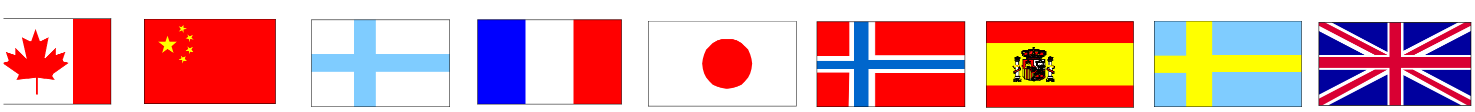
Fish Passage at Small Hydro Sites

IEA Technical Report

IEA Hydropower Agreement



OVERVIEW OF THE IEA IMPLEMENTING AGREEMENT FOR HYDROPOWER TECHNOLOGIES AND PROGRAMMES

The Hydropower Implementing Agreement is a collaborative programme among nine countries: Canada, China, Finland, France, Japan, Norway, Spain, Sweden and the United Kingdom. These countries are represented by various organizations including electric utilities, government departments and regulatory organizations, electricity research organizations, and universities. The overall objective is to improve both technical and institutional aspects of the existing hydropower industry, and to increase the future deployment of hydropower in an environmentally and socially responsible manner.

HYDROPOWER

Hydropower is the only renewable energy technology which is presently commercially viable on a large scale. It has four major advantages: it is renewable, it produces negligible amounts of greenhouse gases, it is the least costly way of storing large amounts of electricity, and it can easily adjust the amount of electricity produced to the amount demanded by consumers. Hydropower accounts for about 17% of global generating capacity, and about 20% of the energy produced each year.

ACTIVITIES

Four tasks are operational, they are: 1. upgrading of hydropower installations, 2. small scale hydropower, 3. environmental and social impacts of hydropower, and 4. training in hydropower. Most tasks have taken about five years to complete, they started in March 1994 and the results will be available in May 2000. To date, the work and publications of the Agreement have been aimed at professionals in the respective fields.

UPGRADING

The upgrading of existing hydropower installations is by far the lowest cost renewable energy available today. It can sometimes provide additional energy at less than one tenth the cost of a new project. One task force of the Agreement is studying certain technical issues related to upgrading projects.

SMALL SCALE HYDROPOWER

Advances in fully automated hydropower installations and reductions in manufacturing costs have made small scale hydropower increasingly attractive. The small scale hydropower task force will provide supporting information to facilitate the development of new projects.

ENVIRONMENTAL AND SOCIAL ISSUES

For some hydropower projects the environmental and social impacts have been the subject of vigorous debate. There is a need to communicate objective information to the public, so that countries can make good decisions with respect to hydropower projects. The environmental task force will provide such information on possible social and environmental impacts and on mitigation measures.

TRAINING

The availability of well-trained personnel is a key requirement in the hydropower sector. The training task force is concentrating on training in operations and maintenance, and planning of hydro power projects.

THE INTERNATIONAL ENERGY AGENCY – IMPLEMENTING AGREEMENT FOR HYDROPOWER TECHNOLOGIES AND PROGRAMMES

Fish Passage at Small Hydro Sites

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Abstract

THERRIEN, J, and G. BOURGEOIS. 2000. Fish Passage at Small Hydro Sites. Report by Genivar Consulting Group for CANMET Energy Technology Centre, Ottawa, 114 p.

The field of small hydro power has seen a lot of new projects in the last decade, generally by private producers. One of the main environmental challenges of small hydropower development is related to fish passage both upstream and downstream. These migrations are ecological imperatives for fish populations, particularly for diadromous species, creating the need for efficient fish passage systems. This study reviews downstream and upstream migration systems, as well as related monitoring activities.

Downstream fish migration at small hydroelectric generating stations is mostly affected by mortality that can occur during fish passage through the turbines, although mortality can also occur upstream or downstream of the power station. The presence of several small generating stations on the same river may also induce cumulative impacts. Four causes of mortality can affect fish passing through a turbine: contact of fish with one of the turbine parts, shear forces associated to variations in velocity, variations in pressure, and cavitation. Nearly thirty migration devices have been tested over the past 50 years which can be grouped in four main categories: bypasses, physical barriers, behavioural barriers, and trapping and transportation systems.

Even though there is no universal downstream migration device, three types of devices showing good efficiency and low selectivity are considered the most adequate: inclined deflector screens, Eicher screens and modular inclined screens (MIS). Louvers can be added to this list although its selectivity is higher. Promising results have also been obtained with hybrid devices using light and sound. Research is actually ongoing to improve existing devices, and to develop “fish-friendly” turbine design.

Fishways have been developed mainly in the first half of the 20th century, with the development of Denil, pool and weir, and vertical slot fishway, as well as “Borland” type fish locks. In recent decades, better understanding of fish behaviour and swimming capacity has allowed for adjustments to these initial designs. The Denil (or its revised version: Alaska steeppass), and pool and weir fishways are the most frequently used systems in North America and Europe. Current research on fishways focus on better understanding of fishway hydraulics as well as behaviour of non migratory and lesser known species. The use of artificial channels, mainly in Europe, has also been the object of recent development.

Monitoring activities are essential to target mortality through turbines, entrainment estimations related to the efficiency of downstream devices, and efficiency of fishways. There are currently five methods to assess mortality rate of fish passing through a turbine: return rates of migrating populations, fishing gear installed at the output of turbine, capture-recapture techniques, inflatable tags, and telemetry. Five methods are used for entrainment estimation: fishing gear at the turbine or bypass outlet, capture-recapture techniques, underwater camera, hydroacoustic, and telemetry. For upstream migration, trapping and counting through observation windows are the most frequently used monitoring techniques. Telemetry is also used to assess delays in upstream migration when multiple dams are found on a same river system.

Key words: Fish migration, fishways, downstream devices, monitoring, small hydropower

Résumé

THERRIEN, J, et G. BOURGEOIS. 2000. Fish Passage at Small Hydro Sites. Report by Genivar Consulting Group for CANMET Energy Technology Centre, Ottawa, 114 p.

La construction de petites centrales hydroélectriques par des producteurs privés a connu un essor au cours de la dernière décennie. Un des enjeux environnementaux des petites centrales est lié à la libre circulation des poissons, que ce soit en montaison ou en dévalaison. Ces migrations sont essentielles pour les populations de poissons, surtout les espèces diadromes, et elles requièrent des dispositifs efficaces. Ce document fait la revue des dispositifs existant pour permettre les migrations en dévalaison et en montaison, ainsi que celle des activités de suivi qui y sont reliées.

La dévalaison du poisson aux sites de petites centrales hydroélectriques peut entraîner une mortalité surtout lors du passage dans les turbines, bien qu'elle puisse également survenir en amont ou en aval des centrales. De plus, la présence de plusieurs centrales sur un même cours d'eau peut engendrer un impact cumulatif. Les quatre principales causes de mortalité de poisson observées lors du passage par une turbine sont: les chocs mécaniques, les forces de cisaillement associées aux variations de vitesses, les variations de pression et la cavitation. Près de 30 dispositifs de dévalaison différents ont été testés depuis 50 ans et ils sont regroupés sous quatre catégories: les exutoires, les barrières physiques, les barrières comportementales, ainsi que la capture et le transport. Bien qu'il n'y ait pas de dispositif universel, trois (3) dispositifs de dévalaison se démarquent par leur efficacité et leur faible sélectivité et ils sont actuellement jugés comme étant les plus performants, soit: les grilles fines inclinées, les grilles écrémeuses de type Eicher et les grilles inclinées modulaires. Les persiennes peuvent être ajoutées à cette liste même si leur sélectivité est plus élevée. Des résultats prometteurs ont aussi été obtenus avec des dispositifs hybrides utilisant le son et la lumière. Des recherches sont actuellement en cours pour améliorer ces dispositifs et pour développer des turbines moins mortelles surnommées "fish-friendly turbine".

Les passes migratoires ont surtout été développées dans la première moitié du 20^{ième} siècle, avec la conception des passes de type Denil, à bassins et à ouverture verticales, de même que les écluses à poissons de type "Borland". Au cours des dernières décennies, une meilleure compréhension du comportement et de la capacité natatoire des poissons a permis d'améliorer ces modèles. Les passes de type Denil (ou la version révisée: Alaska steeppass) et les passes à bassins sont les plus fréquemment utilisées en Amérique du nord et en Europe. La recherche actuelle vise surtout une meilleure compréhension de l'hydraulique et du comportement d'espèces non diadromes ou moins bien connues. Les canaux artificiels, en usage depuis peu en Europe, font aussi l'objet de développements récents.

Les activités de suivi sont essentielles pour vérifier: la mortalité du poisson lors du passage par une turbine, l'efficacité des dispositifs aménagés pour prévenir leur entraînement vers les turbines, ainsi que l'efficacité des passes migratoires. Il y a actuellement cinq (5) méthodes d'évaluation de la mortalité: les taux de retour des populations, l'installation d'engins de pêche à la sortie des turbines, les techniques de capture-recapture, les étiquettes flottantes et la télémétrie. L'estimation de l'entraînement peut aussi être réalisée de cinq (5) manières: l'installation d'engins de pêche à la sortie des turbines, les techniques de capture-recapture, la caméra submersible, l'hydroacoustique et la télémétrie. Pour les migrations de montaison, l'utilisation de trappes et le dénombrement dans des fenêtres d'observation sont les méthodes les plus répandues. La télémétrie est aussi utilisée pour déterminer les retards dans la migration si de multiples barrages sont présents sur le même cours d'eau.

Mots clés: migration de poisson, passe migratoire, dispositif de dévalaison, suivi, petite centrale hydroélectrique

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BROCHURE

A brochure for the general public is available. It is entitled “Hydropower – a Key to Prosperity in the Growing World”, and can be found on the Internet (www.usbr.gov/power/data/data.htm) or it can be obtained from the Secretary (address on the inside back cover).

1. INTRODUCTION

Small hydro power project development has been, for the last decade, one of the sectors in the energy field that has been very active. Where the preceding decades saw a fair number of large hydroelectric developments, the last decade was almost exclusively made up of smaller projects that were essentially developed by private producers. In future years, with the broad deregulation that is being seen in North America, it is likely that hydro energy can be a valuable resource to develop, specially for local or regional development purposes. As such, many new players could become involved in small hydro projects, such as municipalities or local industries. Moreover, many of the regulatory bodies (i.e. Environment Canada, Fisheries and Oceans, provincial Environment ministries, etc.) are decentralising their permitting to local levels where usually there is less specific expertise available to evaluate the impacts of these projects on aquatic resources. Therefore, information on environmental issues related to hydro projects would be required by many people, to understand and eventually put in place an optimal development project from an economical and environmental point of view.

One of the main environmental challenges of small hydropower development is related to fish passage both upstream and downstream. These migrations are ecological imperatives for populations of anadromous fish. Entire populations of these migratory species can be eliminated if either up or downstream migrations are blocked. Small scale hydro developments are often an impediment to these migrations. Efficient fish passage is required under many jurisdictions in order for regulating agencies to approve hydropower projects, whether they be new developments or under relicensing.

Hydroelectric dams can also cause other impacts apart from blocking fish migrations. For instance, dams can have an effect on water temperature, flow regimes, dissolved gas content, species diversity, and other ecological parameters that may have a direct or indirect effect on fishes.

The objectives of the study that was contracted to Genivar were to:

- carry out a literature review on recent developments in fish passage, both downstream and upstream;
- discuss all aspects related to fish passage such as migratory vs resident species, notion of efficiency, etc;
- present fish passage systems that are commonly used such as downstream migration devices as well as fishways for upstream migrating fish.

The report is divided in three main themes, downstream migration, upstream migration and monitoring activities. Chapter 2 discusses issues related to downstream fish passage devices such as fish behaviour, types of devices and efficiency. A similar approach is presented in Chapter 3 for upstream migration systems. Finally, monitoring activities related to fish passage are discussed in Chapter 4.

2. DOWNSTREAM MIGRATION

This chapter looks at the general approach used in the context of fish downstream migration at small hydroelectric generating stations. We will describe the species of fish affected, the causes of mortality and the devices used to avoid mortality. The most frequently used devices in North America and in Europe, followed by the research work done on a "friendly" turbine, and the general design considerations for these devices will then be presented.

In this chapter, the expression **migration device** is used to describe the entirety of the structures or devices used to facilitate the safe migration of fish by avoiding their passage through turbines.

2.1 General Approach

2.1.1 General Aspects

The problem of fish downstream migration at small hydroelectric generating stations is mostly related to the mortality that can occur by their passage through the turbines, although passage over spillways or in falls can also be a problem. The use of devices to remedy this problem is relatively new. The first reports that describe the attempts or applications of such devices date back about 50 years ago. However, it is only in the last 15 years that their use has spread and that governmental agencies have put more pressure on hydroelectric producers to solve this issue.

The devices built up to now were targeting migrating fish species that need to travel down river as an important part of their life cycle. Several of the devices that were installed only operate during fish migration periods while others are permanently in place. The approach of governmental agencies that are responsible for authorising hydroelectric projects and requiring mitigation measures (i.e. migration devices), varies according to the country, the province or state, or even sometimes the region.

Factors influencing the magnitude of the induced mortality

Even though the passage of fish through a turbine can cause mortality, its magnitude and precise estimate vary greatly. As a matter of fact, fish passage can affect a small or high number of fish depending on the turbine and site characteristics, and according to the species of fish. Also, often the mortality estimate varies according to the method used to derive the estimate (see section 2.3.4).

When dealing with a low waterfall for example, and a generating station that uses one or several large size turbines at low rotation speed, the mortality rate induced by the passage of fish through those turbines can be sufficiently low that no migration devices are required. In this case, the implementation of a migration device may be less efficient to protecting fish than passage through the turbines alone. (Winchell *et al*., 1992; C. P. Ruggles, 2000, pers. comm.). Likewise when fish entrainment through the turbines is low, or in the case of an important fish population where the main migrating channel passes through a spillway or any other similar structures designed to permit the survival of the majority of the fish. This last example is most often seen in run-of-the-river generating stations where the turbine capacity is usually less than the flow rate of the river at the moment of floods, which result in a significant portion of the flow not going through the powerhouse. At other times, the only flow that does not go through the turbines is the instream flow that can be maintained for biological, aesthetic, social or other uses.

However, if we are dealing with a small size turbine with a high rotation speed and a high entrainment through the turbine, the mortality rates can then be important. Furthermore, if the species of fish is migratory and must necessarily go down the river during its life cycle, then the loss of fish can become highly significant for this population, even to the point of putting it at risk.

Cumulative impacts

Another aspect of the downstream passage issue is the presence of several small generating stations on the same river. A convincing example of the complexity that this situation can bring with regard to fish downstream migration can be seen in France where there are more than 1 500 small hydroelectric generating stations and more than 20 of them can be located on the same river. This situation brings significant cumulative impacts. For example, if the efficiency of the migration device is 95% at each site, with 10 sites, the cumulative mortality rate will be 40%.

2.1.2 Regulatory Agencies

This section presents three examples of how governments manage hydroelectric operations. Governmental agencies are responsible for issue and enforcement of licenses for hydropower projects, and to demand proper infrastructures to attenuate environmental impacts associated with this type of project. However, the approach advocated by them may vary.

Canada

Two levels of responsibility exist in Canada depending upon the province in which the project is taking place. For some provinces, like Quebec, two levels of government (federal and provincial) are involved in permitting, while in others, only the federal government is involved.

At the federal level, the Ministry of Fisheries and Oceans enforces the laws related to fish habitat and therefore, to small hydropower projects which can affect them. The management rules applied serve to assure that development projects result in no net loss of the production capacity of habitats that support or have the potential to support fishing for subsistence, sport or commercial purpose. One of the management objectives is to also increase the production capacity of fishing resources by preserving, restoring and enhancing fish habitat. Another objective is to maintain the population of endangered or vulnerable fish species.

At the provincial level, the ministry responsible for environmental issues is generally the one responsible for enforcing the laws in relation to small hydropower projects. This ministry usually takes a similar approach based upon the principle of no net habitat loss. In some provinces, like Quebec, this ministry has to issue a certificate of authorisation before a small hydropower project is accepted, and can also require the installation of fish migration devices.

This approach has been in place only since 1993 for new projects, for generating stations that are being modified (additional capacity, etc.) or that restart their operation after being out of commission for a certain period. As for previously installed generating stations that are still operating, no requirements are imposed regarding migration devices. Thus, many generating stations causing damage to fish are still operating and may be so for a long time to come.

USA

In the United States, it is the Federal Energy Regulatory Commission (FERC) that has the main responsibility to issue the necessary authorisations to operate private hydroelectric generating stations. This covers issuing preliminary permits, project licences and exemptions from licensing, as well as ensuring dam safety, assessing payments for headwater benefits, and coordinating with other agencies. It is the FERC who requires mitigation measures such as migration devices when there are clearly identified environmental impacts. The US Fish and Wildlife Service (USFWS) for the eastern part of the country, and the National Marine Fishery Service (NMFS) for the western part, are other governmental agencies that make recommendations on each of the projects. These organisations operate in a somewhat similar manner as Canadian agencies by targeting no fish production loss.

Even if the FERC, and the Federal Power Commission before 1977, had this responsibility since the passage of the Federal Water Power Act in 1920, this no net loss approach has only been in effect since 1986 with the passage of the Electric Consumers Protection Act. It applies for new projects and for any projects for which the hydraulic lease is expiring. In fact, each generating station owns a contract of variable duration that can range from 30 to 50 years, and it has to be renewed at its expiration in order to continue the operation of the station. From this, many stations had to put in place new devices in recent years. This will ultimately bring environmental conformity in most installations. In 1993, around 13% of the 1 825 American hydroelectric generating stations were fitted with migration devices, however they were not all efficient (Francfort *et al*., 1994).

Exemptions can be obtained in perpetuity in two cases. The first case covers small hydropower projects of less than 5 MW built on an existing dam, or operated as run-of-the-river, or existing projects of less than 5 MW which increase their production capacity. The second case is when a power plant with a maximum capacity of 15 MW (non-municipal) or 40 MW (municipal) is added to an existing conduit (e.g. irrigation canal) located on non-federal land and primarily constructed for other purposes.

For projects requiring license, resource agencies have developed criteria for five design aspects of downstream passage facilities (Odeh and Orvis, 1998): 1) approach of flow to the turbine intake; 2) protection mechanism and guiding device; 3) flow attraction to the bypass; 4) conveyance mechanism; 5) tailrace characteristics (plunge pools, etc).

The licensing process usually takes 3 years to complete, sometimes longer, but it may be less than one year if the stakeholders achieve consensus rather than litigated or mandatory solutions. In such cases, mitigation measures can be implemented before the license is issued.

France

In this country, it is the Environment Ministry that is the agency responsible in issuing the hydroelectric exploitation authorisations. For small hydropower stations, the Ministry delegates its authority to local administration (“departement”) where, nevertheless, a representative of this agency is generally in place. Since 1984, migration devices or other infrastructures are required by law, if needed, to insure a safe upstream and downstream passage for fish. The agency can officially act at any time in the case of rivers classified "for migration" where anadromous or catadromous species are present, but it initially allowed a 5 years period in 1984 for the producer to comply with the law and, since no universal technology was available and research is still ongoing, this delay has been extended since then (M. Larinier, 2000, pers. comm.). For other rivers however, the agency has to wait for the renewal of the power purchase agreement to compel the promoter to add devices that will permit unrestrained fish passage. These power purchase agreements bind the private producer to Électricité de France (EDF), a public society.

Therefore, the measures in this country are the most severe. Generating stations located on rivers harbouring migrating species are systematically modified and every station will eventually be in environmental compliance. In the meantime, stations with migration devices are seen alongside others that have no systems. This situation implies an almost random distribution of devices for fish migration and therefore explains the absence of devices on some of the generating stations.

2.1.3 Sustainable project development

The designer of a small hydroelectric generating station (which is generally the promoter or a hired expert) and the governmental agency that has the responsibility to authorise the project have, for a long time, showed different approaches on a given project. On one hand, the designer uses technical and economical aspects as a basis to evaluate the project and decide if it is safe and viable. For the agency on the other hand, these aspects are examined to verify its safety and if it is profitable enough to allow the undertaking of every expected constituent of the project, especially the environmental and social mitigation measures.

Environmental aspects of the projects such as the presence of productive aquatic habitats or the species potentially affected, were previously only considered as secondary aspects for the designer, if even considered. These aspects were generally perceived as a constraint that adds further costs. Governmental agencies were then more permissive with respect to environmental impacts.

However, the approach of the designer has changed in the last decade and the environmental aspects are generally part of the main design criteria. The refusal of some projects by governmental agencies because of environmental concerns demonstrates that there should be no investment in the detailed technical design of a project before proper assessment of potential environmental impacts is done.

As an example, the Richelieu River hydropower project in Quebec (Canada) was abandoned because of the presence of Copper Redhorse (*Moxostoma hubbsi*) that was susceptible to be designated as an endangered or vulnerable species. Another example is the Edwards Dam that had to be dismantled in 1999 on the Kenebec River, Maine (USA) because of the constraints imposed on migrating fish, notably the Atlantic Salmon (*Salmo salar*) and the Atlantic Sturgeon (*Acipenser oxyrynchus*). It is the first case when relicensing was refused by FERC. Similarly, the Condit Dam on the White Salmon River in the Washington State (USA) will be dismantled between now and 2006 by the owner in order to avoid costs which would be related to the modifications required by the FERC to allow its continued operation (Howe Verhovek, 1999).

These examples illustrate how environmental issues have become a primary factor in determining whether a project can receive the authorisation by the appropriate agencies. Most often, it is those agencies that will require the inclusion of mitigation or compensation measures for the project.

The designer generally takes into consideration the environmental impacts that are most common, which are habitat loss in an altered reach and migration constraints for the fish. Other environmental impacts are mostly considered by governmental agencies, as the cumulative effects of several generating stations on the same river.

2.1.4 Site by Site Approach

Each of the sites considered for a small hydropower project must be studied separately in order to identify the actual environmental constraints and the most appropriate measures to overcome them. As stated by the majority of people working in that field, EPRI (1986), Sale *et al*. (1991), Clay (1995), Odeh and Orvis (1998) and several others, there is no universal migration device that allows safe fish passage and each site has unique aspects. It is for this reason that environmental monitoring is necessary to evaluate their efficiency. Each site is a development project by itself, and small hydropower projects are often as complex to solve as those needing larger equipment (C. P. Ruggles, 2000, pers. comm.).

The only exception to this approach is in the case where other generating stations or new development projects are existing on the same river. Cumulative effects must then be considered and new infrastructures allowing safe downstream fish passage could be pooled together if upstream capture and downstream transport of fish is a viable solution.

2.2 Fish Species

2.2.1 Migratory vs Resident Species

There are two categories of fish species moving downstream in a river: the true migratory species that must move downstream to achieve their life cycle and the resident species that make regular downstream movements which cannot be described as a through run. In the first case, they are species called anadromous or catadromous. For anadromous species, the adults migrate from saltwater to freshwater, and the juveniles, migrating downstream toward ocean feeding grounds, may be affected by the presence of generating stations. For catadromous species, the adults migrate downstream toward their sea spawning sites. Due to their larger size, these are more subject to higher mortality rates when going through a turbine. In this second case, the issues are different since the downstream movements are limited to a number of individuals, not involving a whole population.

It is necessary to distinguish impacts that have a biological effect at the fish population level and those impacts that effect individuals rather than populations. The eventual fate of all individuals comprising plant and animal populations is death. Therefore, it is important to distinguish between discriminate impacts of hydro dams on individual fish and the indiscriminate impacts of dams that threaten entire fish populations (C. P. Ruggles, 2000. pers. comm.).

For example, entire populations of anadromous fish spawning above a given dam are exposed indiscriminately to local adverse impacts created by the dam (a blockage to their migration) when all members of the population attempt to migrate past the dam. On the other hand, certain species may flourish in the impoundment above the dam, even though individuals of the species may become entrained by turbine flow and killed during turbine passage. This discriminate impact, although fatal to the individual, may have no impact at the population level because of normal biological compensatory regulation that will tend to mitigate against these losses. Hence, entrainment in turbine flows is sometimes not an issue at hydroelectric dams located on rivers that support non-migratory species. At the very least, fish protection at these dams do not justify the same level of attention as the dams on rivers supporting anadromous species (*Op. cit*.).

Cada (1990) states that the migratory species are more likely to be flushed down through turbines. In fact, several surveys carried out on migratory species for run-of-river hydropower project showed small percentage of entrainment for resident species. In Quebec, spring surveys (1993 to 1995) done on smolts in cold water captured less than 0.1% (on more than 33,000 fish captured) of resident species (G. Tremblay, Genivar, unpublished data), while summer shad survey in warm water showed about 0.2% (on almost 2600 fish caught) of resident species (Couillard and Guay, 1989). In France, surveys done in cold water streams showed similar results with captures of less than 2% of resident species (Carry *et al*., 1996; 1997). For reservoir hydropower projects, results are quite different as the catches of resident species were larger, sometimes more than a thousand per hour (Brouard and Doyon, 1991; Navarro *et al*., 1996; Doyon, 1997).

The protection of resident species remains an overall goal, but the production and harvesting rates of a given population must be taken into account rather than the survival of individual fish. If the proportion of individuals going through the generating station is relatively low and the population is not over harvested, the small loss of biomass will have little negative impact on the population. Species behaviour and the type of habitat will rule the overall impact. Certain species may well make substantial movements between different habitats to spawn (from still waters to fast flowing reaches, from great depths to near surface habitats, etc.).

Often, entrainment through turbines results from a redistribution of fry from overpopulated habitats. It occurs mostly in the spring and summer and basically affects the smaller individuals, 90% measuring under 200 mm as compiled by Winchell *et al*. (1992) from 40 different cases. More recently, sampling done in the tailrace at two sites in the Netherlands showed that the majority of entrained fish were less than 10 cm (Haddering and Bakker, 1998). The reproduction strategy of *centrarchidae* (sunfish and bass) results in an overproduction of fry in terms of habitat availability. Therefore, a fair number of fry inevitably move downstream, but the resulting loss of biomass does not affect the overall population equilibrium (Winchell *et al*., 1992).

There is very little research addressing this aspect of population dynamics where some biomass is lost through turbine entrainment at generating station. More data is needed regarding this issue.

In most of the agencies, only migrating species are targeted for run-of-river hydropower project environmental enhancement, although resident species are targeted for industrial intakes, irrigation systems, etc.

The potential impact on migratory fish species differs for different types of hydropower project. Generally, with run-of-the-river projects, only a portion of the downstream run is passed through turbines since migrations are often synchronised with floods where only part of the river discharge goes through the turbines. The proportion of entrainment varies with different species. Those swimming near the surface are less likely to be entrained since flood spillways are generally at the surface and the turbine intakes are near the bottom. Incidentally, most North-East USA migrant fish are found in the upper portion (e.g. 1-4 m) of the water column (several authors *in* Odeh and Orvis, 1998; C. P. Ruggles, 2000, pers. comm.; J. Therrien, pers. obs.).

For hydropower projects supplied by a reservoir, all the water stored will be entrained except if a minimum flow requirement has been granted or if the reservoir is at full capacity. Other exceptions include spillway testing or maintenance operations, or if there is a ship lock at the dam site. In any case, the proportion of the flow not entrained by the turbine remains relatively low.

For resident species, the impact is the same for any type of project. These are species that do not really migrate. Nevertheless, they do move within the river and their passage through the turbines is a function of the depth of the water intake and the depth at which the species move. However, what little monitoring data is available indicates that the number of fish flushed through turbines is higher at hydropower projects supplied by a reservoir than at run-of-the-river ones.

The potential impact of a run-of-the-river hydropower project on migratory fish species also depends on the type of watershed. When the generating station is built in a cold water river, in hilly terrain with a strong slope gradient, the fish biomass is generally less diversified and relatively small. In a warm water river, with a more gentle slope, the number of species and the overall fish production are definitely higher.

2.2.2 Migratory Species

Table 1 lists the migratory species frequently encountered at small generating stations in North America. This is by no means an exhaustive list, but it contains a sufficient variety of species to be indicative of the potential situation for other species. The same rationale applies to European species and to several resident species. See the above section for definition of catadromous and anadromous species.

The spawning seasons of each species will influence whether entrainment will be total or partial, as they can be related to flood event periods. It is then possible to determine when the migration devices must be in operation. When the devices are implemented solely for migratory species, they are only required during the migration periods which are generally known with sufficient precision.

Robustness and resistance to shocks, to pressure changes and to shear forces, for each species, are qualitative data that provide a general idea of the fragility of the species when turbine passage occurs. Sturdiness and resistance are inferred from the highly variable survival rate for different species going through similar power equipment, assuming that the main source of variation is the fragility of the species.

As for fish swimming capacity, only general data are provided. The maximum swimming peak speed possible over a very short period of time (generally about 10 seconds) may vary in relation with physical variables such as temperature or fish size. Appendix 1 provides an example for Atlantic salmon swimming speed and endurance are presented as a function of smolt sizes (i.e. the stage at which salmon migrates downstream toward the sea). For a 150 mm smolt, the maximum speed varies from 1.1 m/s to 1.6 m/s, for a period of 4 to 10 seconds, when water temperature is between 5 and 10°C. The minimum value of 30 cm/s, used in several countries as the approach speed for a physical barrier to prevent smolts from being flushed through turbines, is the minimum swimming speed possible for salmon, size notwithstanding. According to Jones *et al*. (1974), velocity required for most tested species to manage an experimental flume tank is 30-40 cm/s. This variable can prove crucial in selecting and designing an efficient device.

TABLE 1. North American migratory fish species frequently encountered in streams with small hydropower projects.

Common name	***Scientific name***	***Migration***		***Speed*** [3]
		Type [1]	***Period*** [2]	***(m/s)***
Alewife	*Alosa pseudoharengus*	A	August-October	-
American eel	*Anguilla rostrata*	C	End of Aug.-October	0.5[4]
American shad	*Alosa sapidissima*	A	August-September	0.05-0.08
Atlantic salmon/Ouananiche	*Salmo salar*	A	April-June	1.1-1.6
Atlantic sturgeon	*Acipenser oxyrhynchus*	A	Summer-Fall	-
Blueback herring	*Alosa aestivalis*	A	Summer	-
Brook trout	*Salvelinus fontinalis*	A	October	0.09-0.26
Chinook salmon	*Oncorhynchus tshawytscha*	A	Spatially variable	-
Chum salmon	*Oncorhynchus keta*	A	March-June	-
Coho salmon	*Oncorhynchus kisutch*	A	February-June	0.35-0.40
Pink salmon	*Oncorhynchus gorbuscha*	A	April-May	-
Rainbow smelt	*Osmerus mordax*	A	May	-
Rainbow trout	*Oncorhynchus mykiss*	A	October-November	0.03-0.25
Sockeye salmon	*Oncorhynchus nerka*	A	Spring	0.4-0.5
Steelhead trout	*Salmo gairdneri*	A	Spring	-
Striped bass	*Morone saxatilis*	A	End of Summer-Fall	0.06-0.24
All species (fry; 2.5 cm TL)				0.15

Source : Brett *et al*. (1958), Webb (1978), Scott and Crossman (1975), Bell (1991), Clay (1995), Peak and McKinley (1998).

1 A : anadromous; C : catadromous
2 Period(s) of downstream migration, indicated as an example for the North-East of North America except for all salmon but Atlantic.
3 Peak swimming speed (at the length when downstream migration occurs)
4 Minimum current velocity causing impingement on a screen (Taft, 1998)

2.2.3 Rare and Endangered Species

Certain resident species may be added to the list of migratory species for which government agencies show special concerns when building small generating stations. These are species appearing, or likely to appear, on the list of endangered, threatened or vulnerable species. This list differs for each country and varies according to acquired scientific knowledge and to the recovery of certain populations due to special protection measures applied because of their status. Appendix 2 gives the list of species for Canada. As stated in section 2.1.3, the presence of any such species in a stream where a small hydropower project is planned may lead to the abortion of the project.

2.3 Causes of Fish Mortality

The mortality induced during the downstream migration of fish at hydroelectric generating stations can occur at three locations: 1) upstream from the powerhouse and dam; 2) during the passage through turbines; 3) downstream from the powerhouse and dam. These aspects are discussed in detail hereafter.

2.3.1 Upstream

Fish mortality above the power station and dam is caused by : direct contact with a migration device, increased predation resulting from delays in downstream migration, or by a weakening of fishes fighting an inadequate water flow. The first and third causes are essentially linked to migration devices implemented to reduce mortality during downstream migration. These issues are addressed in more details in section 2.4. Contacts with the migration devices include impingement on small mesh screens, if current velocity is too high or if the screen angle is not appropriate. Weakening of fishes above the power station is generally the result of a poorly designed migration device or inadequate maintenance, inducing hesitation and resistance to use the bypass. The resulting mortality is sometimes only perceptible below the obstacle and is sometimes confused with mortality occurring below the power station.

Finally, delays in the migration caused either by the power station or by the migration device, can result in increased predation by piscivorous fishes or birds attracted by the abundance of fish above the dam site.

2.3.2 Turbine passage

At the power station, fish mortality is essentially caused by turbine passage, if entrainment in the water intake is sufficient. Entrainment depends upon site characteristics (configuration, hydraulics), proportion of flow being entrained, and species involved.

2.3.2.1 Types of mortality

The causes of mortality can be grouped in four categories (Ruggles and Collins, 1980; Travade *et al.*, 1987; Larinier and Dartiguelongue, 1989; Cada, 1990; Eicher, 1993; Ferguson, 1993; Cada *et al.*, 1997; Cook *et al.*, 1997; Franke *et al.*, 1997; Turnpenny,1998a) :

1) contact of fish with one of the turbine parts. Injuries are caused by strike, abrasion or grinding (passage through the gap between blade and hub);

2) a sudden acceleration or deceleration. The variation factor may reach 30 times the reference velocity (increase or decrease), inducing turbulence, particularly at the trailing edge of the runner, which creates shear forces that could literally tear fish to pieces;

3) variation in pressure which may become negative or increase to three times the reference pressure, potentially causing the rupture of the swim bladder. The usual pattern involves an increase (double) in pressure during the entrainment phase, a fast decrease (less than 1/3 in less than 3 seconds) during the passage into the turbine, and a second increase (3 times and more) in the discharge phase;

4) cavitation, which is caused by the creation of gas bubbles in a liquid, by a reduction in pressure below vapour pressure, that collapse or implode, and may cause various injuries to the fish.

Pressure or velocity variations may occur anywhere during fish passage, but contacts and cavitation occur only in specific areas, on small surfaces, and may be avoided by turbine design and setting (Cada, 1990).

The probability of fish mortality induced by contacts with turbine parts is higher for larger fish. Survival tests conducted during passage through a Francis turbine for different fish species of various sizes demonstrated an increase in the proportion of fishes exhibiting contact marks, when size exceeded 300 mm (Matousek *et al.*, 1994). This size value may vary depending upon turbine and site characteristics (rotation speed, number of blades, head, etc). On the other hand, entrainment is higher in smaller fishes. A review of 40 cases studied (Winchell *et al.*, 1992) showed that 90% of fishes entrained were less than 200 mm, for any species and any type of turbine. Some species (such as clupeids: shad, blueback herring, alewife) are more frail, scale more easily and often reported to have higher mortality rates. However, C. P. Ruggles (2000, pers. comm.) believes species differences in turbine induced mortality have been overstated. From experiments done with salmonids, blade-strikes affect mainly fish bigger than 20 g (Turnpenny, 1998a). The probability of contact will increase when the turbine is not at best efficiency, such as stated by several authors and well described in two experiments by Haddering and Bakker (1998). Mechanical related injuries have been reported as the dominant cause of fish mortality at low head (< 30 m) projects (Franke *et al*., 1997).

The typical changes in velocity in shear zones are in the order of 10 m/s although extreme values of velocity could be from near zero to almost 40 m/s, depending on the head (U.S. Army Corps of Engineers, 1995 *in* Cook *et al*., 1997). The intensity of shear forces decreases when the turbine is running at best efficiency (*Op. cit*.), which is usually slightly less than maximum operation (Several authors *in* Cook *et al*.,1997). Shear effect seems to be species and site specific, larger fish being less injured (Franke *et al*., 1997).

Pressure-related damage to fish rarely occurs at heads lower than 18 m, but is significant at heads higher than 30 m, even in free fall without turbine (Franke *et al*., 1997). Fish with pneumatic duct (Physostome as salmon, minnows, catfish, etc.) are able to adjust to pressure change more quickly than fish without (Physoclist as bass, sunfish, perch, walleye, etc.), and therefore are less susceptible to be injured by pressure variations (Cada *et al.,* 1997).

The implosion related to cavitation may damage nearby fish tissues or the turbine wheel, although the fish may be more resistant than turbine parts as was proven for a low energy testing with herring and sole (Turnpenny and Everard, 1999).

Cavitation seems to be the most frequent cause of mortality (Cada, 1990). Ruggles and Collins (1980) also stated cavitation as the main cause of mortality, except in situations where the probability of contact is higher. This probability is determined by the turbine design and by fish size. Cavitation is minimum when full downstream turbine submergence is attained, and when best efficiency turbine output is reached. A higher mortality rate has been observed in turbines not running at full capacity (Taylor and Kynard, 1985). This cause of mortality should be very low in high-performance works, under optimum exploitation. Besides submergence, other conditions influencing cavitation are general or local low pressure zones, high velocity zones, abrupt changes in flow direction, blade surface roughness, atmospheric pressure, and air content of water (U.S. Army Corps of Engineers, 1995 *in* Cook *et al*., 1997).

The mortality observed in fish descending the river at a generating station site, without considering the location of the mortality (upstream, powerhouse or downstream), can be direct or indirect. In the first case, the observation is generally easy since fish that can be recovered are already dead. In the second case, we are dealing with a latent mortality or morbidity that can only be observed after a certain time lag. In general, when monitoring studies are done to verify the efficiency of a migration device, it is recommended to verify latent mortality over a 96-hrs period.

Latent mortality can result from external wounds (fish are displaying obvious scars), and internal wounds (haemorrhages, rupture of the swim bladder, gaseous embolism, fractures, etc.) which are often difficult to detect without autopsies, as well as behavioural problems related to stress, to disorientation or to similar factors which are generally very difficult to detect and demonstrate since mortality is thus often linked to a higher predation susceptibility.

2.3.2.2 Types of injuries

The types of injuries induced by turbine passage have been documented by several authors (Munro, 1965; Eicher *et al.*, 1987; Larinier and Dartiguelongue, 1989; Cook *et al.*, 1997; Franke *et al.*, 1997; Turnpenny, 1998a) and the following resume is based on these studies. In general, injuries are grouped according to their origin (mechanical or non-mechanical), or according to whether they are external or internal injuries. These two classifications are equivalent; injuries caused by mechanical factors are usually external, etc. Some authors add a separate category for injuries induced by shear forces. Besides injuries, stress can make fish more susceptible to predation, by weakening, disorientation, and changes in their instinctive survival behaviour.

External injuries include fractures, severances, isthmus tearing, contusions, lacerations, abrasion, scaling, torn gill covers and eye lesions (from red-eye to complete removal), caused either by contact with the turbine or by shear forces induced by differences in current velocity. The second category covers internal injuries, such as eye bulging, external (eyes, base of fins) and internal haemorrhages, rupture of the swim bladder, and gaseous embolism, which are caused mainly by pressure variations and cavitation. The stripping of external mucous, although not considered as an injury, can be harmful and lead to death by fungal infections, and was evident in shear stress and blade strike experiments (Turnpenny, 1998a).

The strike probability depends in part on the fish weight and is related to the possibility to be swept aside by the water moving around the blade (Turnpenny, 1998a). For salmonids of less than 20 g, this probability is only 1,2%, 37% for 20-200 g fish, and 47% for fish over 200 g (*Op. cit*.). For the lighter fish, the strike will occur in its centre of gravity, about in the middle of the body, on about 1/10 of its total length. This strike surface will extend with body weight to 80% of the length, with the exception of the two extremities because of the sweeping effect (*Op. cit*.).

The risks of injuries caused by pressure variations are higher if the head is greater than 20 m, or if the water intake is located in deep water (Larinier and Dartiguelongue, 1989). Gaseous embolism is related to the head and to site configuration. For low head systems (< 30 m), the predominant cause of injury will be blade-strike (Turnpenny, 1998a) and, therefore, it will affect mainly larger fish as is shown by several studies (*Op. cit*.; Ruggles, 1985; Winchell *et al.*, 1992; Haddering and Bakker, 1998).

2.3.3 Downstream

Below the power station and the dam, fish mortality results from : 1) contact with a structure (migration device, spillway, dam, deflector, etc.); 2) too high a free fall from the dam; 3) supersaturation of water in nitrogen; 4) increased predation induced by fish weakening or disorientation; 5) site configuration where fishes return to the river after crossing the dam.

Mortality is direct when a fatal contact occurs, when the head is too high, or when water is oversaturated in gas. Fatal contact can occur with dam structures (dam, spillway, etc.), with downstream passage devices (bypass canal) or with river bed or banks. Adequate design of the spillway or bypass canal can reduce this type of injury (Section 2.4) and the plunge pool and tailrace characteristics will influence the survival of fish downstream. The pool depth should have a minimum of 0.9 m and be equal to a quarter of the differential head, and the volume of the pool must be about 10 m^3 for every cubic meter of flow to allow for an adequate energy dissipation in the flow (Odeh and Orvis, 1998). A recent flow spreader has been developed in laboratory to reduce the plunge depth and increase the flume width, to improve survival of fish in the outfall (Den Bleyker *et al*., 1997).

Bell and DeLacy (1972), Ruggles (1980a), Sweeney and Rutherford (1981) and Ruggles and Murray (1983) have calculated maximum falls for Atlantic and Pacific salmon at 21 to 40 m for smolts (15-18 cm in length) and at approximately 13 m for adults (longer than 60 cm) for complete survival. Above these heights, mortality occurs and varies with species, height and site, anadromous species being able to survive at 98% even at 90 m free fall (Ruggles, 1980a). Nitrogen supersaturation is related to the height of fall and the deep plunging action of the spill (Clay, 1995).

Mortality is indirect when fish condition is altered by an injury, including abrasion and descaling, stress or gaseous supersaturation, or when fish is exhausted after clearing the obstacle or offering resistance to passage. In the two latter cases, mortality is often related to easier predation by piscivorous fishes and birds, which can be very significant, reaching up to almost one third (32%) of the downstream migrating population (Dawley *et al*., 1993). In the case of gas bubble disease, it severely disables the lateral line function, which lowers the ability of the fish to avoid predators and underwater objects, and to orient in water current (Popper and Carlson, 1998). Finally, site configuration may also favour predation through low current velocity in the river, low dispersion of fish at the exit site, stress, disorientation and exhaustion .

2.3.4 Mortality estimation

2.3.4.1 Difference between mortality and entrainment

There is a significant difference between fish entrainment in the turbine and mortality. Entrainment is defined as the proportion of a population entrained toward the turbine. For a resident population, the rest of the population remains above the dam, while for a migratory population, the specimens not entrained must clear the obstacle by migrating through a device designed for this purpose, or by passing through a spillway (dam, sluice, etc.). There are three ways to estimate mortality : mortality related to turbine passage (between the intake and the exit), mortality related to crossing of the obstacle, which takes into account the other sources of mortality possibly occurring above and below the dam (sections 2.3.1 and 2.3.3), or the relative mortality affecting a resident fish population since only a percentage will be entrained. In general, mortality induced by turbine passage is most frequently estimated in the course of monitoring programs. However, depending on the protocol implemented, this estimate also includes most events occurring above and below the dam, except for predation.

Considering that mortality assessment takes into account most of the sources related to the presence of a structure, a negligible mortality will always have a minor impact at any entrainment rate. However, a relatively high mortality may induce a different impact for a negligible entrainment (low impact), or for a substantial entrainment (high impact). For example, a 50% mortality during turbine passage produces a very low total mortality rate (0.005%) when entrainment is negligible (0.01%), but represents a relatively high rate (30%) if entrainment is high (60%). The methods of mortality estimation being different, these two aspects are treated separately; entrainment is addressed in section 2.3.5.

2.3.4.2 Methods of mortality estimation

The mortality estimation treated in this section is mainly related to turbine passage. However, it may integrate other sources of mortality, as specified above.

There are currently five methods to evaluate mortality induced during turbine passage : a comparison of return rates for migratory fishes caught above and below the dam; the use of fishing gears at the turbine site; capture, tagging and recapture; use of inflatable tags; and telemetry. These methods are described in detail in chapter 4.

2.3.4.3 Mortality rates vs types and characteristics of turbine

Overview studies on mortality caused by turbine passage indicate mortality rates ranging from 0 to 100% for Francis turbines (Bell *et al.*, 1967 *in* Ruggles and Collins, 1980; Bell,1990; Turbak *et al.*, 1981; Montén, 1985; Dartiguelongue and Larinier, 1987; Eicher *et al.*, 1987; Dartiguelongue, 1988; Larinier and Dartiguelongue, 1989; Mills, 1989; Winchell *et al.*, 1992; Larinier, 1992a). In general, it appears that the mortality rate is rarely below 10% (Eicher *et al.*, 1987). In resident species, the rate averages 6% and it may be only 1% to 2% according to some studies (Winchell *et al.*, 1992), while other studies report an equivalent rate to migratory species (M. Larinier, 1996 pers. comm.).

The mortality rate varies from 0 to 90% in propeller turbines (11 studies *Op cit.*), but it generally ranges from 5% to 20%, with a mean value of 15% (Eicher *et al.*, 1987; Larinier and Dartiguelongue, 1989; Larinier, 1992a). Propeller turbines include Kaplan turbines, bulb groups and horizontal Kaplan known as "tubular turbines". Incidentally, the bulb group turbines are very promising, the rare studies indicating mortality rates lower than 10% for salmonids (Winchell *et al.*, 1992).

For other types of turbine (i.e. crossflow, Pelton, etc.), the high rotation speed and the flow configuration induce a mortality rate practically reaching 100% in all cases (11 studies *Op cit.*).

Table 2 summarizes the mean mortality rates observed for different species in Francis and Kaplan turbines, based on recent studies in which the most frequent sampling biases have been avoided. Figures 1 and 2 describe Francis and Kaplan turbines, respectively. The spiral well shown in figure 1 may be required for both types of turbine if the head is greater than 4-6 m.

For Francis turbines, the major area of concern for induced mortality is the runner entrance where the wicket gates, the blades and the runner’s peripheral speed may harm fish (Eicher *et al*., 1987). Higher mortality has been correlated with higher peripheral runner speed and greater wicket gate opening, the latter perhaps because of less clearance between the trailing edge of the wicket gates and the runner (*Op. cit*.). For Kaplan turbines, the major area of concern is the clearance between the blade tips and the discharge ring (*Op.cit*.). Unlike the Francis turbine, there is not a strong relationship between peripheral runner speed and fish mortality (*Op. cit*.). For both types, the plant head is not correlated with mortality. It has been often stated that head had an influence on mortality rate, but it may only be due to the fact that mortality is higher on Francis turbines which are generally at higher head than Kaplan (Cook *et al*., 1997)

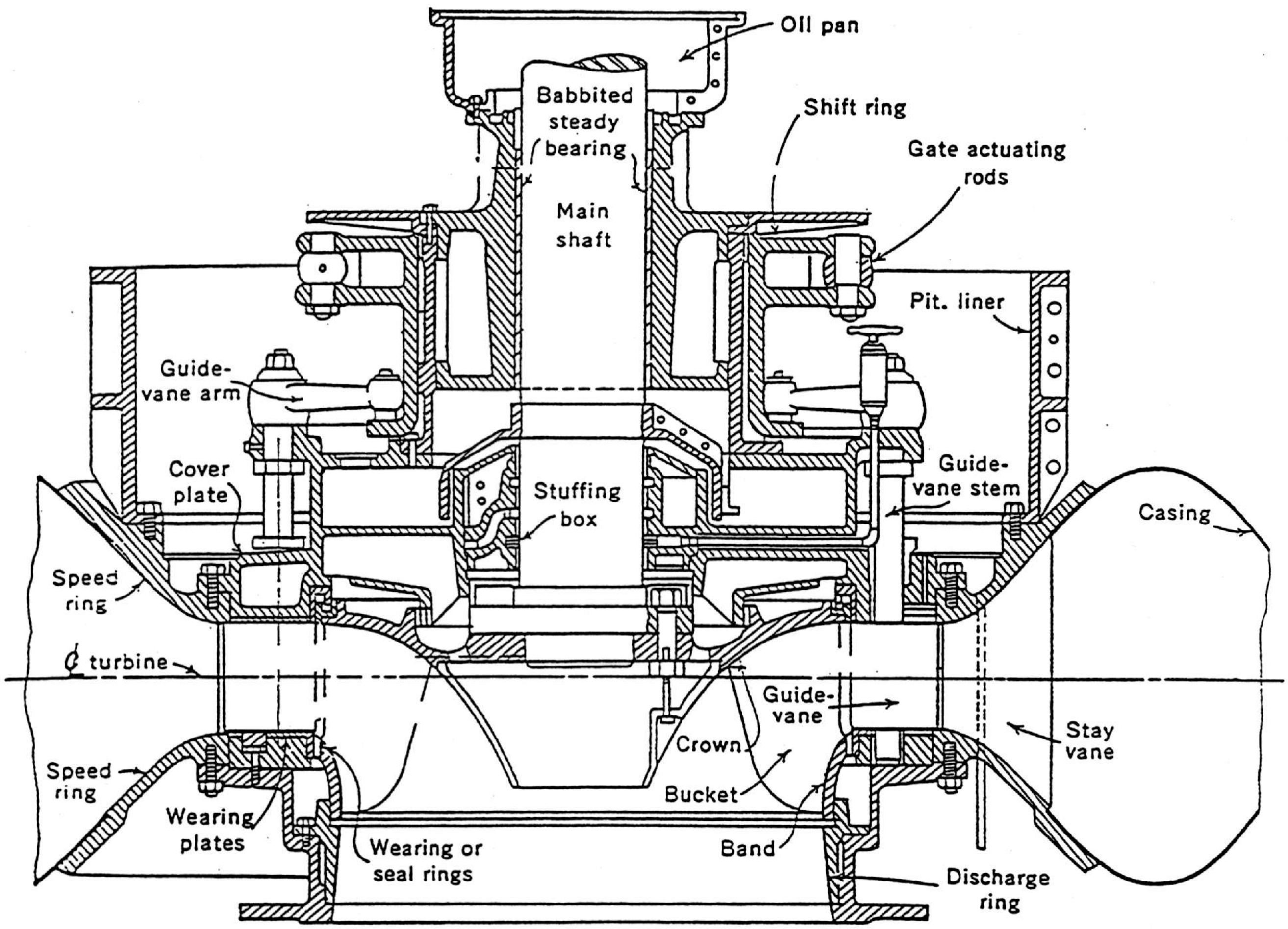

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FIGURE 1. Schematic cross-sectional view of a Francis turbine (from Doland, 1954 in Cook *et al.*, 1997).

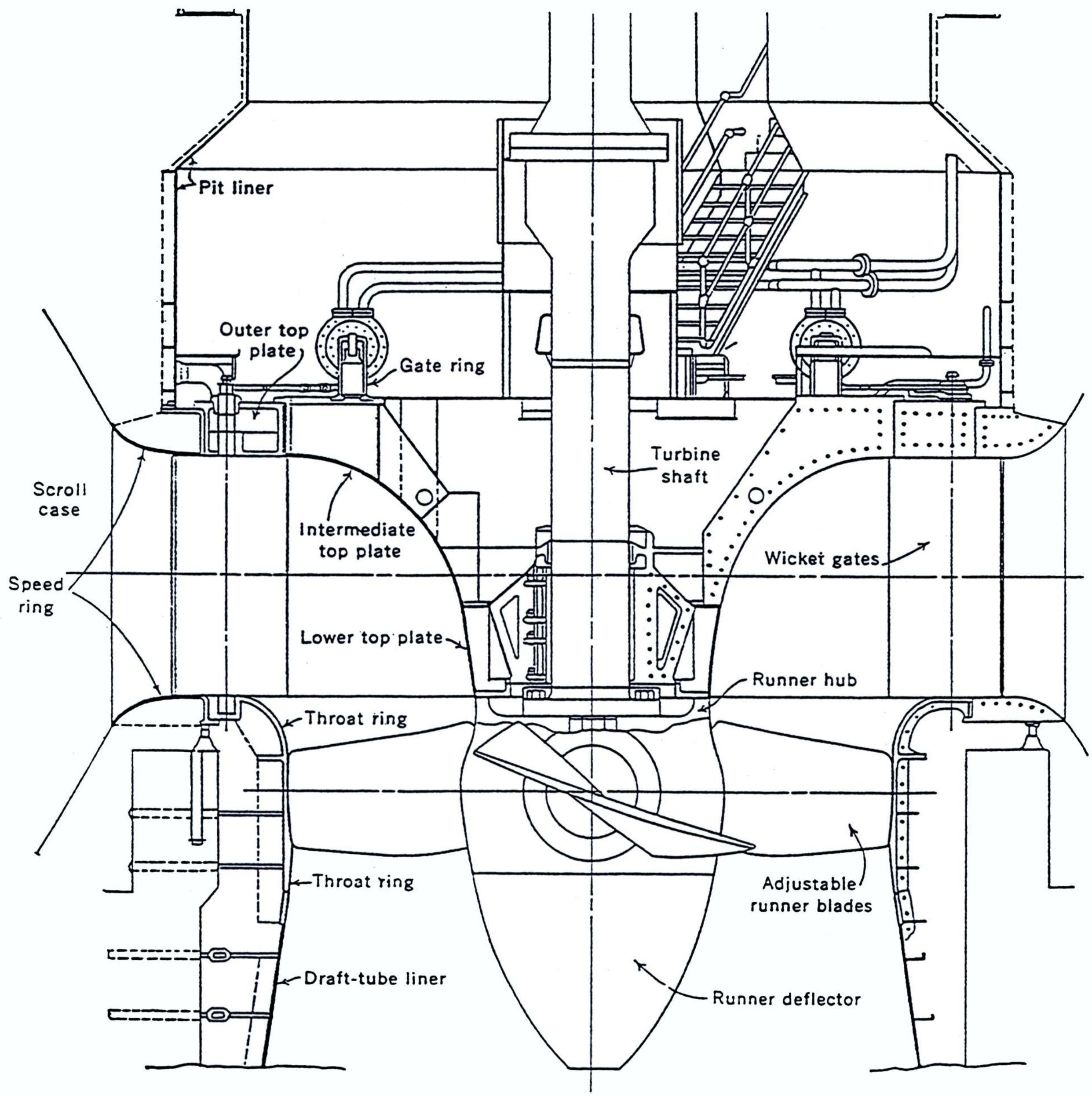

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FIGURE 2. Schematic cross-sectional view of a Kaplan turbine (from Doland, 1954 in Cook *et al.*, 1997).

TABLE 2. Average mortality rate of passage through Kaplan or Francis turbines according to species.

SPECIES OR GROUP OF SPECIES		AVERAGE MORTALITY RATE (%)	
		Kaplan Turbine	*Francis Turbine*
Resident[1]			
Wild		6.3	5.8
Introduced[2]		30.2	37.0
Migratory species[3]			
Salmonids (salmon, trout)		7.6	18.2
Clupeids (shad, alewife)	- adult	3.6	16.0
	- juvenile	19.1	28.6
Centrarchids (crappie, bass)		8.5	11.7
Percids (walleye, darter, perch)		--	23.6
Esocids (northern pike)		--	22.3
Catostomids (suckers)		--	24.0
Cyprinids (shiner)		--	20.0
Ictalurids (bullhead)		11.3	--

(From Winchell *et al.*, 1992)
1 Unspecified species
2 Hatchery fish injected in the turbine for the test
3 Includes true migratory fish and species doing only migration within a watershed

2.3.4.4 Estimation models

Predictive models for mortality related to turbine passage were developed from the results of monitoring studies conducted on certain types of turbine. However, these models are dependant on the values on which they are based, and because of the frequent biases in these studies, the models are generally imprecise and tend to overestimate actual mortality, as recorded for American eel (Therrien, 1999b). They may be used to roughly estimate mortality when a true evaluation cannot be conducted.

The current predictive models vary with the type and characteristics of the turbine, as well as with the species investigated. The parameters most likely to affect mortality caused by turbine passage appear to be : wheel rotation speed; gap between blades; the type of turbine, its regime and the operating conditions of the mobile parts of the wheel (blades, wicket gates); the occurrence of cavitation zones; head; fish size; and fish species (Ruggles and Collins, 1980; Travade *et al.*, 1987;

Eicher *et al.*, 1987; Larinier and Dartiguelongue, 1989). However, the data used for these results were frequently inaccurate, or certain significant parameters were not available. Therefore, further investigations are needed (Eicher, 1993; Ferguson, 1993). For example, the increase of mortality with increasing rotation speed or decrease with increasing wheel size is not necessarily linear, and an equivalent mortality can be obtained for a relatively wide range of each of these parameters (Matousek *et al.*, 1994).

A review of existing models by Larinier and Dartiguelongue (1989) demonstrates that models used in the past 30 years are very imprecise. They propose models for salmonids and eel, based on the analysis of more than 100 experiments. Specific models are proposed for Kaplan turbines, including bulb groups and other propeller turbines, and for Francis turbines. They are grouped in two categories: the first group of models takes into account the nominal characteristics of the turbine, values that are readily available; the second group uses more complex data, not always available, such as angles and speeds at various positions on the wheel or its components. Larinier is preparing an update of this publication which should be available sometimes in 2000 (M. Larinier, 2000, pers. comm.).

In the USA, the most frequently used equations are those of Bell (1991), which can be applied to a larger group of species, but which also use parameters often hard to measure. They concern the probability of fish impact with the mobile parts of the turbine, as well as the proportion of space available between blades which produces a sufficiently low pressure to cause mortality in fish. Recently, the US Department of Energy (Franke *et al.*, 1997) published a document presenting a review of models and proposing new ones based mostly on tangential angles and speeds. However, no information is provided on the precision of the equations (coefficient of determination, etc.).

Two models are described below: one proposed by Dartiguelongue and Larinier (1989), using the nominal characteristics; and one by Franke *et al*. (1997) using tangential speeds. They are presented only to show the type of data needed and the calculations required. For a site specific study, it is suggested to refer to the actual reports. However, on the basis of the considerations previously stated, it is recommended to conduct monitoring at each site as long as standard models are not developed and accepted by the majority of the experts in this field.

Kaplan or propeller turbine

Larinier and Dartiguelongue (1989) present a fairly reliable equation for salmon juveniles and adult eels which explains 94% of the observed variance. In other words, almost 95% of the differences observed between different tests conducted at different sites is taken into account by the model. The equation will be revised in 2000 since part of the data included turbines running at less than full capacity. This led to an increase in mortality and, therefore, caused a slight overestimation of mortality in the equation (M. Larinier, 2000, pers. comm.). The equation is as follows:

AMO = $12.2 + 72.7\,(TL^{1.125}/esp^{0.843})$ degrees

where AMO = a transformed variable = ARCSIN (% mortality)$^{0.5}$;
TL = total fish length (m);
esp = π Dm / NAP;
Dm = wheel diameter at mid-blade (m);
NAP = number of blades;

and where mortality% = 100 * [SIN (AMO)]^{2}.

Francis turbine

Franke *et al*. (1997) present several equations for several turbine types and types of injury. As small hydropower projects usually deal with low head and mechanical injuries are the most frequent in that case, the equation given below refers to the probability of strike by the leading edge of blades. The equation is as follows:

$$P = (NL / D) * [(\omega D * \sin\alpha / 2\pi * V) + \cos\alpha / \pi]$$

where N = number of buckets;
L = fish length ;
D = wheel diameter;
ω = rotational speed;
α = angle to tangential of absolute flow upstream of runner;
V = radial velocity;

2.3.4.5 Examples

From the experimentation done in St. Lambert (St. Lawrence River, Quebec, Canada) on the survival rate of adult eels passing through a Kaplan turbine (Therrien, 1999b), results were as followed: global survival rate of 84.9% for eels tested (length from 59 to 130 cm), with partial survival rates of 90.5% for small eels (59-83.5 cm) and of 79.3% for large eels (84-130 cm).

Using the above equation of Larinier and Dartiguelongue (1989), using three different lengths corresponding to the extreme values of the two categories of eels, the data are as follows:

TL	=	total fish length (m):	0.59, 0.84 and 1.30;
Dm	=	wheel diameter at mid-blade (m):	3.075;
NAP	=	number of blades:	3;
esp	=	π Dm / NAP:	3.22;
AMO	=	12.2 + 72.7 ($TL^{1.125}$/esp $^{0.843}$) (radians):	27.18, 34.50 and 48.64;
mortality	=	[SIN (AMO)]^2 (%):	20.9, 32.1 and 56.3;
survival	=	79.1% (at 59 cm), 67.9% (at 84 cm), and 43.7% (at 130 cm).	

The survival rates are higher from the experimentation than when calculated with the model. For small eels, the model gives a rate between 67.9% and 79.1% when the test shows 90.5%. For large eels, estimates are of 43.7% to 67.9% compare to the test result of 79.3%.

2.3.5 Entrainment estimation

Currently, five methods are used to estimate entrainment : fishing gear at the outlet of the turbine, usually nets or traps; capture, tagging and recapture; telemetry; hydroacoustic; and underwater camera. These methods are described in detail in chapter 4.

In general, a complete evaluation of entrainment can only be provided by the capture-tagging-recapture method, or by telemetry. The absence of entrainment is considered a satisfying result. Otherwise, the actual impact of entrainment can be determined only if the proportion of fish entrained is known. The proportion of the population entrained cannot be determined by other methods unless an evaluation of the overall population is done. In certain exceptional situations, site configuration may allow to monitor fish numbers at other migration pathways (device, dam, sluices, fishways, etc.) using the same method, but only for migratory species in which the whole population must pass through the study site. Underwater cameras and hydroacoustics still induce biases which complicate this type of study, and, in general, do not provide precise evaluation.

2.4 Migration Systems

Nearly thirty migration devices have been tested over the past 50 years. They can be grouped in four main categories: bypasses, physical barriers, behavioural barriers and trapping and transportation systems.

For each device, a brief description, the advantages and drawbacks, and a general cost estimate are presented. Performances and reliability of the devices are based on the views of experts capable of assessing the sometimes optimistic interpretations provided by manufacturers or authors looking for future fundings (Ruggles, 1991 *in* Popper and Carlson, 1998). Caution to this effect is recommended to laymen (Taft, 1993; C. P. Ruggles, 2000, pers. comm.; Popper and Carlson, 1998). The cost estimates are based on documentation available, personal experience of the authors, and on comments from experts. They represent an order of magnitude for the year 2000, and a more thorough evaluation is required for each individual project. For some of the devices, the costs are relatively the same, whether they are installed before or after the construction of the dam and the power station. For others, particularly screens and bypasses, the cost of the device can be reduced by as much as 50% if installation is done at the same time as the power station is constructed.

The information is presented following four themes corresponding to the categories previously mentioned. In order to lighten the text, references are grouped at the end of each sub-section dealing with a specific device. These sections are preceded by a discussion on the notion of efficiency.

2.4.1 Notion of Efficiency

The notion of efficiency when dealing with migration devices intended mostly for the downstream migration of migratory species is based on the following considerations: the species targeted, the delay in migration, the proportion of individuals using the device and the proportion of individuals surviving the migration. Currently, the most widespread definition of device efficiency seems to be the proportion of individuals avoiding the turbines and surviving the migration. This implies that post passage phenomena, such as delayed mortality or predation below the dam site (Section 2.3.3), and delay in the migration above the dam, that may favour predation on large concentrations of potentially weakened fish (Section 2.3.1), are taken into account in the estimate.

However, since some devices are used only to prevent fish from being entrained by the turbines, without leading them to a bypass channel, the notion of efficiency varies when a device is tested. Also, the notion of efficiency is not always defined in many of the studies available (EPRI, 1986). Nevertheless, the following remarks apply to most studies:

- some devices are intended to prevent fish from entering the turbines intake. Their efficiency is often measured by the proportion of fish diverted, and can be referred to as a diversion efficiency index;

- other devices are designed to lead fish above or through dams, avoiding turbines. Efficiency is then based on the proportion of fish using the device, or a transit efficiency index (measured below the powerhouse);

- the total efficiency index applies where, in addition to diversion and transit efficiency, mortality due to delays in migration or to release downstream of the fence, is accounted for.

In general, for both physical and behavioural devices, a bypass is included in the design for maximum efficiency. For such devices, the efficiency index is a combination of both the diversion and the transit index. This is typical of devices designed for migratory species (inclined screens, louvers, etc.). In these cases, it is hard to determine the proportion of efficiency related to either the guiding device or the bypass. In the following description, the efficiency will usually be of transit for bypass, and of diversion and transit for others.

2.4.2 Bypasses

Up to now, two types of bypasses have been tested. The depth of the water intake plays a preponderant role in the design of these devices and greatly influences their efficiency, particularly if they are not coupled with an avoidance barrier for shallow water intakes, as most of the migrant species are in the upper portion of the water column, at least for the North-East USA (several authors *in* Odeh and Orvis, 1998).

2.4.2.1 Spillway

Description

In this type of device, fish leave the head race with surface flows (Figure 3), through debris gates or spillway gates, or by any other opening implemented for surface spills. In some cases, surface collectors are added to lead the fish through the spillway. Subsurface flow from a notch between 0.4 and 4.7 m of depth have also been tested and it showed better results than surface spilling (2.1 and 3 m of depth) for salmonids. Spills originating at great depth are generally ineffective but it may be efficient in some cases where the flow and depth are high, a deep slot of 24.4 m being successful for salmonid fry.

The discharge must be designed to avoid any contact with fish and to ensure that, at its base, turbulence is minimised, fish are not caught in eddies, or that there is no mortality induced by nitrogen supersaturation. For example S-shaped or "ski-jump" structures can reduce contacts at the base of the dam (Figures 3b and 3d). The digging of a basin below the dam also reduces the risks of contacts, but it increases the risks of nitrogen supersaturation. The use of deflectors is also recommended to reduce nitrogen supersaturation, but, depending on site configuration and water depth at the base of the dam, they may become a constraint if they induce collisions with fish (Figure 3e). The head must not exceed 30 to 40 m for fish 150 to 180 mm in

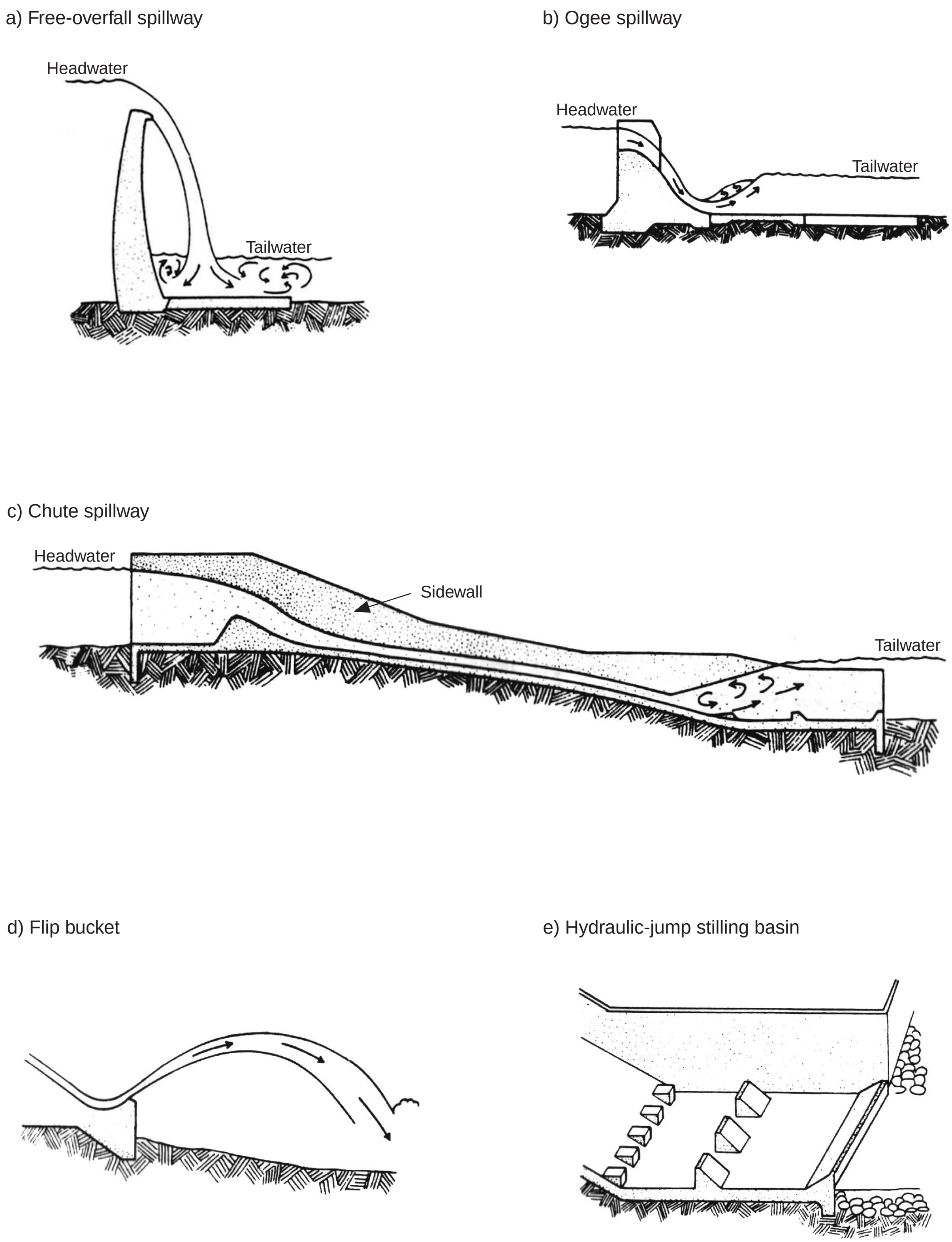

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FIGURE 3. Several spillway types (from Ruggles and Murray, 1983).

length, and 12 m for fish larger than 60 cm at facilities where a free fall occurs (Figure 3a). Apparently, the net head is not limiting for fish smaller than 130 mm. In general, these constraints are likely to be more limiting at structures higher than 30 m, although excellent results (98% survival) had been obtain with a free fall of 90 m. Injuries may also occur by abrasion on the structure if it is not smooth, or by sudden pressure changes.

The general shape of the upstream end of spillways should be broad-crested to prevent avoidance reactions by fish.

Advantages / drawbacks

This device is relatively inexpensive if the design is modified prior to construction, but it becomes costly if the spillway is added to existing facilities. The risk of clogging by debris is low, and therefore maintenance is not a limiting factor. Direct mortality was usually low (in the order of 2%) with these devices prior to concern about their shape and tailrace configuration.

Often, the device must be coupled to physical or behavioural barriers in order for all the fish to use it. The passage through a surface spillway may cause injuries, and even some mortality by exhaustion, stress or predation at the outlet. The *a posteriori* construction of this device may require that the generating station production be modified for a certain period of time, depending on the amount of work to be done. The reduced production attributed to water used for the spillway can be important, depending on the size of the spillway if the migration of the species targeted occurs during a period when all of the river discharge could be used for power production.

Costs

The design, the construction and the cost vary greatly depending on the site characteristics and are generally included in the original design of the hydropower generating station.

Sources

Bell and DeLacey, 1972; Clay, 1995; EPRI, 1986; Ferguson *et al*., 1998; Iverson *et al*., 1999; Mathur *et al*., 1999; Odeh and Orvis, 1998; Ransom and Steig, 1995; Ruggles, 1980a; C. P. Ruggles, 2000, pers. comm.; Ruggles *et al.*, 1981; Ruggles and Murray, 1983; Ruggles and Collins, 1992; Sale *et al.*, 1991; Shoneman *et al*, 1967 *in* Odeh and Orvis, 1998; Travade and Larinier, 1992; Tremblay *et al.*, 1994.

2.4.2.2 Surface bypass collector and diversion channel

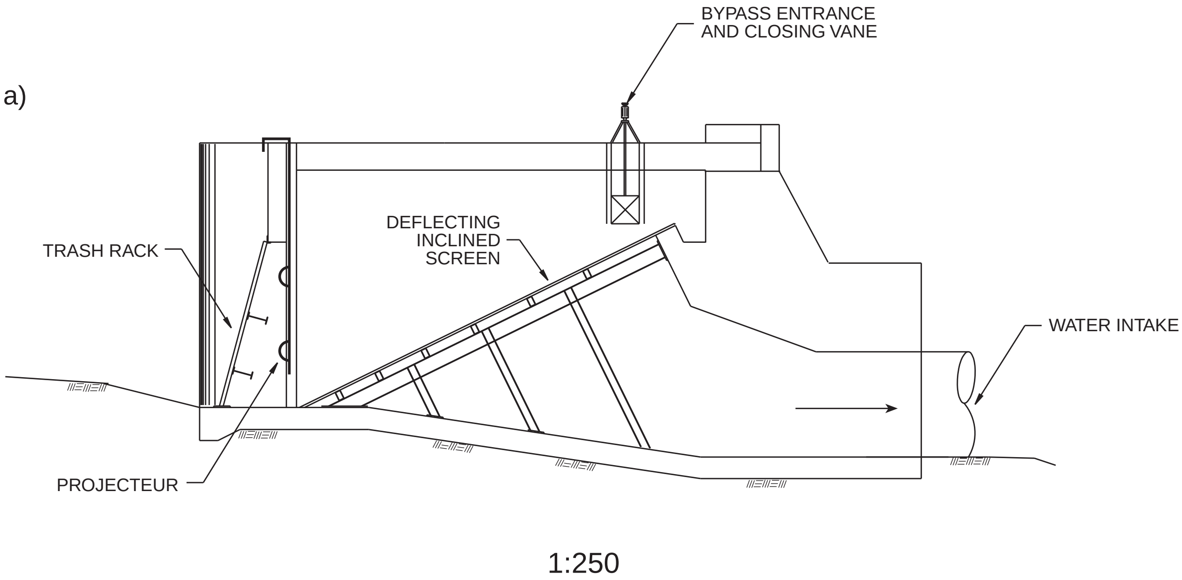
Description

A flushing or a diversion channel, or any other structure specifically designed for fish, is added to the headrace or to the water intake of the generating station, allowing fish to migrate downstream without transiting through the powerhouse (Figure 4) . When used alone or in association with a trash rack (in which case the screen acts more like a behavioural barrier since it cannot physically intercept fishes because of the wide spacing between bars), more than one channel may be needed if the water intake is very wide. Conclusive results were obtained with only one bypass at widths up to 30 m. The device may be extended by a channel alongside one of the structure walls, like the channels to evacuate ice or trash, which are frequently used for this purpose. The flow in the bypass must be on surface.

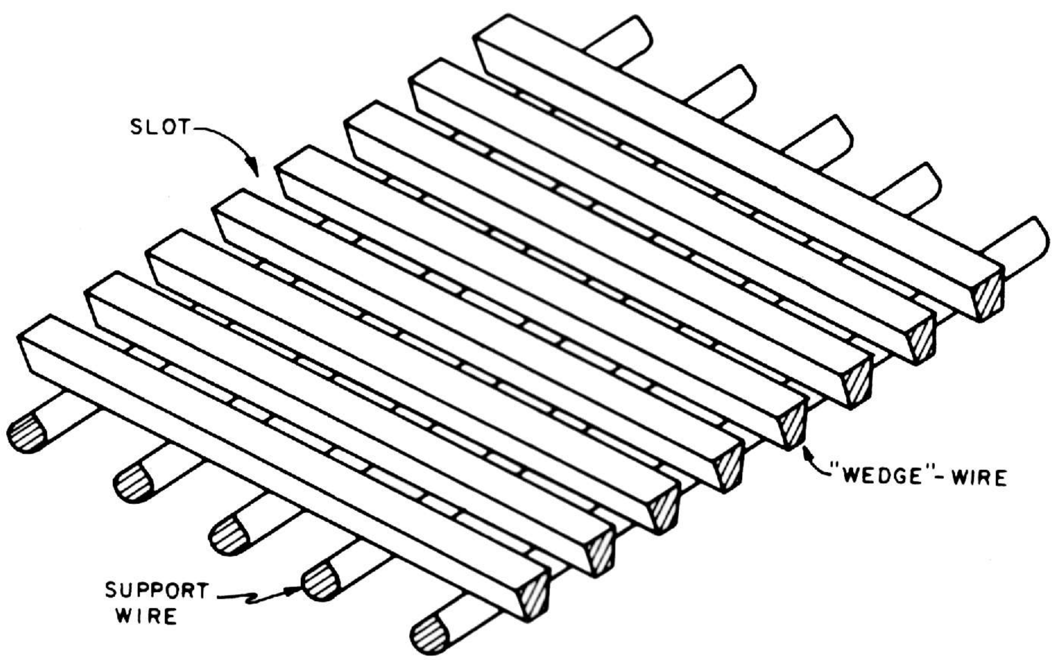
A depth of at least 40 cm is necessary, and it corresponds to a minimum flow of 0.5 m^3/s per meter of width. Acceleration at the approach and within the bypass must be progressive, and velocity should not exceed 15 m/s. The structure must be designed so as to avoid turbulence, shocks and friction. Broad-crested structures with uniform spatial flow increase, as the NU-Alden weir, show better attraction to fish than sharp-crested design. The discharge of the bypasses must represent at least 2 to 5% of the turbined flow, reaching sometimes more than 10%. In some cases, pump back systems or screen dewatering are added to withdraw as much as 80% of the bypass flow, the minimum residual flow being in the order of 0.6 m^3/s. It can be done to save cost in returning water to the forebay or to decrease the bypass flow in order to obtain reduced water flow and velocity in the tailrace, allowing more flexibility to design the outfall to minimise predation.

The layout of the bypass is critical in order for fish to be attracted and find the entrance. The acceleration gradients should be uniform and gradual near the bypass entrance to prevent avoidance by fish. In addition, the flow pattern of currents and zones of turbulence, counter-currents, tangential currents or upwellings have a great effect on the efficiency of the device. The use of rounded inverts with open flumes and the smoothing of surface reduces injury (abrasion, descaling) and the risk of formation of eddies and areas of turbulence. When closed conduits are used, pipe shape should be chosen, bends should have a minimum radius of 3 m, and installation of air vent should be added to reduce injury and avoid severe pressure gradient and siphoning effects. A new flow spreader has been developed to reduce the depth of plunge and to increase the width of flume in the tailrace, which permits reduction of predation, gas bubble disease and other negative effects associated with outfall.

a)



b)



From Odeh (1999a)

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FIGURE 4. Schematic cross-sectional view of deflecting inclined screen and bypass diversion canal.

The entrance to the bypass must be around 45 to 60 cm wide and its height may exceed 1 m. These dimensions can be reduced if the bypass is located in the water intake, below an Eicher screen, for example (Section 2.4.3.2). The height of the entrance can then be reduced to only a few centimetres. The walls of the entrance should be shaped to avoid sudden changes in the velocity gradient. Flow velocity at the outlet of the bypass should not exceed 15 m/s.

Six sites were monitored in France and showed an efficiency of 17 to 85% for salmon smolts and sea trout (*Salmo trutta*) when the bypass is coupled to a trash rack. Efficiency rates ranging from 7 to 96% were also recorded in the USA for devices, installed in a water intake or upstream from a dam, to which deflectors (log boom, partial louvers, etc.) were sometimes added to increase current velocity and attract fish.

When coupled to other devices, the total efficiency of the system may reach almost 100%, as is the case with louvers or screens. In the latter case, the bypass must be installed very close to the end of the louvers or the screen. In addition, the flow required becomes much lower and is easily within the optimal range (2-5%).

The nature-like bypass channel is another alternative mostly used in Europe for upstream migration, but it has also been proposed for downstream use. The interest for these design is increasing, particularly for low head or small scale projects. Less engineering technology is involved but conceptual guidelines exist, mostly based on river size and general morphology, and fish assemblage.

Advantages / drawbacks

This device causes only a small production loss for the generating station, and only when the total river discharge is used for power generation.

The device is relatively inexpensive if constructed with the generating station, but it must be coupled to physical or behavioural barriers to increase its efficiency above 85%. There is a risk of clogging by floating debris and a regular and adequate maintenance is required, except when it is located below a trash rack. The *a posteriori* construction of a bypass may require that the generating station production be modified for a certain period of time, depending on the amount of work to be done.

Costs

Costs vary according to the size and characteristics of the site, but mostly if the device is installed during or after the construction of the generating station. In certain cases, a simple breach in an existing structure is sufficient. In other situations, a trough must be installed to ensure the passage of fish beyond the generating station.

Sources

Adams *et al*., 1999; Clay, 1995; Dawley *et al.*, 1993; Dehart, 1993; Den Bleyker *et al*., 1997; Erho *et al.*, 1987; Ferguson, 1992, 1993; Ferguson *et al*., 1998; Hanson, 1999; Haro *et al*., 1998; Kynard and Buerkett, 1997; Larinier and Boyer-Bernard, 1991; Larinier and Travade, 1999; Mathur *et al*., 1999; Mills, 1989; Odeh and Orvis, 1998; Parasiewicz *et al*., 1998; Ruggles, 1992; C. P. Ruggles, 2000, pers. comm.; Ruggles and Ryan, 1964; Ruggles and Collins, 1980; Sale *et al.*, 1991; Shively *et al*., 1996; Skalsky *et al*., 1996; Steig and Adeniyi, 1999; Travade and Larinier, 1992; Tremblay *et al.*, 1994.

2.4.3 Physical barriers

Seven types of deviation devices have been developed using a physical barrier impassable by fish. Among these, three cannot be used at small hydropower projects because of the low current velocity allowable for the device to be efficient. These devices are generally used to prevent fish from entering thermal generating stations where pumped water velocity is never greater than 0.15 m/s. They are inefficient at higher velocities, or when the water carries debris, as is often the case in streams (EPRI, 1986; Taft, 1993). These devices include net screens, cylindrical barriers, as well as filtering river beds. They will not be described in the following sections. A fourth device consists of fish guiding walls, generally partial and covering the upper half or less of the water column. They are called curtain walls when added to existing structures (trash racks). These devices can cause a significant reduction of power production if they are near the intake, have usually an efficiency below 90% even with species migrating in the upper portion of the water column (84% at Bellow Falls, Connecticut River; Odeh and Orvis, 1998), and can be efficiently replaced by screens. They will not be described in more details in this paper.

The three remaining devices are deflecting screens, high flow screens, and rotating screens.

2.4.3.1 Deflecting screen

Description

These screens can be fixed or mobile and all have the same biological effect. They prevent fish passage and usually direct them toward a bypass in the case of migratory species. The only different feature concerns mobile screens which allow more stable hydraulic conditions than fixed screens because they are less likely to accumulate debris.

These screens can be installed upstream from the water intake, in a head race or at the level of the trash rack. The trash rack is made of vertical bars spaced 2.5 to 20 cm apart. It prevents bulky debris, such as branches or logs, from entering the turbines. When a fixed deflector screen is installed at the level of the trash rack, it can be superimposed on the rack, or the trash rack is modified by reducing the gap between bars. It is then known as a “Bar rack”.

When vertical deflector screens are installed directly above the water intake, the current velocity should not exceed a certain threshold. In the USA, the maximum velocity tolerated by the Federal Energy Regulatory Commission is 30 cm/s for salmon smolts on the East Coast and, on the West Coast, 24.4 cm/s for smolts and 12 cm/s for parr. These standardized values are based on recommendations by Aitken *et al.* (1966) and Clay (1961), as a function of fish swimming speeds. In the United Kingdom, the suggested value, although without legal status, is 25 cm/s (Turnpenny, 1998b).

However, these velocities may be adjusted for certain species to reflect their swimming capacity (Table 1). This velocity corresponds to the current velocity perpendicular to the screen. For a screen horizontally or vertically inclined (Figure 4), the maximum horizontal velocity tolerated can exceed 3 m/s if the angle of the screen is sufficiently small.

The gap between the bars of the screen may vary and was usually in the order of 2 to 2.5 cm 20 years ago, based on government recommendations. This spacing is adequate for large specimens of certain species, but it is insufficient for most juvenile stages and for certain species such as adult eel and salmon at the smolt stage. In these cases, gaps ranging from 0.9 to 1.2 cm have proven adequate, which led to regulation modifications in certain countries. For example, a gap value of 1.25 cm was adopted in Scotland in 1994. With smaller gaps, the design of the screen (distance between frame sections, choice of material) should provide a clear opening of at least 50% to reduce headloss. For example, at a 0.15 m/s current velocity, the headloss will have almost a three fold increase between a 50% and a 30% opening, and at 0.3 m/s, il would be more then a four-fold increase.

It is of major importance that the deflector screens follow perfectly the beds and walls of the river or of the water intake. Otherwise, fish will, especially eels, attempt to thread their way below or on either side of the screen. An inclined angle of about 10º to 20º is also desirable to optimize the efficiency of the device. The screen can be inclined either vertically or horizontally, and in the latter case, the screen resembles louvers. The efficiency can also be improved for certain species such as salmon, if the screen is lighted. When the design conforms to the preceding standards, the diversion efficiency of the device can be close to 100%. But since screens have to be coupled with other devices (bypass) to protect the downstream migration at the generating station, the total efficiency including a screen rarely reaches 100%.

Modified versions of this device, covering only the upper third (“Submerged travelling screen” or STS) or the upper half (“Extended-length submersible travelling screen” or ESTS) of the water intake have resulted in a maximum efficiency rate below 90%, and it does not seem that can be improved upon. The latest prototypes of STS have produced disappointing results, mortality being higher than the mortality experienced during turbine passage.

Advantages / drawbacks

If the gaps are small enough, deflector screens can be 100% efficient. Inclined deflector screens are among the devices recommended for large scale implementation.

There is a risk of fish impingement on the screen, and, consequently, of injuries and mortality if the current velocity exceeds the fish swimming speed. Fish scaling problems (0.8 to 26.0%) were also recorded. There is also a risk of predation or impingement if fish cannot easily find the downstream bypass always associated with this device, especially for vertical screens. The mortality induced by these drawbacks may sometimes be higher than during turbine passage. In fact, in Scotland, the “Bar rack” screens have been systematically removed for falls less than 30 m. However, the context was very peculiar and it would not be pertinent to proceed elsewhere with similar removals, especially with Francis turbines.

Deflector screens may induce a headloss, sometimes significant, which impacts on power production. There is also a risk of clogging of the screens. Therefore, this type of device requires adequate and constant maintenance. There are automatic screen cleaning systems using brushes or air streams. There are also dimension constraints related to the approach velocity desired, which increases the costs of purchase, implementation and maintenance of the device. Indeed, to reduce the current velocity perpendicular to the screen, the angle sometimes has to be reduced and consequently the screen dimension and related costs are increased.

Costs

Costs vary with site dimension and type of deflector screen. Generally, an investment of about 1000 $\$/m^2$ is required for fixed screens, and even more for mobile screens because of the lifting mechanism.

Sources

Clay, 1995; Ferguson, 1992; Frankfort *et al.*, 1994; Mills, 1989; Odeh, 1999a; Ruggles, 1992; C. P. Ruggles, 2000, pers. comm.; Sale *et al.*, 1991; Struthers, 1993; Taft, 1993; Therrien and Verreault, 1998; Therrien, 1999a; Travade and Larinier, 1992; Tremblay *et al.*, 1994; Turner *et al.*, 1993.

2.4.3.2 High flow screens (Eicher or MIS)

Description

These screens form an inclined plane in the penstock directly upstream from the turbine, in order to lead fish to the surface of the water column and to a downstream bypass, natural or artificial, adjoining the device (Figure 5).

The Eicher screen is made of a series of parallel bars spaced by about 2 to 3 mm. The screen has a 15° to 20° incline and allows average perpendicular velocities up to 1 m/s, the effective velocity increasing from upstream to downstream of the screen. Beyond this velocity, the risks of injuries and scaling increase. To remain below this perpendicular velocity threshold, the maximum velocity suggested in the penstock must be less than 2.4 m/s. On the other hand, current velocity at the entrance to the bypass must be fairly high, at least 90% of the velocity in the penstock. It can also be slightly superior to the latter. The efficiency obtained is above 98% for smolts and above 91% for alevins of various salmonids. Scaling, in the order of 2% at velocity less than 1.5 m/s and up to 40% at 2.4 m/s, occurred during the tests and was a major cause of injuries. A device with variable screen porosity has been designed and it allows an increase in current velocity of 10% in the penstock, without a significant impact on efficiency.

Another version of this device, using certain features of the Eicher screen, the Modular inclined screen (MIS), was tested in laboratory and in a sluice gate at the Green Island generating station on the Hudson River. A full scale testing in an intake still needs to be done. The screen was installed in a water intake at an angle ranging from 10° to 20°. The average size of fish tested ranged from 47 to 170 mm for the following species : bluegill (laboratory and field), rainbow trout (l&f), Coho salmon (l), Chinook salmon (l), brown trout (l), blueback herring (f), yellow perch (f), clupeids (l), smallmouth bass (f), largemouth bass (f), golden shiner (l&f), walleye (l), channel catfish (l) and Atlantic salmon (l). Efficiency levels varied depending on species and current velocities (ranging from 0.23 to 3.05 m/s). Laboratory tests showed efficiency above 98% for salmonids at all current velocities, except for Chinook salmon at 3 m/s (94%). Rainbow trout had survival rates over 99% at velocities up

a)

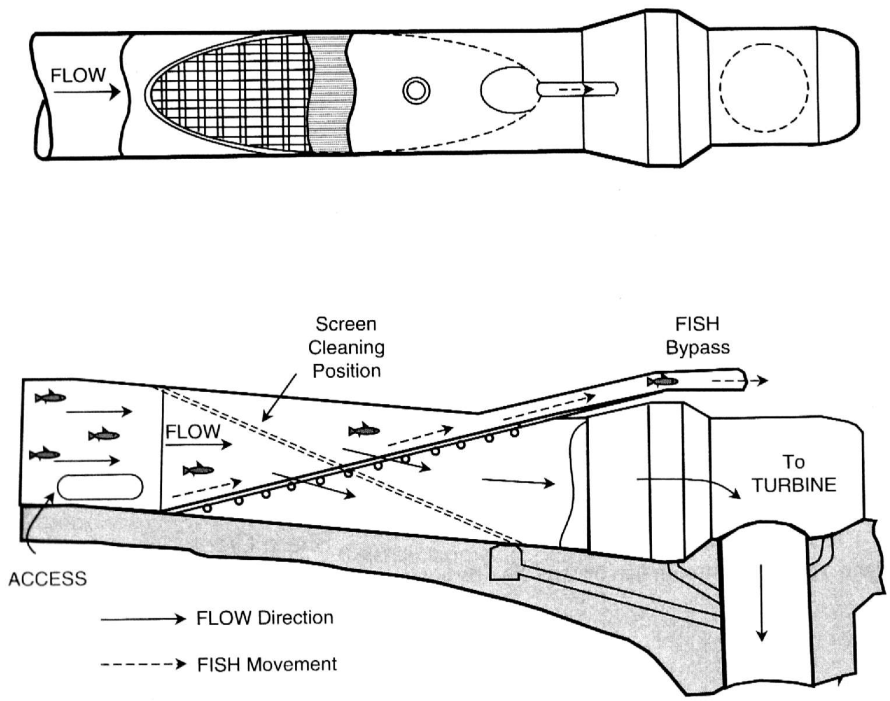

FIGURE 5. Schematic cross-sectional view of an Eicher screen in a penstock (from Eicher, 1982).

b)

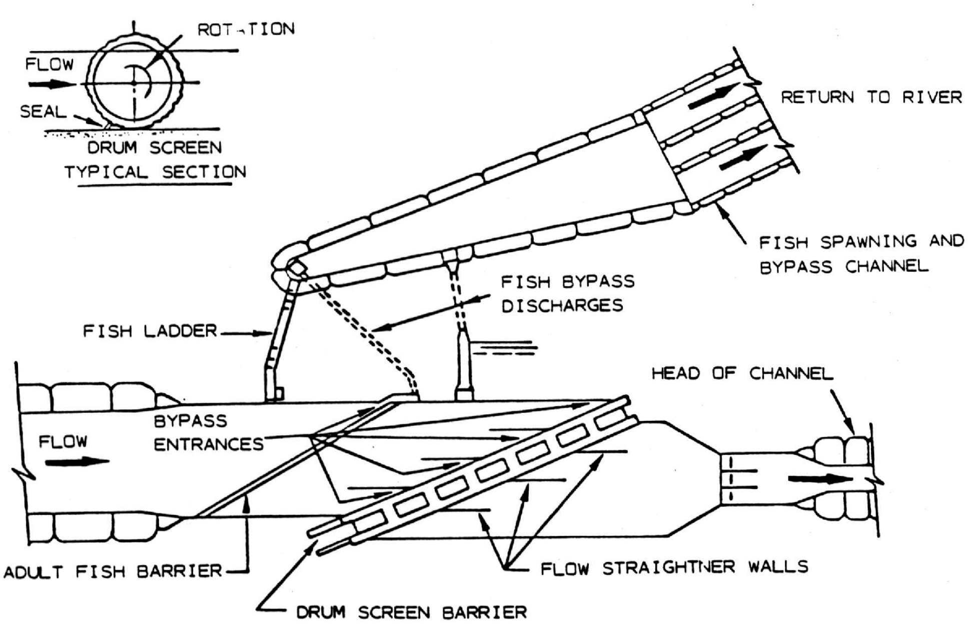

FIGURE 6. Schematic cross-sectional view of a drum screen perpendicular to flow (from EPA, 1976).

to 2.4 m/s on the field. For other species, efficiency was generally above 92% in laboratory or field for current velocities up to 2.4 m/s, except for clupeids, including blueback herring, where the efficency was generally low: under 86% at 0.6 m/s and below 35% at 1.8 m/s in the field (75% in laboratory). Scaling seems to be the major cause of injury, particularly for clupeids (87% of diverted fish at 1.2 m/s) and for bluegill (49% at 1.8 m/s). For this screen, the maximum velocity suggested in the penstock is also 2.4 m/s, to avoid risks of scaling and injuries, except if the target species are clupeids.

Advantages / drawbacks

These screens, because of their incline, accumulate less debris. They can be tipped up around a central pivot to facilitate cleaning. However, this operation reduces the efficiency if the recurrence is high.

They may induce a headloss, sometimes significant, impacting on power production. There remains a risk of fish scaling which varies with species and current velocity. Their overall cost is relatively high.

Costs

Costs vary considerably depending on the support structure selected, but they are generally in the order of 3000 \$ to 5000 \$/m^2.

Sources

Amaral *et al*., 1999; Clay, 1995; Francfort *et al.*, 1994; Mills, 1989; Odeh and Orvis, 1998; Ruggles, 1992; Ruggles and Collins, 1980; Smith, 1993; Travade and Larinier, 1992; Taft, 1993; Taft *et al.*, 1993; Tremblay *et al.*, 1994; Winchell *et al.*, 1993.

2.4.3.3 Drum screen

Description

The rotation of the revolving drum screen induces a current perpendicular to the rotation axis which entrains fish to a wasteway (Figure 6). This type of screen is efficient in channels where depth is less than 2 m and for a maximum approach velocity of about 0.15 m/s for screens installed perpendicular to the current. Screens that have an angle with the current are clearly more efficient and cover a broader range of velocity. The maximum perpendicular velocities tolerated are the same as for deflector screens. The screen mesh size could also be around 1 cm, for certain species such as juvenile salmon. This system, initially design for irrigation ditches, was adapted to hydropower projects, but mostly on large ones.

Advantages / drawbacks

This method is already used at several hydropower generating stations where it reaches an efficiency level of nearly 97% for Atlantic salmon, Chinook salmon and rainbow trout. However, the efficiency decreases if the above mentioned criteria are not followed. Drum screens set at an angle with the current are recommended for large scale use.

The installation and maintenance operations for these screens are very expensive. The device requires a trash rack upstream to prevent debris from reaching the rotative screen. Incidentally, clogging of the screen by debris or algae is a frequent problem. The device is quasi-permanent because of the complexity and costs of installation. Consequently, ice may cause clogging and even prevent operation of the device. Because of the high costs, this device is normally used at large hydropower generating stations and in irrigation channels. The installation of rotative screens requires a reduction or a total stopping of the generating station operations for a relatively long period of time compared to other types of screens.

Costs

The design, installation and equipment costs can be fairly expensive and varies on average from 30 000 $ to 55 000 $ per m^3/ s of turbined flow, based on irrigation or large projects.

Sources

Clay, 1995; EPRI,1986; Neitzel *et al.,* 1991; Taft, 1993; Tremblay *et al.,* 1994; Travade and Larinier, 1992.

2.4.4 Behavioural barriers

Nearly ten behavioural devices have been designed to influence the behaviour of fish to prevent turbine passage. The devices which attract fish are usually more efficient than those which induce an avoidance reaction based on fear, except in the case of a water intake not associated with a dam (e. g. irrigation, thermal power generating station) where it is not necessary to lead the fish to a given location. These systems are generally less expensive (installation, operation and maintenance) and non-intrusive compared to physical barriers (Nestler and Ploskey, 1996).

Three devices are not presented in detail: water jet curtain, flexible strips curtain and chemical stimulation. The water jet curtain is not recommended because of high operation costs and the lack of data available on its efficiency (EPRI, 1986; Taft, 1993). The flexible blade curtain, made of fine metal strips which whirl in the current, is still undergoing test and trial. Preliminary experiments reveal a 33.3% efficiency for salmon with a system where the strips were interspersed between chains with a 20 cm space between each component (Tremblay, 1994). This device requires further studies to assess its utilisation potential. Chemical stimulation did not provide conclusive results. It is expensive, costs are recurrent and, mainly, the risks of accumulation in the environment are unknown (EPRI, 1986; Taft, 1993).

Other devices are : louvers, underwater lights, strobe lights, acoustic screens, electric fields, chain curtain, air bubble curtain and hybrids.

2.4.4.1 Louvers

Description

Louvers are made of a curtain of rigid plastic blades directing fish toward a bypass (Figure 7). They can be fixed or floating. In the latter case, louvers cannot exceed 2 m in height if the design of the bypass prevents current returns. Ideally, louvers must be set at a certain angle (11° to 40°) in relation to the river current and the efficiency decreases when the angle increases. Each louver blade must be almost perpendicular to the current. The average spacing between louvers varies in relation with species and regulatory requirements. The maximum spacing tested so far is 30 cm for Atlantic salmon. Efficiency would be better at a smaller spacing (2.5 cm) for several other species including catfish and smelt. For American shad, a spacing of 15.2 cm provides better results than at 7.6 cm, fish transit speed being higher with a larger spacing. In addition, a decrease in spacing from upstream to downstream reduces the velocity required at the bypass.

Fish tend to face the current and, usually, they do not make sudden changes of direction. When nearing the louvers, they perceive a certain turbulence and a decrease of current velocity, and they tend to swim away laterally. They swim along the louvers walls toward an adequate downstream bypass (natural or artificial).

Current velocity between louvers must be lower than the fish swimming capacity. However, velocity alongside the louvers can be greater than swimming speed to transport fish toward the bypass. In order to minimise headloss, louvers are generally equipped with deflectors or current rectifiers distributed at regular intervals along the louvers line. The deflectors are made of the prolongation of a blade and its branching along the louvers line (Figure 7). Where headloss is not a great concern, the flow deflectors are often omitted. The water velocity in the bypass must be

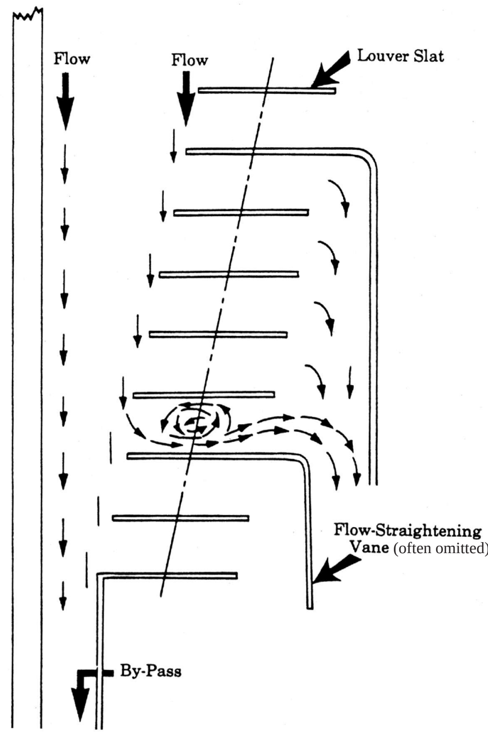

FIGURE 7. Schematic overview of louvers (from Bell, 1984).

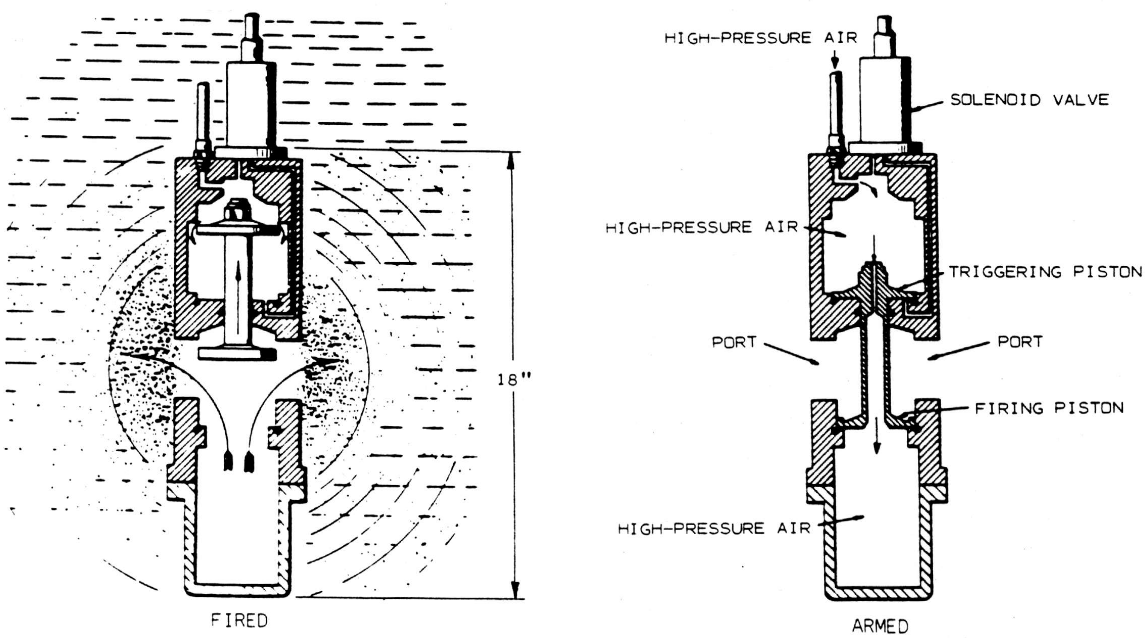

FIGURE 8. Schematic representation of a sound popper (from EPRI, 1986).

approximately 1.4 times the velocity near the louvers. If there is a decrease of velocity between the device and the bypass, efficiency decreases.

The efficiency of this device varies between 80 and 100%. An excellent efficiency was demonstrated for adult and juvenile salmonids (Atlantic salmon, Chinook salmon, rainbow trout), as well as American shad. However, efficiency is low for alevins and very small specimens (< 5 cm) of these species as well as for other species (e.g. striped bass), especially for bottom migrating fish, when partial depth louvers are used.

Fixed louvers provide good results at current velocities ranging from 0.3 to 1.2 m/s, and retain high guiding efficiency with salmonids smolts up to 1.8 m/s. However, for floating louvers, the current velocity should not exceed 1 m/s and the present design criteria favor approach velocities in the order of 0.6 m/s. The best efficiency is obtained when the device is installed in the head race of a powerhouse or in an intake canal. Louvers have proven to be the best behavioural device, especially in streams where current velocity is high and where site configuration is optimal.

Advantages / drawbacks

Louvers are currently used in hydropower facilities where the site permits such use. They provide satisfying results. Site configuration providing a formalised flow regime (e.g. power canal) is a preponderant factor in selecting this device.

This device produces a low headloss, inducing minor negative impacts on power production. Clogging can occur and adequate maintenance is required. Louvers must occasionally be removed and scraped clean.

Costs

Costs vary considerably with the support structure selected, but are generally above 100 000 $ for fixed louvers, and in the order of 500 $ per linear meter for floating louvers.

Sources

Bates and Vinsonhaler, 1956; Ducharme, 1972; EPRI, 1986; Francfort *et al.*, 1994; Kynard and Buerkett, 1997; Mills, 1989; Odeh and Orvis, 1998; Ruggles, 1980a; 1992; C. P. Ruggles, 2000, pers. comm.; Ruggles and Collins, 1980; Ruggles and Ryan, 1964; Ruggles *et al.*, 1993; Travade and Larinier, 1992; Tremblay *et al.*, 1994; Vinsonhaler *et al.*, 1958; Buerkett, 1994.

2.4.4.2 Underwater lights

Description

Underwater lights generally attract fish and lead them to a natural or manmade bypass. This attractive effect could transform into a repulsive effect if fish get too close to the system. Efficiency of this device is species specific and generally varies between 80-100% for studied species, particularly groundfish and warm water fish. It remains highly variable for some species (e.g. American shad) and totally inefficient for others (walleye, smallmouth bass, catfish), particularly pelagic species and most salmonids. For species like eel, the repulsive effect will be intense because of its negative phototropic behaviour, but results have been poor, always under 70%. Lights are significantly more efficient when combined with other devices. Most testing was done with wavelengths of 430 to 580 nm. Both incandescent and fluorescent lights have been used, as well as mercury or sodium.

Advantages / drawbacks

Installation and maintenance costs are minor. Installation does not impose long term diminution in the generating station performance. This device can be theoretically used on any stream, independently of its dimension, flow or current velocity. However, velocity could become limiting for the swimming capacity of some species.

Guidance efficiency varies with species, water temperature, turbidity, suspended solids and natural light.

Costs

Costs are variable, but are in the order of 2500 $ for each lamp. Number required and installation costs vary with site. Maintenance costs are relatively low and covers cleaning (algae) and replacement.

Sources

EPRI, 1986; 1990; Gibson and Keenleyside, 1966; Haddering and Bakker, 1998; Johnson *et al*., 1998; Kynard, 1993a; Larinier and Boyer-Bernard, 1991; Nestler and Ploskey, 1996; Patrick, 1985; Popper and Carlson, 1998; Robitaille, 1994; Solomon, 1992 *in* Lambert *et al*, 1997; Taft, 1993; Tremblay *et al.*, 1994.

2.4.4.3 Strobe lights

Description

This type of lighting has a repulsive effect on fish (300 to 600 flash/min for salmon). Water turbidity, concentration of suspended sediments and current velocity can influence the efficiency. When currents are weak, strobe lights have had 90% success for shad, smelt and alewife. For salmon, the efficiency of this device ranges from 20 to 93%, and is related to current velocity, and time of day (day/night). Variable results were also obtained for eels (65-92%). The device is also considered efficient for largemouth bass, catfish and walleye. In general, the efficiency ranges from 65% to 99%. However, it seems to be low at velocities above 1 m/s for all the species tested. Strobe lights are significantly more efficient when used in combination with other devices.

Advantages / drawbacks

Installation and maintenance costs are low. The repulsive effect of strobe lights decreases with increasing current velocities. Strobes are significantly more efficient in darkness. As for underwater light, guidance efficiency varies also with water temperature, turbidity and suspended solids. Responses of fish may changes with age and physiological conditions.

Costs

Strobes cost 5000 $ per unit and the number required is site-specific. Installation costs are generally in the order of the purchase price. There are no particular maintenance costs, except for regular cleaning (algae) and periodical replacement.

Sources

EPRI, 1986; 1990; Johnson *et al*., 1998; Odeh and Orvis, 1998; Patrick, 1985; Popper and Carlson, 1998; Robitaille, 1994; Ruggles, 1992; Solomon, 1992 *in* Lambert *et al*, 1997; Taft, 1993; Travade and Larinier, 1992; Tremblay *et al.*, 1994.

2.4.4.4 Acoustic screens

Description

Sound screen (constant) and pneumatic generator or poppers (intermittent) are two ways to transmit sounds repulsive to fish. Sound waves fall in three groups: infrasound (< 35 Hz), audible sound (35-2000 Hz) and ultrasound (> 20,000 Hz).

Testing done over the last 50 years primarily used audible sound of low frequency (20-1000 Hz) with variable results and devices were considered relatively inefficient. Recent experiments showed better efficiency (75-100%) with Chinook salmon and rainbow trout for a sound projector array (SPA) using specific sound waves for each species. However, these devices remain more efficient where repulsion is the sole objective (e.g. repulsion from a cooling water intake), rather than to guide fish to a specific area (bypass). Infrasounds, despite some interesting results, are not favourable because of a limited range and a high directional component. A recently patented innovation combines sound with air bubble curtain and is called the bioacoustic fish fence (BAFF). It shows interesting results (90%) in guiding fish as it creates a more sharply defined sound field but to date is unproven for large scale use.

High frequency sound devices (> 100,000 Hz) seem constantly more efficient on guiding fish with tested species (alewives, blueback herring, shad, cod, striped bass, northern pike, perch, and Atlantic salmon). It uses pulsating sound which is much more persistent and attenuates slower than vibrating sound.

Fish can detect sound as a vibration or a change in pressure, via the lateral line or the inner ear. With the first organ, it can be done only from a short distance (i.e. a few body lengths). In most teleost (bony) fish, the inner ear is connected to the swimbladder and the effectiveness of detection varies with species. The cyprinids (carp, dace, chub, etc.) and the clupeids (herring) are highly sensitive. The salmonids and the percids (perch, etc.) have moderate sensitivity. Fish without or almost without swimbladder (flat fish) and cartilaginous fish (sharks, rays) are mostly insensitive to sound. The response of fish to a frequency changes with age, sometimes within a single season, and a major lack of knowledge exists in this matter.

To design an acoustic system, the background noise level should be monitored to choose the best frequency to be recognised by the fish, and the minimum intensity to avoid the masking effect. The acoustic system has to produce sounds with at least 10 dB over the background level. Also, to prevent acclimation of fish to sound, it is necessary to randomly alternate different signals in sequence.

Advantages / drawbacks

Installation and maintenance costs are low to medium. The performance of this device, compared to most behavioural barriers, is not influenced by turbidity, solids in suspension nor coloration of water.

Several authors consider the efficiency of sounds to be less than 50% and few *in situ* utilisations were done. Poppers would be more efficient but some acclimation can occur. Moreover, the mechanical reliability is low because of the fast break down of sealed gaskets (Figure 8). However, latest results with SPA and BAFF, as with high frequency sounds, show a promising future, and are worth further experimentation. However, better knowledge is also required on behaviour of concerned fish species.

Costs

Costs varies greatly as it is a site specific migration altering device.

Sources

Desrochers and Couillard, 1990; Dunning *et al*., 1992; EPRI, 1986, 1990; Johnson *et al*., 1998; Lambert *et al*., 1997; Knudsen *et al*., 1992, 1994, 1997; Loeffleman *et al.*, 1994; Nestler *et al*., 1992; Nestler and Ploskey, 1996; Popper and Carlson, 1998; Ross *et al*., 1993; Ruggles, 1992; Taft, 1993; Tremblay *et al.*, 1994.

2.4.4.5 Electric field

Description

The occurrence of an electric field in the vicinity of hydropower facilities tends to repulse fish and direct them toward artificial or natural bypasses (Figure 9). The frequency and intensity of the current, as well as water quality and temperature affect its efficiency.

Experiments made with three species of salmonids in downstream migration (Chinook salmon, Coho salmon and rainbow trout), at varying current velocities, have demonstrated an efficiency ranging from 40 to 84%. An efficiency of 84% was also recorded for rainbow trout, brown trout, largemouth bass, gizzard shad and golden shiner. This method has better results in preventing upstream migration than in preventing downstream migration or guiding fish in a desired direction. In the latter case, fish that do not respond quickly to the stimulus can become shocked when entering in the stronger portion of the electric field, and then be entrained by the turbine intake flow without any possibility of avoidance. A new device using a gradual electric field has recently been developed, but it has only been tested on upstream migrations to prevent access to potentially hazardous zones.

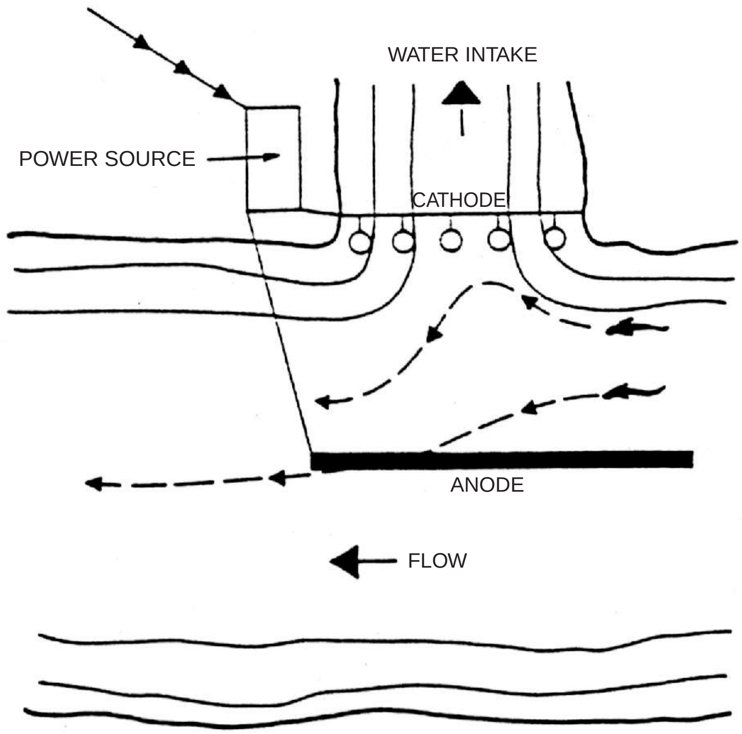

FIGURE 9. Schematic view of an electric field (from Landry and Grondin, 1992).

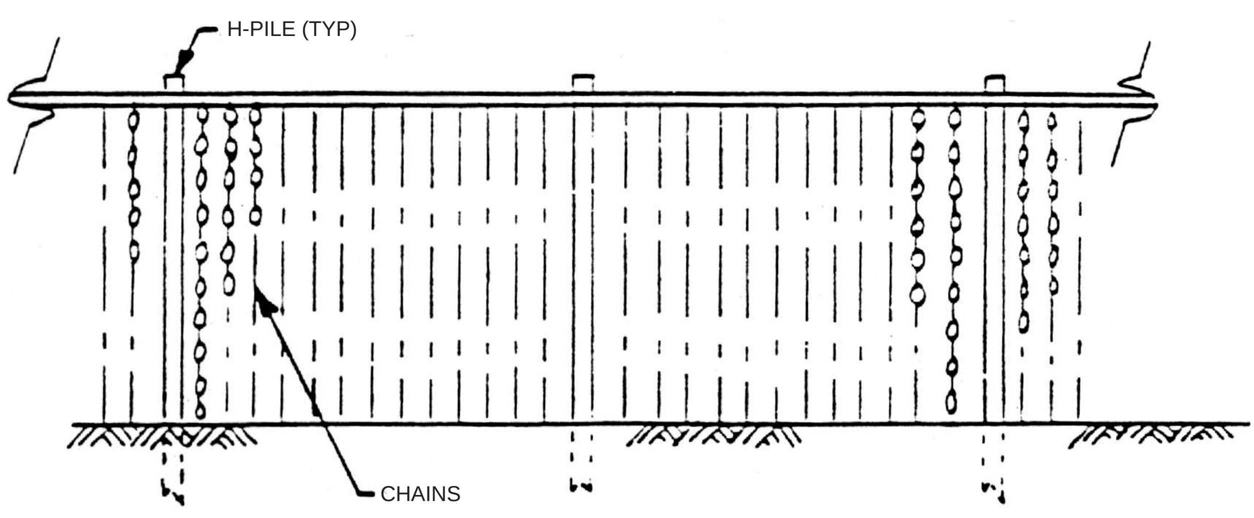

FIGURE 10. Schematic view of a chain curtain (from EPRI, 1986).

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Advantages / drawbacks

Installation and maintenance costs are in the average range.

The efficiency of the device decreases at a current velocity greater than 0.3 m/s. Fish passage in the electric field may cause injuries and even mortality in large specimens. It requires daily maintenance to remove debris which accumulates and clogs the electrodes which must also be regularly replaced. The device is not perfectly safe either for fish, or personnel of the powerhouse, or people having access to the site. Currently, this technology is not considered reliable, despite the claims by manufacturers.

Costs

Costs vary with fish size, water conductivity, etc. It could easily reach a quarter of a million dollars. For example, the device at the Boatlock station on the Connecticut River (USA) cost 198 000 $ (1980 $ U.S.) and costs 10 000 $/year for utilization. This device is relatively simple and includes six cathodes and two anodes installed at the entrance of a sluiceway, and an additional cathode upstream from this channel.

Sources

Barwick and Miller, 1990; EPRI, 1986; Hilgert, 1992; Mills, 1989; Popper and Carlson, 1998; Taft, 1993; Tremblay *et al.*,1994.

2.4.4.6 Chain curtain

Description

This type of barrier is repulsive to fish primarily from visual effects but it may also have acoustic interaction from chains clinking (Figure 10). Experiments done with salmonids showed efficiency of 70 to 90% with some species. Best results are obtained when the curtain is at an about 60° angle from flow with a 10 cm spacing between chain. Fish tend to pass through the curtain in absence of light. Thus light, turbidity and current velocity influence efficiency, the latter being better when this device is combine with others (i.e. light, nets).

Advantages / drawbacks

Installation costs are very low.

Some species, such as Coho salmon, are not guided by this device. Trash can clog the curtain, increasing maintenance needs. It is quite inefficient with strong current. Laboratory experiments showed better results than *in situ* testing and this technology is not in development anymore.

Costs

Costs varies greatly, from 6 000 $ to 150 000 $. The chain curtain cost is only about 1 000 $ but the supporting frame can reach 5 000 $ for a small boom and as much as 150 000 $ or more for a steel structure anchored in concrete with cleaning mechanism.

Sources

EPRI, 1986; Taft, 1993; Tremblay *et al.*, 1994.

2.4.4.7 Air bubble curtain

Description

Through a diffusion system, a continuous air bubble curtain is formed, creating a barrier through which fish tend not to venture. Temperature, turbidity, light intensity, current velocity and direction are parameters that can affect the efficiency of the device.

Experiments conducted in laboratory on smelt and shad resulted in efficiency ranging from 56 to 98%. However, this method proved inefficient with several other species. Efficiency increases when the device is used in combination with mercury lamps.

Advantages / drawbacks

Installation and maintenance costs are low.

The efficiency of this device is very variable depending on species and no experiment has been conducted on Atlantic salmon. The air bubble curtain may get clogged, if the supply system is not stainless steel or if it is set in a zone of heavy sediment deposit, furthermore it is totally inefficient in darkness. This technology is not used anymore.

Costs

In the order of 20 000 $ if installed near the water intake, which includes an anchoring system (˜ 5 000 $), pipes, air compressor (˜ 2 000 $), and engineering work.

Sources

EPRI, 1986; Patrick *et al*., 1985; Solomon, 1992 *in* Lambert *et al*, 1997; Taft, 1993; Tremblay *et al.,* 1994.

2.4.4.8 Hybrids

Description

A hybrid device consists in coupling a visual barrier such as louvers or curtains (bubbles or chains) with a light barrier such as lamp or strobe lights. This composite device has not been tested extensively, but it is known that adding strobe lights to a visual barrier would increase the efficiency of the barrier for shad, capelin and alewife. The increase is always very variable. Adding a light barrier to a visual barrier would not have a significant influence on salmonids, as shown by experiments conducted so far. Results around hydropower generating stations have been very disappointing. The best and more constant results have been obtain with the combination of light and sound.

Advantages / drawbacks

The advantages of both devices are added and the efficiency increases.

The drawbacks related to both devices are also added and costs are higher, although they remain relatively low for certain combinations. Additional investigations are required to properly assess the efficiency of various combinations.

Costs

They vary greatly depending on the combination of devices.

Sources

EPRI, 1986; Popper and Carlson, 1998; Ruggles, 1992; Taft, 1993; Tremblay *et al.*, 1994.

2.4.5 Trapping and transportation system

Description

Fish may be captured above the dam(s) and powerhouse(s), and transported downstream by truck. Trapping of fish usually requires deviation structures to lead fish to the traps. Powerhouse with a head race may be advantageous since the trap system can be installed directly in this channel. However, in the case where there are several dams on the same water course, this option is only practical if a single device is used at the most upstream dam, and if fish production is low between dams.

This system can also be used in combination with one of the previous devices, when neither a bypass nor a trough are used to allow downstream passage of fish.

Advantages / drawbacks

This system does not require a preliminary study if the capture device has a permanent structure directing fish to the traps. Its efficiency is near 100%. It is an interesting system for water courses with several dams, if fish production is low between dams, in which case costs can be shared by several power producers.

This method is recurrent every year. It may become costly on the long term. Although survival rates are sometimes higher than for fish passing at dams, latent mortality is sometimes significant despite careful handling.

Costs

Costs vary greatly with site characteristics, method of capture and the amount of fish to be transported. A permanent capture system may run into several hundred thousand dollars.

Sources

EPRI, 1986; Ruggles, 1980b; Ruggles and Collins, 1992; Tremblay and Boudreault, 1994; Tremblay *et al.*, 1994.

2.4.6 Comparison between devices

Table 3 summarizes the data collected on the various devices presented in the preceding sections. First, the criteria used are described, followed by a comparative analysis.

TABLE 3. Comparative evaluation of downstream migration devices.

Device	Bypass required	Selectivity	Efficiency	Affects energy production	Maintenance and operation	Tolerated current velocity (m/s)	Limiting factors	Cost	Remarks
BYPASSES									
Spillway	No	Low	ID	Yes	Minor	All	Headfall (< 30 - 40 m), piscivorous predators	Generally included within dams	Potential constraint: stress, Nitrate oversaturation, wounds, predation, energy production loss
Surface bypass and diversion canal	No	Low	7-85 % (alone), up to 96 % if coupled	Yes	Moderate	≤ 15	Outfall configuration (depth, height)	Variable	Potential constraint: clogging, stress, migration delay, predation. Better if coupled with another device.
PHYSICAL BARRIERS									
Deflecting screen	Yes	Low	74-100 %	Yes	Major	0,12 - 0,30 PS	Screen angle (10-20°), bar spacing (0.9 – 1.25 cm)	≥1000 $/m²	Potential constraint: headloss, dimension (vs velocity), clogging, wounds (descaling)
High flow screen (Eicher or MIS)	Yes	Low	91-99 %	Yes	Variable	< 2,4 (≤ 1,0 PS)	Screen angle (10-20°)	3-5000 $/m²	Potential constraint: headloss, clogging, wounds (descaling)
Drum screen	Yes	Low	ID	Yes	Major	< 0,15	River depth (< 2 m)	500 000 $	Permanent, clogging problem (debris, algae, ice), best at angle with current
BEHAVIOURAL BARRIERS									
Louvers	Yes	Moderate	80-100 %	Variable	Minor	0,3 – 1.2 (fixed) ≤ 1,0 (floating)	Screen angle (11-40°)	Variable (fixed) 500 $/m (floating)	Type depends on site (depth, current velocity)

Note : ID : insufficient data   PS : perpendicular to the screen.

TABLE 3 *(cont'd).* Comparative evaluation of some downstream migration devices.

Device	Bypass required	Selectivity	Efficiency	Affects energy production	Maintenance and operation	Tolerated current velocity (m/s)	Limiting factors	Cost	Remarks
BEHAVIOURAL BARRIERS (Cont'd)									
Underwater lights	Yes	High	0-100 %	No	Minor	Low (ID)	Temperature, turbidity, suspended solids, natural light	2500 $/lamp (without installation)	Potential constraint due to limiting factors, low efficiency for salmonids, better if coupled with other devices
Strobe lights	Yes	Moderate	20-99 %	No	Minor	< 1,0	Temperature, turbidity, suspended solids, natural light	5 000 $/unit	Potential constraint due to limiting factors, low efficiency for salmonids, better if coupled with other devices
Acoustic screen	Yes	High	0-100 %	No	Moderate	Low	Gaskets break down in «Poppers»	20 000 - 30 000 $ minimum	Site and species specific, further behavioural knowledge needed
Electric field	Yes	ID	40-84 %	No	Moderate	< 0,3	Water quality, Temperature	200 000 $	Not perfectly safe for fish or personnel
Chain curtain	Yes	High	0-90 %	No	Minor	Low (ID)	Light, turbidity,	6 000 - 150 000 $	Debris constraint, best at angle ≅ 60°, no recent technological development
Air bubble curtain	Yes	High	0-98 %	No	Moderate	Low (ID)	Suspended solids, turbidity, light	20 000 $	Inefficient in darkness, no recent technological development
Hybrids	Yes	Variable	Variable	Variable	Variable	Variable	Variable	Variable	Depends on coupling
Trapping and transportation system	No	Low	Generally high	No	ID	Variable, depends on site configuration	Stress induced by manipulations	ID	Yearly recurrence

Note : ID : insufficient data PS : perpendicular to the screen.

2.4.6.1Criteria

Eight criteria are used to summarize the information available on the various devices investigated. They are interpreted as follows:

- ***bypass required*** determines if a bypass must necessarily be added to the device investigated to allow for downstream migration of fish;

- ***selectivity*** refers to the diversity of species that were tested : a low selectivity indicates that the device is efficient for a wide variety of species; a moderate selectivity indicates that the device is efficient for the majority of species, except for some priority species for which it is not efficient; a high selectivity reflects efficiency restricted to only a few species;

- ***efficiency*** corresponds to the results obtained for the species tested. As specified in 2.4.1, it can refer to a efficiency for devices designed with that purpose, or to total efficiency. The range of values covers those obtained for all the species, and a high specific variability can be expressed;

- ***affects energy production*** refers to a decreased power production or to a headloss induced by the device. A “variable” rating means that the site configuration may, under certain circumstances, reduce the power production if the device is implemented;

- ***maintenance and operation*** discusses the frequency of maintenance work and the annual costs of maintenance and operation. The level is considered minor when these aspects are low. It becomes moderate when one of the components is high. It is rated major when daily maintenance is needed and that costs may be relatively high, over 10 000 $ per year. The rating is “variable” depending on the specific features of the device : as a function of the type of combination for an hybrid device; or depending on the presence or absence of self-cleaning equipment for the Eicher screen;

- ***tolerated current velocity*** indicates the range of velocities for which the device is most efficient. The rating "weak" indicates that the value is not specified but that, according to the range of values observed during experiments with the device, the velocity is clearly below 1 m/s;

- ***limiting factors*** identifies those that, excluding factors used as a distinct analysis criteria, have a strong influence on the efficiency of the device and are related to the environmental conditions at the site, for example turbidity or water temperature, or if the device is affected by daylight or darkness;

- ***cost*** refers to the purchase and installation cost of the device. A "low" cost represents an unspecified cost but clearly below 10 000 $, while a "high" cost is in the order of several hundred thousand dollars.

2.4.6.2 Analysis

The main discriminating factor is the efficiency of the device for the species targeted, such as migratory species, or threatened or vulnerable species. Thus, devices combining a good efficiency and a low selectivity are considered the most desirable. Three types of devices can be considered as such: inclined deflector screens, Eicher screens and modular inclined screens (MIS). Louvers can be added although their selectivity is higher and site configuration plays a preponderant role. Drum screens at an angle with the current are also efficient but they are mostly targeted for large scale sites. In fact, the inclined deflector screens, drum screens at an angle with the current and louvers are the only devices recommended for large scale use by Taft (1993).

Taft (1993) also mentions that Eicher screens are efficient but that additional studies are required to properly assess their true efficiency. The same comment can be given about the MIS. Other devices likely to be further developed and investigated by the manufacturers are underwater lights, strobe lights, sound barriers and deflector screens. However, these devices can only be used when current velocities are low and results still vary depending on species, site configuration and apparatus characteristics. Lack of complete understanding of fish behaviour depending on age, species and life stages are commonly pointed out as a major cause for ineffective or inconstant results with behavioural devices (Popper and Carlson, 1998). Thus, increased knowledge on this aspect is a major goal for upcoming studies related to downstream fish passage.

Bypasses are special cases since they are frequently required in combination with other devices. Their total efficiency can be increased if their design is adequate and if they are combined with devices designed to lead fish to the bypasses.

Data is insufficient to assess the efficiency of water jet screens or blade curtains, of possible hybrid combinations, and of trapping and transportation systems. Except for hybrid devices, these other devices are not likely to be developed in the short term since they are less popular and are generally not recommended by American authorities. Hybrids offer a high potential of development by firms manufacturing one of the components of the system, and several experiments have showed promising results with different combinations, particularly light and sound.

Among the four devices selected at first analysis, louvers come through as having a low cost (for floating louvers), providing easy maintenance, withstanding relatively high velocities and bearing the possibility of minimising headloss, but depend more on site configuration than the other three devices. The self-cleaning Eicher screen and MIS require little maintenance and cover a broad range of current velocities. Finally, the inclined deflector screen has the advantage of being simple and of being the improved version of the vertical deflector screen which is the most widely used device at this time. However, the latter often induces the greatest headloss, along with the Eicher screen and MIS.

Finally, it should be added that for any device, the greatest source of variation in the results is probably related to the bypass. For any new construction, the design of the bypass remains the greatest challenge. For existing structures, the operating bypass may already represent a constraint to the efficiency of the device.

2.5 Systems Used in North America and Europe

2.5.1 North America

In North America, there is a similar context in the United States and in Canada when developing a small hydroelectric project. An authorisation must be issued by an agency that oversees the requirement of mitigation measures, such as migration devices, when necessary.

United States

According to a 1994 assessment, of the 1 825 hydroelectric generating stations overseen by the FERC in the United States, 237 (13%) have devices that protect fish during downstream migration (Francfort *et al*., 1994). More than 48 generating stations have more than one device in place working simultaneously, for a total of 285 devices installed.

Among these 285 devices, the most frequently used is the screen (74,9%) in its many forms. The modification of the trash rack into a "bar rack" accounts for 16,7% of these systems. The bypass channel is present in 27% of all the cases. Devices using light or sound only make up 1,3% of the total. The remaining 16,7% includes various non-specified devices (*Op. cit*.).

In a sub-sample of the 70 projects studied by Cada and Sale (1993), 70% were operating 12 months a year while 26% were operating during certain periods or seasons, and 4% only during certain hours in some of the seasons.

In a sub-sample broadened to 85 projects that included devices under construction, 55% were planned with the adults of the resident species in mind, 41% for the juveniles of the same species, 25% for the juveniles of anadromous species, and 8% for the eggs and fish larvae (Cada and Sale, 1993). It must be noted that these proportions total more than 100% since some of the projects were targeting more than one group of species.

We should remember that there are no perfectly efficient devices at the present that protect downstream migrating fish for all site configurations. In fact, there are no devices that give similar results for different sites, as there are no devices that are unanimously accepted by researchers that experiment in this field.

The lack of monitoring following the installation of devices is one of the factors responsible for this situation, and it is considered an obvious gap for several projects already in place in the United States (Cada and Sale, 1993). As a matter of fact, over a certain period of time the type of device was chosen and imposed on the promoter by the governmental agency in charge, without any systematic level of efficiency objectives or any required monitoring study. For example, of 66 already completed projects in operation, 82% had no follow-up studies in order to assess the efficiency level of the device used and 70% had no precise efficiency objectives (Sale *et al*, 1991; Cada and Sale, 1993). Therefore inefficient devices might have been installed at several sites, bringing no improvements, which might have been detected through monitoring studies. This can lead to poor results, like the *a posteriori* examination of 20 devices installed in the North-East United States that demonstrated that none of them were efficient (C. P. Ruggles, 2000, pers. comm.).

Due to the reports of low efficiency and the comparative analyses carried out on all existing devices, there is an evolution taking place and this situation should adjust itself in the coming years.

The main avenues of research in the USA at present are the improvement of already existing devices, more specifically screens (deflecting, MSI) and behavioural barriers, and perfecting "friendly" turbines. This aspect is explained in more detail in section 2.6.

Canada

In Canada, no recent assessments has been made on downstream devices currently in use. In 1988, there were more than 325 small (< 15 MW) hydropower plants in Canada (Fawkes, 1988) and there could be approximately 400 sites in 2000. The proportion of sites with downstream devices is probably of the same order of magnitude than in the USA (13%). A brief overview is given for the coastal provinces.

For the Maritimes, the most widespread device is the surface bypass which is in use at more than a dozen sites (P. G. Amiro and P. Hubley, DFO, 2000, pers. comm.). Among these, two sites also have louvers, one has an experimental sonic barrier, and a small mesh inclined screen has been installed upstream of a series of four generating stations (*Op. cit*.). There are over 500 fishways that are, at least partially, also used for downstream passage by migrating species.

In Quebec, bypasses are also the most utilised device. The other systems used in conjunction with bypasses are fine mesh inclined screen (6 sites), louvers (1 site), and a modified modular inclined screen (1 site).

In British Columbia, the small hydroelectric power plants are generally built where impassable obstacles (e.g. falls) prevent migrating fish to move upstream on the river (H. Smith, BC Hydro, 2000, pers. comm.). Therefore, there is usually no downstream devices added to the generating stations. The few exceptions are the implementation of Eicher screens (2 sites), of experimental louvers (1 site), and of a diversion screen installed upstream of several power plants (*Op. cit*.).

2.5.2 Europe

Three examples will be given for the European situation. First, in France, where there are numerous hydropower stations in operation. Most of them have relatively low (average of about 10%) mortality rates induced by fish passage through the turbine, the only utilised device up to now being the surface bypass, on about 40 sites (M. Larinier, 2000, pers. comm.). This device was successfully used because of the small spacing of the trash racks bars (commonly 3-5 cm) and it could be used as a behavioural barrier. In some cases, modification of the trash screen was done to decrease the bar spacing below 5 cm. Also, about 80% of the powerhouses have an adequate automatic cleaning system.

In the United Kingdom (UK), different regulatory acts require hydropower stations to screen their water intake against fish entry, since 1966 (Northern Ireland), 1975 and revised in 1999 (England and Wales), and 1994 (Scotland). As an example, in the last country, the 1994 act requires all stations to have an effective screening device in place by January 1998. The grid should be 1.25 cm square mesh or 1.25 by 2.5 cm rectangular mesh, or any other alternative proven to be effective. Screening devices are the most utilised devices in these countries but use of louvers is increasing (Turnpenny, 1998b).

Finally, in Denmark, a similar legislation regarding mesh size has been in effect since 1994. This led to the closure of some small plants that have become economically nonviable (Odeh, 1999a).

2.6 Friendly Turbines

Because there is no universal downstream migration device and because of variable results from site to site, research is still ongoing to improve existing ones. At the same time, the development of more “fish-friendly” hydraulic systems and turbine design has been emphasised since 1994, within the Advance Hydropower Turbine System Program (AHTS), with a joint effort from the Department of Energy (DOE) and the hydropower industry in the U.S.A. (Odeh, 1999b).

Research done in this field aims mostly at reducing the four causes of injury for fish passing through turbine: strike, shear force, pressure, and cavitation which is considered separately although it is related with pressure. A recent literature review has been produced describing these causes of injury (Cada, 1997). Besides efforts done on specific aspects (Cada *et al*., 1997; Sale *et al*., 1997), the AHTS program main goal was to design friendly turbines and to do so, two contractors were selected to design a new turbine runner, and to produce new fish-friendly design criteria for units in rehabilitation projects or in new facilities (Odeh, 1999b).

The new turbine runner has been designed using computational fluid dynamics (CFD). The biological design criteria selected for this design were as follows (Cook *et al*., 1997):

- **peripheral runner velocities should be less than 12 m/s**, and preferably less than 6 m/s to minimise mortality from strike and shear force;
- **minimum pressure through the runner should not be significantly less than 10 psia**, assuming that migrating fish are in the top 10.4 m of water (about 30 psia) and that no mortality is expected if the minimum pressure is limited to some 30% of the acclimation pressure;
- **the rate of pressure change through the runner should be less than 80 psi/s**, about 50% (conservative value) of the rate of pressure across a typical Kaplan runner (160 psi/s) based on a 0.2 second travel and on an average head of 22.5 m (mid-range);
- **the rate of velocity change across a shear zone should not be more than 4.5 m/s per inch (2.54 mm)**, about 50% (conservative value) of the maximal velocity change which did not cause injury to alewifes and smelts, two fragile species;
- **the clearance between the rotating and stationary components should be less than 2 mm**, based on testing done by the U.S. Corps of Engineers (*in* Cook *et al*., 1997), because the gap between the blade and the hub is suspected to be a major cause of mortality in Kaplan turbines;

- **the flow passage opening in the runner should be as large as possible**, to reduce the potential of mechanical injury because of larger volume of water to the surface area of the runner;

- **the number and length of the runner blade leading edges should be minimised**, as it is related to mortality both on Kaplan and Francis turbines.

The new design is two-bladed and has a screw/centrifugal shape, each blade wrapping around the hub about 360°. At maximum efficiency, the runner has a diameter of 5.25 m, but can be reduced significantly with a small drop of efficiency. The estimated best efficiency of the runner is 90%. The next step should be a pilot study.

The other study proposes new design concepts to improve the survival of fish passing through Kaplan and Francis units (Franke *et al*., 1997). For the Kaplan, primary issues are: 1) reduction of the runner gaps, 2) reduction of the wicket gate overhang, 3) optimised hydraulic design considering the two precedent issues with the use of CFD, 4) change the lubrication oil to newer special biodegradable oil more suitable for environment, 5) smoothing of the surface roughness for all components (stay vane, wicket gate, blade, etc.), 6) adjustable rotational speed to be able to attain the optimum operating point at all heads, 7) advanced control system to advise the operator of the best settings to do in order to optimise the operation and to warn if trash clogging occurs. Secondary issues are also considered: interaction of wicket gates and stay vanes, rotational speed, draft tube piers, runner cones, inlet valves, sharp corners, and gate slots.

For the Francis turbine, the primary issues are: 1) lower number of runner blades, 2) increase in inlet edge thickness, 3) reduce interaction of runner blades, wicket gates and stay vanes by changing their shape and relative position, 4) optimised hydraulic design, 5) change lubrication, 6) smooth surface roughness, 7) adjustable runner speed, 8) advanced control system, 9) reduction in pressure change for operating head above 35 m. Secondary issues are again considered: rotational speed, draft tube piers, runner cones, inlet valves, sharp corners, and gate slots.

Besides these design criteria, some research was also done on the aerating of Francis design to increase dissolved oxygen content in the turbine, but the results were not yet available in the report produced (*Op. cit*.). The next step is to test some of the design concepts already implemented at hydropower facilities in the Pacific Northwest (Odeh, 1999b).

Finally, it should be mentioned that the use of friendly turbines implies a small production loss due to lower efficiency, and a higher purchase cost. However, the promoter should consider the cost of an efficient downstream migration device and possible recurring energy loss (e.g. screen clogging) to carry out a complete cost analysis prior to choosing turbine type.

2.7 General Fish Passage Design Considerations

2.7.1 <u>General Guidelines and Strategic Approach</u>

The general guidelines and strategic approach given in this section refer primarily to new hydropower projects. The development of the private industry in that field in the last decade, particularly for small hydro plants, has brought a need to standardise the way development should be made in order to improve environmental efficiency, to reduce related costs, and to avoid unnecessary time and money expenses for sites which can rapidly be discarded because of environmental constraints that render the project non viable. For old sites where a device has to be added, the general principle is the same, but the choice of device is generally lower due to site constraints.

This section also deals specifically with migratory species in relation to small hydropower projects. If resident species were to be considered, the same principles and the same strategy would apply, knowing that fish drawn to a turbine generally cannot back-up and will inevitably be passed through the turbine.

Protection devices for downstream migrating fish must be designed to provide an optimal integration of small hydropower projects into the environment. Thus, environmental issues must be given similar consideration as given to technical or financial feasibility. The costs of this integration must be included in the initial assessment of the project feasibility and profitability to avoid unnecessary detailed calculations for projects that will be aborted because of environmental concerns. Environmental issues should not be viewed as an added restraint during on-going projects, in which cases the investments made to study a site could already be too substantial to actually abort the project. The additional efforts to address environmental issues would then be perceived as a costly addition rather than as a integral part of an adequate solution, thus creating unnecessary frustrations to promoters.

All studies have come to an unavoidable conclusion: currently, there are no totally efficient devices to protect downstream migrating fish, notwithstanding site configuration. Therefore, consideration must be given to fish migration concerns and to solutions properly addressing these issues. Priority should be given to the number of generating stations reasonably acceptable on a stream where the fishery resource is of potential biological or economic value or requires specific protection measures. A limited number of projects on this type of stream would efficiently mitigate the cumulative impacts (Winchell *et al*., 1992; Larinier, 1992a).

Consideration should also be given to a thorough assessment of the project in respect to: the method to identify and assess environmental issues and risks related to a small generating station should be standardised; the criteria on which the decision to implement or not a protection device should also be standardised; the promoters should be provided with all the necessary warnings and with a detailed knowledge of all the parameters to be addressed for the design of an efficient device; and the development of standardised design patterns of these devices. With these measures, the most efficient device for each individual site can be identified and projects at high environmental risks can be readily dismissed, avoiding additional costs to the promoters without the certainty of an efficient mitigation measure.

Another aspect to take into account is that each site has its own particular problems and that solutions are site-specific. Thus, although project assessment must be standardised, each project represents a new challenge in a relatively new field of research and each solution must be adapted to specific projects.

Therefore, it becomes crucial to properly define the notion of efficiency. We suggest the use of total efficiency (i. e. the proportion of individuals surviving the passage). It takes into consideration events such as latent mortality and predation above and below the power station in estimating total mortality and survival rates.

Attempts are generally made to reach 100% efficiency, but in light of the previous remarks, this value is not likely to be reached on a regular basis. Government agencies should use a grading system to assess the efficiency of a device. Larinier *et al*. (1996) recommend that the efficiency level should be defined for each individual site on the basis of the biological objectives aimed at, rather than using an absolute index. These objectives may vary depending on species present, site configuration, the number of generating stations on the stream, the proportion of total discharge actually turbined, etc. A minimum efficiency level could be set up in view of the objectives and of the technology available to design a protection device for downstream migrating fish. An efficiency level slightly below this minimal value could be acceptable if it is demonstrated that the promoter sought the optimal solution rather than the least costly one, and if the difference is compensated for.

As there are no universally satisfactory devices, a recurring 100% efficiency is hardly possible at any given site, and as there is a great variability in each device's efficiency depending on site configuration, government agencies should not try to impose a specific device for all sites. A strategic approach should be established to provide for a logical procedure and maximum efforts put into the design, implementation, and efficiency monitoring of a device that will satisfy all stakeholders.

It would be wise that all stakeholders involved in the implementation of a protection device (promoter, government agencies, fisheries managers, and designer) be part of the procedure for efficient results. This type of global involvement has already been used for several projects, mostly on salmon rivers having interesting salmon production potentials.

The general incompatibility of anadromous fish production and hydro development creates an antagonistic setting between the concerned parties and often leads to conflict and tension. In some cases there is a lack of technical fish passage knowledge among the participants. Advocates on either side make unsubstantiated claims and arguments. Fifty years ago virtually all of the fish passage expertise and knowledge resided with the fish agencies and other government institutions. Today, hydro developers and their consultants often have as much fish passage knowledge and expertise as the government agencies (C. P. Ruggles, 2000, pers. comm.).

Most of the research on fish exclusion systems has not been reported in the scientific literature. Some of the experimental results contradict others, thus care must be exercised in interpreting this information and conclusions reached must be considered tentative. Several of the proposed solutions are promoted on the basis of incomplete assessments. Advocates on both sides of the fish/power issue pick and choose from this diverse body of information to substantiate their particular beliefs or points of view. Thus, there is an urgent need to separate the scientific and advocacy roles of the participants. The need for better science is particularly urgent for the development of fish exclusion systems to prevent fish entry into turbine intakes. Hopefully, the technical solutions derived will reflect both the biological imperatives associated with fish conservation, and the engineering and financial imperatives associated with hydroelectric energy production (*Op. cit*.).

The following sections present the general considerations related to the design of a protection device, and a procedure to design an efficient device.

2.7.2 Information Required

The information required for the design is presented by subject, however all aspects of a device project must be integrated to obtain an overall picture and to provide an adequate analysis of the project and related environmental concerns.

Fish production potential

The fish production potential of a stream is based on the biological or economical value of the species present. In some cases, hydropower projects may even be aborted based on these considerations (see examples in section 2.1.3).

Also, the promoter must be aware that the value of a wildlife potential underexploited or underdeveloped must be taken into account in the project assessment. Thus, the construction of a small hydropower generating station may become an asset in increasing this potential if devices are implemented to make new territories accessible to migratory species. Fishways have been successfully installed on certain salmon rivers (e.g. Rimouski and Jacques-Cartier Rivers in Quebec), while other devices have been added to increase their efficiency, such as the diverting weir installed at Morgan Falls in Nova Scotia, to better attract salmon through the fishway entrance (S. Mason, Morgan Falls Power, 2000, pers. comm.).

Besides the development of new territories, other improvements have been made within hydropower project to increase the productivity of rivers, as part of the “no net loss” approach requested by DFO, which not only refers to habitat but also to productivity. For example, beneficial results of controlling predation by piscivorous birds were demonstrated at a DFO fish culture station near Parksville (BC), in the early 1980’s (G. C. Baker, 2000, pers. comm.).

Fish behaviour

The fish behaviour approaching a device, especially in the case of a bypass, must be taken into account for maximum efficiency of the devices. This aspect has generally been underrated as shown by various studies (Kynard, 1993ab; Vogel, 1993; Popper and Carlson, 1998).

Collecting behavioural data may be costly, especially for species rarely studied or for migratory species requiring studies during periods of hydraulic or physical constraints, or when the environmental stakes are high.

Hydrological conditions

Knowledge of hydrological conditions at a proposed site is essential to assess whether a whole population or only a part of it is likely to be flushed through the turbines. In the case where a reasonable proportion of the total discharge goes through a channel or spills over the crest of a dam, combined with other biophysical factors, a small hydropower station should not reduce fish production below an acceptable level, even without a protection device or if the device is not 100% efficient.

Site configuration

The general configuration of a site reveals probable fish behaviour near the water intake, the tailrace or the spillway. The configuration is evidently site-specific. The turbine capacity and the depth of the water intake will influence the possibility of entrainment through the turbine, as most of the migrant species are found in the upper portion of the water column, at least in the north-east USA (several authors *in* Odeh and Orvis, 1998).

The physical conditions affecting the downstream migration of fish must be analysed in view of favourable (e. g. presence of pools) or unfavourable parameters (e. g. presence of rocks) just below the dam. Depth soundings above and below the structures are also required. Other parameters which have to be considered are: height of obstacle, fish size, and the speed of fish falling from the dam. All of these parameters will influence the mortality rate of free-falling fish (see section 2.3.3).

Current velocity and direction

The behaviour of fish in the upstream reach of a reservoir is generally affected by variations in current velocity and direction. Site configuration, general hydrology, turbine and spillway management modify current speed and orientation, thus affecting fish behaviour. Understanding of the approach velocity (i.e. 30 cm upstream of trash racks or screens) is essential for the adequate design of a device (Odeh and Orvis, 1998).

The design of a protection device must take into account the speed gradient along the whole length of devices such as louvers, or near physical barriers such as deflecting screens and Eicher screens. Speed gradients near screens must be measured with accuracy to avoid erroneous estimates calculated from mean values taken on small sections of the total discharge. This technique is usual in general river hydraulic studies, but it is not adapted to assess the behaviour of fish near an obstacle or a protection device. It has induced errors in assessments of effective flow velocity near certain diversion works.

Tests conducted on a screen have shown that flow speed is not uniform over the whole surface of the screen. It is much higher in the area of maximum entrainment. A mean speed calculated for the whole screen would be valid only if the flow is distributed evenly (Fletcher, 1994).

It is also essential that the speed gradient be continuous between the device and the exit of the bypass channel (Ruggles and Ryan, 1964; Ducharme, 1972).

Mortality rate and entrainment rate

The mortality rate in the turbines can be estimated by theoretical models (section 2.3.4). For certain species presenting a wide range of sizes (e. g. for species where both adults and juvenile fish are involved), several mortality rates are to be calculated. In certain cases, a sound assessment of the environmental risk could readily prevent a project with too many environmental constraints. Ideally, an *in situ* validation of the theoretical model is desirable. It should be required if the mortality rate is estimated to be insignificant, and a protection device is considered unnecessary.

The entrainment rate can only be assessed by *in situ* monitoring, using fishing gear for a capture-recapture study (see chapter 4).

Selection of a turbine

Broad efforts and substantial amounts of money have been invested to develop friendly turbines (section 2.6). When site configuration allows it, it is already possible to choose a type of turbine inducing lower mortality rates for fish passing through it.

The current types of turbines are grouped into three categories: low heads (less than 10 m); moderate heads (from 5 to 100 m); high heads (from 50 to 400 m). Three other categories can be given based on the mechanical type of turbines: propeller (Kaplan, bulb, S type or pit), reaction (Francis), and impulse (Banki-Mitchell, Pelton or Turgo). The range of heads where they can be installed overlaps and can be generally described as: under 30 m for propeller, between 15 and 200 m for reaction, and above 100 m for impulse (with the exception of Banki-Mitchell which can be installed at heads as low as 1 m).

All models of impulse turbines induce almost total mortality (section 2.3.4). There is no other solution than systematically implementing a fish protection device, if required by the presence of vulnerable fish populations. At low heads (less than 10 m), low rotation speed turbines should be given priority. In many cases, a protection device will not be needed, depending on turbine specifications and fish species present. With moderate head turbines, a device is usually required. However, in certain cases, a large slow rotating turbine will induce only low mortality rates, especially with small size fish, in which cases a device may not be needed. It also depends on the actual or potential presence of other generating stations on the same river.

Comparative analysis

Variable development efforts are needed, depending on the environmental issues and concerns related to a project. The environmental risk is site-specific and the selection of a given device rests entirely on decisions made after an objective and total analysis of the situation.

The parameters described previously must be integrated to compare several devices for a given site. Respecting the critical path presented in the following section (2.7.3) and defining clearly the performance expected from a given project will allow the various stakeholders to address properly the issues pertaining to each project. Such an approach can be costly and may extend the duration of the pre-project phase but it constitutes a safe and reasonable assessment, and in the long run should be satisfactory to all stakeholders.

Monitoring

The efficiency of a fish protection device must be monitored. Several projects already completed in the USA lack a thorough follow-up program (Cada and Sale, 1993). This aspect is presented in detail in section 4.1. Adequate monitoring should be spread over a minimum of two years to provide sampling under various hydrological conditions.

Various follow-up protocols are available to monitor the expected efficiency of a device (see chapter 4). In any case, the protocol must be submitted to and approved by the various stakeholders. Experts should be consulted to avoid inappropriate procedures that would cost time and money. The protocol should include the possibility of modifications to the device, if needed, to reach the efficiency level desired.

Maintenance

The site analysis must also consider the maintenance of the device. For most devices, maintenance is essential for maximum efficiency, especially when operating during flood events when the river carries large amounts of debris. This is the case for physical barriers which require frequent cleaning. Automated cleaning systems seem very promising and should eventually improve the overall efficiency of these devices. In certain cases, site configuration makes maintenance operations impossible for certain types of device. These devices must be rejected during project planning as they, in addition to recurring maintenance costs, could actually affect the economic viability of the project.

2.7.3 Strategic procedure

There are four types of small hydropower projects:

1. Totally new construction (powerhouse and dam);

2. Existing dam to which a powerhouse is added;

3. Existing structures (powerhouse and dam) where the powerhouse is modified;

4. Existing structures to which a fish protection device is planned.

For new projects where the powerhouse has to be built, it is essential that the design of the fish protection device be integrated into the overall design. This prevents constraints found at existing structures and reduces the costs of device implementation by as much as 50%.

For an existing powerhouse lacking a protection device, the problems are generally more complex. The dam is already built and its configuration cannot be readily adapted to reach maximum device efficiency. This may prevent the use of certain types of devices.

In any type of project, the first step in project planning must consider the discriminant factors previously mentioned to determine the necessity of a fish protection device. The following sequence should be followed:

1. Identification of species present and determination of fisheries potential;

    - when there are no commercial species, sport fishing or rare species, and the fisheries potential is low, a device may not be needed. This decision belongs to government authorities, and is managed in accordance with existing environmental policies;

    - in other cases, the analysis proceeds with the calculation of expected mortality rates. When a river presents a good potential for introducing a commercial or game species, the potential mortality must also be estimated in case this potential is eventually developed.

2. Mortality estimates

Mortality estimates for fish passing through a turbine are based on the following elements:

- type and specifications of the turbine;
- fish sizes;
- head.

For any size of fish, expected mortality with propeller or Francis turbines is calculated from existing equations (see examples in section 2.3.4). No evaluation is needed for other types as the mortality rate is assumed to be high. At present, the equations available do not provide sufficient precision in mortality estimates to actually dismiss the implementation of a protection device, and an *in situ* validation is needed. Also, the equations apply only to certain species. The equations may eventually be improved upon to a level of reliability acceptable for decision making.

At this stage, the cumulative impacts of several generating stations on a stream must be considered. The overall mortality rate estimated must be validated for the whole stream.

If the mortality rate estimated is considered to be high, the analysis continues to the next step.

3. Estimate of entrainment rate

Entrainment rate is estimated by considering:

- site configuration;
- proportion of river flow that is used for power production.

When the flow to the turbine is high or the site configuration shows constraints, a protection device is required. In this case, the project analysis follows the decisional path shown in Figure 11 and described below.

In other cases, entrainment and survival tests must be conducted to assess the necessity of a protection device. These experiments can only be conducted when the generating station is in full operation. Low impact is a very unlikely situation since exceptional conditions would be required for the entrainment to be negligible, or for the combined entrainment and related mortality rates to be so low as to have no significant impact on the fish population.

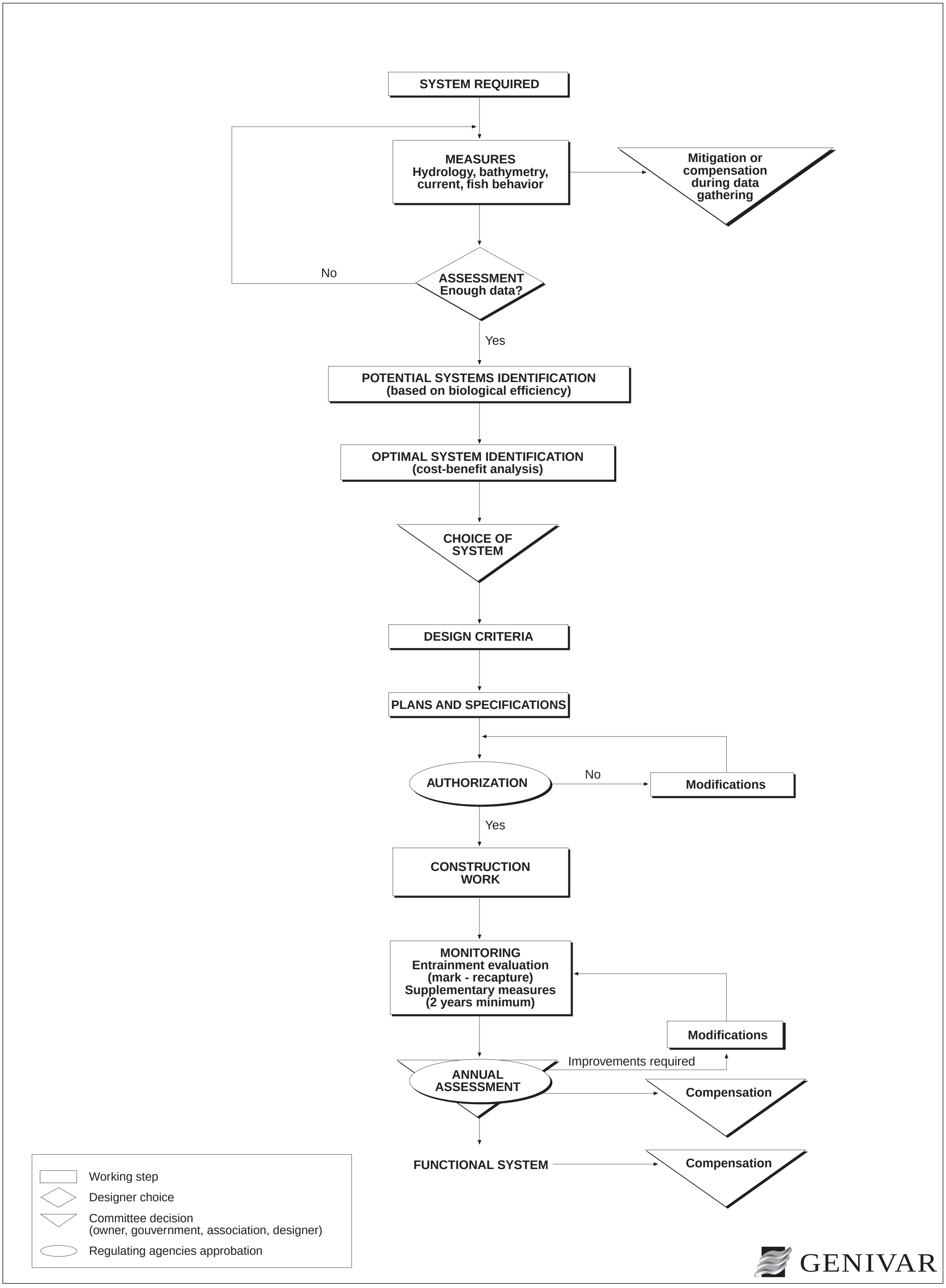

FIGURE 11. Decisional path to elaborate a downstream migration system for small hydropower plants.

In the case of a new construction (dam and powerhouse) where a device is needed after the tests have been conducted, the addition of the device to the newly built powerhouse and dam could increase the total cost by as much as 100%. Also, the request for funding by the promoter is greatly simplified when the total investment is known, including the cost of the fish protection device integrated in the overall design. If tests demonstrate that a device is after all needed, the total investment increases considerably, threatening the project viability.

Decisional path

The proposed decisional path (Figure 11) includes various stages marked by decisions by the designer, decisions involving all the stakeholders (designer, fisheries managers, government representatives and promoter), and finally by approvals or official authorisations granted by the government agency in charge of regulating water uses on streams.

The different stages of this decisional path are:

- conduct measurements and sampling needed to characterise the implementation site. Data must be collected during the whole period when the device will be operating in order to obtain a detailed picture of the site. Mitigation or compensation could be required from the promoter if the generating station is already operating and a substantial migration occurs during this stage;

- produce a preliminary assessment and, if needed, continue sampling over a period of several years;

- identify possible devices on the basis of the data collected and of the biological protection desired;

- identify an optimal device in relation to wildlife benefits – implementation and maintenance costs analysis;

- select a device approved by all stakeholders. Ideally, the device should be the one proposed by the designer. But other potential options may be considered. Currently, several government agencies impose a minimum requirement (i.e. a predetermined device) without a thorough analysis of site conditions to find a more efficient solution. This device is often a 2-cm mesh deflecting screen which has proven highly efficient at several sites. In cases where another option was approved, the promoter may eventually have to install a screen if the original device is not efficient enough. This could happen if the designer lacks experience or if insufficient data was collected for the analysis. In any case, the device must prove efficient. Thus, a predetermined solution may not be suitable for all sites. For maximum efficiency, screens must be inclined and have adequate spacing based on the species present;

- collect design criteria, prepare plans and specifications which are to be submitted to the government agency granting authorisations; modifications may be required;

- implement the device and begin efficiency monitoring;

- produce an assessment of device efficiency after one year of operation. If the device is inefficient, corrections are made, compensations are granted by the promoter, if needed, and monitoring is reconducted. A yearly assessment is produced until the system proves adequate and efficient. Monitoring goes on for a second year for a recurrence analysis. The efficiency level desired is determined by the government agency, usually over 90%. However, a lower level may be acceptable, depending on the biological objectives and the available technology. This level, as set by different American agencies for generating stations, varies from 85% to 100%, depending on the species present. If efficiency is not total, a yearly compensation may be required from the promoter by the agency, equal to the estimated cost of biological losses. A favourable environmental assessment of the project may help lower this compensation.

The total duration of the process may vary according to data availability and to the past experience of people involved in sampling and data analysis. When funding depends upon a firm cost estimate where approximations are not permitted, a poor analysis may prove costly for the promoter in terms of time and money. The Québec and French experience with fish migration has shown that the expertise of specialists is essential to prevent unnecessary expenditures. The specialist must determine without a doubt that a device is required; if there is a reasonable probability that it is not required, additional testing may prove worthwhile. It is also the specialist who will advise the promoter on the choice of a device. An experienced specialist can only conduct these two analysis given a reasonable time frame.

3. UPSTREAM MIGRATION

3.1 General considerations

3.1.1 Historical perspective

Upstream fish migration systems (further referred to as fishways) have historically been observed for several centuries, mainly in Europe, although systems used in the past were fairly primitive. At the turn of the century, Denil (1909) was the first to propose a system based on more scientific principles of hydraulic energy dissipation within a fishway. During the first part of the 20^{th} century, the hydraulic aspects of fishways were studied, as well as swimming abilities of main migratory species such as salmonids. Construction of the Bonneville dam on the Columbia River in the late 1930's and work done by Nemenyi and McLoead in the early 1940's on performance of fish in relation to a number of types of fishways brought a giant step forward in the understanding of upstream fish passage (Clay, 1995). The construction of the Hells Gate vertical slot fishway in the late 1940's was also a milestone in the development of this type of fishway.

Nowadays, fishways are fairly well standardised and much experience has been gained on efficiency of various types of fishways and the general fish performance using these installations, especially for migratory species such as salmonids and alosids. However, migration characteristics of resident species are less well known, and its only recently that habitat fragmentation concerns and specific research on these species have been carried out (see section 3.2.2).

3.1.2 Fish passage policy and regulation

Fish passage policy and regulation have managed in a similar manner for upstream and downstream fish migration (see Section 2.1.4). However, upstream passage has been the object of regulation long before downstream migration was recognised as being a problem. The laws and regulatory agencies require that dam owners provide appropriate facilities for upstream fish passage.

In North America, the biological objectives (species of interest, migration period, etc.) for these fishways are usually set by the governing agencies. The agencies, or a consultant working closely with the government, would then give to the owner the general design for the fishway that would meet approvals. However, the owner is responsible for investments related to the construction of the fishway.

In Europe, a similar approach is used as mandatory free fish passage is required from dam owners (see Section 2.1.4 for France). In the UK, this regulation applies for salmon and migratory trout rivers where a new dam or major modification to an existing dam is proposed. Furthermore, final approval by the agency is only given if the fishway is proved to function adequately (Cowx, 1998).

3.1.3 Sustainable project development

The survival of fish species (both migratory and resident) requires full access to their spawning, and feeding habitats. For this, efficient fishways, especially in the context of multiple hydropower installations on a single watercourse, are essential in order to minimise migration impacts induced by these facilities.

Contrary to most downstream migration devices, fishways rarely interfere directly with power plant operation. The only direct implication is through flows required to operate the system (fishway, and attraction flow). For sites with multiple turbine configuration, the flow pattern in the tailrace is sometimes modulated in order to provide optimal attraction to the fishway. However, this rarely requires turbine shutdown or reduction in power output if the fishway entrance is adequately positioned.

The selection of a fishway type is mainly related to the biological objectives (fish species, size of the fish run, and migration period) and the site configuration. For this, fishway selection is very much site specific. However, it has been observed in the past that regional preferences tend to favour certain types of fishways over others that are less known but could be just as efficient if not more so. The design of a fishway should be carried out with a multidisciplinary team approach, where biologists and engineers pool their mutual expertise in order to come up with a fishway that will be both efficient for fish passage and economically viable for the owner of the dam.

3.2 Fish Species

Fish species can be divided in two broad categories; migratory and resident. The first category groups species that during their life cycle migrate from the ocean to freshwater. On the other hand, resident species can go through their life cycle without substantial migration within a river system.

3.2.1 Migratory species

The presence of dams whether it be for hydropower development or other uses has long been recognised for its negative impacts on migratory species (anadromous and catadromous). Anadromous fish spend their juvenile stage in freshwater. They then migrate to the sea to reach their adult stage and eventually come back to spawn in their native rivers. Catadromous fish show the opposite life cycle. The adults spawn in the ocean and juveniles move up river until they reach their adult size at which point they will migrate to the sea to spawn.

Most of the earlier fishways were built for passage of salmonids (salmon and trout). Over the years, physiological capacities of these species were established and various authors (Larinier, 1983; Bell 1984; Beach, 1984) presented characteristics such as sustained swimming speed, and burst speed which combined with the hydraulics of fishways allow for better design. The table below presents swimming characteristics for certain salmonid species.

Table 4. Range in swimming speeds for some adult anadromous salmonids (from Northcote, 1998; Larinier, 1992a)

Species	Swimming speeds (m/s)	
	Burst	Sustained
Rainbow trout	4.2 – 8.1	1.4 – 4.2
Chinook salmon	4.4 – 6.7	---
Sockeye salmon	3.1 – 6.3	1.0 – 3.1
Coho salmon	3.7 – 5.3	---
Chum Salmon	2.5 – 5.0	0.8 – 2.5
Pink salmon	2.5 – 5.0	0.8 – 2.5
Atlantic salmon	6.0 – 8.0	2.0 – 3.0

Even within the salmonids, it should be noted that there are weak-swimming species such as graylings (*Thymallus sp*.) and whitefish (*Coregoninea*) that show difficulty during upstream migration even at moderate flow rates (Behlke *et al.*, 1991). Fishway design should be modified accordingly if passage for these species is required.

Although not as well documented, characteristics for non-salmonid anadromous fish such as alosids (i.e. shad, herring, etc.) are given by some authors (Travade *et al.*, 1998; Haro *et al*, 1999; Beach, 1984)). In these references, it is stated that adult shad can attain burst speeds ranging from 4–6 m/s. However, alosids do not have the jumping capacity that salmonids have.

3.2.2 Resident species

The problem of upstream passage for resident species has only more recently been addressed (Northcote, 1992; Gowan *et al.*, 1994, Fausch and Young, 1995, Jungwirth, 1998). Essentially, these authors examine the problems caused by hydroelectric and other dams on habitat fragmentation. Even resident species must, to a certain extent, displace themselves between various habitats during their life cycle. These movements can take place within a few meters, hundred meters or many kilometres. The presence of dams can block off essential habitat types for certain fish species.

In North America, upstream movements by resident species within hydroelectric projects is not as high a concern as for diadromous species. The main reason is that many of these projects are located on natural falls that prevented any previous upstream movement for resident species. However, regulatory agencies may suggest upstream fish passage facilities as a mitigation measure.

In Europe and Australia, passage for resident species has been studied by several authors (see in Jungwirth *et al*, 1998 for studies in Belgium, France, Austria, Germany, Switzerland, Portugal, and Greece; see Mallen-Cooper, 1992, 1994 for Australia). In many cases, fishways such as the ones presented in the next section allowed for appropriate upstream access by these species.

3.2.3 Rare and endangered species

In North America, the situation of rare and endangered species was discussed earlier (see section 2.2.3 and the list in Appendix 2). The main issue regarding upstream migration is the loss of fish stocks due to inadequate access to spawning habitats. This situation was observed on the Fraser River where major tributaries have been impounded for hydroelectric purposes causing severe loss to migrating salmon stocks. However, the provision of large effective fishways has resulted in considerable rebuilding of these upriver stocks (Northcote, 1998). The situation of the Atlantic salmon stock in Maine is fairly similar. After having almost completely lost all wild salmon stocks due to river impoundments, removal of dams, (i.e. Edwards dam) is seen as one possible solution for restoring habitat and stocks.

Northcote (1998) reported that for European species whose cause for endangerment was known, problems with passage around dams accounted for almost 60% of the cases. Passage problems were noted for two species of lampreys, three species of sturgeon, three species of clupeids, two species of salmonids, five species of cyprinids and three species of percids, indicating the broad range of the problem (*Op. cit.*).

3.3 Migration Systems

3.3.1 Notion on efficiency

The notion of efficiency is closely related to the legal requirement to ensure free fish passage, but it is rarely clearly defined as mentioned by Larinier (1998). The concept of efficiency should consider the species of interest, the number of obstacles on the river, and their location and the biological objectives of the project.

For migratory species, it is essential that fish pass all obstructions to reach their spawning grounds, making sure that the delay at each dam be minimised to arrive at the spawning grounds at the appropriate time. For example, in Quebec, the regulating agency (Ministère de l'Environnement) usually considers that a two week delay is the upper limit in order to consider a salmon fishway efficient.

For resident species, a main biological objective is to prevent population fragmentation. In such a case, a fishway is considered efficient if it is used by a certain number of individuals, and not necessarily the whole population (*Op. cit.*).

3.3.2 Types of devices

This section describes the various types of fishways that can be usually found at hydroelectric sites. Although other types of fish migration devices exist such as passage through culverts, or small dams (i.e. < 2.0 m) these configurations are not typical of hydroelectric installations and won't be discussed further.

3.3.2.1 Denil Fishway

The Denil fishway was developed in the early 1900's in Belgium (Denil, 1909). Its design consists mainly of a canal with a slope of around 1:3 to 1:5 in which baffles are installed at a 45° angle with the bottom slope of the canal. The use of baffles allows for excellent energy dissipation and thus reduces energy requirements for fish to migrate through the system.

The original design was modified by the Committee on Fish Passes (1942) in order to simplify its construction (Figure 12a). This version of the Denil fishway still forms the basis for many of the fishways used today. A modification of this version was developed in Alaska by Zeimer (1962). It is designed to be constructed out of aluminium sheets, so that it can be prefabricated and flown into remote sites in Alaska (Clay, 1995). This type of fishway is commonly known as an Alaska steeppass fishway.

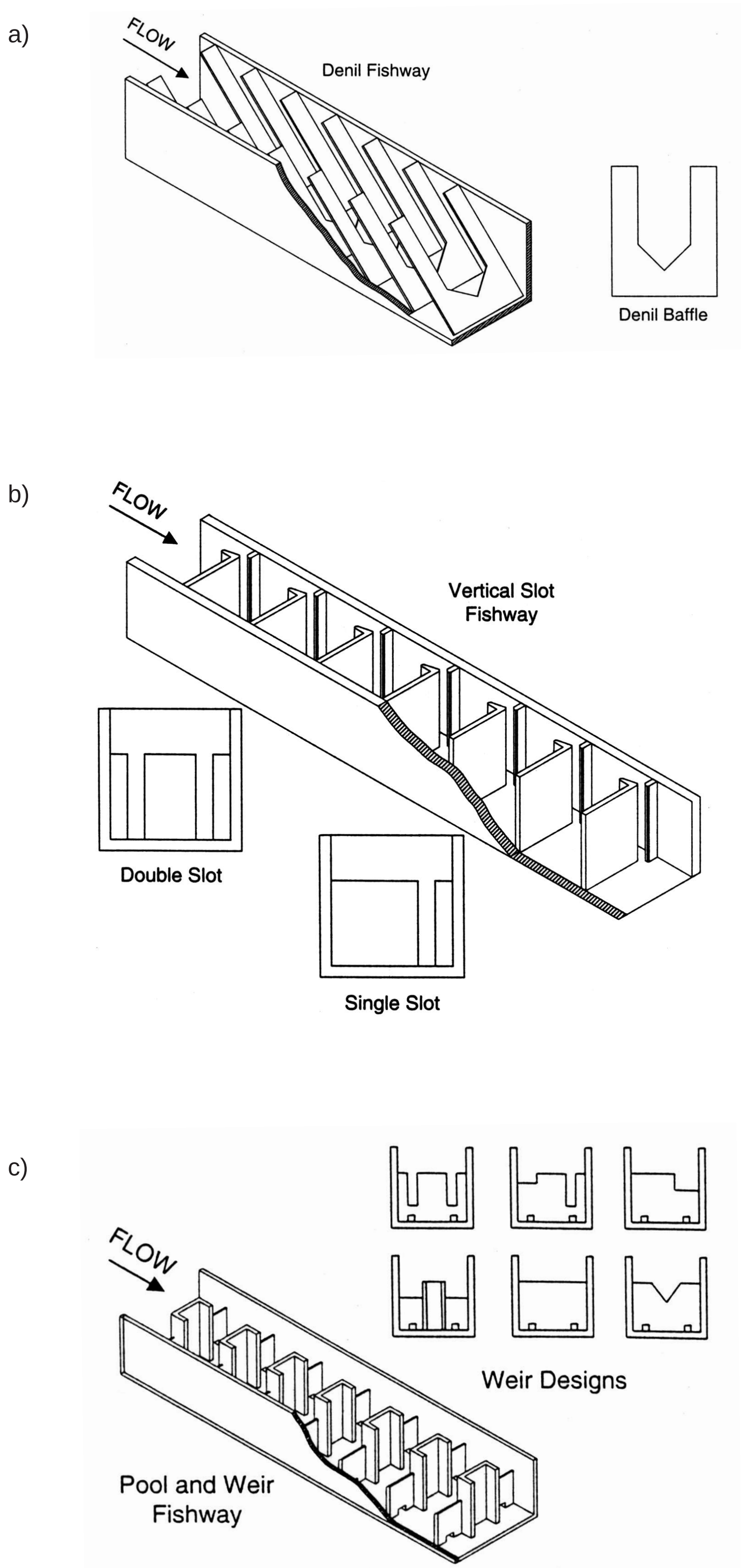

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FIGURE 12. Typical illustration of a) Denil fishway, b) Vertical slot fishway and c) Pool and Weir fishway (from Odeh, 1999a).

It is important to note that the Denil fishway cannot be readily scaled up to pass large numbers of fish. It also requires more water to operate compared to pool and weir or vertical slot fishways. However, this feature is a definite advantage in attracting fish to the entrance.

3.3.2.2 Vertical slot fishway

The vertical slot fishway has been used for several decades and is composed of a canal in which baffles are placed with single or double vertical slots (Figure 12b). This type of fishway is commonly used where high variations in water levels are observed. One of the advantage of the vertical slot design is that ascent of the fishway is possible at any depth the fish chooses. There can be considerable variation on depth selection by fish, depending on the time of day, light conditions, turbidity of the water, etc. (Clay, 1995).

The vertical slot fishway is characterised by a slope of around 1:5 to 1:10. Typical sizes of the fishway are around 2 m width with 3 m long basins. Each basin has a headloss of around 0.3 m. In some cases, such as the Hells Gate fishway on the Fraser River in BC, the size of the fishway is 6 m wide with 6 m long basins and has a double vertical slot.

3.3.2.3 Pool and weir fishway

The pool and weir fishway is seen frequently for salmon migration in Eastern Canada. Its design and construction is fairly simple. It consists, just like the vertical slot fishway, in a canal into which vertical baffles are installed (Figure 12c).

However, these baffles act as weirs and thus control the hydraulic conditions within each pool. The pool and weir fishway is more sensitive to water level fluctuations than the Denil or vertical slot fishways.

The use of orifices in the baffles is frequently seen in this design. Such orifices allow for passage of certain fish species that show less swimming capacity than salmonids. The presence of an orifice (usually at the bottom of the baffles) also allows fish to migrate from one pool to another without having to jump.

Typical configuration of a pool and weir fishway for Atlantic salmon uses 2 m X 3 m basins with a 0,3 m drop between basins.

3.3.2.4 Fish locks, elevators, and traps

The first of modern fish locks was built in Ireland in 1949 based on a design by J.H.T. Borland. Since that time, more than a dozen have been built in Scotland and

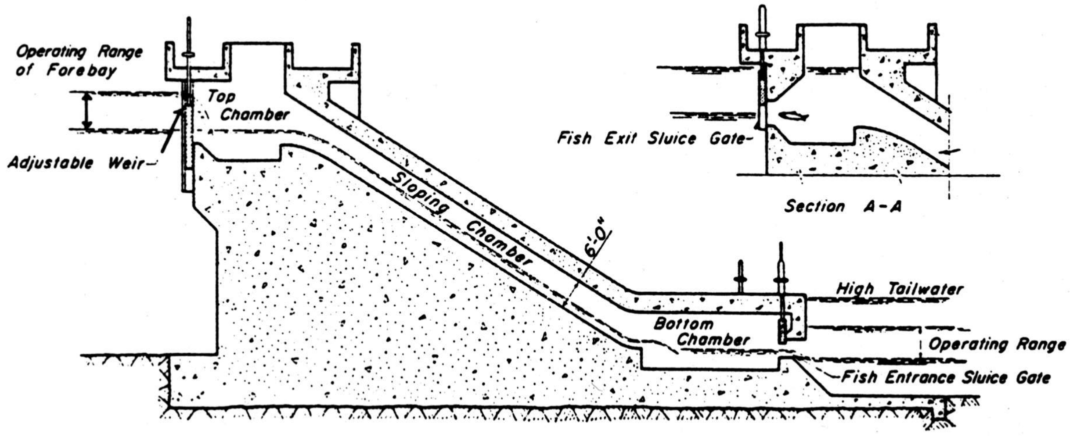
Ireland surmounting dams of up to 60 m (Clay, 1995). In France, locks have been used on a few occasions but they have not proven to be very effective, as it has been observed that some fish remain in the lock chamber instead of passing into the forebay (Larinier, 1998). Similarly, on the Connecticut River near Holyoke, MA a fish lock was installed to pass American shad but was found to be unsatisfactory and has since been replaced by a fish elevator. However, a lock was built on the Haines River in Ontario and is reported to pass large numbers of rainbow trout and chinook salmon over a 7.3 m dam (Clay, 1995).

The principle behind the fish lock is that fish enter the lock at the tailwater level. A downstream gate closes, and at the same time, an upstream gate allows water to fill the lock. Once the water level has reached the headpond level, fish can leave the lock into the forebay (Figure 13a).

One of the limiting factors for the use of the fish lock is the fish passage capacity, because of the size of the lock chamber, and the duration of a complete lock cycle. For this reason, this system is not practical for the Pacific Coast of North America, where large salmon runs are frequently encountered.

Fish elevators are also used to pass fish over high-head dams (Figure 13b), where conventional fishways would be too expensive. Fish enter a holding chamber where they are lifted with a hopper directly to the forebay level. In France two such fish elevators are in place and convey shad upstream of the Golfech and Tuiliere hydropower dams. The main advantages of such systems are initial costs which are independent of the height of dams, and tolerance to upstream water levels. They are also considered more efficient for species such as shad that have difficulties in more traditional fishways (Larinier, 1998).
A modification to the fish elevator is the trapping system where instead of lifting the fish with a hopper to the headpond elevation, fish are simply dumped from the hopper into a truck and then transported upstream to a release point. This system is fairly frequent on salmon rivers in Quebec as it gives river managers flexibility for optimal distribution of the salmon resource on the river reach. In rivers where multiple barriers are present on the main river channel, trapping at the first downstream obstacle and transporting upstream of the last one can prove to be an interesting alternative as this would avoid having to build fishways at all obstacles, and would reduce delays of fish migration through all these fishways. However, trucking costs can be substantial depending on the distance that needs to be travelled from the trapping point to the release point. Moreover, care must be taken during the fish manipulation so not to induce undue stress.

a)



b)

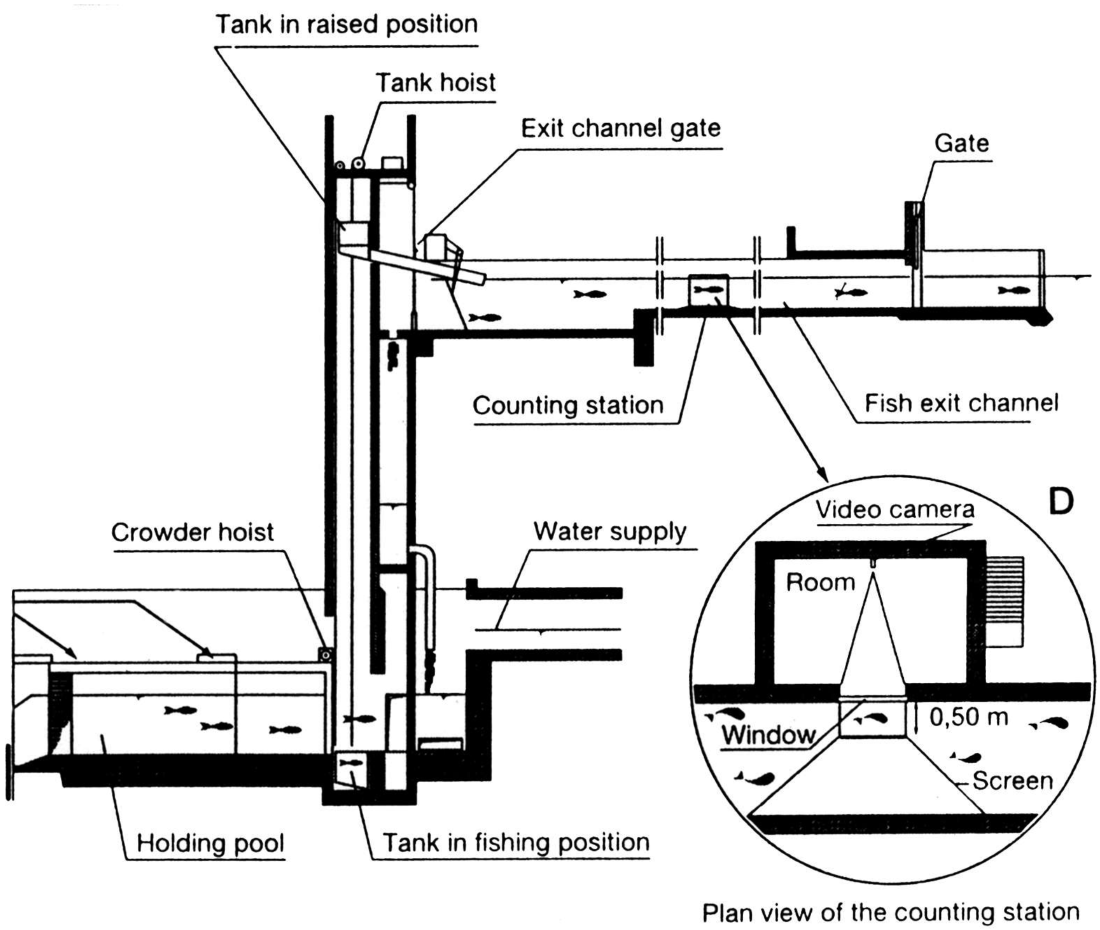


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FIGURE 13. Typical illustration of a) Borland fish lock and b) fish elevator (from Clay 1995 and Travade *et al*,1998).

3.3.2.5 Eel fishway

Eel fishway are fairly different from standard fishways described above. Eels are catadromous fish meaning that the juveniles (elvers) migrate up river to their habitat and pass many years in freshwater until they reach their adult size. Once they have reached their adult size, they migrate downstream to the sea to spawn. At their juvenile stage, eels are like snakes in that they can slither out of the water to pass obstacles, in as much as there is a minimal amount of water (i.e. even on wet grass, elvers can migrate upstream). A typical eel fishway is illustrated in Figure 14a. It is generally composed of a steep channel with bristles installed at the bottom. A minimal amount of water is used for this type of fishway.

3.3.2.6 Artificial channels

An alternative to fishways discussed earlier is to put in place an artificial channel. The use of this type of environmentally friendly design allows not only for fish passage (both upstream and downstream), it also creates fish habitat. However, their low gradient from less than 2% to a maximum of 5% to surmount a given dam height means that they will be very long compared to other systems mentioned earlier. Furthermore, artificial channels require more space than other fishway, so they would not be appropriate if space is limited, unless an in-channel configuration is possible.

This type of fishway is not common in North America and has only been recently applied in Europe (France, Germany, Austria, see Jungwirth *et al*. 1998). In Austria, some artificial channels have been built with slopes from 10–12%, and heads exceeding 10 m. These channels are constructed with natural material, and provide habitat for salmonid species (Figure 14b). Other similar installations have been documented in Australia in recent years (Harris *et al.*, 1998). These installations have heads varying from 0.8 to 1.5 m.

3.4 Systems used in North America and Europe

3.4.1 <u>North America</u>

Canada

In Canada, few authors have reviewed upstream passage. Washburn &Gillis (1985) have investigated some fish passage facilities, mainly the larger ones such as on the St-John River in New-Brunswick, and on the Fraser River in BC. Pool and weir fishways were predominant in the Maritime provinces with one of the worlds highest at the Tobique hydro development. At other large hydro development on the St-John River, fish lifts were installed at the Beechwood and Mactaquac dams.

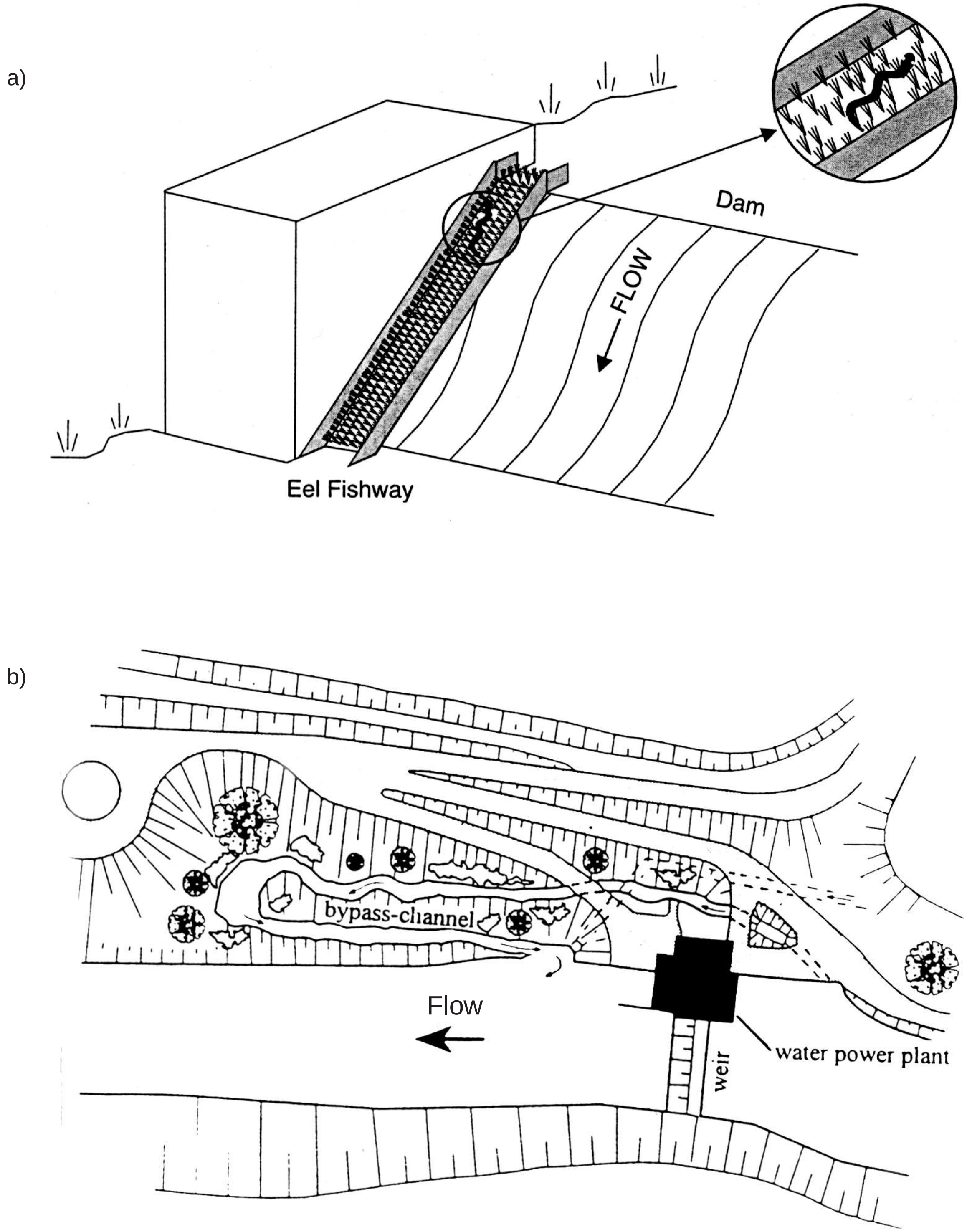

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FIGURE 14. Typical illustration of a) eel fishway and b) artificial channel (from Odeh, 1999a, and Gebler, 1998).

More recently, Beaulieu (1993) completed an extensive review of fish ladders in the province of Quebec. The eighteen fishways investigated are located on rivers with Atlantic salmon or ouananiche populations. Most of these fishways (16) are pool and weir type, with three of them that include Denil type sections within the fishway. Two more fishways are fish lifts. Most of these fishways were reported to perform relatively efficiently, although substantial readjustments were required in some of these ladders. Since that time, several other fishways were constructed, including a Denil fishway on the Jacques-Cartier River at the site of the McDougall dam, and a fish lift on the Malbaie River.

In his book, Clay (1995) noted that in Atlantic Canada, most of the fishways (more than 200) were of pool and weir type, even though some vertical slots and Denil fishways were also constructed. A similar situation is found in Ontario and the Prairie provinces where pool and weir fishways are predominant, although interest in Denil type fishway is growing. Fish passed in the Prairie provinces include northern pike, walleye, cisco, brown trout, Arctic grayling, and mountain whitefish (*Op. cit*.). In BC, the Hells Gate fishway constructed in the late 1940's represents a worldwide reference for the vertical slot fishway.

United States

This situation for fishways in the USA is similar to the one in Canada since species in the West Coast, Great Lakes area, and East Coast are similar for both countries. However, the number of impoundments in the USA is more substantial than in Canada and in this regard, high level expertise was developed on fish passage issues on river systems such as the Columbia River.

In 1990, the U.S. Department of the Interior constructed a research facility on the Connecticut River at Turner Falls, MA, dedicated to anadromous fish passage research. There, biologists and engineers collaborate on laboratory and field projects involving hydraulic design of fish passage systems, understanding fish behaviour and physiology, and population dynamics of migratory fish (Odeh, 1999a).

Recently, the Alaska steepass fishway has been used in several small dams in Delaware and New Jersey to help rebuild stocks of river herring lost due to dam construction (C. P. Ruggles, 2000, pers. comm.).

3.4.2 Europe

A recent inventory that was carried out in the UK (England and Wales) suggests that there are approximately 380 fishways in operation, the vast majority targeted for salmon and/or sea-run trout (Cowx, 1998). Most of these fishways are pool-weir type or Denil fishways. In Ireland and Scotland, Borland locks fishway have been successful in passing salmon on high head dams. They have also been known to pass downstream migrating smolts (Clay, 1995).

According to a review carried out by Larinier (1998) in France, since the passing of the 1984 law on fish passage, more than 400 fishways were built or improved over the last 15 years. The most common type is the pool-type fishway (vertical slot, weir, orifice) with over 150 installations. The Denil fishway is also common with more than 100 passes in operation. The experience of fish locks (these were built in the late 1960's) proved to be inefficient, although 8 fish elevators have been installed and give good results (*Op. cit*.). Finally, bypass channels have also been installed, although these are relatively recent installations and their efficiency is not well known.

In Spain, an inventory of fishways was made and their effectiveness and level of maintenance were estimated (Elvira *et al.*, 1998). A total of 108 fishways were observed, many of them built since 1990. The most common design is the pool-weir (87%) followed by the Denil (5%), and are mainly devoted to salmonid passage (i.e. brown trout and Atlantic salmon). The large majority of Spanish dams (1100) lack a fish passage facility, and alternative fish passage facilities (i.e. fish locks, lifts, bypass channels) are absent from Spanish dams (*Op. cit*.)

The use of bypass channels is mainly seen in Austria and Germany (several authors in Jungwirth *et al*., 1998). Relatively interesting migration success has been observed in both cases.

In Russia, pool and weir fishways are found to be successful for salmon, but fish passage in the basins of the Caspian and Black Seas for sturgeon, herring, carp and perch is a problem at the site of hydroelectric development (Pavlov, 1989). Fish lifts and traps were developed in order to resolve this problem (Clay, 1995).

3.5 General design consideration

3.5.1 General guideline and strategic approach

The installation of a fishway within the context of a small hydropower project is first and foremost a requirement of regulatory agencies in light of biological objectives for the river on which the project is located. As mentioned earlier, past concerns and requirements from agencies were generally directed towards streams with migrating species such as salmonids. However, in recent years, scientists started raising questions on free passage for resident species. This issue will surely evolve in coming years as much research is needed to assess efficient design for these species.

The various fishways that were presented each have their characteristics, but these are well documented as most of them have been operating for more than 50 years. The selection of a particular type of fishway should be based on biological objectives as well as site specific conditions. However, it has been pointed out that on a regional basis, designers or agencies tend to recommend a fishway type with which they feel comfortable, sometimes excluding alternate designs that could be just as, if not more efficient. With a larger distribution of information, whether through technical conferences or publications such as this report, stakeholders in the fish passage issue will have better information on which to base their decision.

Finally, the biological objectives for installation of a fishway need to incorporate the notion of efficiency. This notion is different when dealing with migratory species and in cases where multiple barriers are found on a same river. Furthermore, fishway efficiency monitoring, even if often neglected in the process, should be systematically carried out in order to verify if the system has reached its objectives, and if not, to try and understand why.

3.5.2 Information required

Two types of information are required for adequate design of fishways. First, biological information is essential to scope out the objectives of a proposed fishway. Then site specific physical information has to be collected in order to come up with an optimal fishway design. The book on fishway design (Caly, 1995) is a readily available reference that is strongly recommended.

Biological information

The first element to assess in relation to biological information is the species that are targeted. Are these migratory or resident species? Which life stages need to be considered (i.e. juveniles or adults?). To this day, most of the regulatory agencies focused on passage for migratory adult fishes (i.e. Atlantic salmon, Pacific salmon, trout, shad, etc.). However, recent studies questioned the opportunity to allow passage for resident species. It should be noted that resident species passage is observed through numerous fishways but most of the systems that were built were generally for migratory species.

A second aspect is the timing of migration and the size of population that migrates. These elements are useful to estimate the passage capacity that would be required from the fishway. Its design would need to be adequately sized to pass fish population without inducing too much delay.

Finally, fish behaviour imposes an additional fishway selection criterion. Most migratory species are well characterised for their swimming capacities (i.e. burst speed, sustained speed). Other behavioural aspects such as preferred migration depth, night or day migration, resistance, etc. are useful in determining the best location for fishway entrances.

Physical information

A first step in designing a fishway is to characterise the river discharge at the intended location. This information is crucial to establish the range of flow for the period during wich the fishway will be in operation. Information such as flow duration curves, mean monthly flow, low flow and flood flow are used in the hydraulic calculations of the fishway. Furthermore, the volume of discharge through the fishway as well as attraction flow should represent between 1 to 5% of the mean stream flow during the migration period.

The hydraulic characteristics for a fishway are site specific as they relate to upstream and downstream rating curves as well as hydrodynamic conditions at the fishway entrance. Rating curves are essential in order to have adequate settings for the fishway. The setting should be such that the fishway flow is optimal. If an inappropriate setting causes too much flow, fish will have difficulty migrating through it because of high energy dissipation within each basin. Similarly, if the setting induces not enough flow, then fish will also find passage difficult for lack of water depth or difficulty of finding the entrance for lack of attraction.

One of the key elements in order to attain acceptable efficiency is the location of the fishway entrance. The entrance is the opening at the downstream end of the fishway through which fish enter the system. Inadequate location of this entrance has frequently been listed as a reason for inefficient fishways in the past. The entrance should be positioned as close as possible to the upstream barrier, but has to avoid high flow or turbulence that could mask the entrance and also avoid areas of eddy formation. In large rivers, or streams where downstream water levels vary greatly, the use of multiple entrance fishways should be considered. Larinier (1992b) illustrated several fishway entrance locations based on various dam and generating stations operations.

The hydrodynamic conditions at the entrance of the fishway being so crucial, it is important to stress the need for full understanding of these conditions at various flows. This can be done by direct field observation and measurement, or by small scale models or numerical models. Recent advances in computer science and numerical modelling make it possible to use 2D and 3D models to simulate hydrodynamic conditions and obtain results that can be incorporated in the design process.

3.5.3 <u>Strategic procedure</u>

Figure 15 illustrates a procedure that can be used to aid decision-making related to the requirement of installing a fishway. Essentially, this procedure covers the biological objectives for fishways. Questions that need to be raised are:

- passage for migratory or resident species

- available habitat upstream from the barrier, and historical distribution of fish population.

- population dynamics if new species are allowed access to upstream habitats

- identify conflicts with other user groups (i.e. anglers)

- is free passage ecologically, economically and socially acceptable

Once these questions have been satisfactorily answered, it is possible to move on with the design of the fishway. In the design process, an adequate time-frame should be planned in order to obtain all relevant data (biological and physical) before the final design is proposed. A one year period is suggested to go through the design process.

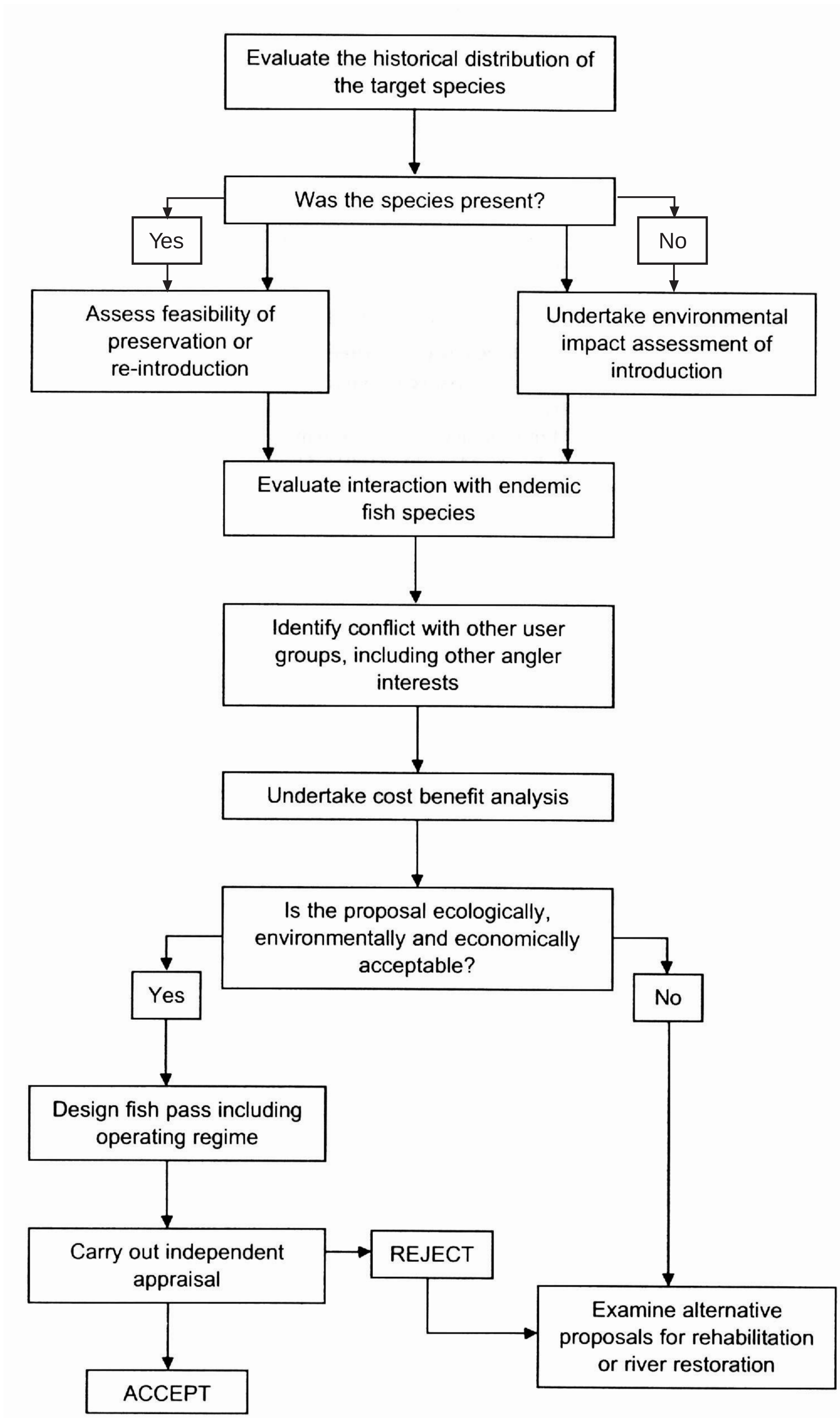

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FIGURE 15. Schematic guideline to aid decision-making for constructing a fishway (from Cowx, 1998).

4. FISH PASSAGE MONITORING

4.1 Importance

It is essential to monitor migration devices in order to make appropriate corrections and to gain further knowledge, especially for downstream migration devices which are still under intense development.

This will avoid situations where inefficient works were constructed and have nevertheless been used as models, thus increasing the number of non-performing facilities. There are examples of inefficient fishways, but this situation has been corrected and the current technology is sufficiently standardized and known to avoid major mistakes. However, development is still ongoing for multi-species fishways and for less studied species.

For downstream migration, examples are more recent and the probability of errors is higher due to the very specific characteristics of each site. For example, there are 20 inefficient sites in north-eastern USA, where imposed devices were implemented without monitoring that would have provided an opportunity for adaptations to be implemented (Section 2.5.1).

Currently, the majority of agencies supervising the implementation of such devices require that monitoring be conducted.

4.2 Downstream migration survey methods

4.2.1 <u>Mortality estimation</u>

The mortality estimation methods treated in this section are mainly related to turbine passage. However, other sources of mortality may be integrated, as specified in section 2.3.

The literature contains much information on tests conducted to estimate mortality during turbine passage. However, the results vary considerably because of significant differences in sampling protocols, some of which do not avoid major biases. For example, certain facilities produce results ranging from one-fold to five-fold depending on turbine functioning mode, either a partial or an optimal output, the latter causing less damage. Other frequent sources of sampling biases include, among others, a high mortality rate in the control group, or a very low recapture rate, 70% being a minimum to obtain a reliable estimate (Mathur *et al.*, 1994). Besides experimental design, species tested and turbine type are others factors influencing mortality estimates (Stokesbury and Dadswell, 1991; Odeh and Orvis, 1998).

The precision of mortality estimates may be influenced by several factors :

- a lower than normal turbine output has impacts on data reliability. A turbine not operating at full capacity causes a higher mortality rate (Taylor and Kynard, 1985). Low loading can result in increased cavitation and shear, so even if entainment is reduced, the increase in percent mortality may lead to an increase in total mortality;
- in methods that involve handling of fish, the related stress may induce a seven-fold increase in mortality rates (Ruggles *et al.*, 1990). The use of control groups minimises the biases related to handling. However, the mortality observed in control groups must be below 10%; above this value, the increase in mortality for the group tested will be exponential and will bias the estimation (Ruggles, 1993);
- the use of nets or traps to catch fish may induce a mortality rate hard to estimate, or even induce mortality from the cumulative impact of the turbine and the fishing gear (Eicher *et al.*, 1987; Eicher, 1993; Ruggles, 1993; Tremblay and Bourgeois, 1999; Therrien,1999a). The most damaging fishing gears are those with knots and those set at an angle greater than 22.5 degrees in relation to the current (Winchell *et al.*, 1992);
- the use of hatchery released fish may induce an increase of the estimated mortality rate (Winchell *et al.*, 1992; Ruggles, 1993). This factor is related to stress caused by transportation, tagging or various handling procedures and, sometimes, by the generally larger size of these specimens, making them more susceptible to injuries during turbine passage. In addition, released fish may be more sensitive or less adapted to the environment, making them more vulnerable. This has been observed in Atlantic salmon where return rates are lower for hatchery released smolts than for indigenous smolts (Caron *et al*., 1999);
- the lack of control groups to identify mortality unrelated to turbine passage. This mortality may be caused by : a high temperature which decreases resistance and induces a latent mortality (Ruggles and Palmeter, 1989), or which increases predation (Eicher *et al.*, 1987); the condition of fish released from a hatchery or if it has been handled (*Op cit.*); handling and stress related to recapture by fishing gear (*Op cit.*). Ideally, three groups of fish are required : a control group, a group released above the turbine and a group released below the turbine;
- latent or delayed or sub-lethal mortality which is not apparent on the day of testing but which may increase mortality after a few days, either from worsening fish conditions or from weakening, making it more susceptible to predation or diseases (Eicher *et al.*, 1987; Ruggles and Palmeter, 1989). In general, it is recommended to verify latent mortality over a 96 hrs period.

For all of the following methods, sampling biases were frequent in the early studies conducted in this field (Heisey *et al.*, 1992; Mathur and Heisey, 1992; Winchell *et al.*, 1992; C. P. Ruggles, 2000, pers. comm.). Among the six sources of biases identified above, the only one potentially producing an underestimate of the mortality rate is latent mortality when fish are not kept for a minimum of 96 hours after the test. All the other sources of biases result in overestimates of the mortality rate. Taking this into account the lowest levels of mortality reported in the literature, for given turbine type and characteristics, are likely to be the closest to actual reality (C. P. Ruggles, 2000, pers. comm.). Winchell *et al.* (1992) found only little variation in mortality estimates by unbiased studies. However, these studies addressed mostly mortality in resident species.

The five following methods are taken from personal observations and from recent analysis of sampling methods conducted by Eicher *et al.* (1987), Larinier and Dartiguelongue (1989), Ruggles *et al.* (1990) and Winchell *et al.* (1992).

4.2.1.1 Return rates

This method uses a comparison of return rates for migratory fishes caught above and below the dam. It is less practical since it requires a large number of fish, and it extends over several years. The results however integrate the cumulative effect of entrainment and of mortality induced by turbine passage, including latent mortality (delayed mortality following turbine passage). An example of experiment is available in Amiro and Jansen (2000).

4.2.1.2 Fishing gear

The use of fishing gear at the turbine site allows the evaluation of a mortality rate for several species simultaneously. It is the only method that recaptures all the specimens after turbine passage, if the set-up of fishing gear is adequate, as mentioned in the previous section. For this method, it is recommended that the collecting nets be located close to a floating live box, where fish can recuperate while resting in lower current velocity. Mortality induced by captures in nets or traps is the most frequent source of imprecision in assessing mortality. The extent of this effect is undetermined since it can vary with site configuration, the methodology used, the type of net used, and the experience of field workers. An example of experiment is available in Navarro *et al*. (1996). An alternative using electrofishing has also been tested (Amiro and Jansen, 2000).

4.2.1.3 Capture-recapture

The capture-recapture method consist in capturing, tagging and recapturing target fish. It offers the same advantages and drawbacks as those mentioned previously, except that the rate of recapture is generally lower. This is not a disadvantage if the statistical method used is adequate. An example of experiment is available in Amiro and Jansen (2000).

4.2.1.4 Inflatable tags

The use of inflatable tags was recently developed by Heisey *et al.* (1992). Fish are recaptured after turbine passage, simply by collecting them at the surface. A deflated balloon filled with a reactive is implanted on the back of the fish. After a variable lapse of time, a chemical reaction occurs and the balloon inflates. With this method, the biases inherent to a low recapture rate, to an incomplete recapture of all dead fish or to mortality induced by inadequate use of nets or traps, are avoided. Two experiments conducted with this device have produced convincing results. An assessment of the mortality of shad using these tags has resulted in a rate of 0 – 2.7% for a Kaplan turbine at the Holyoke dam on the Connecticut River, while a previous assessment (undertaken by Taylor and Kinard, 1985) indicated a rate of 62 - 82% at the same site (Ruggles, 1992). A decrease of 50% of the mortality estimate was also recorded using this method (Winchell *et al.*, 1992).

The method is especially efficient if mortality is assessed for only one species. The stress caused by handling, including the presence of the inflatable device on the back of the fish, and predation on specimens surfacing are factors that can influence the results. Since no fishing gear are used to recapture fish, the recovery effort is high since several field teams are needed to conduct recapture in a short period. Also, the copyright associated to this type of device makes it relatively expensive. The method has been used in Quebec by Hydro-Québec, on American shad, at the dam on the La Prairie River (Desrochers *et al.*, 1993). On this occasion the inflatable tags were compared with a Styrofoam floater which provided comparable results. This alternative was also successfully used with Atlantic salmon smolts at the Mitis II generating station on the Mitis River (Desrochers, 1994), as well as on adult American eel at the Beauharnois power station and at the Saint-Lambert power station on the St. Lawrence River (Desrochers, 1994, 1995; Therrien, 1999b). Another recent evaluation involving inflatable tags was done on the Columbia River with Chinook salmon smolts (Mathur *et al.*,1996).

4.2.1.5 Telemetry

Telemetry is a limiting method since the condition of fish cannot be assessed. Because fish are not recaptured, the loss of transmitters (regurgitation, rupture of holding straps) and predation induce biases in the results.

4.2.2 Entrainment estimation

The following synthesis is based mostly on the work of Larinier and Dartiguelongue (1989), and of Winchell *et al.* (1992), as well as on specific studies, too numerous to be listed here. There are currently four methods to evaluate the efficiency of devices which all rest on estimating entrainment : fishing gear, usually nets or traps, set at the outlet of the turbine or at various locations for a capture-tagging-recapture survey; underwater camera; hydroacoustic; and telemetry. First, we will address the different approaches for resident and migratory species, respectively.

4.2.2.1 Migratory vs resident species

The monitoring of a device is not the same for migratory and resident species. For migratory species, it must be ascertained that there is no entrainment and that fish can find the bypass for downstream migration. For resident species, it may be necessary to evaluate the total population in the stream in order to assess the entrainment proportion, if the number of fish entrained is relatively high. Navarro *et al*. (1996) show an example of a survey done for resident species.

4.2.2.2 Fishing gear

At the turbine or bypass outlet

Setting fishing gear at the outlet of the turbine remains the best evaluation method when all species are investigated. The gear must cover the whole outlet. Partial coverage at the outlet, or gear set at the intake of the turbine or in the gallery may lead to inaccuracies, which has often occurred in previous studies. This method determines turbine passage for all species, and the final result is generally reported in average number of fish per hour. However, for migratory species, other fishing gear or tools must be used at the spillway or similar structures to evaluate the number of fish that are not entrained in the turbine, thus efficiently guided in the bypass, in order to assess the proportion of entrainment and verify the complete efficiency of the device. Larinier and Dartiguelongue (1989) give some criteria to evaluate the size and type of gear to use depending on flow and size of outlet. Other examples of experiments are available in Navarro *et al*. (1996), Haddering and Bakker (1998), and in Tremblay and Bourgeois (1999).

Capture-tagging-recapture

The general fish capture-tagging-recapture method offers more flexibility when dealing with migratory species. It provides a quick answer, at relatively low costs, with an evaluation of the precision of the estimate. However, depending on procedures, the sampling biases may vary considerably. The fraction of the population being tagged must be sufficient for the evaluation to be significant. Also, the hypothesis that tagged fish have the same capture probability as untagged fish is not always verified. Examples of experiments are available in Tremblay (1993,1995), Tremblay and Boudreault (1994), Larinier and Travade (1996), and Therrien and Verreault (1998).

4.2.2.3 Camera

Underwater cameras can be used to evaluate entrainment or to monitor fish behaviour. However, the proportion of entrainment is usually not evaluated, unless the site configuration is particularly favourable and cameras can be installed in other migration pathways (device, dam, etc.). Also, the method is less efficient, even with infrared light, when water has high levels of turbidity or colouration, or high concentrations of suspended solids. The site dimension or its configuration may also imply using several cameras for the same structure, making the analysis more complicated and increasing the cost of the study. Larinier (1998) presented an automated camera device, using movement detectors to control the monitoring, that is used in almost a dozen sites in France (M. Larinier, 2000, comm. pers.). Other examples of experiments are available in Carry *et al*. (1997), Ploskey *et al*. (1998), Johnson *et al*. (1998), Haro *et al*. (1998), Therrien (1999a), and Peven and Mosey (1999).

4.2.2.4 Hydroacoustic

Hydroacoustic surveys provide interesting results, especially on fish behaviour as they induce no interaction with the fish. This method consists in catching the echo produced by fish with sound wave transmitter-receiver, based on the same principle as echosounders used in navigation. The reliability of the results is influenced by the type of instrument used (single beam, split beam), by site configuration (interfering echos of concrete structures), by the density of fish and by the potential presence of other species generating the same type of target as the species investigated. This latter phenomenon almost always occurs and the current technology cannot provide a clear discrimination between species, thus inducing an unavoidable bias in entrainment assessment. In that case, sampling by fishing gear is required to identify the species present and their respective proportions. This may reduce the bias if it is sufficiently important. Split beam and dual beam techniques allow to follow movements of fish in 3D while single beam only follows the passage of fish within the tracking area. High densities of fish could lead to underestimating because of shadowing, a phenomenon that can also occur at air-water or soil-water interfaces.

Several early examples of experiments are available in Thorne and Johnson (1993), and more recently in Skalsky *et al*. (1996), Nestler and Ploskey (1996), Ferguson *et al*. (1998), Haro *et al.* (1998), Steig and Adeniyi (1999), and Iverson (1999).

4.2.2.5 Telemetry

Telemetry is an efficient method to monitor fish behaviour in the vicinity of hydropower stations. It has been used at several sites, on a wide scale basis and with a wide range of species. It is particularly interesting for operating sites where a migration device must be added, in order to optimize the location of the device. However, the number of fish used in the experiment must be sufficiently high to provide adequate precision on entrainment rates, which induces high costs to purchase transmitters and to catch fish if they cannot be provided otherwise. Briefly, this method consists in implanting transmitters on the fish investigated and following them with reception antennas for radiotelemetry, hydrophones for acoustic tags, and fixed receptors for passive integrated transponder (PIT) tags. Fixed antennas can be used in groups of three and more to allow for triangulation and, if a depth probe is added to the transmitters, 3D positioning can be obtain. Programmable receivers synchronised to sequentially scan all the transmitters at the same time permit precise positioning. Hydrophones can provide the same results, and can be mounted on a mobile device to follow a specific target instead of receiving only signals as fish enter in the tracking range (Hedgepeth *et al*., 1999). In both cases a preliminary survey of the background noise frequency should be done to choose the optimum frequency. For radiotelemetry, depth can also be a problem if the conductivity is high, maximum detection depth passing from 25 m for low conductivity (e.g. 15 µSiemens) to 8 m for high conductivity (e.g. 100 µSiemens).

The reliability of the results is influenced by the stress induced by handling, especially for small size or more sensitive fish, transmitters (radiotelemetry or acoustic) being introduced in the stomach or the abdomen, or being fixed on the back of the fish. Predation and transmitter losses (regurgitation, rupture of fixations) are two factors also affecting the results. Intra-abdomen implantation offers less biases than gastrically implanted radio transmitters: losses are very low, except in cases of encystment and expulsion through the abdomen wall (Adams *et al*., 1998); feeding and growth are normal compared to gastrically implants where coughing behaviour and difficulty to swallow food occur (*Op.cit*.); and the behaviour of fish is not very affected when implantation is conducted sufficiently ahead of the monitoring (*Op. cit*.). For pit tagging, if the use of a receptor in a small bypass structure (channel, etc.) is not possible, then the fish have to be recaptured below the dam, which increases the complexity, the probability of bias and the cost of the study. However, implantation is more easy and cheaper than other telemetry techniques.

Examples of experiments are available in Larinier and Travade (1996), Travade *et al.* (1996), Carry *et al*. (1996), Chanseau *et al*. (1997), Haro *et al*. (1998), Therrien (1999c), Peven and Mosey (1999), and Hedgepeth *et al*. (1999).

4.3 Upstream migration survey methods

Fish passes have been directly or indirectly monitored for a long number of years. In fact many fishways include traps or observation windows. Historically, it's been easier to document upstream migrating fish. Population counts at fishways have regularly been used by stock managers to assess fish population.

The most common monitoring method at fishways is to capture them in a trap installed within the pass or at its outflow. Such a system is fairly easy to install and allows to obtain viable biological information (i.e. fish species, length, weight, sex, etc.). However, trapping can induce risks of injury or stress and requires appropriate staffing for the operation of the system. Furthermore, certain species such as shad are reluctant to enter traps and therefore, they can have a negative impact on overall fishway efficiency.

Visual counting of fish swimming by an observation window has the main advantage of allowing for the identification of most fishes without having to handle them. Counting can be carried out in real time by an observer, but this approach is very time consuming. In France, the use of video technology coupled with a triggering system that activates the video when fish enter the counting zone, has shown interesting results (Larinier, 1998).

Radio telemetry, as described in section 4.2, is also an interesting tool to assess the performance of fishways, especially in cases where multiple fishways are present on a river system. In a study in France, it was observed that salmon upstream migration was delayed on the Gave the Pau River because of insufficient attraction flow or a lack of maintenance of fish passage facilities (*Op. cit*.).

5. CONCLUSION

The fish passage issue is an essential element in the environmental impact assessment of small hydropower projects. These projects not only create a barrier for upstream movement, they can also induce mortality to fish population by passage through turbines.

Downstream fish passage at hydropower stations is a relatively recent issue, and devices to safely transit fish downstream of turbines are still under development. Most of the devices that were installed were on existing generating stations, so owners usually did not have much flexibility in the type of device that was installed. Three types of devices are usually found at hydroelectric sites, bypass channels, physical barriers (i.e. screens), and physiological barriers (louvers, lights, sound, etc.).

The efficiency for downstream migration devices varies according to site configuration and species present. Even though high efficiencies were found for certain salmonids such as Atlantic salmon, no single device has attained 100% efficiency. The use of certain devices such as fine mesh screens has direct impact on generating station operation because of high maintenance needs, and headloss through the screens which lowers power production.

Upstream fish passage is better known as most of the types of fishways that are in place have been so for a long time. Consequently, these systems are well standardised and many authors have presented guidelines for their design. The most common fishway is the pool and weir which is found in many countries around the world. The Denil fishway that was developed in the early 1900's is also frequently seen. Fish locks, elevators and traps are not as numerous but offer an interesting alternative, mainly for high head dams (> 30 m). Finally, another alternative for fishway design is the use of artificial channels. This solution is relatively recent and is interesting from an environmental point of view since habitat creation can also be integrated in such a design. Multiple species fishways are still under development as the aspect of free passage for resident species has only been a concern in recent years.

Finally, the monitoring of fish passages at hydropower sites should be an integral part of the project. This activity is frequently left aside, but needs to be carried out to evaluate the efficiency of systems that are built for fish passage. Mark-recapture techniques, or telemetry are tools that can be used for such a purpose.

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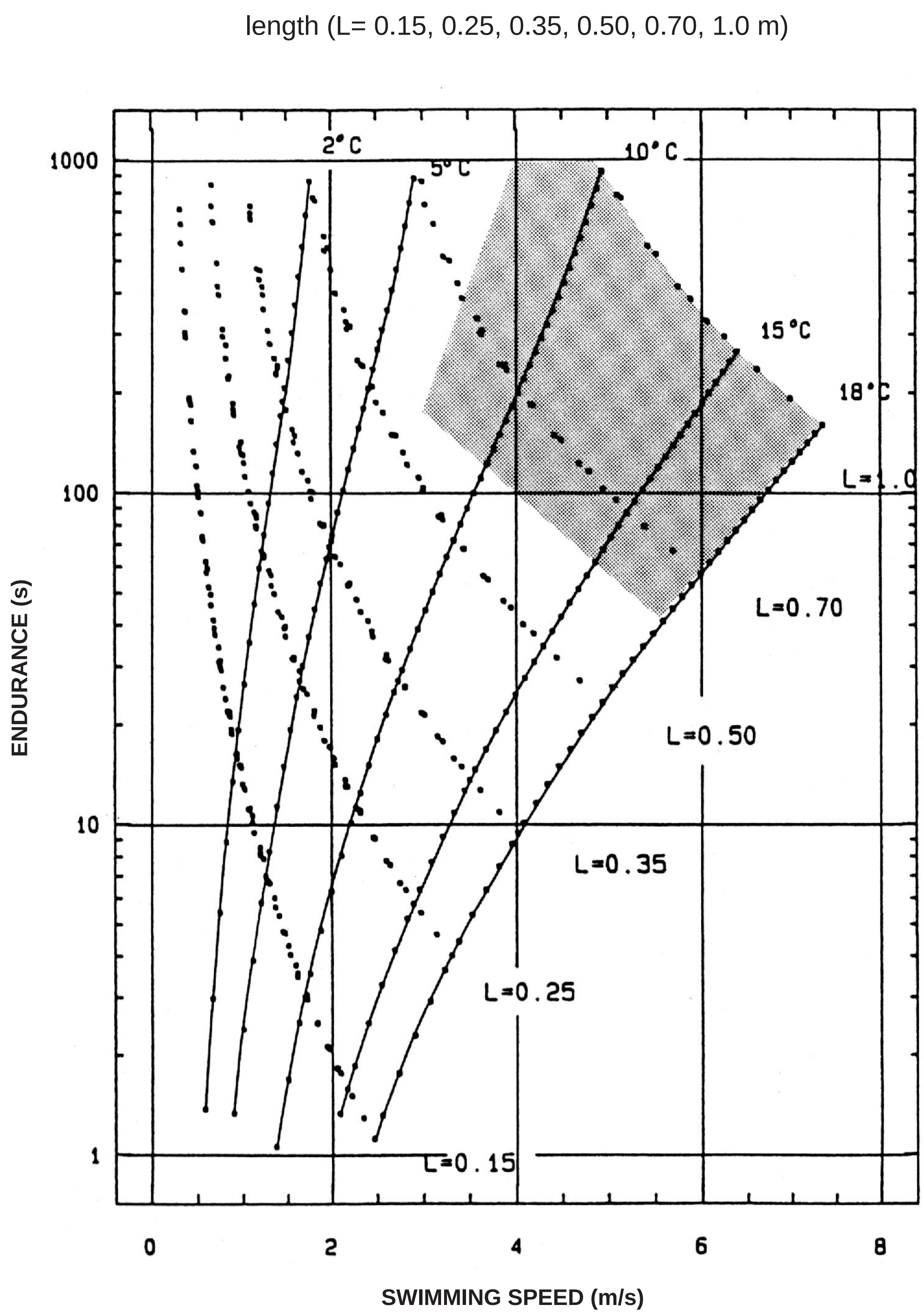
APPENDIX 1

Swimming speed and endurance
related to water temperature and fish length
for salmonids (from Larinier, 1992)

APPENDIX 1. Swimming speed and endurance related to water temperature and fish length for salmonids (from Larinier, 1992).



APPENDIX 2

Fish species at risk in Canada
As designated by the COSEWIC

APPENDIX 2. Fish species at risk in Canada as designated by the COSEWIC[1].

STATUS[2]	COMMON NAME	LATIN NAME
Extirpated	Gravel Chub	*Erimystax x-punctatus*
	Paddlefish	*Polyodon spathula*
Endangered	Atlantic Whitefish	*Coregonus huntsmani*
	Aurora Trout	*Salvelinus fontinalis timagamiensis*
	Nooksack Dace	*Rhinichthys sp.*
	Salish Sucker	*Catostomus sp.*
Threatened	Benthic Paxton Lake Stickleback	*Gasterosteus sp.*
	Benthic Vananda Creek Stickleback	*Gasterosteus spp*
	Black Redhorse	*Moxostoma duquesnei*
	Blackfin Cisco	*Coregonus nigripinnis*
	Channel Darter	*Percina copelandi*
	Copper Redhorse	*Moxostoma hubbsi*
	Deepwater Sculpin (Great Lakes population)	*Myoxocephalus thompsoni*
	Eastern Sand Darter	*Ammocrypta pellucida*
	Enos Lake Sticklebacks	*Gasterosteus spp. (2 spp)*
	Lake Simcoe Whitefish	*Coregonus clupeaformis*
	Lake Utopia Dwarf Smelt	*Osmerus sp.*
	Limnetic Paxton Lake Stickleback	*Gasterosteus sp.*
	Limnetic Vananda Creek Stickleback	*Gasterosteus sp.*
	Margined Madtom	*Noturus insignis*
	Morrison Creek Lamprey	*Lampetra richardsoni*
	Shorthead Sculpin	*Cottus confusus*
	Shortjaw Cisco	*Coregonus zenithicus*
	Shortnose Cisco	*Coregonus reighardi*
Vulnerable	Atlantic Cod	*Gadus morhua*
	Banded Killifish (Newfoundland population)	*Fundulus diaphanus*
	Bering Wolffish	*Anarhichas orientalis*
	Bigmouth Buffalo	*Ictiobus cyprinellus*
	Bigmouth Shiner	*Notropis dorsalis*
	Black Buffalo	*Ictiobus niger*
	Blackline Prickleback Arctic Ocean population	*Acantholumpenus mackayi*
	Blackstripe Topminnow	*Fundulus notatus*
	Bridle Shiner	*Notropis bifrenatus*
	Brindled Madtom	*Noturus miurus*
	Charlotte Unarmoured Stickleback	*Gasterosteus aculeatus*

APPENDIX 2. *(cont'd)* Fish species at risk in Canada as designated by the COSEWIC[1].

STATUS[2]	COMMON NAME	LATIN NAME
Vulnerable *(cont'd)*	Chestnut Lamprey	*Ichthyomyzon castaneus*
	Cultus Pygmy Sculpin	*Cottus sp.*
	Fourhorn Sculpin (Freshwater population)	*Myoxocephalus quadricornis*
	Giant Stickleback	*Gasterosteus sp.*
	Green Sturgeon	*Acipenser medirostris*
	Greenside Darter	*Etheostoma blennioides*
	Kiyi	*Coregonus kiyi*
	Lake Chubsucker	*Erimyzon sucetta*
	Lake Lamprey	*Lampetra macrostoma*
	Northern Brook Lamprey	*Ichthyomyzon fossor*
	Northern Madtom	*Noturus stigmosus*
	Orangespotted Sunfish	*Lepomis humilis*
	Pacific Sardine	*Sardinops sagax*
	Pugnose Minnow	*Opsopoeodus emilae*
	Pugnose Shiner	*Notropis anogenus*
	Redbreast Sunfish	*Lepomis auritus*
	Redside Dace	*Clinostomus elongatus*
	River Redhorse	*Moxostoma carinatum*
	Rosyface Shiner (Manitoba population)	*Notropis rubellus*
	Shortnose Sturgeon	*Acipenser brevirostrum*
	Silver Chub	*Macrhybopsis storeriana*
	Silver Shiner	*Notropis photogenis*
	Speckled Dace	*Rhinichthys osculus*
	Spotted Gar	*Lepisosteus oculatus*
	Spotted Sucker	*Minytrema melanops*
	Spring Cisco	*Coregonus sp.*
	Squanga Whitefish	*Coregonus sp.*
	Umatilla Dace	*Rhinichthys umatilla*
	Warmouth	*Lepomis gulosus*
	Western Silvery Minnow	*Hybognathus argyritis*
	White Sturgeon	*Acipenser transmontanus*
Indeterminate	Bering Cisco	*Coregonus laurettae*
	Chiselmouth	*Acrocheilus alutaceus*
	Darktail Lamprey	*Lethenteron alaskense*
	Flathead Catfish	*Pylodictis olivaris*
	Mira River Whitefish	*Coregonus clupeaformis*
	Pixie Poacher	*Ocella impi*
	Spinynose Sculpin	*Asemichtys taylori*

APPENDIX 2. *(cont'd)* Fish species at risk in Canada as designated by the COSEWIC[1].

Note 1 : COSEWIC : Commitee on the Status of Endangered Wildlife in Canada

Note 2 : STATUS

Extinct	:	A species that no longer exists.
Extirpated	:	A species that no longer exists in the wild in Canada, but occurs elsewhere (for example, in captivity or in the wild in the United States).
Endangered	:	A species facing imminent extirpation or extinction.
Threatened	:	A species likely to become endangered if limiting factors are not reversed.
Vulnerable	:	A species of special concern because of characteristics that make it particularly sensitive to human activities or natural events.
Indeterminate	:	A species for which there is insufficient scientific information to support status designation.

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