY, 1983). In Denmark mortality rates were respectively 81-85 % and 99 % for salmon and sea trout smolts migrating through low depth impoundments installed on two streams (RASMUSSEN *et al.*, 1996).

4. DOWNSTREAM MIGRATION FACILITIES

4.1 Overview

Passage facilities for fish migrating downstream are installed to prevent fish from being entrained in the turbine intakes, and to guide them to a bypass that will transport them safely downstream around the installation.

During downstream migration fish tend to move with the current. Engineers must take this characteristic pattern of behaviour into account when designing downstream fish passage facilities. The facilities must be designed so that the fish are guided to the bypass by the hydraulic flow pattern and are not required to swim upstream to find a safe route around the facility (ASCE, 1995).

Although there are many different systems for preventing fish from being entrained into water intakes, they are by no means all equally effective. They may take the form of barriers that physically exclude fish from the turbine intakes, or they may take the form of behavioural barriers which guide (attract or repel) fish using some form of stimulus. Whichever of these types are used, both include direct transfer, or else capture and transport devices to bypass the obstacle.

4.2 Physical barriers

An obvious way of excluding fish from the turbines is to use screens with such small openings that fish cannot pass through them

Screen or filtration area

The area of the screening surface is determined according to the swimming performance of the species. Flows in front of the screens must be slow enough to allow fish the time to find the bypasses, otherwise they may be impinged against the screens.

The water velocity towards the screen (*i.e.* the velocity component perpendicular to the screen face as measured about 10 cm upstream) should be adjusted to suit the swimming abilities of the species and life cycle stages concerned. It must be lower than the upper limit of the fish's cruising speed (around 0.15 + 2.4 L, L being the total length of the fish in metres, VIDELER, 1993). For salmon smolts (15-20 cm long fish) the flow velocity can be around 50 cm/s. Slightly lower values (30 cm/s) have been used in Scotland (AITKEN *et al.*, 1966), where smolts seem to be smaller (12-15 cm). On the West Coast of the USA, where juveniles are smaller still, significantly lower values are generally adopted: 25 cm/s for juveniles longer than 6 cm and 15 cm/s for juveniles under 6 cm (CLAY, 1995; ASCE, 1995).

Orientation of the screen surface

The screens are positioned across the water intakes in such a way that they guide the fish towards a bypass. This is achieved most effectively by placing the screens diagonally to the flow, and by locating the entrance of the bypass at the furthest downstream end of the screen. The fish may be guided in one of two ways:

- the screen may be placed vertically or nearly vertically, at a slight angle to the general direction of the flow, (instead of at 90° as in most existing installations), and with the entrance of the bypass at the furthest extremity downstream,

- the screen may be tilted from the vertical to divert fish upwards in the water column, with one or more bypass entrances either through the screen itself or else just above it.

The angle of the screen surface to the general direction of the flow is in all cases less than 45°, and can be as low as 20° in certain facilities. Depending of the angle of the screen surface, a component of velocity is created parallel to the surface of the screen (tangential velocity), which can reach between one and three times the normal velocity.

Types of screen (material and free gaps)

Physical screens come in various forms including perforated plates, metal bars, wedge-wire, plastic or metal mesh.

The free gap between the bars or in the mesh depends on the length of the smallest fish to be excluded. With bar screens, a bar spacing of less than 1/10 of the length of the fish (L) seems sufficient to exclude fish from intakes. However, to avoid the risk of fish becoming wedged between bars, a smaller free gap should be adopted (around L/12-L/15).

Screen hydraulics

The efficiency of a physical barrier is closely related to its ability to guide fish towards the bypass, and to the configuration of the bypass (see section 4.5). Not only do flow velocities have to match the swimming capability of a given species, but the approach velocity to the screen also needs to be uniform. There must be no zones whose velocity is either too high or low and which could thus adversely affect fish guidance and passage. High velocity areas will result in impingement, while areas with a velocity that is too low may cause migrators to accumulate, making them vulnerable to predation.

Protection and maintenance

The screens must be protected from physical damage by large objects and also kept free of any significant amounts of debris. Accumulation of debris causing clogging can result both in physical damage to screens, and also changes in the velocity pattern which can result in impingement of the fish on the screen. A trashrack is commonly used to protect the integrity of the fine mesh screen and to limit debris accumulation at the bypass entrance. The spacing between the bars of the trashrack should take into account the size and behaviour of fish that are expected to pass through it.

Examples of physical barriers

Various types of screen have been used:

- Fine-mesh screens (2.5 cm by 2.5 cm for Atlantic salmon smolts) are installed temporarily during the migration season on the existing trashracks of water intakes (AITKEN *et al.*, 1966). The installation of such screens imposes very tight constraints both on the size of water intakes (since the velocity must be lower than 0.30 m/s) and on maintenance needs (necessity of removing the screens for cleaning).

- Fine vertical bar screens placed at an angle to the flow are widely used in the USA (ASCE, 1995). Depending on the width of the channel, the screens may be placed either at a shallow angle in a straight line, across the channel, or else in a “V” configuration to reduce the total length of the system. The angle of the screen in relation to the current should be as small as possible (15° to 45°), so that fish may be easily guided towards the bypass placed at the downstream end, and also to ensure that the screen is self-cleaning as far as possible (Figure 1).

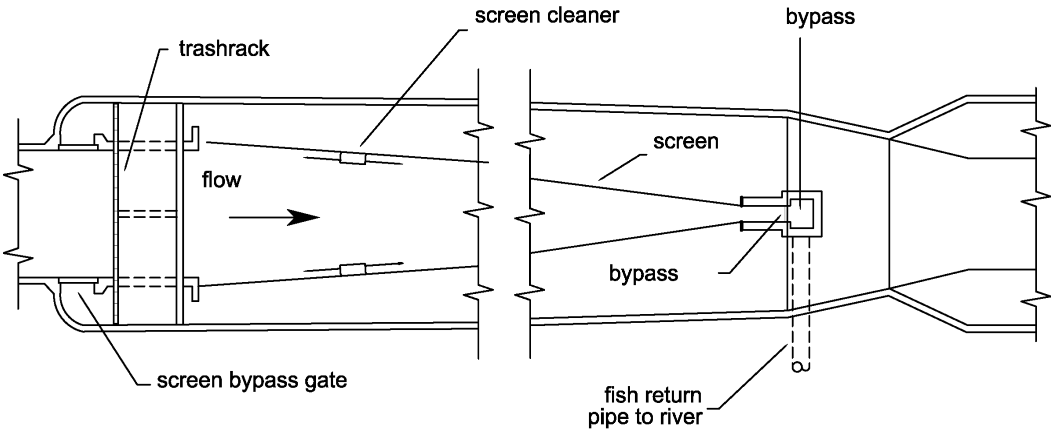

Figure 1: Angled screen (from EPRI, 1994).

- Rotating, self-cleaning drum screens are commonly used in irrigation channel intakes in the USA (NIETZEL *et al.*, 1990; RAINEY, 1990). These screens, which are generally powered by an electric motor on larger installations, provide a very effective solution to the problem of diverting fish into shallow channels (Figure 2). Existing drum dimensions can vary from 0.45 m in diameter by 0.90 m long up to 6 m in diameter by 7 m long (ASCE, 1995). They are installed across a channel at a specified angle (around 26°) to guide fish into a bypass. The mesh is made either of stainless steel or galvanised wire. The use of drum screens is limited to sites where water level variations are very limited since the screens must be 70 to 80% submerged to remain effective. Experience shows that drum screens can be highly effective in guiding salmon fry and juveniles to bypasses with very little damage to the fish.

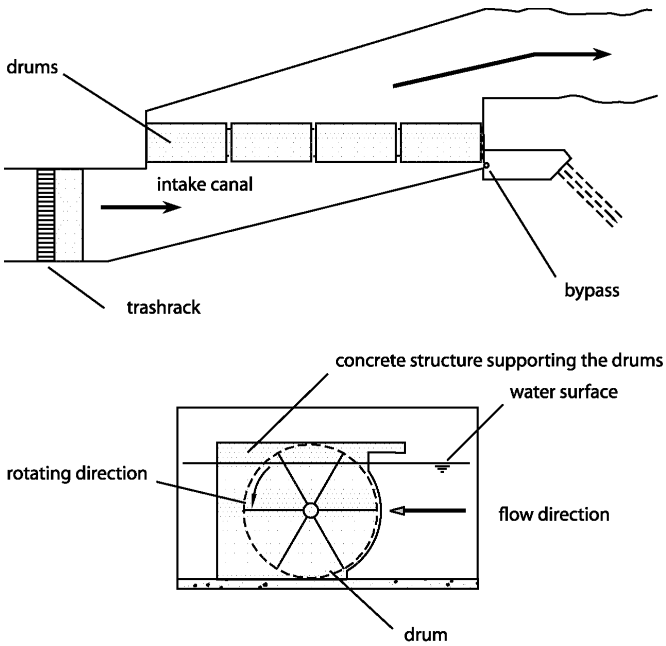

Figure 2: Angled rotary drum screens (from EPRI, 1994).

- Submerged travelling screens are used at several large hydroelectric projects on the West Coast of the USA (Columbia River and its tributaries), where the turbine flow can vary from 340 to 570 m^3/s (WILLIAMS, 1990; TURNER *et al.*, 1993). These 6 to 12 m-long screens are installed in the upper portion of the turbine intake to deflect fish into bypass systems, which then route fish either to the tailwater or to transport facilities. The design was based on observations that most out-migrating salmon smolts passed into the intake near the top of the water column. The efficiency of these screens varies greatly (20% to 75%), depending of the site, species and hydraulic conditions at turbine entrances (Figure 3). These systems are mechanically complex and are considered to be difficult to operate and maintain (NORDLUND and RAINEY, 2000).

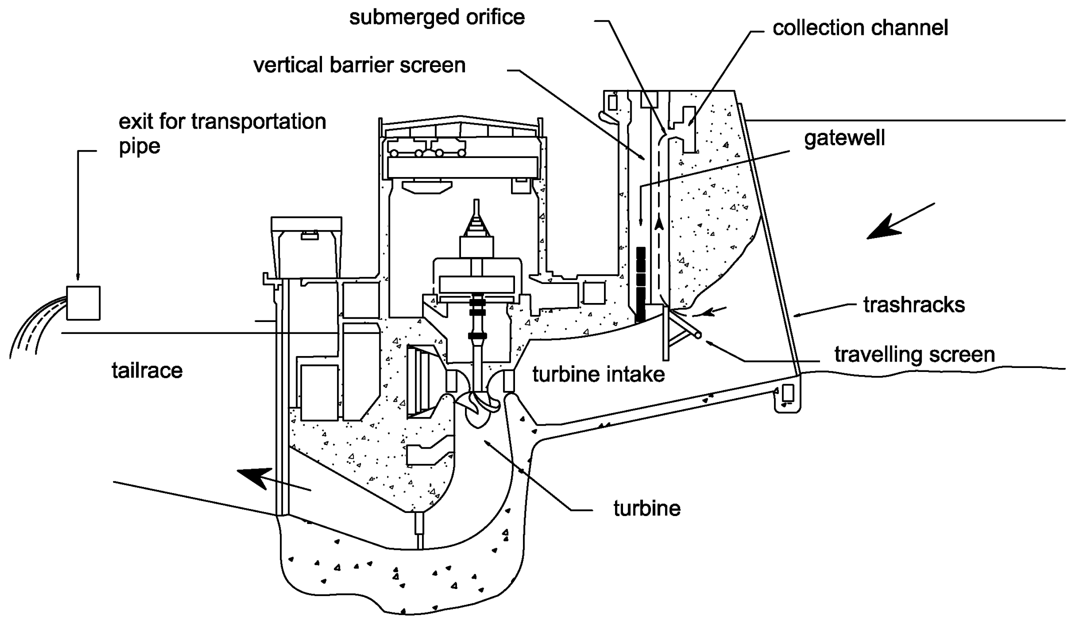

Figure 3: Submerged travelling screen.

- Eicher or “skimming” screens (EICHER, 1985) are installed at a shallow angle to the flow inside a turbine water intake, pipe, or penstock to divert the fish towards a bypass (Figure 4). The screen consists of wedge-wire bars of 2 mm triangular section spaced at intervals of 2 mm. The maximum mean flow velocity in the pipe is approximately 2.4 m/s. The normal velocities through the screen and towards the bypass entrance are 0.45 m/s and 1.5 m/s respectively. The screen is designed to rotate on an axle so that the mesh can be reversed to face the flow, thus washing off any debris. The main advantages of this type of screen are that it can operate at high approach velocities and the very smooth stainless steel profile wire, made of stainless steel, reduces the risk of injury to the fish. Survival rates greater than 90% have been observed for several species of Pacific salmon smolts with approach velocities reaching up to 2 m/s. In addition it is practically self-cleaning. These screens require protective trash-racks to be placed upstream of them to prevent large-sized debris from entering the system (WINCHELL *et al.*, 1993).

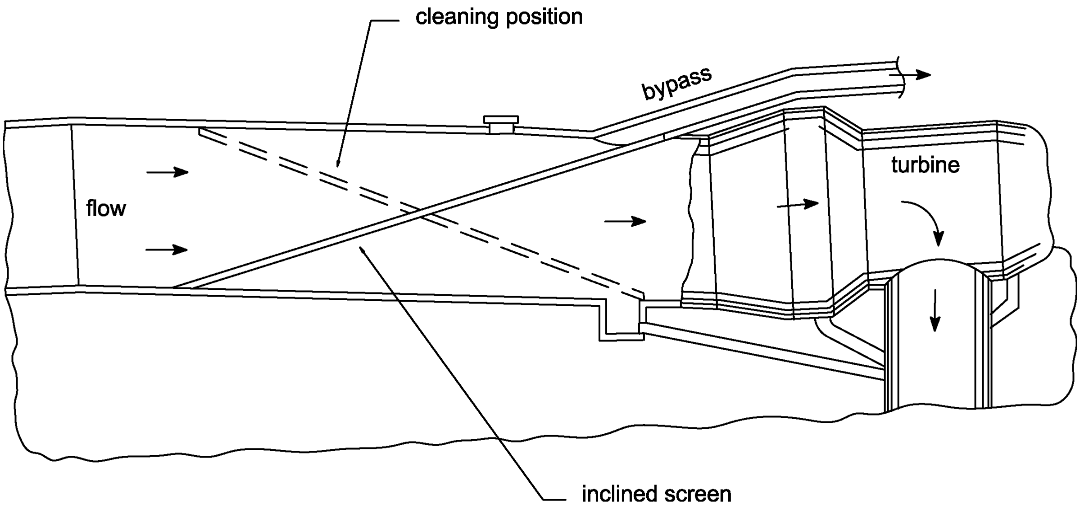

Figure 4: Eicher screen.

- The "Modular Inclined Screen" (MIS) (TAFT *et al.*, 1992) is a recent screening concept similar in many ways to the Eicher screen described above, but designed for a conduit of rectangular cross section which itself is intended to accommodate a wide range of intake and flows. The system consists of a funnel-shaped entrance with trash-racks and stop-log slot, a rectangular flat screen made of wedge-wire, placed at a slight angle to the flow (10° to 20°), and a surface bypass to guide fish downstream through a conduit. The MIS screen is axle-mounted like the Eicher screen. Scale-model tests carried out to study the hydraulic characteristics and fish behaviour have given promising results, with a fish deflection and survival rate of over 99% at high approach velocities (0.6 m/s to 3 m/s) (TAFT *et al.*, 1993).

4.3 Behavioural barriers

These are facilities which induce fish to swim in a given direction by taking advantage of their natural response to various stimuli, either attracting or repelling them. Such barriers are convenient for designers and users alike because, unlike physical barriers, they require only minimum protection against blockage, and minimal cleaning.

Visual, auditory, hydrodynamic and electrical stimuli have all been used in a wide variety of experimental barriers. These include bubble screens, sound screens, fixed and movable chain screens, attractive or repellent light screens, electrical screens, and hydrodynamic ("louver") screens. Promising results have been obtained with various experimental behavioural screens in laboratories or on test sites. However not many full scale installations have been evaluated. Furthermore the technology has not matched the expectations, and the results obtained in field applications have been much less reliable than those obtained under controlled conditions.

Care should be taken when using behavioural barriers, especially since manufacturers of these products have a vested interest in promoting the use of their technology and may deliberately overestimate their effectiveness.

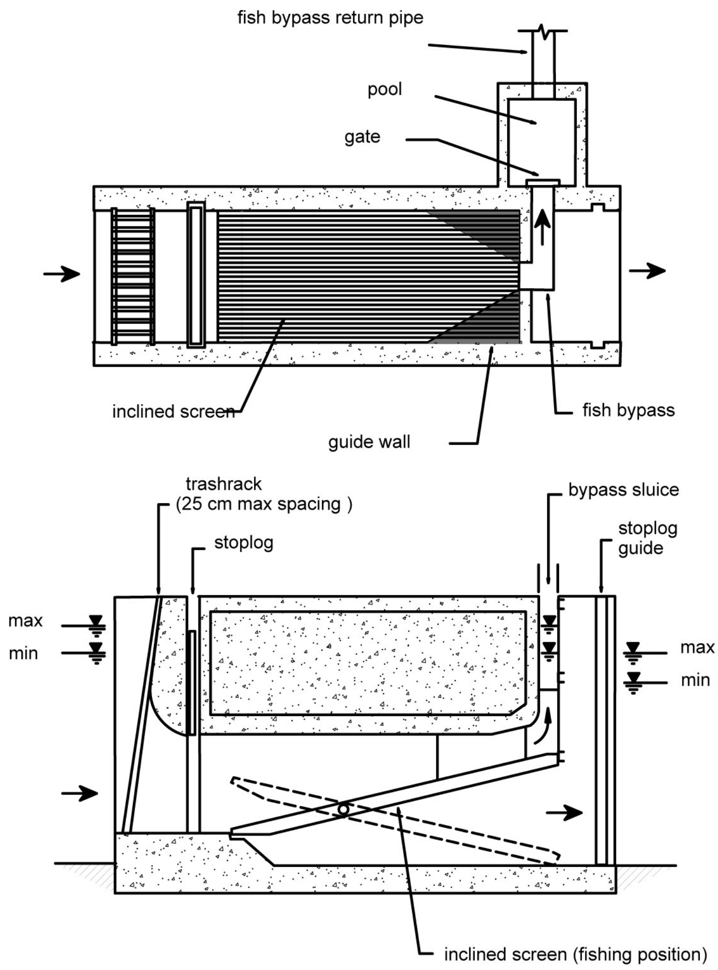

Figure 5: Modular inclined screen (MIS).

Light

Strobe lights are thought to repulse fish. Several *in situ* tests have been carried out in the United States and Canada using submerged stroboscopic lamps to divert migrating fish from water intakes. Their efficiency varied considerably from acceptable to nil (EPRI, 1994). Except in specific instances where the configuration of a site was particularly suited to the technique, it was not found to be reliable.

In terms of efficiency, promising results were obtained using 'repellent' light screens to divert adult eels travelling downstream (HADDERINGH *et al.*, 1992). These screens, which consisted of submerged, continuous light sources, exploited the lucifugous behaviour of the eel to divert it into darker areas.

Observation has shown that salmonids are attracted to a constant light source during nocturnal downstream migration. In France, the first promising results were obtained using intermittent low wattage lighting (mercury vapour lamps), where the light attracted fish to the vicinity of a bypass. The fish then tended to enter the bypass once the lamps were switched off (LARINIER and BOYER-BERNARD, 1991a; 1991b; LARINIER and TRAVADE, 1996; 1998; GOSSET and TRAVADE, 1999). Some very recent results obtained in monitored installations in France (Guilhot powerplant on the Ariège river and Poutès dam on the Allier river) have shown that using a constant light source significantly increases the efficiency of downstream surface bypasses. In the USA trials have shown that results obtained with mercury vapour lamps vary depending on the species, with some species being attracted while other are repulsed by such light (EPRI 1994).

Electricity

Electric screens have been used in several countries, including France, in the last few years but have not proven their efficiency (EPRI, 1986; EPRI, 1994). Experiments carried out over several years on Atlantic salmon smolts at a site on the Nive River in France were not encouraging, with an efficiency of only around 15% (GOSSET and TRAVADE, 1999).

Sound

Acoustic barriers are particularly attractive to power plant operators since the physical components - and hence clogging problems - are minimal. A number of experiments were conducted in the late 1980's in North America, using repellent sound effects generated by transducers. Two systems were subsequently developed and patented in the United States, one was a low-frequency (<3kHz) system from EESCO (Energy Engineering Services Company) while the other was an ultrasound system developed by Sonalysts (Fish Startle™). The low frequency system is intended to be able to deflect a wide range of species, whereas the ultrasound system is principally effective against Clupeidae (EPRI, 1994).

Other low-frequency systems have been developed in the UK by Fish Guidance systems Ltd (FGS). One, known as the SPA (Sound Projector Array) system, uses the first electromagnetic transducers developed specifically for fish deterrence rather than those developed for military or other purposes. The second is a patented device known as the BAFF (Bio-Acoustic Fish Fence). It uses a combination of acoustic transducers and an air bubble curtain. In the BAFF the sound is trapped within the air curtain, allowing the production of an acoustic "wall" that can be used to divert fish into a bypass.

To date trials with both SPA, and BAFF to divert Atlantic salmon smolts have given variable results. In the UK tests conducted in a favourable situation (small and shallow rivers, relatively large bypasses with a proportionately high discharge) gave relatively good results during the night (around 70% efficiency) but poor results (around 30%) during the day (WELTON *et al.*, 1997). In France, the trials on guiding smolts to a surface gate and to a small bypass at a small-scale hydro plant proved disappointing, since the efficiency was practically nil (GOSSET and TRAVADE, 1999; TRAVADE *et al.*, 1999).

These results may be explained by the fact that salmonids are not very sensitive to frequencies higher than 50 Hz. The maximum sensitivity has been observed at between 10 to 30 Hz, as was recently demonstrated by KNUDSEN et al (1994). Tests are being conducted in the USA to develop infrasonic barriers for salmonids (TAFT *et al.*, 1996).

Louvers

Hydrodynamic or 'louver' screens (Figure 6) consist of a series of vertical slats, each of which is at right angles to the direction of the flow (ASCE, 1995). They have been used at several sites since the 1950s, most notably at irrigation channel intakes on the West Coast of the USA (with flow rates of up to 140 m^3/s), and experimentally in water intakes of small hydroelectric stations in the maritime provinces of Canada. On the West Coast of the United States, they are gradually being replaced by inclined, rotating drum screens (NIETZEL *et al.*, 1990; ASCE, 1995). The move away from louver screens was requested by the Fisheries Agency since their efficiency, in the order of 60-90%, was considered to be inadequate for protecting juvenile salmonids given that it was much lower than that of physical barriers.

The angle of the screen across the flow generally varies between 10° and 15°. The spacing between slats varies from 2.5 cm to 15 cm depending on the size of the fish being diverted. The flow velocities towards the screen must remain constant and uniform, depending on the size and swimming abilities of the species (from 0.6 to 1 m/s for Atlantic salmon smolts). The flow velocities in the bypass itself must be 1.5 to 2 times the velocity of approach to the screen (RUGGLES, 1980; ASCE, 1995).

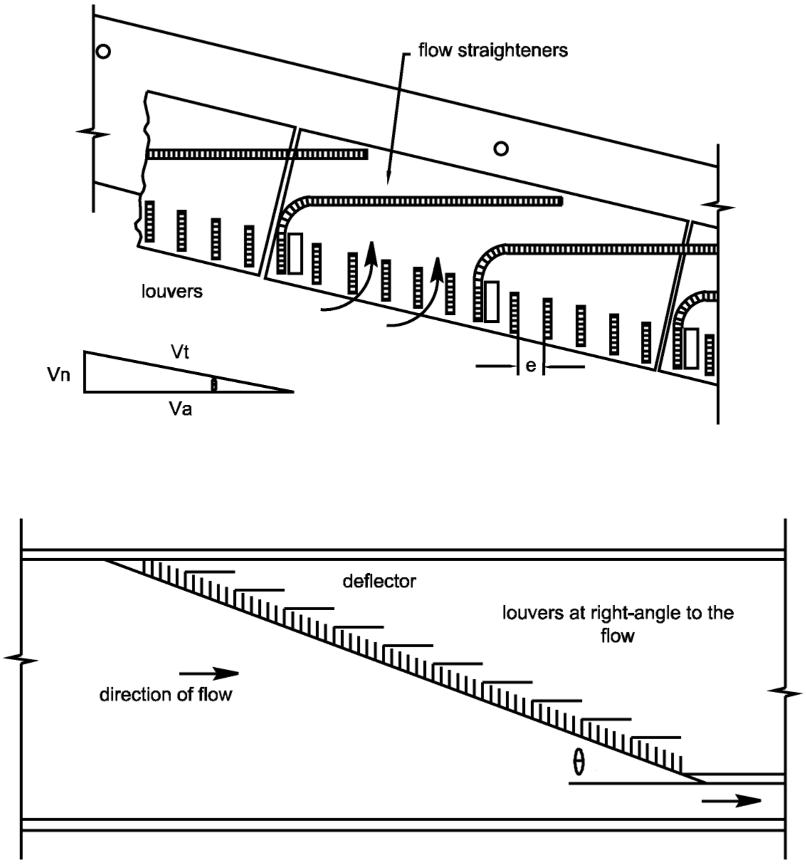

Figure 6: Louver screen.

The first louvers were installed over the full depth of the approach channel. However, more recently, several ‘partial-depth’ louver systems have been installed in the USA, based on the observation that migrating Atlantic salmon smolts and juveniles clupeids remained in the upper portion of the water column.

A partial-depth system was recently installed in the 40-meter wide and 6-meter deep intake channel (maximum flow 140 m^3/s) of the Holyoke hydroelectric power station on the Connecticut River. This very long installation consists of over 120 m of polyethylene louvers, 2.75 m deep, guiding fish towards a bypass in which the flow discharge is about 4 m^3/s. The system has an efficiency of 86% for juvenile clupeids and 97% for Atlantic salmon smolts (ODEH and ORVIS, 1998). A floating version of the system has been installed at another site (Eastman Falls power station on the Merrimack River) where results appear to be promising (RUGGLES *et al.*, 1993).

Louvers may be considered for sites where river discharge and water velocities remain relatively constant during downstream migration periods. Their efficiency is highly dependent on the flow pattern in the channel intake. The louver system generally requires a trashrack to protect the structure from debris which can seriously compromise the fish guidance efficiency.

Surface guide walls

Guide walls installed at an angle to the channel intake can be used to deflect those species that migrate in the surface layers, such as salmonids. Such a device has been installed on the East Coast of the USA at the Bellow Falls power station (Connecticut river). The wall extends vertically halfway down the 9 m deep water column, at an angle of 40° across the channel and guides fish towards a sluice gate and a channel leading to the tailrace. An auxiliary bypass located near the trashrack is intended to accommodate fish which have passed under the wall. The efficiency of the guide wall was estimated at 84%, with 10% of the smolts passing through the secondary bypass and 6% through the turbines. The efficiency of the device is probably closely related to the angle of the wall with respect to the flow and above all to the depth at which (4.5 m) the wall is submerged (ODEH and ORVIS, 1998).

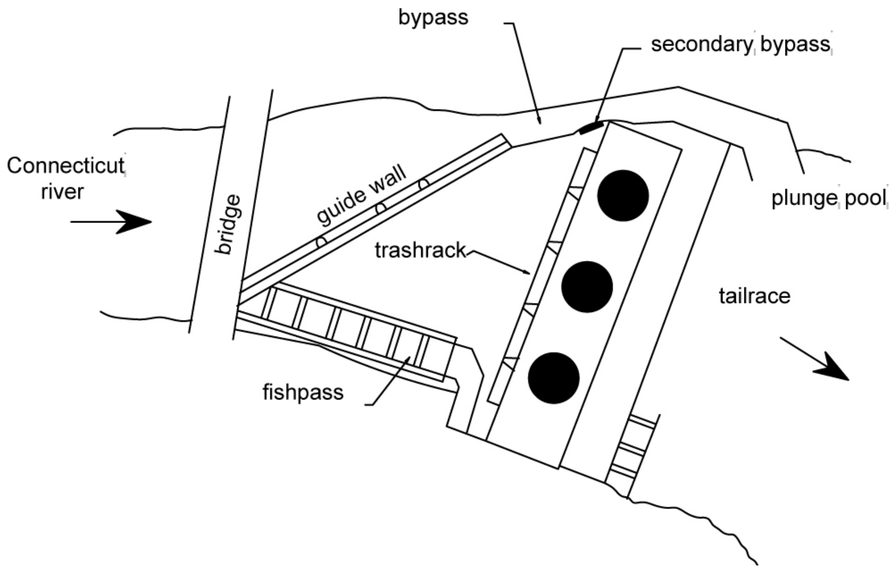

Figure 7: Guide wall at Bellows falls power station (from ODEH and ORVIS, 1998).

4.4 Conventional trashracks combined with downstream bypasses

In France most hydro-schemes were constructed before the importance of downstream migration facilities became clear. Retrofitting existing facilities with the installation of physical barriers, such as fine mesh screens, was considered to be unrealistic. This was because it would have required enlarging most of the water intakes, in order to reduce approach velocities and increase filtering areas. Research has thus focused on less expensive and less cumbersome technology.

Initial promising experiments, conducted to assess the efficiency of surface bypasses in association with the existing conventional trashrack for diverting juvenile salmon and sea trout gave promising results. In most installations the trashracks are installed at the surface and can act as a physical barrier for large fish (downstream migrating adults). In certain conditions they also act as a behavioural barrier for the juveniles which have been observed to be naturally reluctant to pass through. This solution is all the more suitable for deep intakes, since it is reasonable to assume that a surface bypass, if properly located and fed, can be an efficient downstream passageway for species migrating in the upper portion of the water column.

Numerous experiments have been conducted in France to quantify the efficiency of surface bypasses associated with conventional trashracks, to optimise their location and dimensions, and to determine the limitations of their use (LARINIER and TRAVADE, 1996, 1999; CHANSEAU *et al.*, 1999; CROZE *et al.*, 1999; TRAVADE *et al.*, 1999).

The experiments have shown that the efficiency of these devices is heavily dependent on two factors:

- the repulsive effect of the trashracks on fish must be sufficient;

- the velocity pattern in the canal intake must enable fish to remain for a sufficiently long time in front of the trashrack (*i.e.* existence of a sufficiently low approach velocity component perpendicular to the trashrack face) in order for them to be guided to the bypass entrance (*i.e.* existence of a well-established velocity component parallel to the trashrack).

Exactly how repellent the trashrack is will depend on both the spacing of the bars in relation to the size of the fish, and on the presence of a tangential flow velocity component creating a more or less marked 'louver' effect.

In order to prevent juvenile salmonids from physically passing through, the bar spacing should be equivalent to about one tenth of the total length of the fish (*i.e.*, 1.5 to 2 cm for individuals measuring 15 to 20 cm in length). However, in experiments with salmon and sea trout smolts, trashracks were found to have a 'behavioural' repelling effect with bar spacing varying from 2.5 cm to 4 cm (*i.e.* 1/8 to 1/4 the fish length). With bigger spaces the repelling effect diminished rapidly, and with a spacing of about 6-7 cm, juvenile salmonids would easily pass through, unless there was a very strong velocity component tangential to the trashrack.

Under favourable hydrodynamic conditions, with moderate velocities perpendicular to the screen and an easily perceptible tangential flow, it would appear that a bar spacing of about 1/7 to 1/8 the fish length ensures a marked avoidance response.

A tangential velocity component is created when the trashrack is installed at an angle to the axis of the intake channel. However, this may also result from a non-uniform approach flow to the intake. This dissymmetry of the velocity pattern can be induced by a change of direction or of cross-section of the intake channel section at a considerable distance upstream of the trashrack.

The maximum current velocity at which Atlantic salmon smolts can remain in front of the screens for a sufficient time is about 0.50-0.60 m/s. When hydraulic conditions in front of the screen are favourable *i.e.*, with a very marked transverse current guiding fish towards the bypass, then significantly higher flow velocities may be accepted.

Bypass entrances should be placed as near as possible to the trashrack face and on the side where fish tend to congregate. If there is a recirculation zone along one of the banks, then the bypass should be located there, since this is generally where fish will tend to congregate.

The effectiveness of the bypass entrance will depend not only on the discharge carried, but also on the hydraulic conditions both near to the entrance and in the bypass itself. The 'zone of influence' of the bypass, *i.e.* the region upstream of the bypass where a fish could detect the flow of water towards the bypass, can be reduced to a significant extent by any upwelling coming from non-uniform approach conditions in the intake channel. This can considerably reduce the horizontal velocity components in the direction of the bypass and thus mask its entrance. In some cases it is possible to reduce the effect of these upwelling currents by installing horizontal submerged screens or plates immediately upstream of the intake. At the Soeix (LARINIER and TRAVADE, 1996) and Camon (CROZE *et al.*, 1999; LARINIER and TRAVADE, 1999) sites, the improvement of flow conditions at the bypass entrances (obtained by installing horizontal screens) increased the efficiencies of the facilities from 15-35% to 60-75%.

The situation becomes more complex when the water intake system consists of several trashrack panels with intermediate support piers that project upstream from the face of the screen. Fish can become trapped in each of the bays created with such a system, and they cannot be easily guided towards the entrance of a single bypass. In this case, a downstream bypass will be needed for each of the intake openings.

Results from recent surveys of sites where trashracks are associated with surface bypasses in France (LARINIER and TRAVADE, 1999) showed that their efficiency varied from 55-85% when hydraulics conditions were considered to be favourable, to 10-20% where they were unfavourable. Examples of the latter were when bypasses were situated on the bank opposite the areas where fish tended to congregate, or when the bypass entrance flow conditions were inadequate, or when the trashrack repulsion effect was not sufficient.

4.5 Bypasses and downstream fish transfer

Bypasses

In order to avoid the entrainment of fish into a water intake, whatever the type of facility, one or more bypasses will be needed. They are necessary to divert fish around the obstacle and to return them safely to their original environment (*i.e.* to the tailrace or watercourse below the dam in the case of hydroelectric installations). These bypasses may be used either in conjunction with physical or behavioural barriers, or else alone, provided that fish are naturally guided to the bypass by suitable flow conditions. The latter may be the case for juvenile salmonids when the water intake to the turbines is deeply submerged.

The efficiency of a bypass depends very much on the response of the fish to the hydraulic conditions (depth of flow, velocities, acceleration, etc.) induced by its structural characteristics (location, dimensions, shape, etc.) (ASCE, 1995; LARINIER and TRAVADE, 1999).

The bypass entrance must be located close to the area where the fish have been guided or have concentrated, *i.e.* at the downstream end of a physical or behavioural barrier. The bypass for juvenile salmonids generally consists of a rectangular opening located at the surface, whose dimensions are related to discharge. Minimum bypass dimensions (width and water depth at the entrance) are based upon the behaviour of the fish which are reluctant to pass through devices which are too narrow and too shallow. For juvenile salmon a minimum of 0.40-0.50 m is recommended for both of these dimensions.

The effectiveness of the bypass is highly dependent on the hydraulic conditions at the entrance. Observations have shown that when the flow acceleration is too high, fish, which are very sensitive to velocity gradients, are very reluctant to pass. Acceleration into the bypass must be both moderate and progressive. It is thus better to control the flow, not at the entrance itself but downstream from an intermediary pool, which will make it possible to reduce and control the acceleration at the bypass entrance (Figure 8). Where it is not possible to install such a pool, the bypass discharge can be controlled by means of a broad weir or a flap gate, both of which are preferable to vertical flat gates since the latter induce intense velocity gradients immediately upstream from the crest. Flow separations and turbulence at the bypass entrance should also be avoided by eliminating sharp bends and, if necessary, rounding off the approach.

The flow in the bypass must be related to the flow through the turbines. In the experiments performed in France, satisfactory bypass discharges varied from 2% to 10% of the turbine discharge. This proportion should be adjusted for each site according to other parameters which affect bypass efficiency (bypass location, hydraulic conditions, trashrack characteristics, etc.). The less favourable the other parameters, the greater the flow that will be needed in the bypass.

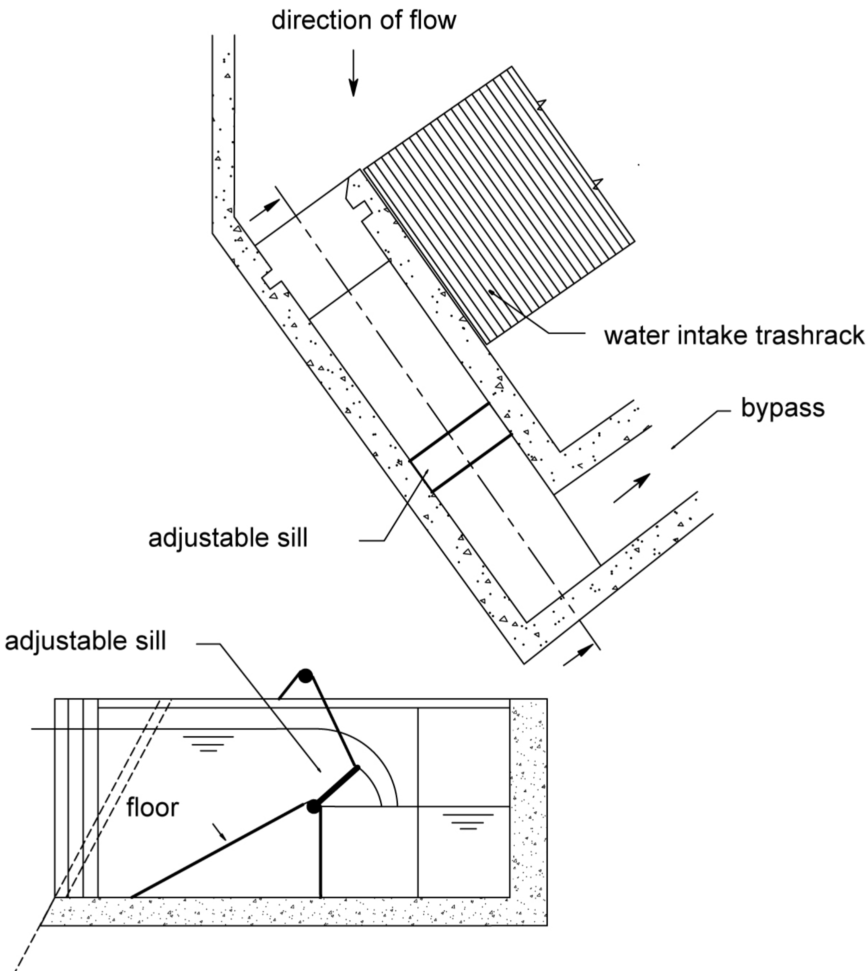

Figure 8: Conceptual plan and section of a downstream bypass entrance.

Current design criteria used in the north-east of the USA are similar to those used in France, *i.e.* 2% of the turbine capacity if there is an inclined guiding device and up to 5% when the approach flow is at right angles to the intakes (ODEH and ORVIS, 1998).

On the West Coast of the USA, surface bypasses are used more and more frequently used in large constructions on the Columbia River and its tributaries. Although the scale and design of these installations are very different to those tested in France, the recommended flow criteria, of the order of 5% to 10% of the turbine discharge flow, are very similar (FERGUSON *et al.*, 1998).

One principle for siting bypasses on water intakes is shown in Figures 9 and 10. When the screen's angle is very acute, the bypass should be installed at the downstream end. In the case of a very dissymmetrical flow pattern at the intake, the bypass should be installed in the recirculating area where fish concentrate. In the absence of any flow dissymmetry, or with unstable flow, it is preferable to install two bypasses. In the case of a deep intake, a collecting gallery equipped with several entrances can be installed. If the filtering plane is inclined to the vertical, the bypass should be installed in the upper part of this plane.

On wide intakes or where the flow pattern in the intake channel does not concentrate fish in one particular area, it is then necessary to install several bypasses.

The main problem affecting operation of these bypasses is blocking by drifting debris. This is because the areas where fish tend to congregate, and hence where the bypasses should be located, are also those where debris accumulates. In order to overcome this problem, the transfer device to the tailrace should be wide enough to carry any floating debris downstream.

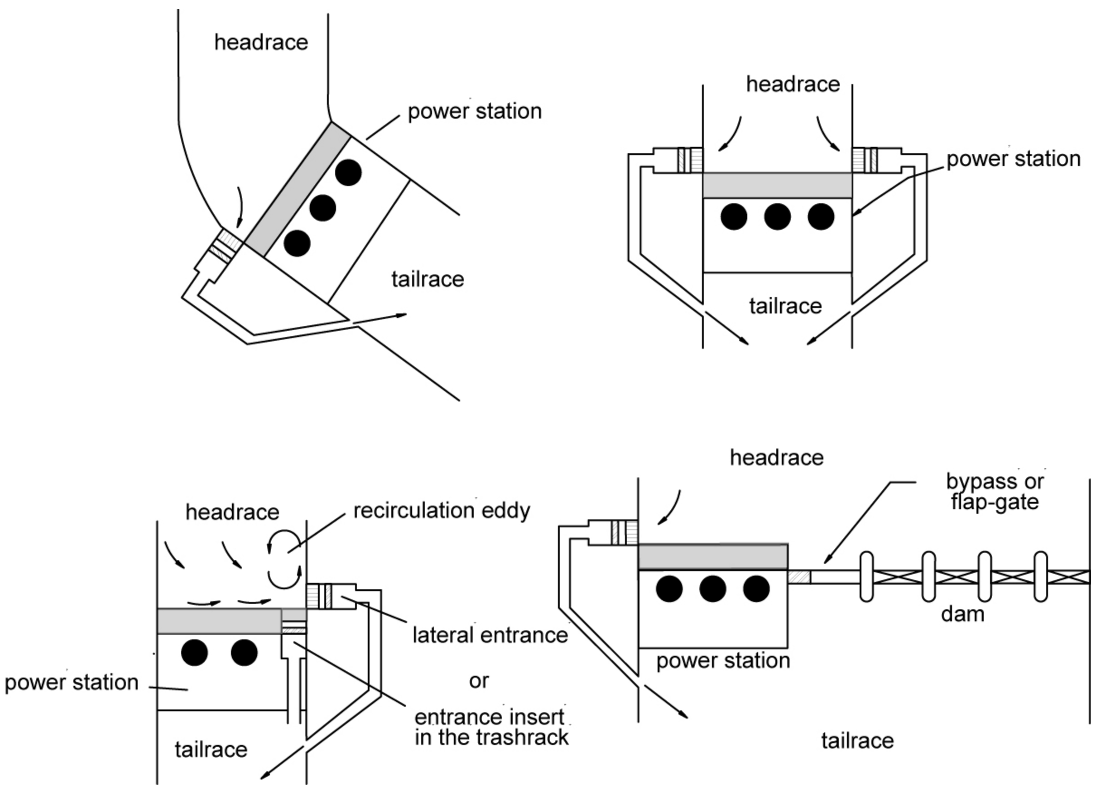

Figure 9: Conceptual plan of the location of downstream bypasses at hydroelectric plant intakes.

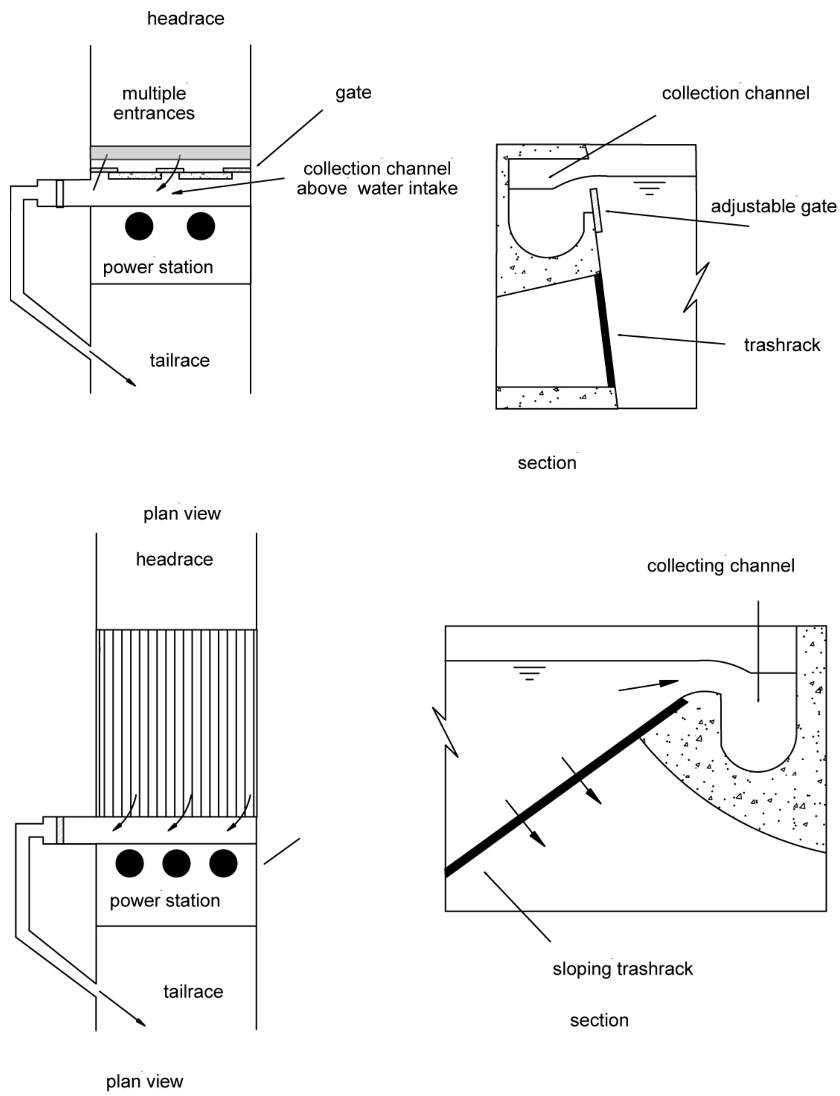

Figure 10: Conceptual plan and section of downstream bypasses at hydroelectric plant intakes.

Transfer of fish downstream

After going through the bypass the fish have to be transferred back into the river. There are two ways of doing this, either by providing transfer facilities immediately after the bypass, or else by providing transportation facilities (*i.e.* truck or barge operation).

The fish are transferred back to the main stream, along with all or part of the bypass flow, through a conduit or open channel that bypasses the power plant before merging with the tailrace. Pipes are more liable to clog, and are less accessible for inspection and maintenance purposes, than are open channels. Pipes and channels may be of many different shapes and sections, depending on the configuration of the site. Whatever the design, it must have smooth interior surfaces and joints and no sharp bends in order to avoid any injury to the fish. Flow velocity (including vertical and horizontal components) at the point of impact where the water discharge hits the downstream water surface should not exceed about 10 m/s. Some agencies even recommend not exceeding 7-8 m/s (ASCE, 1995). To limit shear effects and to avoid the jet penetrating too deeply into the downstream pool, it is preferable for the water jet to spread out. Fish should not be transferred into still or slack water where predators are likely to congregate.

When the flow in the bypass becomes too great (several m^3/s), fish should be guided towards a smaller discharge flow by means of an inclined screen. The screen may be inclined laterally or horizontally. This allows the sizes of the pipes or channels required to transfer the fish to be reduced. The screens are usually barred (wedge-wire screens are to be preferred), and the free gap between bars will depend on the species. In the case of Atlantic salmon smolts the bars should be 1cm in width with a 1cm free gap (*i.e.* porosity 50%). The free gap may be less for smaller fish.

Fish capture and transport facilities

In some cases fish either cannot be returned to the river immediately below the power plant, or else need to bypass a series of obstacles. In these situations fish are captured and transported downstream by lorry or boat. The operation involves trapping the fish in a holding pool, in which the water volume and flow are adjusted according to transport frequency (usually once or twice a day). Most traps work with an inclined screen filtering the fish out of the bypass flow from below, and guiding them towards the holding tank via a chute. The volume in the holding tank has to be determined according to the maximum quantity of fish expected to be in the trap at any one time. It is calculated on the basis of 30 l per kg of fish (*i.e.* about 35 kg of fish per cubic metre of water). The water inflow rate into the tank has to be sufficient to renew the total volume of water in the tank once or twice every hour. The volume of the transport tank is determined on the basis of 15 l per kg of fish (*i.e.* about 70 kg of fish per cubic metre of water) (BELL, 1986; ASCE, 1995).

4.6 Passage through turbines and/or spillways

In most small-scale hydroprojects, current techniques, whether physical barriers or surface bypasses combined with conventional or angled trashracks, can significantly reduce damage to juveniles and adult salmonids. Although this sometimes requires significant changes to facilities, the usefulness of such devices is obvious.

On the other hand, at the low head but high discharge facilities often found on the lower reaches of major rivers, it may prove difficult to prevent a large proportion of the migrating fish from passing through the turbines unless extensive and costly modifications are made. Furthermore, mortality rates of juveniles passing through the turbines at such sites are usually very modest. It may therefore be more cost-effective to provide lower levels of protection. Voluntary spill through spillways, trash and ice sluiceways, or specific surface bypasses, can pass a significant percentage of fish, depending of their location related to the turbine intakes. Where there are several spillways and/or turbines with different characteristics then these should be carefully assessed, and those that involve the least potential risk of damage for fish should, as far as possible, be used during the downstream migration period.

4.7 Other species

The problems related to downstream migration for species other than salmonids have only very recently been tackled.

For shad juveniles, whose migration behaviour appears to be similar to that of salmonids (downstream migration in surface layers), it would be reasonable to assume that devices designed for the latter should be just as efficient. This is provided that their dimensions are adapted to take into account the size and swimming abilities of the species. Moreover, in France this species is most often concerned with respect to low-head facilities fitted with low-speed and large turbines, responsible for a low to moderate rate of mortality (less than 5%). Where on any stretch of river important to the species there are only a limited number of installations each inducing moderate damage, then the total number of fish killed may not be significant enough to endanger the survival of the population. Consequently, given the current state of technology, specific downstream migration facilities for shad is not considered to be a priority, and will only be envisaged for medium or long-term projects as and when the technology evolves.

In the case of eels (*Anguilla anguilla*), no specific solutions have yet been implemented in France since their migration needs have only been recognised relatively recently. Only physical barriers are likely to be effective, but their installation would require re-sizing most of the flow intakes to maintain filter areas while reducing the free gaps between bars. Due to the demersal behaviour of the species, there is no certainty that the approach used for juvenile salmonids with surface bypasses combined with existing trashracks would be efficient. Experiments on bottom bypasses need to be undertaken, although it must be recognised that even if this technique were to prove efficient, there would be a considerable challenge to design facilities that did not create significant maintenace problems. Given the lucifugous nature of the species, the principle of using repellent light barriers appears to be a promising one, (HADDERINGH *et al.*, 1992). However, as for other behavioural barriers, it is to be feared that field applications will be much less reliable than those obtained under controlled conditions. Some experts have considered stopping the turbines during the downstream migration period and also capturing individuals upstream of the hydroprojects (*Anguilla rostrata* in the USA (EUSTON *et al.*, 1998), *Anguilla dieffenbachi* in New Zealand (MITCHELL, 1995). However, these solutions assume that it is both possible to predict the downstream migration period and that it will be sufficiently short not to significantly affect generation capacity. Neither seems to be the case for the European eel (*Anguilla anguilla*) which appears to have a relatively lengthy downstream migration phase.

For brown trout it may be possible to use similar solutions to those used for Atlantic salmon and sea trout. However the criteria for bar spacing and velocities upstream of the screen need to be adapted to take the wider range of individual sizes into account.

Little information is yet available for other species, like cyprinids, esocides and percides in respect of either their migration characteristics (periods, sizes, etc.) or migration behaviour. However, it is known that juvenile cyprinids (of a few cm in length) are likely to migrate in greater numbers during their redistribution in the river, in particular in summer (SOLOMON, 1992). Among the existing facilities for hydroelectric intakes, it is difficult to recommend physical barriers, which would require reducing grid spacing to the order of a few mm and especially very slow approach velocities of the order of 10 to 15 cm/s. These would generally be incompatible with existing facilities. Given the current state of technology, the only solution appears to be surface bypasses, but their efficiency remains to be proven. On low-head installations, it is sensible to consider carefully whether a downstream migration facility is actually necessary, given that the mortality rate due to the turbines is moderate and that these species generally only migrates over limited distances. This means that they may only be affected by a very small number of installations thus limiting the possible additive effects. This is in contrast to the diadromous species like salmon which generally migrate large distances and therefore frequently have to pass many barriers, thus suffering considerably from cumulative mortality. The rare studies of the subject have never observed entrainment and related damage which would be likely to threaten the survival of the populations (EPRI, 1994; SORENSON *et al.*, 1998).

CONCLUSION

We have reviewed the various techniques used for reducing the impact of hydroelectric installations on downstream migration of fish. Physical barriers appear to the most efficient techniques available at the moment. The range of application of surface bypasses combined with conventional existing trashracks and louvers is limited. Other behavioural barriers can only be considered to be experimental solutions, given their low rate of reliability at present.

The need to take into account the effects on downstream migration mean that much more severe environmental constraints will have to be applied (velocities in intake canals, surface area, orientation and spacing of water intake screens, etc.) for hydroelectric facilities when operating licenses are being renewed or granted. The same is true for new abstraction water intakes. This is provided that it is reasonable at all to accept the principle of new installations on watercourses where migratory fish populations are being restored.

In order to find efficient and less restrictive solutions than physical barriers for operators to employ, it is obvious that a lot more research and development will be needed than is being done at the present time in France. Any progress in the field will necessarily require increasing our knowledge of fish behaviour so as to be able to predict how they will react to environmental stimuli, in particular to hydrodynamic conditions in intake channels. Relatively efficient techniques such as telemetry (radio or acoustical telemetry), hydro-acoustics and video can be used for monitoring the behaviour of fish at intakes.

More research and development is also needed in respect to the design of water intakes, which must be configured with migration problems in mind (for instance, MIS screens). At the same time it is necessary to reduce damage to fish which pass through turbines. There is no particular reason why turbines should kill fish, especially in low-head facilities. Studies are now being conducted in the USA to adapt turbine design for fish migration (OTA, 1995; CADA 1997).

Finally, when determining the efficiency target required at any particular installation, it is important to put it in the context of the whole river catchment and to consider the additive impact of all the installations present. This is in addition to evaluating which is the most appropriate technical solution for the specific site.

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Photo 1: Conventional drum screens at an irrigation water intake in USA.

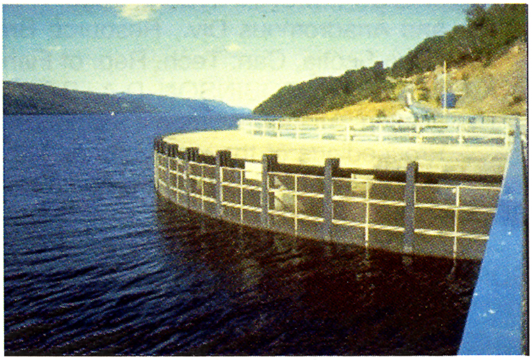

Photo 2: Fine mesh screens at a pump storage hydroelectric intake in Scotland.

Photo 3: General view of the surface louver screens at the Holyoke Canal project on the Connecticut river (USA).

Photo 4: Surface louver screens (view from the bypass entrance) at Holyoke Canal project (Connecticut river, USA).

Photo 5: Experimental electrical screen at the Halsou power station (river Nive, Pyrenees).

Photo 6: Downstream surface bypasses at the intake of the Castetarbe powerstation (Gave de Pau river).

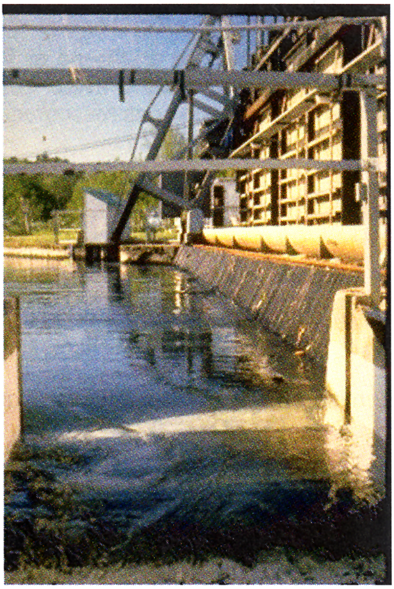

Photo 7: Downstream surface bypass at the Halsou power station intake (river Nive, Pyrenees).

Photo 8: Downstream surface bypass at the Soiex power station intake (Gave d'Aspe river, Pyrenees).

Photo 9: Downstream surface bypass at the poutes dam (Allier river). The 10 m deep power intake is located on the left.

Photo 10: Surface bypass at the Poutes dam. Note the shape of the bypass entrance to create a gradually accelarating flow.

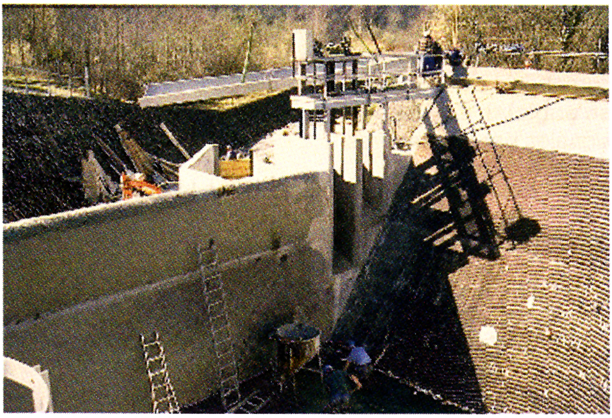

Photo 11: Surface bypasses at the power intake of St Cricq scheme (Gave d'Aspe river, Pyrenees). Note the two entrances at different elevations.