CHAPTER 11

DESIGNING FISHWAYS, SUPERVISION OF CONSTRUCTION, COSTS, HYDRAULIC MODEL STUDIES

J.P. PORCHER (1) and M. LARINIER (2)

(1) Conseil Supérieur de la Pêche, DR 2, 84 Rue de Rennes, 35510 CESSON SÉVIGNÉ - France.

(2) CSP-CEMAGREF, GHAAPPE, Institut de Mécanique des Fluides, Avenue du Professeur Camille Soula, 31400 TOULOUSE - France.

1. DESIGNING FISHWAYS

1.1 Gathering preliminary information

A fishway must meet two equally important criteria:

- It must be suitable for the species for which it is intended.

- It must be suitable for the site at which it is installed.

Fish passage design must therefore begin by gathering biological, hydrological, topographical, hydraulic, and water quality information. These elements must be included in any project file on a fishway, since this knowledge is crucial to enable informed decisions to be taken during consultation and planning.

1.1.1 Biological data

Firstly, all the migratory species that are to be taken into account must be identified:

- For existing obstacles, by examining statutory legislation and orders which specify those migratory species which must be taken into account in the sections of watercourses classified under article L.432-6 of the Environment Code;

- For renewal or amendments to existing licences, concessions and also for new plant, the requirements for preserving the aquatic environment may give rise to more extensive demands than those specified under article L432-6. If requested by the local authorities this will mean taking account of the requirements of the passage of any other specified migratory species either already present (diadromous and potamodromous), or else intended to be the subject of a restoration programme.

In all cases, the list of migratory species must be clearly specified before the project is developed.

Article available at http://www.kmae-journal.org or http://dx.doi.org/10.1051/kmae/2002100

The technical file must specify the list of species and, for each of them, the data available on:

- The actual or potential numbers present;

- Timing of upstream and downstream migration;

- The means by which the various types of information were obtained (literature searches, other enquiries, field observations, monitoring stations downstream, etc.).

1.1.2 Hydrological and water quality data

The file must include the hydrological characteristics of the watercourse obtained from the nearest gauging station. These include mean annual daily flow, mean monthly flow, characteristic low and high flow*s* (Q10 and Q90). The extent of the variation in the flow during the migration season must be specified, together with information about any effect of the management of any installations upstream.

In the case of small watercourses it is rare for there to be a gauging station near to the site of the proposed works. Reference sites should therefore be researched, preferably in the same hydrographic catchment, or in the absence of this, in a catchment with comparable geology from which satisfactory correlations of flows can be established. It is not generally necessary to obtain highly accurate data, but rather to define the order of magnitude of the characteristic flows as well as the amplitude and the behaviour of river discharge variation during the migration period. With the exception of some limestone areas, direct correlations with river basins of similar geology are usually sufficient.

Data concerning the water quality at the site must also be researched:

- The water temperature is likely to have a significant effect on the efficiency of a fish pass due to its effect on the swimming and leaping ability of the migrators, particularly in mountain rivers which are subject to low temperature regimes. On the other hand, temperatures in the lower reaches of large rivers may attain high and limiting values for migratory salmonids during some periods;

- The physico-chemical quality of the water (in particular the presence of pollutants and the oxygen content) used for the supply of water to the fish passage facility and the auxiliary flow must be taken into account. Particular attention should be paid to water intake from an impoundment, where thermal or physico-chemical stratification may occur. Depending upon the water depth at which the supply is drawn off, unsuitable temperatures or low oxygen concentrations may be encountered at different times of the year.

1.1.3 Characteristics of the obstruction

a. Plans of the structure

It is necessary to have:

- A general plan of the whole of the site location which shows all features that may be of importance to the project. This must include a layout of all the various water channels, power intakes, spillways, etc.;

- A detailed survey of the area(s) where the migrators are obstructed at the barrier;

- Detailed plans and cross-sections of the plant at the locations where the fish passage facility might be installed;

- Detailed survey of the dimensions and elevation of all hydraulic control facilities (weirs, sluices, water intakes) as well as the characteristics of the turbines;

While existing plans may be used, their accuracy must be verified by a site inspection.

b. River discharge and water levels

The technical file must include the relationship between river discharge and the upstream and downstream water levels.

The fishway is designed with respect to upstream (supply of water to the facility) and downstream (entrance for the fish) water levels. The water levels during low flow periods, which generally correspond to the maximum difference in possible levels, must be clearly shown on the plans. It is also important to clearly indicate the expected normal, maximum and minimum flows and expected operating levels of the fishway.

In some cases water level monitoring equipment should be installed at the site, either a water level gauging board or else an automatic level recorder. In the case of new installations it is often difficult to determine precisely what the downstream water level will be following construction, since this depends on the nature of the works and the subsequent evolution of the river-bed. It is therefore recommended that a safety margin be allowed in the design of the downstream section of the facility, in order to accommodate any subsequent lowering of the downstream water level.

In some cases (fixed weirs), estimation of the expected upstream water level for any given discharge in the river is possible by applying classic discharge equations for different types of weirs.

c. Study of the operating regime

The technical file should include a precise description of the operating regime for the installation. It should also include an analysis of any changes in flow patterns that the regime brings about at different flows, together with their probable effect on both upstream and downstream migration (attraction of the fish to discharge from the turbines or spillways, for example). The effect of practices such as shutdowns and intermittent operation should be examined. If applicable, new operating protocols should be considered and implemented in order to improve the efficiency of the fish facility.

d. Investigation of the holding areas and locations where migrators try to pass.

In the case of an existing obstruction, efforts must be made to localise where fish congregate below the structure, and where they attempt to pass. This may be established by direct observation, or by enquiries with fishery departments, riverside residents and fishermen. This provides a good guide to the location of the fish pass entrance. For large projects it is advisable that preliminary studies be carried out (direct observation, radio-tracking, etc.).

1.2 Design of the facility

The data listed above provides the basis for the design work. The various phases of design can be described in chronological order as follows:

1.2.1 Determination of the operating range of the fish passage facility in terms of flow and water levels

The range of river flows for which the fish passage facility is to operate is established from the hydrological data that has been collected, and the migratory periods of the target species. It is especially important to minimise delays to migration when the migratory "window" for the species concerned is narrow, and when the migration period is very close to the spawning period.

Generally, the objective should be to have the fish passage facility functioning correctly when flows in the watercourse are between low flow (Q90) and approximately 2 to 2.5 times the mean annual daily flow. In most rivers in France this higher discharge is only exceeded for about thirty days p.a. on average, and then only for a few days in succession. This approach generally ensures that the fish passage facility operates constantly during the whole of the shad migration season, and for a satisfactory period for salmonids.

Once the range of river flows over which the fish passage facility must operate has been determined, the corresponding upstream and downstream water levels must be established. Indeed, **precise knowledge of the water levels** is absolutely essential for correct design of the fish passage facility.

1.2.2 Choice of discharge the fishway

The discharge to be used in the fish passage facility must be determined bearing in mind both the need to attract the migrators, and to ensure that they will pass. In regulating and licensing a plant it is usual to fix a minimum acceptable ecological flow that can be used wholly, or in part, for the operation of the fishway facilities (for upstream and/or downstream passage). It should be borne in mind that the flow within the pass should, at all times, represent a satisfactory proportion of the competing flow in the river or the plant.

1.2.3 Choice of type of fishway

In many cases the final decision will be a compromise. Several types of facilities or several configurations may be suitable, each of which will have its own advantages and disadvantages.

The main factors involved in determining the type of fishway can be summarised as follows:

- The **species concerned**. Some fishways are very specific. This is clearly the case for elvers and small eels;

- The **flows** in the installation. When flows are small (several tens of litres/second) or, in contrast, very large (several m^3/s), they may be incompatible with some types of fishways;

- The **variations in the upstream and downstream water levels**. Different types of facilities have different sensitivity to variation in the upstream and downstream water levels;

- The **topographical restrictions**. The choice of a type of fish passage facility may be determined by topographical constraints. Flights of baffle fishways must be in straight lines and changes in direction must only be made at resting pools, hence they are not as flexible as pool fish passes. A fish lift can generally be integrated fairly easily into existing plant, since it requires only a small ground area;

- The **head drop at the obstruction**. This is an important factor to be considered when choosing the type of pass since it has a direct bearing on the cost of the facility. A baffled fish pass may be relatively cheap at a low dam, but may be less suited (because of the necessity to install resting pools) to moderately high dams than a pool type fish pass. Then again, on a high dam, a fish lift may be a cheaper solution than a pool pass;

- The **cost of operation** and maintenance of the fish passage facility, which may represent a significant expenditure in the long term. This factor must not to be overlooked in the choice of fish passage facility. If there is a choice, preference should be given to static fish passage facilities (pool or baffle fish passes) rather than to installations with numerous moving parts (fish locks and lifts). Particular attention should be paid to any potential problems with the blockage of water intakes and screens that might require frequent and costly maintenance work. Preference should be given to those configurations that minimise the need for maintenance;

- **Sediment transport** in the river. Where there is significant movement of large bed materials (pebbles, cobbles, boulders), both baffle fishways and deep pool fishways should be avoided because of the risk of sedimentation;

- The **climatic conditions**, particularly ice formation, which could affect operation of the moving parts and/or fine screens. This factor must be taken into account particularly when designing fish lifts in mountainous areas.

1.2.4 Fish pass location

Location of the fish passage facility must take account of:

- The available space;

- The flow patterns at the site across the whole range of flows over which the fishway is intended to operate;

- The information collected on areas where migrants congregate and where they attempt to pass;

- Maintenance problems.

1.2.5 Dimensions and design of the facility

The facility must be designed to the very smallest detail, using the latest design criteria established from experience at other sites, *i.e.* current best practice. The design file will contain the following sections:

- Plan of the location of the facility and all its auxiliary structures;

- Detailed longitudinal and cross-sectional profiles;

- Descriptive notes giving the characteristics of the fish passage facility: dimensions of the pools, traverses between the pools (dimensions of the notches, slots or orifices), characteristics of the baffles, gradient, etc.;

- Precise details of the estimated hydraulic behaviour of the fishway (discharge, drops between pools, velocities, etc.), for several configurations considered to be characteristic of the water levels upstream and downstream during the migration period;

- Method of capturing, dissipating, and injecting the attraction flow into the facility;

- Flows and velocities at the entrance to the pass in relation to the discharges in the river;

- Means of protection against trash.

2. CONSTRUCTION

2.1 General

When fish pass facilities are constructed as part of a bigger project (*e.g.* a fish pass at a new small hydroelectric plant) or are retro-fitted to a large construction which already exists, then civil engineers will generally oversee all aspects of construction management. Their methods will not be discussed in detail here, except to point out the necessity of ensuring that quality materials are used, that any hydro-mechanical equipment used is reliable, and finally that essential levels (fish pass floor and inverts of all walls and sills, water feed channels etc.) are verified.

When fish passes constitute a small engineering project and are constructed by local contractors, then the following guidance may be helpful.

2.2 Construction programme

The selection of the starting date for the construction must take into account its anticipated duration and the hydrological regime in the river. The project should normally be completed at a time of low to moderate flows, since otherwise there is a risk of the works being flooded. This would significantly increase the cost. Every effort must be made to ensure that sufficient labour and material resources will be available to carry out the work within the most favourable period.

Particular attention must be paid to the related problems of coffer-dam construction and of keeping the construction dry. Experience has shown that attempts to cut costs at this stage generally lead to an increase in budget later, or else to a facility that fails to meet its specification. It is therefore essential to estimate precisely the requirements for keeping water out of the site to protect the construction works, to anticipate the difficulties for construction access or for delivering of materials to site, and to take all necessary measure to ensure that the construction progresses smoothly.

Specific guarantees may be required from the contractors, such as indemnity to cover for the risk of floods, or penalties for delay for all or for certain phases of the works. The specific constraints (precision of levels in certain parts of the facility, *e.g.* trapping pools, traverses) should be stated in the specification.

2.3 Performance of the work

2.3.1 Interpretation of the plans and construction of the facility

The plans of the installation must be very detailed (*i.e.* they should reject any draft not based on a precise topographic survey of the site, or worse, on documents “drawn up on site"). The levels should be accurate to the nearest centimetre and must be referenced to a well-defined point.

Dated plans must be used and, as soon as work on site commences, it must be verified that the contractor has the latest draft (and only this one). The plans will be discussed with the contractor's representative and it must be ensured that he knows whom to contact in the case of a problem over interpretation, or if it is necessary to make any modifications due to conditions onsite. No matter how minor, the designer of the fish pass must approve any modifications to the original plan.

The ground footprint of the installation must be accurately established and marked when the contractor first arrives on site.

2.3.2 Monitoring the work

Periodic visits by a person familiar with both the function and the design criteria for the fish passage facilities must be scheduled for the main stages of the work. Visits at the following stages are particularly recommended:

- Completion of demolition or excavation work;

- Establishment of reinforcements for foundations and floors;

- Completion of any shuttering, before pouring any concrete;

- Completion of any other critical elements of the work;

- Final completion.

The level of the floors and the sills (and of all sections which control discharge, velocities and head drops in the facility) should be verified at each stage, especially in the downstream section where there might be a tendency to build the installation too high in order to limit demolition work. In particular, a check should be made to ensure that a pool of sufficient size remains at the foot of the installation, since contractors have a tendency to fill them in because they are afraid of the structure being undermined.

To prevent injury to the migrators there should be no sharp edges in the installation. Particular attention should be paid to the interconnection with the existing facility, to corners, deflectors and traverses, and equally importantly to the edge of any metal sections of baffles. Rubber flaps can be used to prevent migrators entering passages that have no exit, or zones where they may injure themselves.

2.4 Acceptance of the work

Before formally accepting the works the client should carefully inspect the structure. It is useful if this inspection is begun before flooding is carried out to enable a general inspection of the civil engineering standards to be completed (*i.e.* unless this has been done during regular monitoring of the site). The acceptance procedure must include the flooding of the installation and an inspection of its hydraulic operation (measurement of the water levels and calculation of the flow passing through). If it proves necessary, the flow over certain weirs or through certain traverses may be adjusted or regulated using temporary measures (modification of the crest levels with small boards). If required these measure, should then be made permanent.

3. COST OF FISH PASSAGE FACILITIES

3.1 Pool passes

The cost of a pool pass is approximately proportional to the internal volume of the civil engineering work, *i.e.* the volume represented by the product of the interior width, the length and average depth of the structure of the fishway.

Statistics (January 2001) based on approximately three hundred pool passes show that the average net cost is around 645 €/m^3 (median 550 €/m^3, first and third quartiles 380 €/m^3 and 800 €/m^3 respectively). However, the unit cost varies fairly widely from less than 100 €/m^3 to more than 1500 €/m^3 for the various installations.

The vast majority of data relate to fish passage facilities retro-fitted to existing obstructions. Where fishways were constructed at the same time as the power plant or the dam, the costs were very much lower than for retro-fitted facilities.

The internal volume of the civil engineering element required in order to estimate the cost of a fish passage facility comprises:

- The volume of all the pools, *i.e.* the fishway itself.

- The volume required for the supply, transit and dissipation of the auxiliary flow.

- The volume required for trapping and/or viewing the fish.

Only the minimum "design" volume of the pools (volume of water in the pools at low water) is quickly and easily predicted for a given facility, since it is proportional to the maximum drop at the obstruction (generally observed at low water) and to the design flow in the fishway. This volume is usually based on a mean volumetric dissipated power not exceeding 150-200 Watts/m^3.

However, the following must be added:

- A volume that takes into account the range of water levels expected to occur in different parts of the fishway over the migration period,

- A volume corresponding to the safety margin required to prevent the fishway from overtopping,

- An additional volume, which can also be very variable, imposed by the topography of the site and the route of the fishway.

It is also possible to estimate the cost as a function of the maximum drop (H) and the design flow (Q) passing through the fishway:

$$C = K\,H\,Q$$

Where:

C is the cost of the pass in Euros (net)
H the maximum drop (in metres) at low water
Q the flow (m^3/s) in the fishway at low water

The average value of coefficient K is around 97,260 € per metre of head drop and per m^3/s of flow (median 80,000 €, first and third quartiles 53,000 € and 115,000 €

respectively). It is likely to vary from less than 15,000 € to more than 300,000 €, depending on the conditions where the fishway is to be constructed.

Estimating costs by using the above formula is obviously much less accurate than using the internal volume of the civil engineering element.

3.2 Baffle fishways

Statistics drawn from around 100 baffle fishways give an average unit cost of 2,750 €/m^3 (median 2,000 €/m^3, first and third quartiles 1,300 €/m^3 and 3,000 €/m^3 respectively). However, as with pool passes, it varies widely depending upon the specific site conditions for the installation (from less than 300 €/m^3 to more than 7,600 €/m^3).

In common with the pool passes, it is also possible to estimate the cost as a function of the maximum drop (H) and the design flow (Q) passing through the facility:

$$C = K\,H\,Q$$

The average value of the coefficient K is around 62,000 € per metre of head drop and per m^3/s of flow (median 51,000 €, first and third quartiles 36,000 € and 83,000 € respectively). The coefficient K is likely to vary between 10,000 € and more than 180,000 €, depending on the installation.

3.3 Fish lifts

The cost of trout lifts varies between 15,000 € and 75,000 € and that of salmon lifts between 50,000 € and 125,000 €. The cost of the mechanical section of large lifts for shad with a mechanical crowder is around 250,000 € to 400,000 €.

To these costs must be added those of the civil engineering work required to install the lift. In particular those works necessary for the water intake, and for the dissipation and injection of the attraction flow into the facility. These costs may vary greatly from one installation to another.

The cost of the Tuilières and Golfech fish lifts were respectively 1,300,000 € and 3,500,000 €.

4. HYDRAULIC MODEL STUDIES

Tests on scale models are frequently used during design of fish passage facilities where the flow patterns are too complex to be treated simply by an analytical approach.

Studies on hydraulic models are generally intended:

- To visualise and optimise the flow in the fishway itself in order to ensure that the velocities, drops and turbulence levels remain compatible with the swimming ability of the migratory species concerned, for all water levels expected to be encountered at the obstruction during the migration period;

- To design the facilities for the intake and discharge of the auxiliary flow, and to protect the installation against water borne drifting debris;

- To resolve any problems connected with installation of the fishway, particularly to determine the optimum location of the entrance in relation to the hydrodynamic conditions at the obstruction.

The majority of types of fish passage facility (vertical slot fishways, Ice Harbor type fishways, baffle fishways, etc.) were developed as a result of systematic studies on models.

The scale of the models used usually varies between 1/3 and 1/10 for a model of the fishway itself, and from 1/10 to 1/25 for models intended only for optimising the location of the facility at the obstruction.

The Froude laws of similitude apply to the flows in the fishways, since the primary cause of fluid motion is gravity and all other forces such as fluid friction and surface tension can be neglected.

Although modelling studies are costly they are indispensable for the design of fish passage facilities at large installations. They allow many mistakes to be avoided that would be difficult and very costly to rectify at a later stage.