ONEMA
The National Agency for Water and Aquatic Environments

Knowledge for action

The ICE protocol for ecological continuity

Assessing the passage of obstacles by fish

Concepts, design and application

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RÉPUBLIQUE FRANÇAISE

Ministère de l'Écologie, du Développement durable et de l'Énergie

The French National Agency for Water and Aquatic Environments

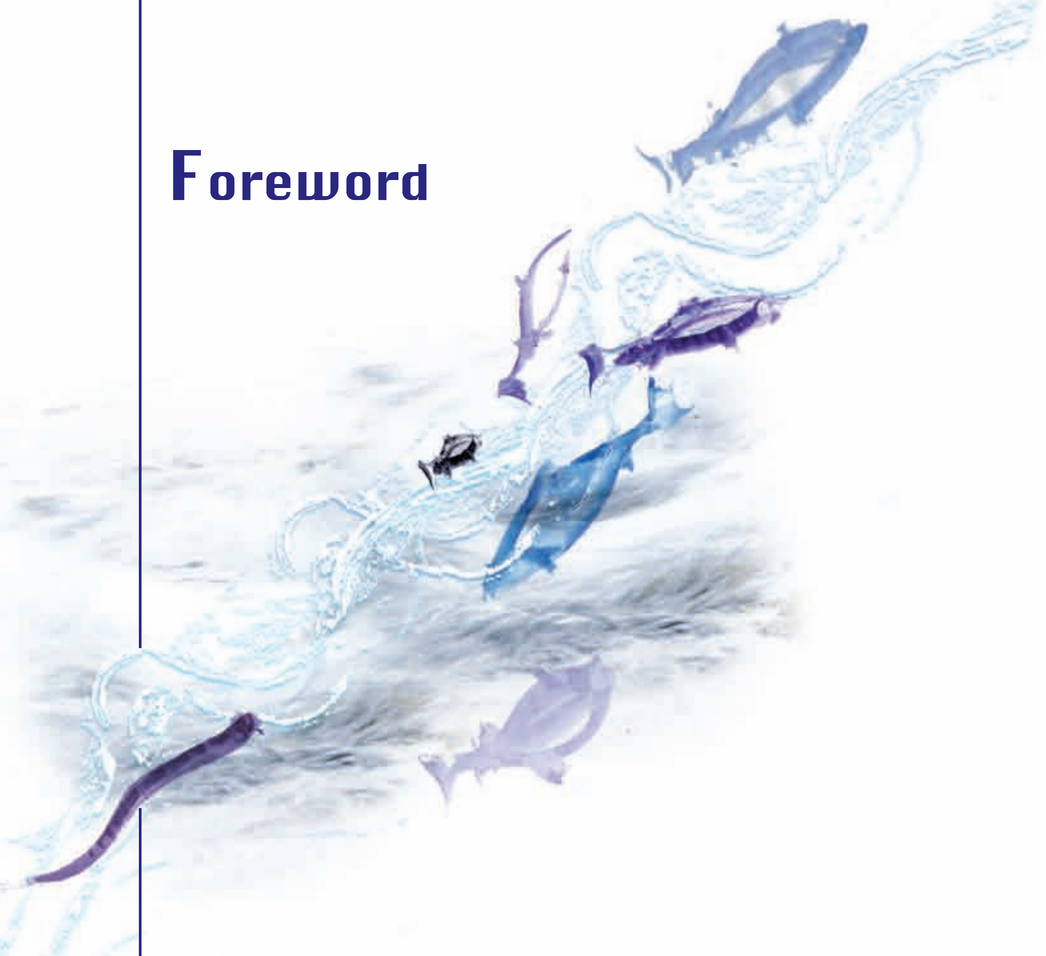
Onema is a public agency operating under the supervision of the Ecology ministry. It was created by the 2006 Water law and launched in April 2007. Onema is the main technical organisation in France in charge of developing knowledge on the ecology of aquatic environments and monitoring water status. Its mission is to contribute to comprehensive and sustainable management of water resources and aquatic ecosystems.
The agency contributes to restoring water quality and attaining the goal of good chemical and ecological status, the objective set by the European water framework directive.

Onema, with a workforce of 900, is present throughout continental France as well as in the overseas territories in the framework of the national interbasin solidarity policy. In carrying out its mission, Onema works closely with all stakeholders in the water sector.

This book continues the ***Knowledge for action*** series of books that provides professionals in the water and aquatic-environment sector (scientists, engineers, managers, instructors, students, etc.) with information on recent research and science-advice work.

The book is available on the Onema site (www.onema.fr), in the Resources section, and at the national portal for "Water technical documents" (www.documentation.eaufrance.fr).

Foreword



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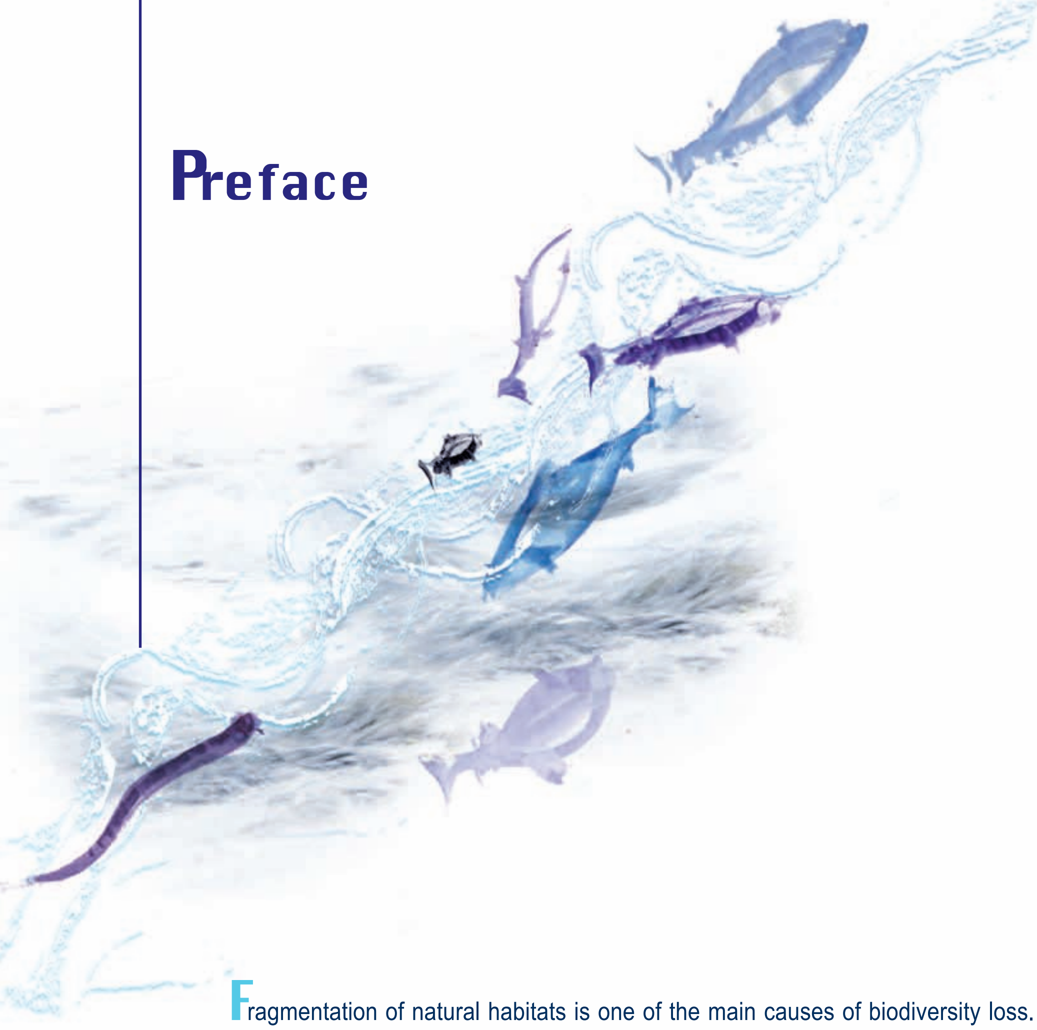
The fragmentation of habitats has been acknowledged for 30 years as one of the five main factors of biodiversity loss, in conjunction with pollution, overuse of natural resources, invasive species and climate change.

Since then, public environmental policies have strived to restore the connectivity of natural habitats. That is particularly the case for water policy, which has made the ecological continuity of rivers a central element in policy planning, a quality element for monitoring programmes and one of the basic guidelines for river-basin management plans (RBMP). The time has thus come for decisions, with the resulting controversy given that any attempt to modify existing discontinuities impacts our perception of landscapes and various uses of aquatic environments. Given that there is, on average, at least one obstacle for every five kilometres of river in continental France, this issue concerns the entire country, its population and all water managers. That explains why it was necessary to have a single set of standardised procedures for selecting the work to be done on the basis of objective and comparable data. For the ecological continuity of fish, we now have the ICE method presented in this book, which describes obstacles in rivers and assesses the capacity of fish to overcome those obstacles during their upstream migration.

The design, development and national deployment of this method required five years of intense, collective effort on the part of numerous scientists and the Onema local and regional offices. The method is the result of an outstanding multi-disciplinary approach involving both hydraulics and ecology, two disciplines that some people might see as irreconcilable, but that must work together synergistically in the effort to restore environments.

The publication of this book in the *Knowledge for action* series marks the transition from the team that developed the method to the people who will use it to acquire better understanding of ecological continuity in rivers and as an operational tool in implementing water policy and enhancing biodiversity.

Preface



Fragmentation of natural habitats is one of the main causes of biodiversity loss. Obstacles to flow in rivers result in degradation of aquatic environments and consequently impact the living communities and the ecological processes in those environments.

Given the vast array of regulatory requirements (Water framework directive, Law on water and aquatic environments, Grenelle environmental agreement, European eel regulation, etc.) and the many environmental issues involved in restoring the ecological continuity of aquatic environments, Onema decided to create a "tool" to assess and quantify the impacts of hydraulic structures on the free movement of fish.

The ICE protocol is a national method to produce information on ecological continuity intended for people involved in environmental work and territorial planning, scientists, teachers, engineering firms and all other interested persons.

It is based on a major review of the current scientific knowledge and on the scientific and technical progress made by a work group composed of French (Onema and Ecogea) and Belgian (University of Liège) experts in this field.

The purpose of this document is to present the issues involved in ecological continuity for fish species, the scientific principles underlying the development of this assessment method and the standardised protocol produced by the work. The method consists of a simple and objective means to assess the risks to upstream migration caused by the main types of physical obstacles for numerous common species of fish in the rivers of continental France. The assessment is based on a comparison of the typological, geometric and hydraulic characteristics of obstacles with the physical capabilities of the fish species analysed.

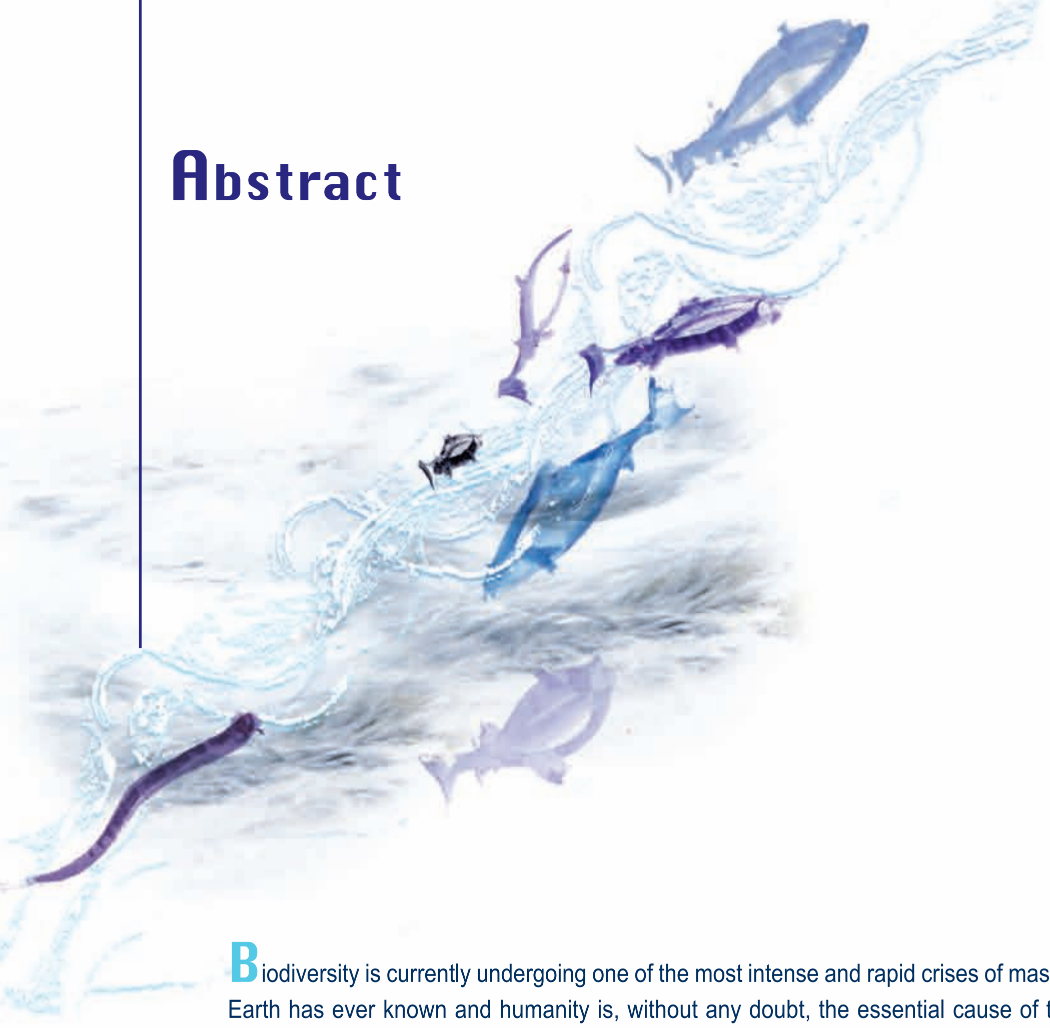
NOTE

When a hydraulic facility is equipped with a fish pass, a "pre-assessment" of the pass should also be carried out under normal operating conditions (normal discharge and maintenance conditions). The purpose of the pre-assessment is to rapidly identify those fish passes that are clearly not well suited to the species in question and for which a more in-depth assessment may be necessary.

However, the ICE protocol is not intended as an assessment of the hydraulic functioning of the fish pass nor is it a means to check the conformity of the pass with applicable regulations.

Concerning downstream migration, given the complexity of the biological mechanisms involved and the in-depth knowledge required on the local hydrology, on draw-off conditions and on the hydromechanical characteristics of each structure, the ICE protocol does not assess the passage of structures in the downstream direction.

Abstract



Biodiversity is currently undergoing one of the most intense and rapid crises of mass extinction that the planet Earth has ever known and humanity is, without any doubt, the essential cause of the drastic losses. Among the many factors are chemical pressures in the form of water, soil and air pollution as well as in the form of climate change, excessive use of natural resources (hunting, fishing, cutting of forests, etc.), and physical pressures such as the destruction or loss of access to the habitats required by numerous species for their survival. The impact of physical pressures and in particular the fragmentation of habitats is today better understood and has been amply demonstrated. The international community has progressively acknowledged this issue and responded with a number of legal texts. In the European Union, the Water framework directive (WFD) is a prime example. The objective of the texts is generally to preserve and to restore ecological continuity and ecological corridors in order to slow or to stop at least part of the loss of biodiversity now taking place.

Before taking action in favour of ecological continuity, it is necessary to assess the degree to which natural areas have been modified and to identify the situations creating the greatest problems. In aquatic ecosystems, hydraulic structures are one of the main causes of degraded ecological continuity, particularly for fish whose survival depends on their freedom of movement. An assessment of the impact of structures on the movement of fish is a prerequisite to determining the seriousness of problems in the field and identifying the priorities for action.

To date, these assessments have generally been carried out by a small number of highly specialised experts. However, the massive (yet often unsuspected) numbers of transverse obstacles on rivers (over 70 000 obstacles have already been inventoried in France thanks to the characterisation reports for the WFD) created a pressing need for a simple, robust and standardised method for assessments that could be used by a large number of persons active in the environmental and territorial-planning fields.

Onema responded to the challenge and coordinated the development of a protocol to assess the impact of obstacles to flow on the movement of the main fish species in continental France.

This *Knowledge for action* document presents the results of that work, namely the ICE protocol designed to produce information on ecological continuity in rivers.

This document is divided into four main chapters.

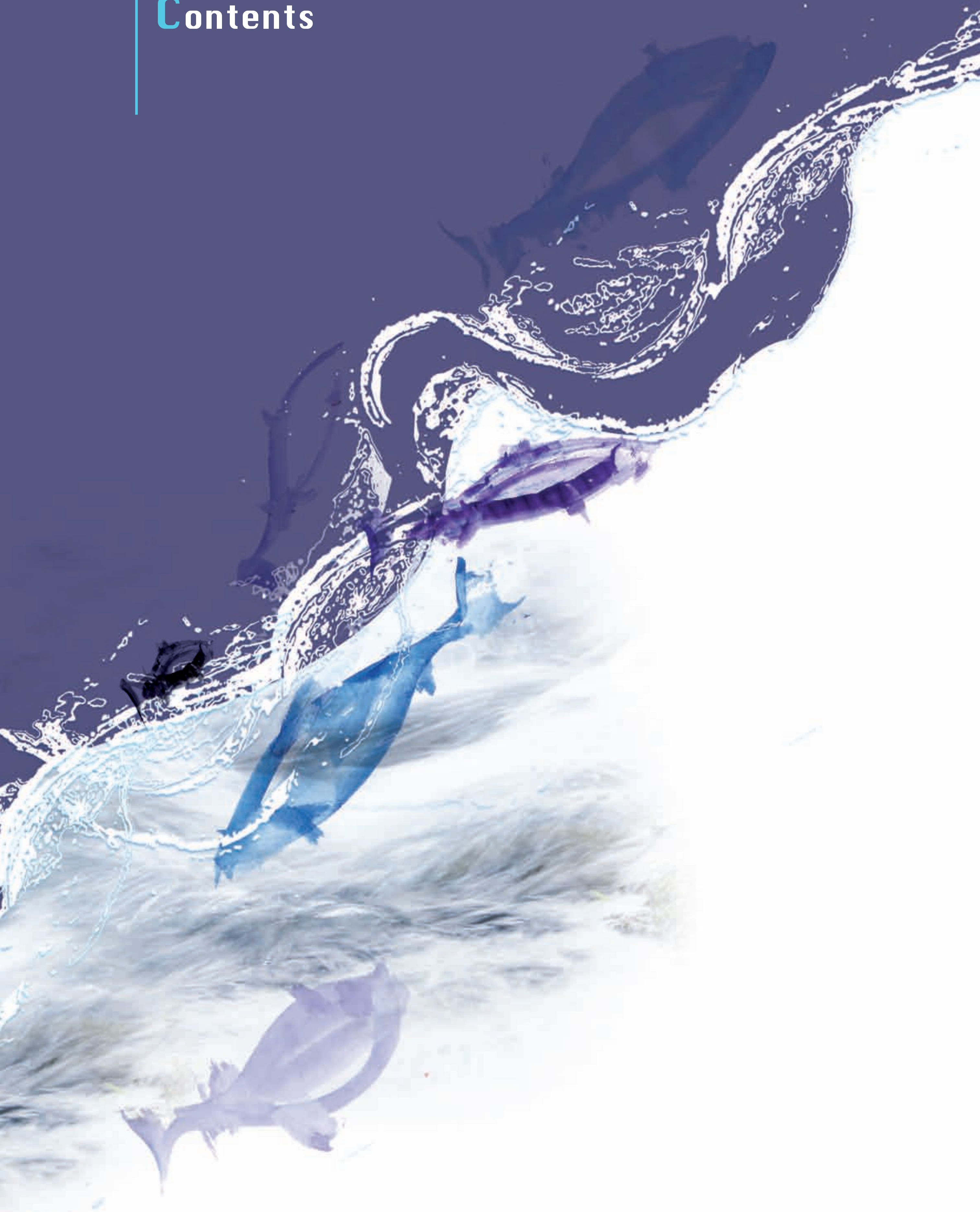
■ **Based on a review of the current scientific knowledge on the international level, it discusses the importance of ecological continuity for fish.** Chapter A looks at the bio-ecological issues involved in the free movement of fish and at the various methods of overcoming obstacles used by species in continental France. Passage of obstacles depends on major environmental factors, on the ethology of species as well as on the physical capabilities of each species. The methods used to determine the physical capabilities are presented, as are the main conditions limiting passage of obstacles. The chapter also discusses the main types of physical barriers and their impacts on fish populations.

■ **The document describes the general principles underlying the ICE protocol.** Chapter B addresses the basic concepts and the general implementation procedure for the method, and presents a typology of the main obstacles analysed by the protocol. In addition, it lists eleven ICE species' groups according to their physical capabilities in overcoming obstacles as well as five "passability" classes intended to inform on the impact of obstacles.

■ **It presents in detail the protocol implementation method and assists readers by delving into each step of the procedure to assess the passability of obstacles during upstream migration.** Chapter C goes into the calculation method for the indicators on each of the five major types of obstacle discussed. It does not neglect the special case of the European eel, which has some very specific movement techniques. All topographical and hydraulic constraints are taken into account and hydrological variations are also included to assist in defining the assessment strategy. Each procedure is presented as a flow chart to assist in decision-making, thus making the protocol easy to use for a wide range of people.

■ **The document also addresses the special case of obstacles equipped with a fish pass.** Chapter D lists and describes various types of fish passes that are commonly found in France. It discusses the main causes of malfunctions and proposes a rapid, pre-assessment method to determine their performance level.

Contents



Introduction

Biological communities are in constant interaction both among themselves and with their environment. They support an array of ecological processes that enable ecosystems to function, to regenerate, to evolve, thus providing humanity with the ecosystem services required for its survival. Since the industrial and agricultural revolutions, humans have considerably increased their impact on biodiversity by vastly augmenting the number and the intensity of the pressures that they bring to bear on natural environments. The contemporary period since 1900 has thus seen one of the greatest extinction events that the planet has ever known. Chemical pollution has long been identified as a source of pressures and numerous measures have been taken to reduce chemical emissions, however awareness concerning the effects of physical alterations in environments is more recent. Those alterations are nonetheless of major importance and habitat fragmentation of living communities is now seen as one of the main causes of biodiversity loss. This new awareness is the result of better understanding of the essential role played by the connectivity of natural areas in the biological cycles of living species and of the functions provided by those cycles for the genetic mixing required to ensure the survival of populations and the evolution of species, as well as for numerous geophysical and geochemical processes within ecosystems.

Ecological continuity

Ecological continuity is a fairly recent concept that was introduced for the first time by the British botanist Francis Rose (Rose, 1974). Continental aquatic ecosystems, organised around the water cycle and the continuum of water flow, naturally evoke the idea. The initial research work on the topic, however, took place in the field of terrestrial ecology, in particular landscape ecology and the study of forestry systems. A number of terms are regularly and fairly indifferently used in the field, such as landscape continuity, biological continuity, connectivity, ecological corridors and ecological networks. Though several definitions of ecological continuity exist, the most common and widely used for aquatic ecosystems is very close to the concept of landscape continuity (Økland et al., 1996; Fritz and Larsson, 1996; Ohlson and Tryterud, 1999), i.e. "*such habitat has been available in patches for a long time within the limits of a landscape, in which the juxtaposition of habitat patches is important for dispersal and metapopulation dynamics of species. The spatial scale of 'landscape continuity' is usually undefined and may be different for different organisms*" (Norden and Appelqvist, 2001). The Water framework directive (WFD) generalised the use of this neologism within the environmental field, but simplified the concept by considering that it could be understood as the conditions enabling "*undisturbed migration of aquatic organisms and sediment transport*".

In France, the 2006 law on water and aquatic environments confirmed the importance of ecological continuity and sharpened the definition. The ecological continuity of a river is defined as "*the free movement of living organisms and their access to the areas required for their reproduction, growth, feeding and shelter, good functioning of natural sediment transport and good functioning of biological reservoirs (connections, notably lateral connections, and favourable hydrological conditions)*".

Obstacles to river flow

The presence and increasing numbers of transverse structures created by humans in rivers (for power generation, drinking water, irrigation, roads and railroads, navigation, bed-stabilisation systems, aquaculture, recreational activities, etc.) have significantly limited the natural free movement of aquatic living communities. These structures also profoundly disturb the hydromorphology of rivers (slowing of flow velocities, increased depths, reduction or halt of coarse sediment transport, etc.) and provoke major physical-chemical modifications in water. In addition to the more limited movement of living communities, obstacles to river flow also impact ecological continuity by altering the quality and reducing the diversity of the habitats available to the various aquatic species. The consequences for biological communities can be drastic. The decline of many populations of diadromous fish is a dramatic example, due notably because access to functional spawning grounds is partially or totally blocked.

A method to assess obstacle passability

This *Knowledge for action* document presents an assessment method, namely the ICE protocol to produce information on ecological continuity, and the general principles guiding its design.

Given the currently available scientific knowledge, the method described here is intended exclusively as a means to determine the impact of transverse structures on the movement of fish. These structures can create obstacles of various types, including thermal, chemical (oxygen, nutrients, toxic substances, etc.) and physical (head-drop, slope, flow velocity, turbulences, depth of the sheet of water, etc.). In this document, only physical, transverse obstacles are discussed.

The ICE protocol is based on a comparison of the topographical and hydraulic characteristics of obstacles with the physical capabilities (swimming, jumping or crawling) of the fish species analysed. It requires the gathering of descriptive information on each obstacle and avoids bringing in experts as much as possible. The result of the analysis is an indication on the risks of a structure constituting a more or less severe obstacle for a given fish species or group of species. Particular attention was paid to the practical aspects of the method (time required and necessary human resources) to facilitate its use in a wide variety of situations and areas.

This *Knowledge for action* document is divided into four chapters.

■ **Chapter A discusses the importance of ecological continuity for fish**, based on a review of the current scientific knowledge. It looks at the bio-ecological issues involved in the free movement of fish, the main types of physical barriers and their impacts on fish populations. It also summarises the physical capabilities to overcome obstacles of different species found in continental France, indicating the parameters used to assess those capabilities and the main factors on which passage depends.

■ **Chapter B describes the general principles underlying the ICE protocol.** It presents method implementation and the main types of obstacle analysed. In addition, it lists eleven ICE species' groups according to their swimming and jumping capabilities and precisely defines five "passability" classes intended to inform on the impact of obstacles.

■ **Chapter C goes into the details of the assessment procedure to determine obstacle passability during upstream migration.** It discusses the calculation method for the indicators for each of the five main types of obstacle considered here and also addresses the special case of the European eel, which has some very specific movement techniques. Each procedure is presented as a flow chart to assist in decision-making, thus making the protocol easy to use for a wide range of people.

■ **Chapter D is devoted to obstacles equipped with a fish pass.** It summarises and discusses the design principles behind the different technical solutions now encountered. In addition, the chapter presents a pre-assessment method for obstacles equipped with a fish pass in order to rapidly identify those fish passes that are clearly not (or not well) suited to the species in question.

A

Ecological continuity and fish

The issues involved in the movement of fish

The biological context, mobility and migration of fish

Similar to many other free (non-attached) animals, fish move continuously to meet needs and fulfil vital functions, i.e.:

- protect themselves against pressures exerted by the environment, by predators and, in some cases, by competitors, in order to ensure their survival;
- acquire food under the most efficient conditions to enable growth and sexual maturation;
- reproduce under the most favourable conditions to perpetuate the species.

These needs change over their life cycle and movements between different habitats fall into a temporal sequence corresponding to the life stages of each individual (larva, alevins, juveniles, adults). The spatial structure of a population is thus the result of the collective behaviour of the individuals making up the population and a function of the available resources in the various habitats that the fish can access in the river.

Depending on the ecological function involved, these movements take place over variable time scales (over a day or over an annual life cycle), over variable distances (ranging from a few centimetres to several thousand kilometres) and in different directions (longitudinal, i.e. upstream or downstream, lateral, i.e. between the main river and side channels, and vertical, in deep rivers and lakes).

According to prevalent theories, the constraints weighing on movements (exposure to predation, energy costs) are compensated by the biological advantages obtained in the new habitat. If the cost-benefit ratio is favourable, habitat use is said to be strategic because the various habitats enable an individual to increase its chances to transmit its genes to a future generation (Lucas and Baras, 2001).

■ The main categories of movement in fish

In dynamic, multi-dimensional environments such as rivers, the use of space results from a combination of active movements requiring energy consumption and passive movements where the fish is transported by the moving environment.

When markers (visual, olfactive, etc.) are available, the fish can actively compensate a passive movement caused by the moving environment and, through its behaviour, control the overall movement. It is therefore important to understand the relative importance of the active and passive movements in order to determine the processes underlying the use of space and the distribution of populations (Mauritzen *et al.*, 2003 in Sonny, 2006).

Transported movements, drift and dispersal

In adult fish, strong floods are often the cause of forced movements downstream. In this particular case, one may observe passive drift (the fish simply lets itself be carried along by the current) or semi-active drift (the fish swims against the current, but its speed is less than that of the current and the overall result is movement downstream). (See Figure 1, Pavlov, 1994).

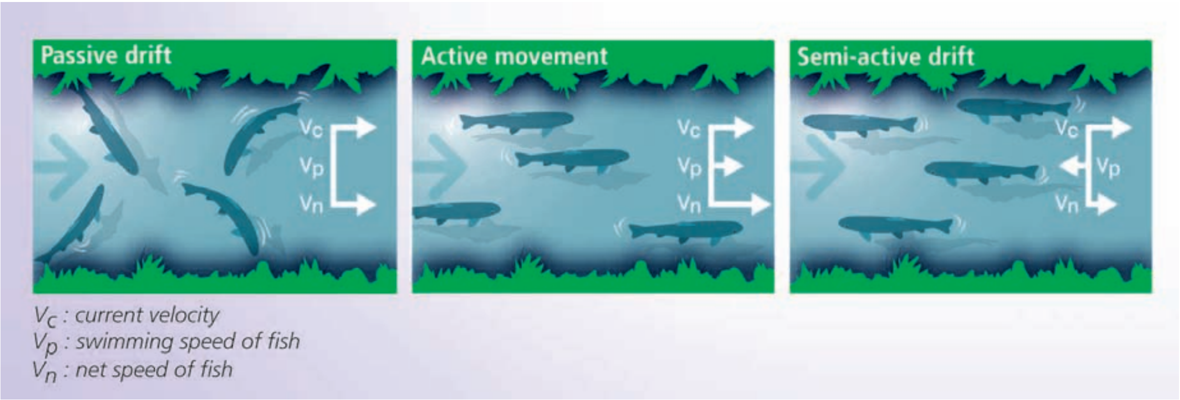
In general, these movements are followed by a return to the original site when the hydrological conditions become more favourable. But during exceptional events, large parts of a population may be carried over large distances and the return to the zones of residence may be difficult or even impossible, particularly if river reaches are fragmented by physical obstacles.

For larvae and alevins, **drift** is an indispensable natural phenomenon of fundamental biological importance. It is defined as a passive movement between the spawning/hatching zone and the initial growth zones. Drift is an important step in the life cycle of fish that makes possible dispersal from the nursery zones. It is generally assumed to be a trophic movement.

Though drift is considered a passive movement, it would seem to be triggered by very precise environmental conditions specific to each species (Sonny, *et al.,* 2006), which would indicate that fish do not let themselves be carried off by the current at just any time. The term drift is most commonly used for movements from upstream to downstream, however it also corresponds to the transport of European eel leptocephali from the Sargasso Sea to the coasts of Europe and North Africa via the Gulf Stream.

In some cases, drift may be an integral part of a species' migration cycle, which means that a majority of the population will take part and a return migration will eventually take place (the situation for eel leptocephali). In other cases, the migration is in a single direction and no return takes place (Hanski, 1999; Nathan *et al.*, 2003; Sonny, 2006).

Figure 1



Types of downstream migration. Drawn from Sonny (2006), modified diagram drawn from Pavlov (1994).

Active movements

Non-periodic active movements are due to sporadic changes in the environment following a non-cyclical disturbance, such as a pollution incident, a dry period or work in the river bed.

Given their unforeseeable nature, they are not part of the biological cycle of a species as shown in Figure 3. They may be seen as tactical reactions that are in fact a departure from the typical biological cycle in an attempt to successfully respond to changes in environmental factors. In this case, the fish adapts its behaviour to the special ecological conditions in order to ensure its survival (Lévêque, 2006). Such movements are generally followed by a return of the fish to the original site, but more or less significant mortalities may occur.

On the other hand, permanent modifications in the physical-chemical and trophic conditions exceeding the tolerance ranges of the species result in the **emigration** of poorly suited species to more favourable areas. Such modifications also constitute an invitation for more resistant and better suited species.

These movements modify the structure of communities and signal the emergence of **new ichtyofauna in the local area**. They must be taken into consideration during studies on rivers and lakes (reservoirs behind dams and hydroelectric plants, ponds undergoing change) likely to encounter such physical-chemical modifications.

Caution. The issues involved in active movements in the current context of global warming of water bodies and consequently increased efforts to find temporary thermal refuge, and even of more long-term adaptations, must be examined very seriously, particularly given that exotic species will probably be less sensitive to warming (Hendrickx *et al.*, 2011).

Daily periodic movements concern the alternating use of rest and activity zones found within the day to day living zone of the fish (Baras, 1992; Ovidio, 1999). The rest and activity zones are most often habitats that differ widely in their hydromorphological characteristics (see Figure 2). The range, direction and frequency of the movements are variable depending on the species involved, on individual fish, on the stage of development within a given species, as well as on the season and the environmental conditions.

Figure 2

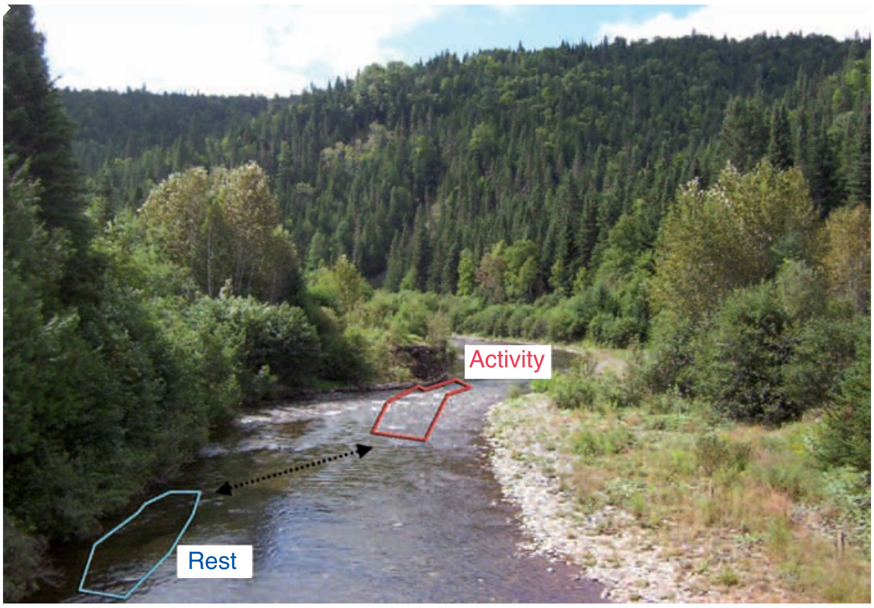


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Illustration showing the spatial separation between an activity zone (rapidly flowing water) and a rest zone (calm waters) for the daily periodic movements of brown trout.

Ontogenetic movements arise from the fact that the different development phases of fish (larva, alevin, juvenile, adult) correspond to different nutritional needs, feeding behaviours and ecological, physiological and biological requirements, which implies in many cases movements to different habitats (Lévêque and Paugy, 2006). For example, larvae can feed only on very small particles, such as phytoplankton, zooplankton and certain organic debris. Fish move as a function of their inherent capabilities and their trophic needs in directions and over distances that are highly variable. In addition, the increasing size of a fish modifies its movement capabilities as well as the size and type of prey (or food) that it consumes.

Migrations are very common, seasonal, periodic movements for fish. According to Northcote (1979), a migration is a movement between two functional habitats that takes place regularly over the life of individual fish and involves a majority of the population.

The need to use separate biotopes during the different development stages and notably the need to find favourable sites for spawning and the growth of juveniles induces species to undertake occasionally very long migrations between habitats used for feeding, rest and reproduction.

For a large number of species, reproduction implies the **synchronised meeting** of a high number of mature fish of both sexes in the reproduction zones over a short period of the year (Lucas and Baras, 2001). The migrations undertaken to the spawning grounds are often the most notable movements.

Migratory behaviour is triggered by a number of internal and external causes (Lucas and Baras, 2001). It is important to note the influence of the interaction between the maturity of a fish, the photoperiod, water temperature as well as the hydrological and meteorological conditions (Lucas and Baras, 2001). For example, spawning generally takes place during a period when the environmental conditions are the most favourable for the survival of the roe and the larvae.

Many species have a **seasonal reproductive cycle** (see Figure 3) and the reproductive strategy of a species in a given environment depends on a number of biological traits such as the age at which the first reproduction occurs, the relation between size (or age) and fecundity, parental behaviour, the reproductive season and the size of the gametes (Lévêque and Paugy, 1999 and 2006).

Migrations are only part of the movements undertaken by fish in their biological cycle, but they are by far the most heavily impacted by **habitat fragmentation** due to the round trip, most often first an upstream migration, then a downstream migration, and to the distances travelled, which can reach several thousand kilometres for diadromous fish.

Up and downstream migrations are the most frequent, but the importance of multi-directional migrations should not be neglected, for example pike must first swim upstream (longitudinal migration), before heading into a tributary channel (side channel, etc.) to find more favourable reproductive conditions.

Figure 3

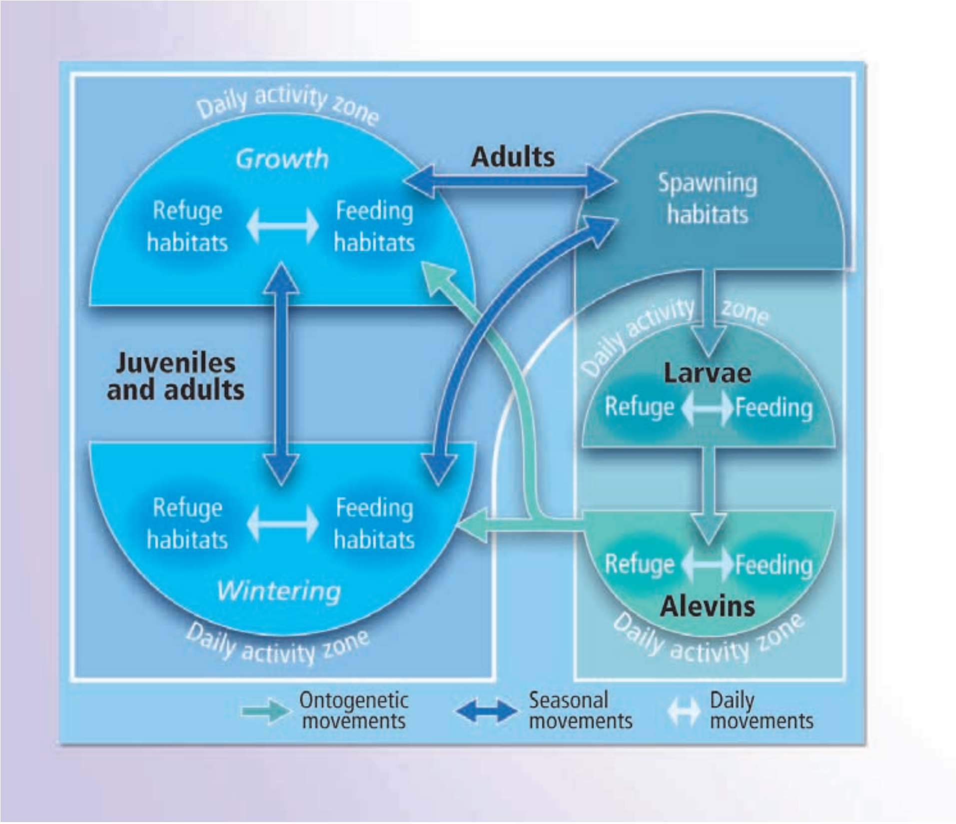


Diagram showing some of the many different movements undertaken by fish during their biological cycle. Drawn from Baras (1992).

Caution. When doing work in aquatic environments, it is very important to be fully aware of the migratory behaviour of the various fish species in the natural and regulated running waters in order to take into account the free movement of all fish species, notably during the critical periods of their migrations.

■ The different types of migratory fish

According to their migratory behaviour, fish species in continental France can be grouped into four main eco-ethological categories (Philippart and Ovidio, 2007).

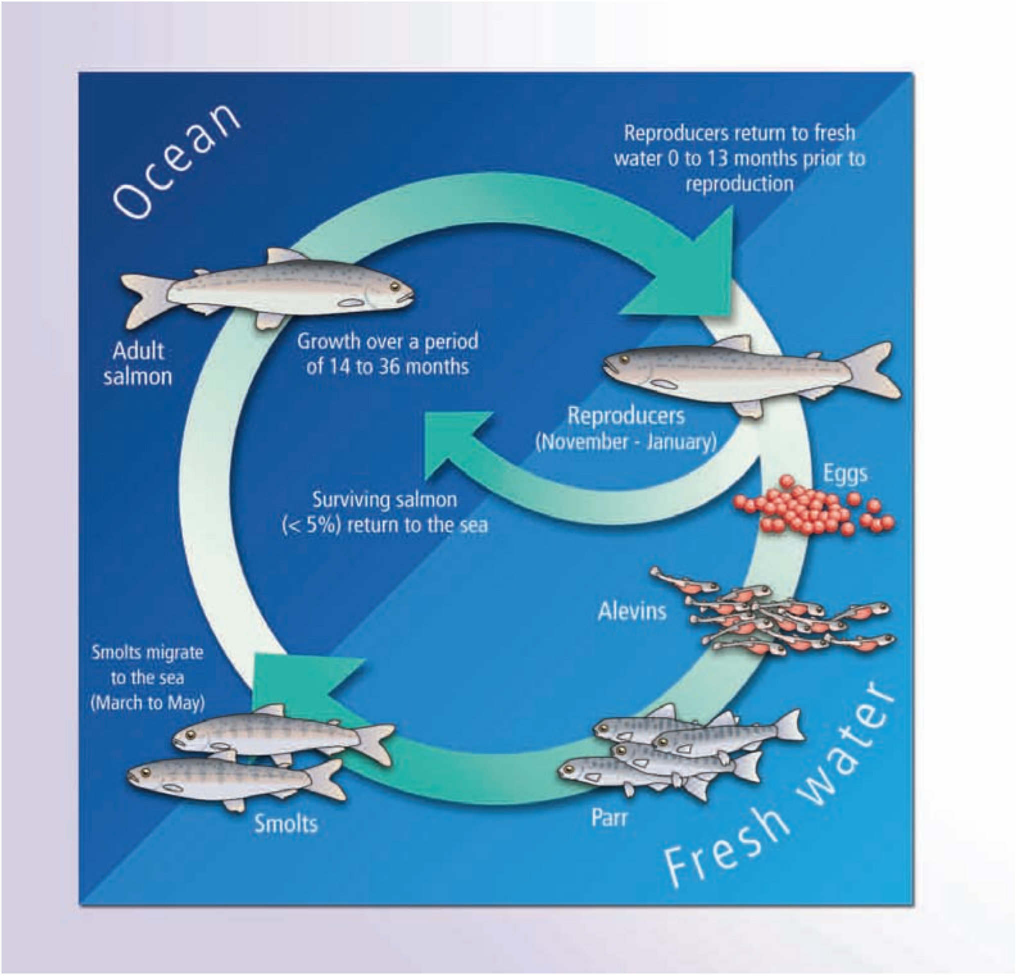
Type 1. Anadromous, amphibiotic migratory species

Anadromous, amphibiotic migratory fish move between fresh water and the sea in the course of their biological cycle. They spend most of their lives in the sea and return to fresh waters to reproduce. The migration to the sea consists essentially of juveniles and, to a lesser degree, adults that survived the reproductive process (see Figure 4).

They travel several hundred and even thousands of kilometres (depending on the variable distances between the growth and reproduction sites) during their life cycle and are commonly called long-distance migrators.

This group includes the species sea trout (Salmo trutta – migratory ecotype), Atlantic salmon (Salmo salar), river lamprey (Lampetra fluviatilis), sea lamprey (Petromyzon marinus), Allis shad (Alosa alosa), Twaite shad (Alosa fallax fallax), mullets (Chelon labrosus and Liza ramada) and sturgeon (Acipenser sturio).

Figure 4



Migratory cycle of an anadromous, amphibiotic migratory species (Atlantic salmon).

Type 2. Catadromous, amphibiotic migratory species

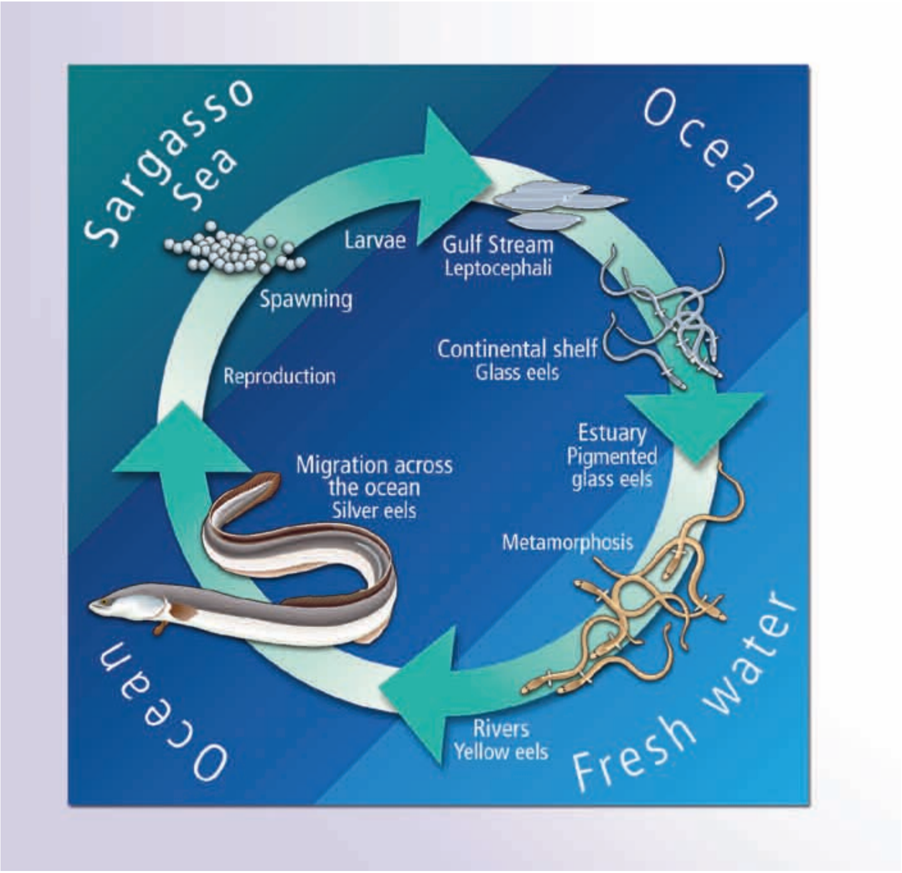
Catadromous fish are also long-distance migrators and must travel from fresh water to the sea in the course of their biological cycle that is the opposite that of anadromous species. They migrate upstream during the juvenile stage and colonise rivers, whereas the adults migrate downstream to the sea in order to spawn (see Figure 5).

Two species in continental France fall into this category, the European eel (*Anguilla anguilla*), for which a major protection and restoration programme is now under way (European regulation and national management plan), and flounder (*Platichthys flesus*).

European eels reproduce in the Sargasso Sea, to the south of Florida, and are consequently all from the same stock. The larvae (leptocephali) travel some 6 000 kilometres across the Atlantic on the ocean currents. Before reaching the European shores, the larvae metamorphose into glass eels (small, transparent eels just a few centimetres long), ready to colonise the littoral and continental waters. A number settle in estuaries whereas the others migrate up rivers over long distances that can exceed several hundred kilometres. After 10 to 25 years of growth (a bit less for the males, a bit more for the females), the fish have become yellow eels and are ready to metamorphose once again into silver eels and start off on the long downstream migration to the Sargasso Sea in order to spawn.

Flounder reproduce in the sea from January to April on unconsolidated substrates at depths of approximately 50 metres, occasionally in large groups (Keith *et al.*, 2011). After hatching and spending a few weeks in pelagic waters, the juveniles approach the coast and enter either brackish or fresh waters to continue their development. They spend most of their lives in estuaries and the fresh waters of rivers and may be found up to several hundred kilometres from the sea. When it is time to reproduce, the adults migrate downstream to the sea to spawn.

Figure 5



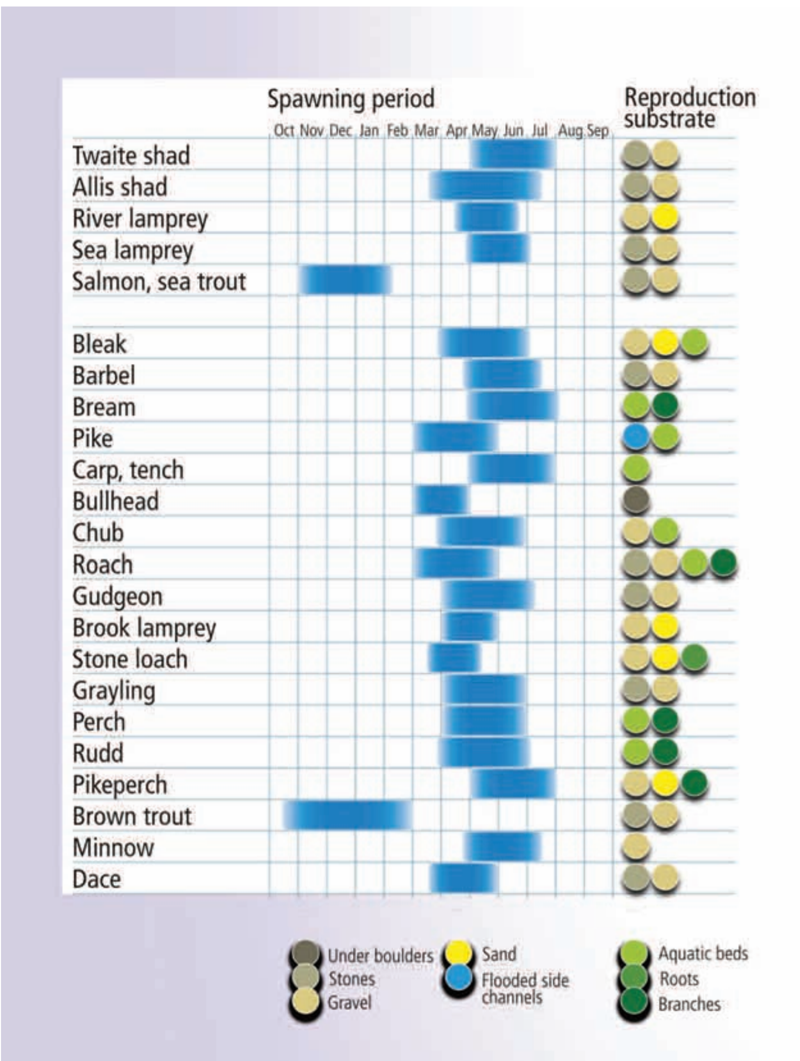
Migratory cycle of a catadromous, amphibiotic migratory species (European eel).

Type 3. Potamodromous, holobiotic species requiring specific substrates for spawning

These species live their entire lives in fresh water and move through rivers and tributaries looking for the very specific spawning grounds required to receive their roe (see Figure 6). The spawning grounds may be:

- fairly loose gravel banks offering high oxygen levels for fish that appreciate fast-moving waters (rheophilic species) and litophilic reproducers (spawning in or on gravel). Among the fish that like fast-moving waters are the salmonids river trout (*Salmo trutta*) and grayling (*Thymallus thymallus*) and the cyprinids barbel (*Barbus barbus*), Mediterranean barbel (*Barbus meridionalis*), dace (*Leuciscus leuciscus*), as well as, to a certain degree, nase (*Chondrostoma nasus*), French nase (*Parachondrostoma toxostoma*) and schneider (*Alburnoides bipunctatus*).
- vegetated areas for fish that appreciate slow-moving waters and phytophilic reproducers (the roe sticks to plants) such as pike (*Esox lucius*) at the end of winter and in the spring, or carp (*Cyprinus carpio*) and tench (*Tinca tinca*) in the summer;
- areas offering large stones or gravel for nesting species such as bullheads (*Cottus spp.*) and brook lamprey (*Lampetra planeri*).

Figure 6



Spawning periods and reproduction substrates for the main fish species in France.

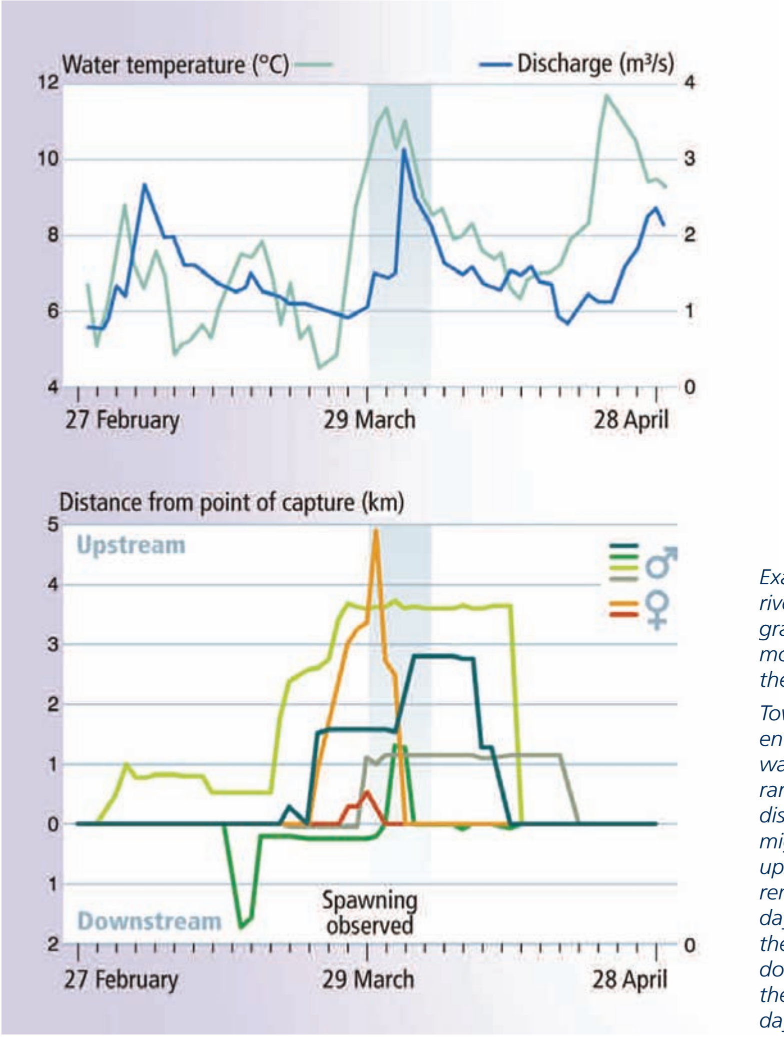
Type 4. Most other potamodromous, holobiotic species

Most of the other potamodromous, holobiotic species (i.e. that spend all their lives in fresh waters) also have a natural tendency to migrate in view of reproduction, however that is not a necessary condition determining reproductive success because there are generally spawning grounds in the area or the river reach where the fish live. That is the case for ubiquitous, high-tolerance species that are not very demanding in terms of the spawning substrate (see Figure 6), such as roach (Rutilus rutilus), common bream (Abramis brama), white bream (Blicca bjoerkna) and perch (Perca fluviatilis).

NB It is important to enable migration of a certain number of fish from these species and the dispersal of young fish in order to avoid the genetic isolation of populations living in reaches between two successive, physical obstacles.

The biological cycles of the "long-distance migrators" (types 1 & 2) have been relatively well understood for many years, however it is more recently that the scientific community became aware of the importance of migratory (or mobility) phenomena for the potamodromous holobiotic species belonging to types 3 & 4 (Gowan *et al.*, 1994). Even though these species spend their entire lives in fresh waters, they have a biological need to move, often over great distances, in order to accomplish all of their biological functions. Their mobility patterns are highly characteristic (see Figure 7).

Figure 7



Example of movements in the Aisne river (in the Belgian Ardennes) by six graylings (Thymallus thymallus) monitored by radio over the reproduction period.

Toward the end of March, specific environmental conditions (increased water temperatures in the 5 to 8°C range and a period of reduced discharges) tripped reproductive migrations to the spawning grounds upstream. Each individual fish remained between one and several days in the spawning grounds and then started a post-reproduction downstream return precisely to the river reach it had left a few days before.

Though not all fish species have undergone in-depth studies on their mobility, checks on the traps installed in **migratory fish passes** have shown that in many fish species, a part of the population can travel long distances upstream, often during the days and weeks preceding the spawning period, but also occasionally at other times (Lucas and Baras, 2001; Slavik *et al.*, 2009; Prchalova *et al.*, 2011).

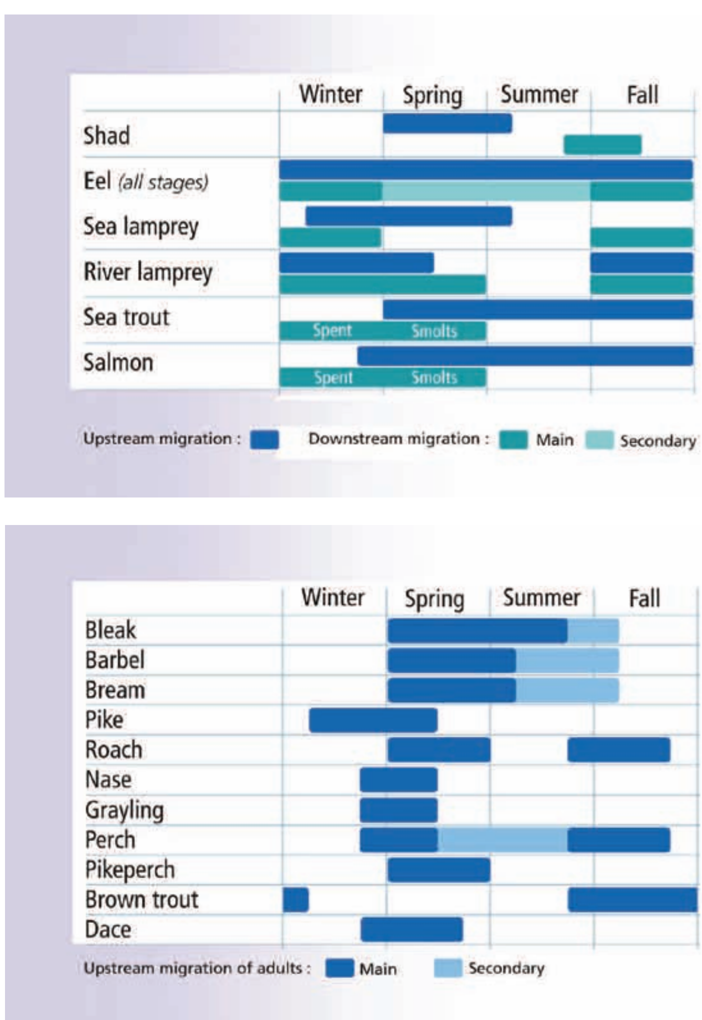
These movements are often dictated by their biological cycle (refuge, activity, reproduction). However, in some cases, they are also undertaken by **"explorers"** (a minute percentage of the population), that develop special behavioural tactics suited notably to discovering new habitats or former habitats, for example following the opening of new migratory channels or channels formerly blocked.

Even among the potamodromous species, upstream migration is always part of general process within the population (with net migratory results following emigration and immigration) that includes a downstream migration of adult reproducers (that have spawned or will spawn) and/or young fish resulting from the reproduction.

■ The main migratory periods

Migrations do not take place at the same time for all species, even if the spring and autumn are the main periods (see Figure 8). Migrations may in fact be observed throughout the year if all the species living in certain rivers or river reaches are taken in to account.

Figure 8



Main migratory periods of amphibiotic species and of adults in holobiotic species.

The different types of obstacles

Many transverse structures created by humans in rivers are likely to reduce longitudinal connectivity and have a more or less negative impact on fish populations.

An installation may represent a complete obstacle to migration if it cannot be overcome by any member of a given species under any circumstances. It may also be a partial obstacle in that it cannot be overcome by some fish and it may be a temporary obstacle in that it cannot be overcome during certain periods of the year.

The negative impact of temporary obstacles should not be underestimated because they can delay fish during their migration and may oblige them to wait in unfavourable areas and/or may result in injuries or mortalities following repeated, unsuccessful attempts to pass.

Obstacles can create problems for both:

- **upstream migration,** i.e. when the fish are heading upstream. This type of migration may involve, for example, the adults of anadromous species (Atlantic salmon, sea trout, shad, lampreys), holobiotic species (pike, grayling, brown trout) prior to reproduction and young fish of catadromous species (glass eels and elvers);
- **downstream migration,** i.e. when the fish are heading downstream (to the sea or to their original living area). This type of migration may involve 1) reproducers of anadromous and holobiotic species that, following spawning, are attempting to return to their original living area, 2) adults of catadromous species prior to spawning such as eels, 3) juveniles of holobiotic and amphibiotic species for reasons having to do with competition between individuals, the presence of predators or the physical-chemical quality of water (temperature, pollution, etc.).

■ Barriers having an impact on upstream migration

There are three main types of man-made, transverse structures in rivers likely to inhibit the free movement of fish during upstream migration, namely weirs, dams and roads.

Weirs

River weirs are fixed (see Figure 9) or movable (see Figure 10) structures that block all or part of the river bed (SANDRE definition, 2008). They are generally less than five meters high (the height of the banks in the largest rivers). Over 70 000 weirs are currently estimated to exist in France (source: ROE 2013).

The oldest structures date back to the Middle Ages when forges and mills were being established.

Starting in the 1800s, industrial development resulted in the creation or modification of many structures to supply water to industrial installations for energy generation (steam engines) or to cool manufacturing systems. At the same time, the French State launched a policy to stabilise the slopes of all mountain ranges throughout the country in order to limit the risks of flooding and landslides in the towns and villages located at the outlets of unstable river basins producing large quantities of sediment load. The Mountain-terrain restoration department of the National forestry agency subsequently constructed thousands of weirs made of wood, masonry or concrete.

In addition, massive extractions of alluvial matter from river beds during the 1960s and 1970s produced a considerable impact on rivers. To limit down-cutting in rivers and to consolidate existing structures (bridges, weirs, etc.), a large number of rock weirs were built to stabilise river beds.

According to an inventory carried out by Onema (National agency for water and aquatic environments), **a vast majority of the weirs initially built to capture the hydraulic force of running water have today lost any economic value they once had.**

Other weirs, creating a relatively high head-drop and installed on rivers with significant discharges, are no longer used for the original purpose and are now equipped with hydroelectric turbines.

The physical characteristics of each structure (height, profile, slope, length of the glacis, etc. for the geometry, concrete, rock-fill, etc. for the construction materials) and the river hydrology, the hydraulic conditions (flow velocity, depth, head-drop, etc.) upstream, downstream and at the structure can make it totally impossible for fish to overcome the weir.

Depending on the design of the downstream face, weirs may have:

- **vertical or subvertical falls that fish can clear exclusively by jumping (see Figure 9a).** Water overflowing a vertical or subvertical downstream face produces a nappe flow (plunging jet) that blocks the passage of non-jumping species and even of jumping species if the head-drop exceeds their jumping capabilities;
- **inclined faces that fish may be able to overcome by swimming (see Figure 9def).** The passability of an inclined weir depends on the flow characteristics on the glacis (water depth, velocity) and the distance to be covered (a direct function of the slope of the glacis and the height of the weir) that must be compared with the swimming capabilities of the given species (swimming speed U_{max} and its endurance at that speed) and the morphological characteristics of the fish (body depth and size of the caudal (tail) fins providing propulsion, etc.);
- **mixed designs comprising a succession of inclined sections and other, more or less vertical sections (steps, etc.) (see Figure 9bc).** A step is a break in the downstream face constituting a clear rupture in the profile of the weir. The presence of one or more steps in a weir (stepped weirs, sills on the weir crest, etc.), particularly during periods of low discharge, can make it much more difficult for fish to overcome the weir.

Figure 9

a © Chanseau - Onema

1. The term "passability" is a neologism commonly used to indicate the degree of difficulty in clearing an obstacle for living beings and particularly for fish. Passage is the action undertaken by an organism to overcome the obstacle whereas passability qualifies the structure itself and the difficulty in overcoming it. The authors decided to use the term "passability" because it is now commonly used as part of the technical jargon of hydroecology.

b, e © Larinier - Ecohydraulic centre
d © Chanseau - Onema
c, f © Burgun - Onema

Examples of fixed weirs.
(a) Vertical weir, (b) weir with numerous steps, (c) inclined weir with a step at the top, (d) inclined weir, (e) rock chute (rock weir with a slight slope), (f) rock weir with a steep slope.

Flows through weirs equipped with gates (lift gates, flaps) can vary significantly depending on the river discharge, management techniques and the type of gate (see Figure 10).

Flows over a spillway gate (see Figure 10d) generally result in vertical or subvertical waterfalls that fish can overcome only by jumping.

For other types of weirs and notably lift gates, the water can flow over the gate (see Figure 10ab) or under the gate when the latter has been partially lifted. Flow velocities under the gate may exceed the swimming capabilities of fish.

Figure 10

a © Voegtlé - Ecogea
b © Burgun - Onema
c © Bouchard - Onema
d © Voegtlé - Ecogea

Examples of movable weirs. (a) Weir equipped with a lift gate allowing flow both over and under the gate (La Vilette weir at Louviers on the Eure River), (b) needle weir (Robertsau weir in Strasbourg on the Ill River), (c) weir comprising several lift gates (gate system at the Autun camp grounds on the Ternin River, (d) weir equipped with a spillway gate (Probert weir on the Sainte-Eulalie River).

Dams

Contrary to weirs, dams (see Figure 11) block a major part of a valley bottom, i.e. much more than the riverbed alone. They are generally tall structures, exceeding five metres in height.

Depending on the valley topography and the type of soil, dams are made of concrete, earth fill, rock or a combination of these materials.

Among the main types of dams, there are gravity dams (see Figure 11a), arch dams (see Figure 11b) with one or more arches, arch-gravity dams, buttress dams and embankment dams (SANDRE, 2008).

They serve a number of purposes. They may be intended to regulate the river discharge and/or store water for various uses including hydroelectric generation, drinking water, flood control, irrigation, industry, recreational activities (boating, bathing), etc.

Due to their height, these structures totally block the passage of all fish species.

Figure 11

a © Voegtlé - Ecogea
b © Baudoin - Onema

(a) Example of a gravity dam (dam storing drinking water in Apremont), (b) example of an arch dam (Bimont dam in the Bouches-du-Rhône department, 87 metres high).

Road, highway and rail structures

Structures intended to restore the natural flow of water under roads, highways and train lines (see Figure 12) may constitute major obstacles to the upstream migration of fish.

If the slope steepens, the flow can suddenly accelerate and given the low roughness values of these structures, particularly when they are made of round culverts (see Figure 12c) or box culverts (see Figure 12ad), the water velocity can quickly reach high values that exceed the swimming capabilities of fish. In structures comprising round and box culverts, the uniform water velocities often preclude any rest zones, thus obliging the fish to clear the obstacle in a single shot. The effort required often exceeds the swimming capability of fish.

In addition, water depths in these structures can often drop to very low levels, particularly during low-flow periods, thus making it difficult for fish to swim and to progress upstream.

The darkness inside the structures or rather the sudden change in luminosity can also make certain species reticent to enter the structure.

Figure 12

a, c, d © Voegtlé - Ecogea
b © Larinier - Onema

(a) Example of a road structure built with box culverts, (b) example of a structure comprising an apron with some riprap, (c) road structure built with round culverts, (d) road structure built with box culverts.

■ Barriers having an impact on downstream migration

Structures (with or without water draw-offs) can represent serious obstacles to the downstream migration of juveniles and adult fish, e.g. if they travel over spillways or through hydroelectric turbines, or are drawn into drinking-water or agricultural abstractions.

Passage over spillways, flood gates and natural waterfalls

Passage over spillways, flood gates and natural waterfalls (see Figure 13) can result in direct deaths (injuries, shocks, etc.) or indirect deaths (vulnerability to predation by shocked or disoriented fish). Studies carried out on several foreign sites, notably on salmon, would seem to indicate that mortality levels vary widely from one site to another depending on the height of the fall, the presence of a sufficiently deep stilling basin at the foot of the obstacle, possible shocks against aprons, rocks, etc.

When passing over a spillway or a natural waterfall, depending on the flow configuration and the discharge, downstream migrators are likely to encounter one of two situations.

■ **Free fall.** The fish plunge outside the nappe and, if the height is sufficient, reach a maximum velocity that depends on their size and morphology. Experiments have clearly shown that significant injuries occur if the velocity of the fish on hitting the water surface exceeds 15 to 16 m/s, whatever the size of the fish (Bell and Delacy, 1972; Larinier and Travade, 2002).

As a result and on the condition that the pool below is sufficiently deep, fish less than 10 to 15 cm long generally suffer no injuries whatever the height of the fall, because they never reach the critical velocity.

For longer fish, injuries are minimal if the fall remains less than 30 metres for fish 15 to 20 cm long and less than 12 metres for fish over 60 cm long.

■ **Fall in the nappe.** When a fish migrating downstream falls with (inside) the nappe, its chance of survival is identical to that of a free fall creating the same impact velocity at the water surface, on the condition that the pool below is sufficiently deep. The impact velocity "V" can be approximately calculated using the equation $V = (2 \times 9.81 \times DH)^{0.5}$, where DH is the head-drop, i.e. the height that the fish falls.

Figure 13

a © Baudoin - Onema
b © Voegtle - Ecogea
c © Archambaud - Irstea

Examples of itineraries for fish migrating downstream and drawn into spillways (b and c) or over natural waterfalls (a).

A nappe reaches the critical velocity of approximately 16 m/s starting from a height of about 13 metres. For greater heights, the fish are severely injured. Mortality rates increase rapidly and reach 100% starting at approximately 50 metres (i.e. an impact velocity of some 30 m/s).

Consequently, free fall is better for smaller fish (alevins and fish less than 15 to 20 cm long). For the largest fish, effects are very similar (falls should not exceed 12 to 13 metres) whether the fish falls inside or outside the nappe.

Fish drawn into water intakes

Fish migrating downstream tend to follow the main current, which means they are likely to be drawn into the water intakes of installations through which part or all of the river discharge passes (see Figure 14).

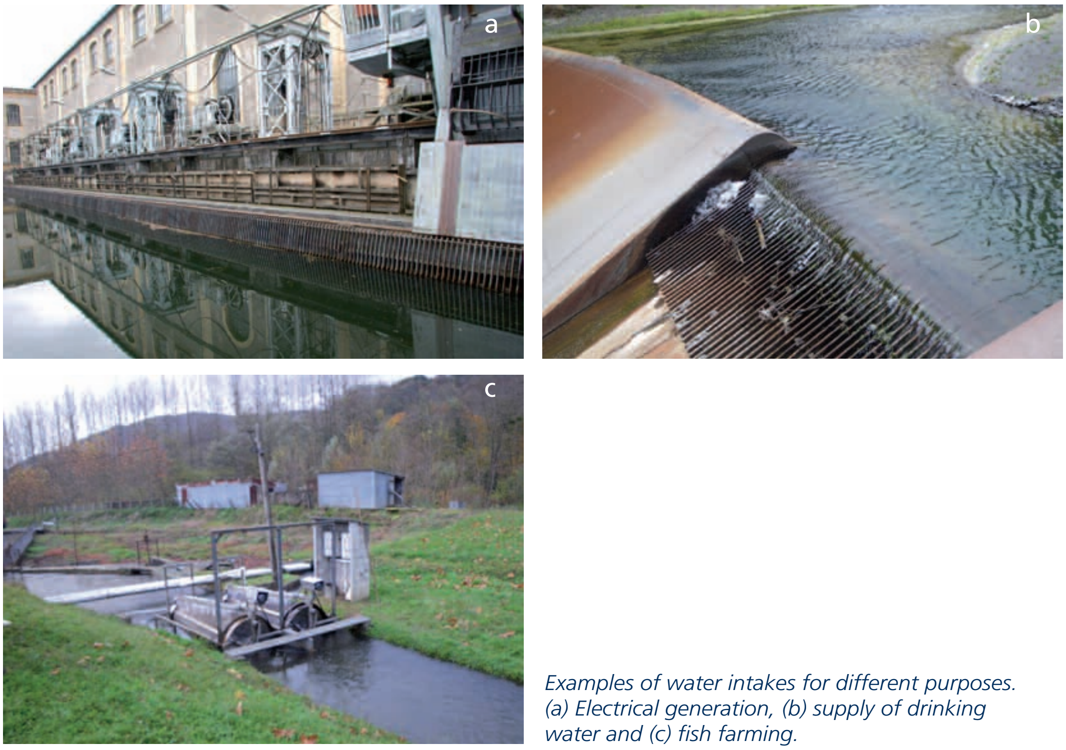
Water intakes may be used for a number of purposes (see Figure 14) including the abstraction of drinking water, irrigation, cooling of industrial machines or nuclear generators, fish farming (ponds, tanks) and electrical generation (hydroelectric plants).

In some cases, notably irrigation and drinking water, the water drawn off is not returned to the river and the damage done to fish can vary widely depending on the quantities involved and on the possibilities for the fish to return to the river.

In hydroelectric plants, the water is returned to the river after having transited through the turbines. Passage through the turbines subjects the fish migrating downstream to a number of dangers likely to cause serious injuries, e.g. shocks against fixed or moving parts of the turbines, brutal accelerations and decelerations, extreme variations in pressure.

A number of studies carried out both in France and abroad have clearly shown that mortality levels vary considerably depending on the characteristics of the turbines and on the species and size of the fish (Larinier and Dartiguelongue, 1989).

Figure 14



a © Larinier - Ecohydraulic centre
b, c © Voegtle - Ecogea

Examples of water intakes for different purposes. (a) Electrical generation, (b) supply of drinking water and (c) fish farming.

Main impacts on fish communities caused by structures hindering passage

Physical obstacles (waterfalls and dams, hydroelectric turbines, zones with high flow velocities, zones with little or no water) along a reach or in a river network can more or less seriously disturb the longitudinal and lateral movement of fish and consequently their access to the full diversity of habitats required for the corresponding biological functions. The result is the regression or even the disappearance of the concerned populations (Ovidio and Philippart, 2002).

■ Direct effects on populations caused by limited access to reproduction zones

The difficulties, more or less serious, encountered by fish during their upstream migration for reproduction may partially or totally block their access to spawning grounds and, consequently, produce different impacts on populations.

Among diadromous fish, the result may be a reduction in abundance or even the disappearance of certain species if no functional reproduction zones can be accessed.

For potamodromous, holobiotic species, a reduction in the number of spawners reaching the spawning grounds in the upstream sections of rivers or in tributaries can lead to fewer numbers of juveniles in the concerned basins and sub-basins. A reduction in populations is subsequently observed in the river reaches located downstream of the obstacles blocking the normal drift of juveniles from upstream.

In rivers or river reaches previously impacted by massive fish mortalities (toxic pollutants, dry periods, epizootics) or in which there is a chronic deficit in reproduction (poor water quality and/or substrates for spawning), the presence of physical obstacles can delay the natural recolonisation of upstream sectors having low population levels by fish arriving from downstream populations (i.e. from the main river to a tributary or from the lower section of a tributary to an upper section). These types of effects have been observed in a number of rivers for several wild species of rheophilic cyprinids (barbel, nase, dace, chub, schneider) that are highly sensitive to the effects of population numbers and very rarely benefit from restocking/reintroduction efforts upstream of obstacles. The fragmentation of the environment also hinders access to refuge zones in cases of disturbances to the environment (notably caused by global warming) and consequently limits the capacity of species to adapt, thus increasing the risks of extinction.

■ Genetic effects

Forced halts or even delays during the migration of fish to their reproduction zones can limit the flow of genes and impact fish populations.

When passage of an obstacle is totally impossible and on the condition that the available habitat is suitable for the species, genetic differences may appear among the populations living upstream or in a tributary, particularly if the population has been cut off for a long time and no restocking has occurred.

Similarly, if the habitat has been degraded, if the carrying capacity is low or if the obstacle is partially passable, there may be a reduction in the input of genes and consequently a loss of genetic diversity. That being said, the actual impact on populations, e.g. loss of adaptation capabilities, increased sensitivity to pathogens, is difficult to prove scientifically. It is also possible that obstacles can "sort" fish by allowing the passage of only certain parts of the population according to sex, size, swimming and jumping capabilities, or the period of migration.

The influence of obstacles on the genetics of fish populations is most likely to be evident in species migrating upstream for reproduction because the obstacle blocking passage also hinders the transmission of the genetic information further upstream. On the other hand, for small, benthic species at the heads of river basins and that are apparently more sedentary during their adult life, it is likely that downstream migration and downstream dispersal of both juveniles and adults play the major role in recolonising downstream sectors having suffered a massive mortality event. In this case, non-passage due to fish being trapped in a dam reservoir or a pond or to mortalities in hydroelectric turbines and pumps directly impacts the genetic diversity of the downstream populations.

■ Delayed migration and mortalities due to fatigue

The cumulative impact of a large number of structures on highly fragmented rivers may be very high, even if no major obstacles have been noted (Chanseau and Larinier, 1999; Ovidio and Philippart, 2002; Thorstad *et al.*, 2005 in Croze, 2008).

The losses caused by a succession of structures are due not only to the number of fish incapable of overcoming all the obstacles located downstream of the first spawning grounds, but also to the fatigue caused by the cumulative delays and efforts involved in clearing the obstacles (attempts to jump and/or active efforts to find passage). Even if, in the process of migrating upstream, the fish finally reaches a potential spawning ground, reproduction may fail if the fish arrives too late, notably because the environmental conditions may no longer be optimum for the survival of the roe or because the energy spent by the fish during the migration leads to a degree of fatigue that the fish can no longer defend its territory or avoid predators.

During downstream migration, the delays caused by obstacles are detrimental above all to long-distance migrators that must overcome a large number of structures and whose migratory periods span less of the year (notably for the Atlantic salmon). These occasionally short periods must be sufficient to enable them to reach the sea within a reasonable amount of time and under suitable environmental conditions.

For the holobiotic species that return home following reproduction, any delays are probably less detrimental for populations because substitute habitats may be a temporary solution before the return to the growth zones (Ovidio *et al.*, 2007).

■ Injuries and mortalities in structures

This type of impact occurs primarily during downstream migration (i.e. when the fish travel from upstream to downstream) when fish are drawn into the water intakes of structures, rather than during upstream migration, though injuries and mortalities may occur during attempts to jump (see above).

Downstream migration may occur during different biological stages depending on the species, notably:

- the juveniles of anadromous, amphibiotic species (Atlantic salmon, sea trout, shad, lampreys, etc.);
- the adults of anadromous, amphibiotic species that survived the reproduction process (salmonids, Twaite shad, etc.);
- the adults of catadromous, amphibiotic species prior to reproduction (eels);
- the juveniles and adults of potamodromous, holobiotic species following reproduction (brown trout, barbel, etc.).

When a structure comprises an intake, some of the fish migrating downstream travel through the bypasses (spillways, gates, flaps, etc.) and others are drawn into the water intake. The proportions vary depending on the configuration of the structure and on the percentage of the total river discharge drawn into the intake.

Generally speaking, passage of fish through spillways rarely causes injuries, particularly if the dam is not very high (less than ten metres) and the stilling basin (a pool of water into which the fish plunges) is sufficiently deep.

Injuries may vary considerably, depending on the structure. In cases where the water drawn off is not returned to the river (irrigation, drinking water, industry, etc.), the mortality rates of the fish passing through the water intake may reach 100% if there are no systems in place to block or limit their entry.

In hydroelectric plants, injuries vary significantly, depending on the species and the size of each fish (Larinier and Dartiguelongue, 1989; Larinier and Travade, 2002) and on turbine flow rates, configuration and characteristics.

Caution. The cumulative impact of obstacles is again a particularly important factor and can, in certain cases, lead to mortality rates making it impossible to maintain or restore the populations of migratory fish.

■ Increased risk of predation and disease

By increasing the residence time of fish in areas not offering optimum characteristics, notably the physical-chemical characteristics, or leading to accelerated fatigue of fish, obstacles are likely to increase predation by birds, fish-eating fish and poachers.

In addition, the stress, fatigue and injuries caused by predators or repeated attempts to jump over obstacles weaken the fish and make them much more susceptible to parasites and diseases.

Similarly, during downstream migration, injured or stressed fish, notably following a high fall or passage through a hydroelectric turbine, are vulnerable and may become more exposed to predation.

The capabilities of fish to overcome obstacles

The different types of passage

During upstream migration, fish encounter man-made and/or natural physical obstacles that are more or less passable. Their chances of overcoming an obstacle depend directly on:

- the migratory behaviour and the swimming/jumping capabilities of the given species;
- the configuration and hydraulic characteristics of the obstacle.

Swimming and jumping capabilities are tied directly to the morphology of the fish and their biomechanical characteristics, which in turn are largely determined by the ecology of the given species and by the types of environments in which they live and/or transit during their biological cycle. Passage capabilities are generally influenced by various mesological factors (physical-chemical quality of water and its temperature) and the physical characteristics of each fish (sexual maturity, general health).

Swimming is obviously one means of overcoming obstacles for fish (see Figure 15a), but only certain species in French rivers (Atlantic salmon, sea trout, brown trout, mullets and grayling) are truly capable of jumping over an obstacle (see Figure 15b) and only if the fish find suitable conditions at the foot of the obstacle enabling them to prepare the jump.

Due to its special morphology and capacity to breathe through its skin, eels can also crawl (see Figure 15c), however the underlying surface must be wet. It is this particular type of movement that enables eels, in some cases, to colonise certain river basins in spite of numerous structures. Eels are, however, a special case and will be discussed separately in this presentation of the ICE protocol.

Figure 15

Examples of how fish overcome obstacles.

a © Dugenay - Hydroscope association
b © Borda - Onema
c © DDTM 40

Swimming

■ The different levels of activity and the concept of endurance

Swimming capabilities of fish may be expressed in terms of their swimming speed and their endurance, i.e. the time during which a fish can maintain a given swimming speed. Several levels of swimming activity have been identified in fish (Beach, 1984):

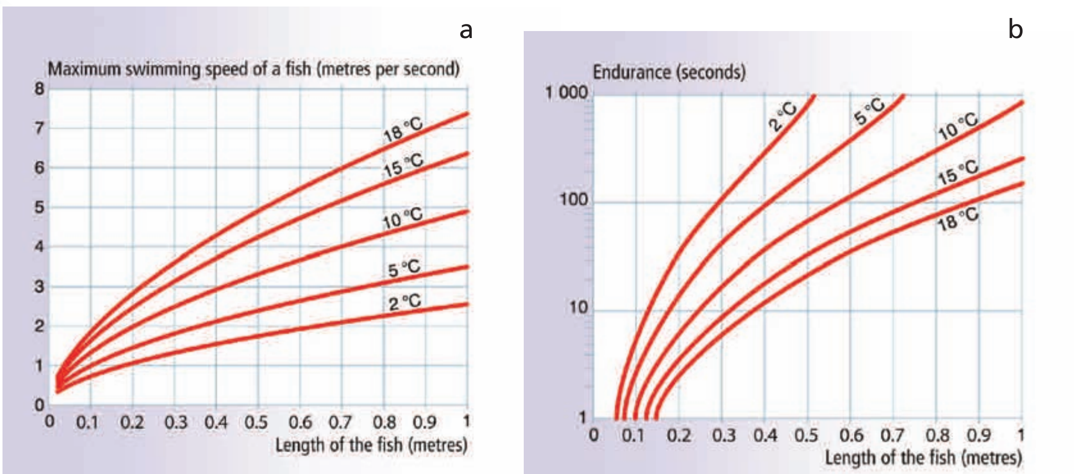
- **cruising,** an activity that can be maintained for hours without causing any significant physiological modifications in the organism;
- **maximum-speed swimming or sprinting,** an activity that requires an intense effort and can be maintained only for a very short time, ranging from a few seconds to a few dozen seconds depending on the species and the size of each fish.

Between the two activity levels mentioned above is the **sustained-swimming** level which can be maintained for a few minutes and even up to ten or twelve minutes, but results in significant fatigue over time. The potential duration of the effort decreases in step with the increase in speed as it approaches the maximum speed.

Endurance t_U is the time a fish can swim at speed U. It depends on the quantity of glycogen stored in the muscles. This reserve energy is used as soon as the fish exceeds its cruising speed. The depletion rate is a function of the swimming speed and the water temperature. Endurance is understood as the duration of maximum effort resulting in total exhaustion of the fish. **Depending on the author, endurance at maximum speed is thought to range from 10 to 20 seconds.**

Endurance and the maximum swimming speed depend above all on the **length of the fish**, its **morphology** (weight/length ratio, percentage of muscle mass) and the water **temperature** (Beach, 1984; Zhou, 1982; Wardle, 1980) (see Figure 16).

Figure 16



(a) Maximum swimming speed as a function of the size of the fish and the water temperature for salmonids, (b) endurance at maximum speed as a function of the size of the fish and the water temperature for salmonids. Adapted from Beach, 1984.

Size of the fish is the main factor determining the swimming speed. Videler (1993) proposed an equation, based on experimental results, indicating the maximum swimming speed (U_{max}) as a function of the length of the fish (Lp). This equation has the advantage of taking into account the results of studies carried out on various species and under different experimental conditions. As a result, it provides a reliable value for swimming speeds based on objective data.

$$U_{max} = 0.4 + 7.4\,Lp$$

The swimming speed is often expressed as the length of the fish per second (Lp/s). The equation proposed by Videler can also be expressed as:

$$U_{max}/Lp = 0.4/Lp + 7.4$$

NB During the development of the ICE protocol, the U_{max} swimming speeds were determined using the Videler (1993) equations presented above as well as experimental studies focusing on the passage of obstacles and visual observations of fish clearing obstacles.

Table 1 shows for each species the size classes selected for adult fish or those approaching their sexual maturity (except for eels which are present in French waters during their juvenile stages). The range of sizes (Lp_{min}-Lp_{max}) was set using the data from the Onema database on fish and aquatic environments (BDMAP), data drawn from the Fishbase site and data published in the Atlas of freshwater fish in France (Keith *et al.*, 2011). Lp_{min} and Lp_{max} are the minimum and maximum sizes, respectively. Lp_{avg} is the average of the minimum and maximum values.

Tableau 1 *Lengths (Lp) selected for adult fish or those approaching their sexual maturity for each species.*

Species	Length of fish Lp (cm)		
	Lp_{min}	Lp_{avg}	Lp_{max}
Allis shad (*Alosa alosa*)	45	58	70
Asp (*Aspius aspius*)	50	63	75
Atlantic salmon (*Salmo salar*)	50	75	100
Barbel (*Barbus barbus*)	30	55	80
Bitterling (*Rhodeus amarus*)	5	8	10
Blageon (*Telestes souffia*)	10	18	25
Bleak (*Alburnus alburnus*)	5	10	15
Brook lamprey (*Lampetra planeri*)	10	15	20
Brown or sea trout [25-55] (*Salmo trutta*)	25	40	55
Brown or sea trout [50-100] (*Salmo trutta*)	50	75	100
Brown trout [15-30] (*Salmo trutta*)	15	23	30
Bullheads (*Cottus spp.*)	5	10	15
Burbot (*Lota lota*)	30	45	60
Chub (*Squalius cephalus*)	20	45	70
Common bream (*Abramis brama*)	20	40	60
Common carp (*Cyprinus carpio*)	30	58	85
Crucian carp (*Carassius carassius*)	15	23	30
Daces (*Leuciscus spp.* except *Idus*)	15	25	35
European eel [glass eel] (*Anguilla anguilla*)	6	9	12
European eel [yellow eel] (*Anguilla anguilla*)	12	26	40
Grayling (*Thymallus thymallus*)	30	40	50
Gudgeons (*Gobio spp.*)	5	13	20
Ide (*Leuciscus idus*)	25	35	45
Mediterranean barbel (*Barbus meridionalis*)	10	18	25
Minnows (*Phoxinus spp.*)	5	8	10
Mullets (*Chelon labrosus, Liza ramada*)	25	43	60
Nase (*Chondrostoma nasus*)	25	40	55
Perch (*Perca fluviatilis*)	15	30	45
Pike (*Esox lucius*)	40	70	100
Pikeperch (*Sander lucioperca*)	30	60	90
Prussian carp (*Carassius gibelio*)	10	20	30
River lamprey (*Lampetra fluviatilis*)	30	38	45
Roach (*Rutilus rutilus*)	10	23	35
Rudd (*Scardinius erythrophthalmus*)	10	23	35
Ruffe (*Gymnocephalus cernuus*)	5	13	20
Schneider (*Alburnoides bipunctatus*)	10	14	17
Sea lamprey (*Petromyzon marinus*)	60	75	90
Smoothtail ninespine stickleback (*Pungitius laevis*)	5	8	10
South-west European nase (*Parachondrostoma toxostoma*)	10	18	25
Spined loach (*Cobitis taenia*)	5	10	15
Stone loach (*Barbatula barbatula*)	5	10	15
Streber (*Zingel asper*)	10	15	20
Sunbleak (*Leucaspius delineatus*)	5	8	10
Tench (*Tinca tinca*)	20	40	60
Threespine stickleback (*Gasterosteus gymnurus*)	5	8	10
Twaite shad (*Alosa fallax fallax*)	30	40	50
White bream (*Blicca bjoerkna*)	15	28	40

■ Minimum water depth

To make full use of its swimming capabilities, a fish must find itself in water of sufficient depth such that it can propel its way forward by undulating its body and using its caudal (tail) fins. This minimum depth depends on the size of the fish and its morphology. Morphology ratios (body depth/length of the fish), with the exception of eel-type species, can vary from approximately 0.17 (salmonids) to 0.30 (bream, carp).

The scientific literature often mentions a minimum depth between one and two times the body depth of the fish. A depth equal to 2.5 times the height of the caudal fins is occasionally recommended, notably when sizing fish passes.

NB For the ICE protocol, the minimum water depth required to enable a species (or group of species) to swim was set at approximately 1.5 times the average body depth hp_{avg} of fish in the given species (or group of species) and at the given development stage. The body depth of fish was determined using a form factor for each species (see Figure 17).

Figure 17

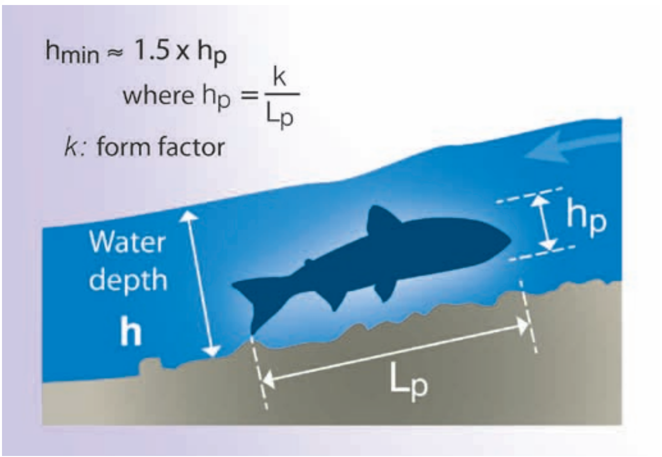


Diagram showing the water depth seen as the minimum required for fish to swim adequately.

For example, the minimum water depth (h_{min}) is approximately 20 cm for large, migratory salmonids and approximately 5 cm for small brown trout (Lp < 30 cm).

Caution. The values calculated for water depths are absolute minimum values required for the passage of obstacles. In fish passes, much higher values are systematically used (2 to 2.5 times the body depth of fish).

Passage by jumping

■ Jumping capabilities

A limited number of species (Atlantic salmon, sea trout, brown trout, mullets, grayling) frequently take advantage of their jumping capabilities to clear obstacles (see Figure 18a).

Other species (see Figure 18b) are capable of jumping (dace, barbel, etc.), but this behaviour is highly infrequent, particularly when overcoming obstacles.

Figure 18

a © Borda - Onema
b © Burgun - Onema

Fish attempting to jump over obstacles. (a) Atlantic salmon, (b) a large cyprinid, however this behaviour is highly infrequent for the Cyprinidae species.

The movement of a jumping fish is comparable to the parabolic trajectory of a projectile. The equation for the trajectory can be expressed as:

$$X = (U_{max} \cos\beta)\, t$$

$$Y = (U_{max} \sin\beta)\, t - 0.5\, g\, t^2$$

where:

X and Y are, respectively, the horizontal and vertical distances travelled by the projectile (i.e. the fish) at time t,

U_{max} is the initial speed, i.e. the top speed of the fish,

β is the angle of incidence with respect to the horizontal and g is the acceleration of gravity (9.81 m/s²).

The maximum height (Y_{max}) reached by the fish depends on its initial speed U_{max} and the angle of incidence β at the start of the jump:

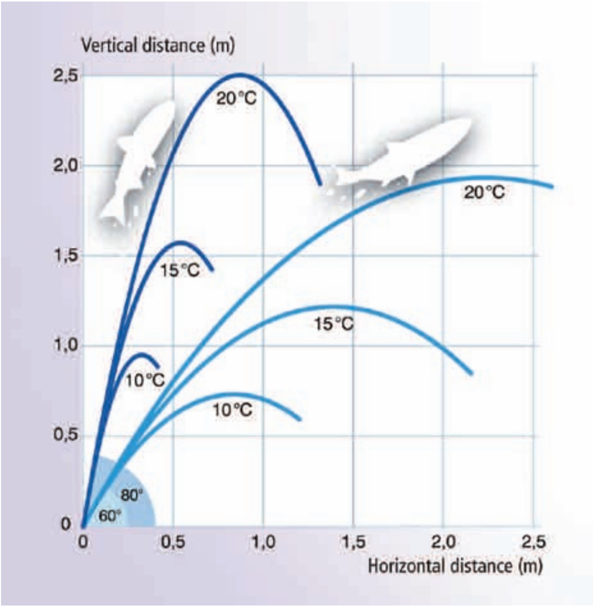
$$Y_{max} = (U_{max} \sin\beta)^2 / 2\, g$$

The horizontal distance (X_{max}) corresponding to the maximum height is calculated as:

$$X_{max} = U_{max}^2 \cos\beta \sin\beta / g$$

The theoretical trajectories of a salmon 0.8 metres long are shown as a function of the water temperature and the angle of incidence of the jump (see Figure 19). The graph makes clear the importance of the water temperature and the angle of incidence for the height attained by the jumping fish.

Figure 19



The theoretical trajectories of a salmon 0.8 metres long as a function of the water temperature and the angle of incidence of the jump. According to Larinier et al., 1998.

Strictly speaking, this maximum height of the jump Y_{max} should be augmented by a value equal to a fraction of the length of the fish because the latter uses its propulsive force until its caudal fins clear the water surface (Powers and Osborne, 1985).

In addition, the equations above do not take into account the ascending speed component at the foot of the obstacle that the fish can use. The jumping values calculated using the equations presented above are therefore minimum values.

For example, Table 2 shows the jumping height that can be achieved by a fish as a function of its length, the initial speed U_{max} (calculated according to its length using the Videler equation), the angle of incidence of the jump (40°, 60°, 80°) and the fraction of the length Lp (0, Lp/2, Lp) added to the theoretical maximum height Y_{max} of the jump.

Tableau 2

Jumping height that can be achieved by a fish as a function of its length, the initial speed U_{max} (calculated according to its length using the Videler equation), the angle of incidence of the jump and the fraction of the length Lp added to the theoretical maximum height Y_{max} of the jump.

Maximum speed U_{max} (m/s)	Corresponding length Lp, according to Videler (m)	Height of jump = Y_{max} (m)			Height of jump = Y_{max} +Lp/2 (m)			Height of jump = Y_{max}+Lp (m)		
		Angle of incidence (β)			Angle of incidence (β)			Angle of incidence (β)		
		80°	60°	40°	80°	60°	40°	80°	60°	40°
7.0	0.90	2.4	1.9	1.0	2.9	2.3	1.5	3.3	2.8	1.9
6.5	0.80	2.1	1.6	0.9	2.5	2.0	1.3	2.9	2.4	1.7
6.0	0.75	1.8	1.4	0.8	2.2	1.8	1.1	2.5	2.1	1.5
5.5	0.70	1.5	1.2	0.6	1.8	1.5	1.0	2.2	1.8	1.3
5.0	0.60	1.2	1.0	0.5	1.5	1.3	0.8	1.9	1.6	1.1
4.5	0.55	1.0	0.8	0.4	1.3	1.1	0.7	1.6	1.3	1.0
4.0	0.50	0.8	0.6	0.3	1.0	0.9	0.6	1.3	1.1	0.8
3.5	0.40	0.6	0.5	0.3	0.8	0.7	0.5	1.0	0.9	0.7
3.0	0.35	0.4	0.3	0.2	0.6	0.5	0.4	0.8	0.7	0.5
2.5	0.30	0.3	0.2	0.1	0.5	0.4	0.3	0.6	0.5	0.4
2.0	0.20	0.2	0.2	0.1	0.3	0.3	0.2	0.4	0.3	0.3
1.5	0.15	0.1	0.1	0.0	0.2	0.2	0.1	0.3	0.2	0.2

Observations on a number of salmonid species (Lauritzen *et al.*, 2005 and 2010) revealed that the most frequent angle of incidence in approximately 60°.

NB For the ICE protocol, the generally selected values are an angle of incidence of 60° and a jumping height equal to Y_{max} + Lp/2.

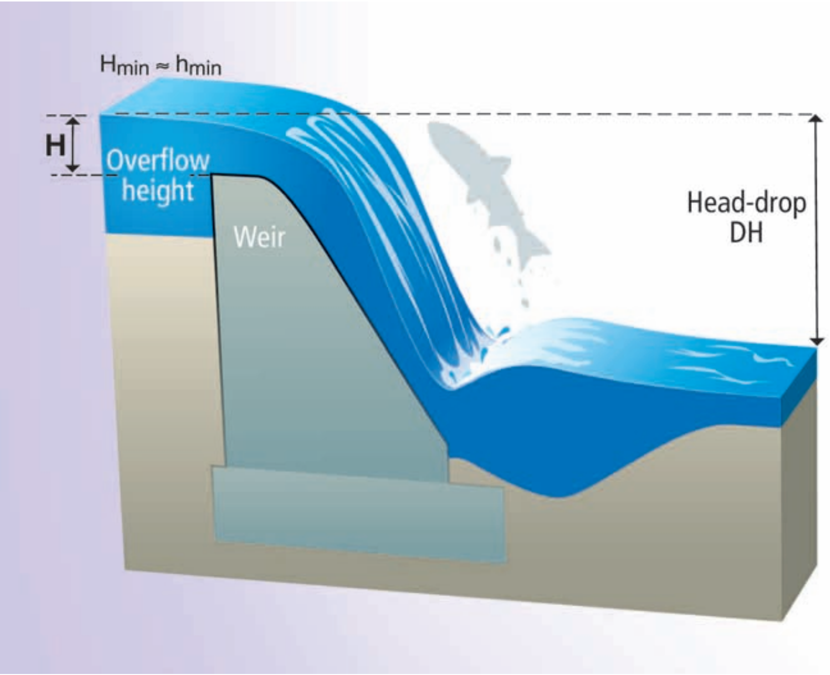
■ Minimum overflow height

For a fish to overcome an obstacle by jumping, the overflow height at the obstacle (weir, natural waterfall) must be sufficient to enable the fish to restart effective swimming immediately on striking the water. This is particularly important for high waterfalls and when the fish lands on the crest of the structure. For smaller falls significantly lower than the jumping capability of the fish, the horizontal distance covered generally enables the fish to fall directly into the upstream reservoir, in a sufficiently deep area where the reduced flow velocities mean the fish can immediately start swimming again.

A sufficient overflow height also creates a clear waterfall and a jet powerful enough to attract fish.

NB For the ICE protocol, the minimum overflow height H_{min} is considered equal to the minimum water depth h_{min} required for a fish to effectively swim (see Figure 20).

Figure 20



Minimum overflow height Hmin over an obstacle required by jumping species to ensure sufficient depth on arrival and effective passage upstream.

Caution. The values calculated for overflow heights are absolute minimum values required for the passage of obstacles. That is why much higher values are systematically used when designing fish passes.

Plunge pools at the foot of a waterfall

Swimming or jumping over an obstacle demands an intense effort for which the fish is generally required to swim at its maximum speed. It is imperative that a sufficiently deep and calm area exist at the foot of the obstacle to provide the fish with the means to prepare the effort (see Figure 21bd).

The impact of the jet on the substratum at the foot of the obstacle creates a pool where the energy arising from the river discharge flowing over the obstacle is dissipated. Experiments (Veronese, 1937; Fahlbusch, 1994) have shown that the scour depth Hf is a function of the unit discharge q (the discharge per meter width), the angle of incidence α of the jet (or the slope of the glacis with respect to the horizontal) and, to a lesser degree, the head-drop DH:

$$Hf = 1.88\, q^{0.5}\, DH^{0.25}\, (\sin \alpha)^{0.5}$$

For an identical unit discharge and head-drop, the depth of the pool will increase with the angle and reaches its maximum value for vertical or subvertical falls. However, the pool may be limited in depth or simply not exist, notably at the foot of certain man-made obstacles, if riprap has been deposited at the foot to avoid scouring or when the structure was built on a rocky substratum (see Figure 21ac).

Figure 21

a © Voegtlé - Ecogea
b © Voegtlé - Ecogea
c © Bouchard - Onema
d © Voegtlé - Ecogea

Examples of plunge pools at the foot of obstacles. (a) and (c) Insufficient pools, (b) and (d) sufficient pools.

The concept of a minimum plunge pool for fish is difficult to quantify because it depends on the size and the swimming capabilities of the fish, as well as on how the jet dissipates downstream.

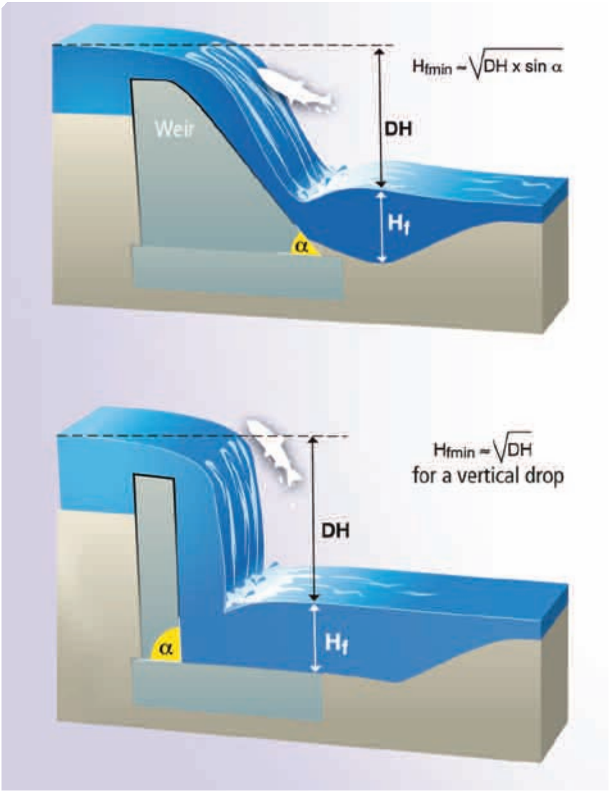
In the scientific literature, highly variable criteria are given for minimum depths. Authors focusing on the length of the fish often mention a minimum depth of the plunge pool corresponding to one to two times the length of the fish (Meixler *et al.*, 2009). This criterion does not take into account hydraulic parameters or the energy dissipation of the falling water. Consequently, for a given species and whatever the head-drop, the minimum depth is the same.

This criterion tends to result in depth values for the pool that are far too high for small head-drops. For example, for a pool depth equal to two times the length of the fish, a salmon 75 cm long would need a depth of 1.5 to 2 metres for a head-drop of 0.5 metres, which is clearly more than necessary.

Other authors recommend a minimum depth of one to two times the head-drop (Lauritzen *et al.*, 2010; Stuart, 1962). However, in that these criteria take into account neither the unit discharge nor the angle of incidence of the jet, they tend to produce minimum pool depths that are far too great for head-drops exceeding one metre (depths of 1.5 metres and 3 metres, respectively, for a head-drop of 1.5 metres).

NB For the ICE protocol, it was decided to calculate the approximate usable depth of plunge pools using an equation integrating both the head-drop and the slope of the glacis (see Figure 22), similar to the equations of Veronese (1937) and Fahlbusch (1994), but voluntarily excluding the unit discharge, a factor that is too difficult to include in the protocol: $Hf \geq \sqrt{DH \sin\alpha}$

Figure 22



Approximate depth of a plunge pool required for fish to overcome an obstacle (swimming or jumping) under satisfactory conditions.

If the depth of the pool at the foot of the obstacle is significantly less than the value calculated using the simplified equation above, the turbulences at the foot of the obstacle may generally be considered excessive and the fish will not encounter optimum conditions in preparing to jump or swim over the obstacle.

The usable depth of the pool should be measured fairly close to the point of impact of the falling water, notably when fish must jump to overcome the obstacle. This is because visual observations of fish have generally shown that a majority of attempts to jump over an obstacle originate relatively close to the point where the falling water strikes the downstream surface.

NB For the ICE protocol, it was decided that the usable pool depth should be measured at a distance of 0.5 to 1 metre from the point of impact, which corresponds to the observations and work carried out by Lauritzen *et al.* (2005).

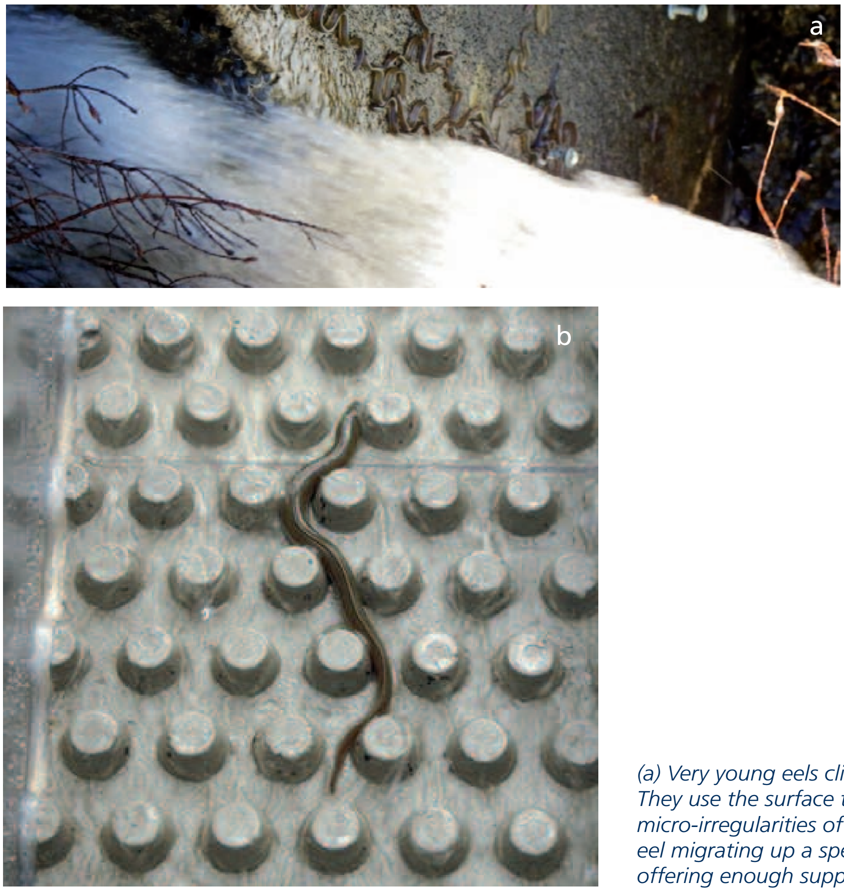
Eels, a special case given their crawling capabilities

Given their morphology and swimming technique, eels have highly limited swimming capabilities compared to other species of similar size.

The maximum swimming speeds noted in the scientific literature for glass eels (juveniles approximately 6 to 8 cm long) are in the 30 to 50 cm/s range (Clough and Turnpenny, 2001; Tsukamoto *et al.*, 1975). For elvers (approximately 20 cm long), the maximum swimming speeds are in the 1 to 1.5 m/s range (Clough *et al.*, 2002; Sörenson, 1951). Mc Leave (1980) studied the performance of glass eels. The distance covered in water flowing at 0.3 m/s is approximately 3 metres and that distance drops to approximately 30 cm in water flowing at 0.5 m/s. But due to its special morphology and capacity to breathe through its skin, eels can also crawl (see Figure 23), if the underlying surface is wet. It is this particular type of movement that enables eels to colonise certain ponds and to circumvent certain structures.

Very small eels can climb up vertical walls offering no particular support (see Figure 23a). They would appear to use the surface tension created by the contact between their bodies and the wet wall to adhere to the surface (Legault, 1986 and 1987). However, in growing, the weight to surface tension ratio, which is proportional to their length, increases, which explains why only the smallest eels (less than approximately 12 cm in length) can use this technique. The type of substrate, the slope and the overflow height, in conjunction with the size of the eels, are the main and often related factors determining whether eels can overcome obstacles. To effectively crawl up an obstacle, an eel must be able to support itself at several points. Crawling performance depends on the density of the support points compared to the size of the eels and on the layout of the support points (Voegtlé and Larinier, 2000) (Figure 23b).

Figure 23



a © Laharanne - Fdaappma 33
b © Larinier - Ecohydraulic centre

(a) Very young eels climbing a vertical wall. They use the surface tension and the micro-irregularities of the wall. (b) A yellow eel migrating up a special crawl way offering enough support points.

B

General principles underlying the ICE protocol

Protocol modus operandi

Protocol objectives and limits

The purpose of the ICE protocol is to objectively assess the passability of obstacles by fish, while avoiding as much as possible the need to bring in experts.

This method may be implemented by a limited team (two to three persons) and in a fairly short time, generally less than two hours.

Caution. There is, however, a limitation concerning downstream migration. Given the complexity of the biological mechanisms involved and the in-depth knowledge required on the local hydrology, on draw-off conditions and on the hydromechanical characteristics of each structure, no simple and integrated criteria have been established to assess the passability of structures in the downstream direction. **An assessment of the potential impact of a water intake on downstream migration will always require a specific study of the structure by specialised technicians.**

The ICE protocol deals essentially with determining the passability of a structure by fish migrating upstream. In the process of implementing the protocol, the collection of field data required to assess downstream-migration conditions is nonetheless carried out.

The assessment of discontinuities in upstream migration using the ICE protocol should make it fairly easy to determine the passability of a structure according to **passability classes** adapted to the given species or **group of species**.

The ICE protocol is essentially based on a comparison of the typological and geometric characteristics of obstacles and the hydraulic conditions around the obstacles with the physical capabilities of the fish species analysed.

For example, generally speaking, the protocol consists of **identifying for each obstacle the potential passageway(s)**, characterising their geometric features and the hydraulic conditions, and comparing the results with the physical capabilities of the given species, as suggested by Ovidio *et al.* (2007).

The description of the geometric characteristics of each section of a potential passageway for fish (see Figure 24) consists essentially of determining the corresponding long profile.

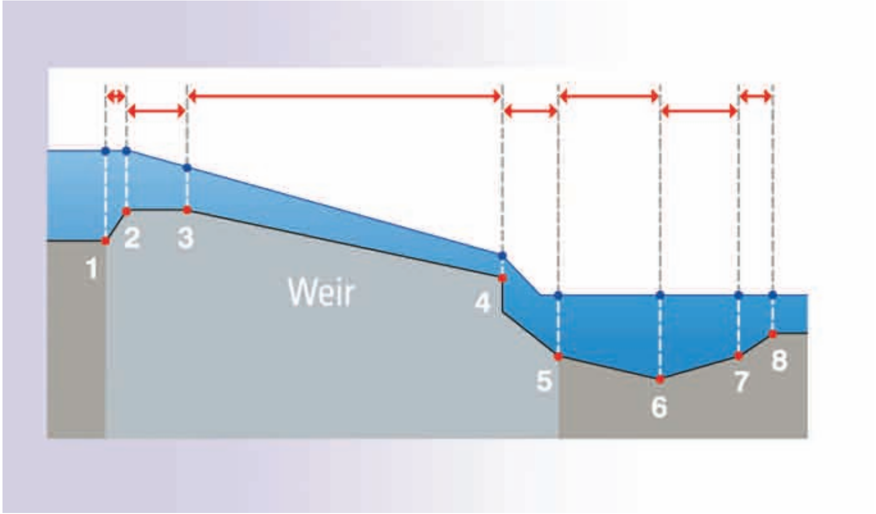
The procedure is therefore to collect the altimetric data for each specific point in a structure corresponding to a significant change in the profile, e.g. a break in a slope. These data should be collected, following the flow of water, from the bottom of the river immediately upstream of the structure to the end of the plunge pool downstream of the structure (see Figure 25). The measurements taken of the altimetric data and of the distances between the measurement points are then used to draw one or more long profiles of the potential passageways for fish.

Figure 24

a, b © Burgun - Onema

Examples of the long profiles that must be calculated in order to characterise a structure. (a) For this type of structure with three identical gates, a single long profile should be sufficient. (b) For this weir, a second long profile should be drafted for the dry section that may be under water if different hydrological conditions arise.

Figure 25



Example of a long profile for a simple structure.

The passability of an obstacle depends above all on the hydraulic conditions pertaining at each point in the structure and that the fish must attempt to overcome, depending on their swimming and jumping capabilities. Mapping of the hydraulic gradient along the entire profile is therefore particularly important and must be carried out simultaneously with the measurement of the physical characteristics of the structure. The hydraulic conditions depend not only on the type of structure (glacis with a continuous slope, stepped weirs, fixed or movable vertical obstacles, structures comprising culverts, flows under gates, etc.) and its geometry (height, profile, slope, length, roughness), but also the discharge flowing over or through it. The discharge depends on the hydrological conditions during the migration period, which can vary widely.

Passability can therefore vary with the river discharge, for example, the structure may be a total barrier during a low-flow period and not represent an obstacle at all during a high-flow period.

Consequently, an ICE assessment should be carried out under the hydrological conditions most common during the migratory period of the given species.

This may create very difficult and/or dangerous conditions when measuring certain important structural features of the structure and make it impossible to determine its passability.

Low-flow conditions make it easy to access structures and measure the various structural features, however they may significantly complicate the passability assessment (maximum head-drop, minimum depths, less depth in the plunge pool, etc.) and they are not particularly representative of the hydrological conditions most common during migratory periods.

For these reasons, a number of visits under different hydrological conditions (low and medium flow conditions) may be necessary to determine or improve the analysis of the ICE passability classes. When an assessment is carried out under hydrological conditions differing significantly from those encountered by a species during the migratory period, it is advised, in addition to the standard assessment procedure, to ignore the disqualifying parameters resulting from the discharge (generally the water depth and overflow height) when determining the passability class. This assessment not taking into account the parameters resulting from the discharge is a means to evaluate the impact of hydrological conditions on the passability of the structure and also whether it would be worthwhile to return to the site when other hydrological conditions prevail.

When a number of passageways have been detected for a structure, each passageway may have a different passability level. In a single structure, some passageways may be considered insurmountable according to the ICE protocol, whereas others may be easily passable. To be truly effective, the passageways deemed passable must also be detectable by the fish. This may be a major problem if they are very narrow compared to the overall obstacle and/or if they receive only a minute and unattractive fraction of the total discharge flowing over or through the structure.

When multiple passageways exist, the ICE protocol cannot determine the degree of attractiveness of each. In such cases, the decision concerning the overall ICE passability class of the structure will call on a fairly high level of technical expertise. That will generally require prior measurements to determine the distribution of discharges at the site as a function of the hydrological conditions.

For the ICE protocol, the characterisation of hydraulic conditions in and over structures has been voluntarily and significantly simplified.

In those cases where more in-depth assessments must be carried out, a hydraulic model of the specific site should be prepared. The model will serve to improve the characterisation of the hydraulic conditions at the site for different discharges and to compare the results with the passage capabilities of the species.

This detailed, hydraulic model will require the development and calibration of a digital application based on a number of physical (precise geometry of the structure, roughness of surfaces) and hydraulic (discharges, conditions at the furthest upstream and downstream points as a function of the discharges, etc.) data points.

Figure 26

a, b © Steinbach - Onema
c, d © Chanseau - Onema
e, f © Burgun - Onema

Examples of structures and different discharge conditions. On the left, (a) (c) (e) show low-flow conditions. On the right, (b) (d) (f) show high-flow conditions.

For example, there are a number of freeware programmes for this type of analysis, notably the two presented below.

■ The FishXing programme was developed by the USDA-Forest Service Pacific Northwest Research Station. The programme, which may be downloaded from **http://stream.fs.fed.us/fishxing/**, was initially designed to analyse the passage of fish through road structures, however it may be used on a more general basis, notably to model simple weirs.

■ The HEC-RAS programme was developed by the U.S. Army Corps of Engineers and may be downloaded from **http://www.hec.usace.army.mil/software/hec-ras/hecras-download.html**. This programme is better suited to modelling the hydraulic conditions in or over any type of structure. On the other hand, it does not correlate the data with the swimming capabilities of fish, as is the case with FishXing. The comparison between the hydrological conditions and the biological factors therefore requires a further step. This software is extensively used by engineering firms specialised in ecohydraulics and in river hydraulics. For example, it was used to determine a number of assessment criteria for the ICE protocol.

The different types of obstacles covered in upstream-migration assessments

The different types of obstacles covered in upstream-migration assessments are the following:
- structures (weirs and dams) made up entirely of fixed parts;
- structures having gates that may be partially or totally opened;
- road, highway and rail structures;
- mixed, more complex structures featuring different types of components;
- tidal structures.

Different criteria have been established to assess the passability of each type of obstacle for the main fish species in continental France. The following chapters are structured around this notion of different types of obstacles and present for each the relevant criteria and the assessment procedure. A separate chapter is devoted to eels in order to fully address their very special passage techniques.

Caution. Some structures are equipped with a fish pass. In the framework of the ICE protocol, a "pre-assessment" of the pass should also be carried out under normal operating conditions (normal discharge and maintenance conditions). The purpose of the pre-assessment is to rapidly identify those fish passes that are clearly not well suited to the species in question and for which a more in-depth assessment may be necessary. However, the pre-assessment is not an in-depth assessment of the hydraulic functioning of the fish pass nor is it a means to check the conformity of the pass with applicable regulations.

Necessary expertise for assessments of obstacles blocking downstream migration

General situation

Downstream migration, i.e. movement heading downstream, may occur during different biological stages depending on the species, notably:
- the juveniles of anadromous species (Atlantic salmon, sea trout, brown trout, shad, etc.);
- the adults of anadromous species following reproduction (salmonids, Twaite shad, etc.);
- the adults of catadromous species prior to reproduction (eels).

During their downstream migration, fish may be confronted with various problems at structures, e.g. modifications in water quality, exposure to predators in reservoirs, delays to migration, falls over spillways and flood gates, passage through turbines in hydroelectric plants, flows drawing them into industrial and agricultural water intakes with possible passage through pumping systems, etc.

Systems designed to limit the impacts

Different technical solutions have been tested more or less recently, mainly in Europe and North America, to avoid or limit the harm done to fish in structures.

The technical progress made and the practical feedback for Atlantic salmon smolts are far greater than for other species, however the studies on eels over the past decade have also produced substantial technical results.

Among the main technical solutions developed to date are:
- the installation of fine screens directing the fish to one or more bypasses (see Figure 27cd);
- shutdown of systems during migration;
- installation of fish-friendly turbines and pumps causing few or no injuries to fish (see Figure 27ab).

Generally speaking, behavioural barriers (lights, noises, electrical fields, bubbles, etc.) have turned out to be relatively ineffective and do not currently provide sufficient results.

Similar to fish passes for upstream migration, structures intended to ensure the safe downstream migration of species must be designed on a case by case basis, be adapted to the specific features of each site and take into account the morphological characteristics and migratory behaviour of the given species or group of species.

Figure 27

a, b, c, d © Ecogea

(a, b) Example of a fish-friendly turbo-generator, (c, d) fish-friendly water intake with a rising incline made of narrowly spaced bars and surface bypasses enabling fish to escape downstream.

For more information on designing and sizing facilities intended to reduce injuries during downstream migration, a number of technical guides may be consulted, notably those listed below.

- *Larinier M., Porcher J.P., Travade F., Gosset C. (1994). Passes à poissons. Expertise, Conception des ouvrages de franchissement. Conseil Supérieur de la Pêche, Collection Mise au point.*
- *Larinier M., Travade F., (1999). La dévalaison des migrateurs : problèmes et dispositifs. Bulletin Français de la Pêche et de la Pisciculture, 353-354, 181-210.*
- *Larinier M., Travade F. (2002). Downstream Migration : Problems and Facilities. Bulletin Français de la Pêche et de la Pisciculture., 364 suppl : 181-207.*
- *Travade F., Larinier M. (2006). French experience in downstream migration devices. In: Free passage for Aquatic Fauna in rivers and other water bodies. International DWA-Symposium on water resources management. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall, pp. 91-99. ISBN 978-3-939057-19-2.*
- *Courret D., Larinier M. (2008). Guide pour la conception de prises d'eau " ichtyocompatibles " pour les petites centrales hydroélectriques. Rapport ADEME – GHAAPPE.*

In addition, Chanseau *et al.* (2012) recently drafted a summary document based current technical and biological information presenting the position of the Onema South-West regional office on the solutions recommended for downstream migration, notably concerning water intakes at small hydroelectric plants, once the decision to reduce their impacts has been taken.

■ Expertise required to assess a hydroelectric plant

Assessment of the potential injuries caused by an installation

Taking the example of a headrace for a hydroelectric plant (see Figure 28), depending on the discharges flowing through the diversion system (dam, weir) and in the headrace respectively, and on the configuration of the dam and the water intake at the plant, some of the fish migrating downstream will transit via the diversion system (spillway, gates, flaps, etc.) and the rest are drawn into the headrace leading to the hydroelectric plant.

Figure 28

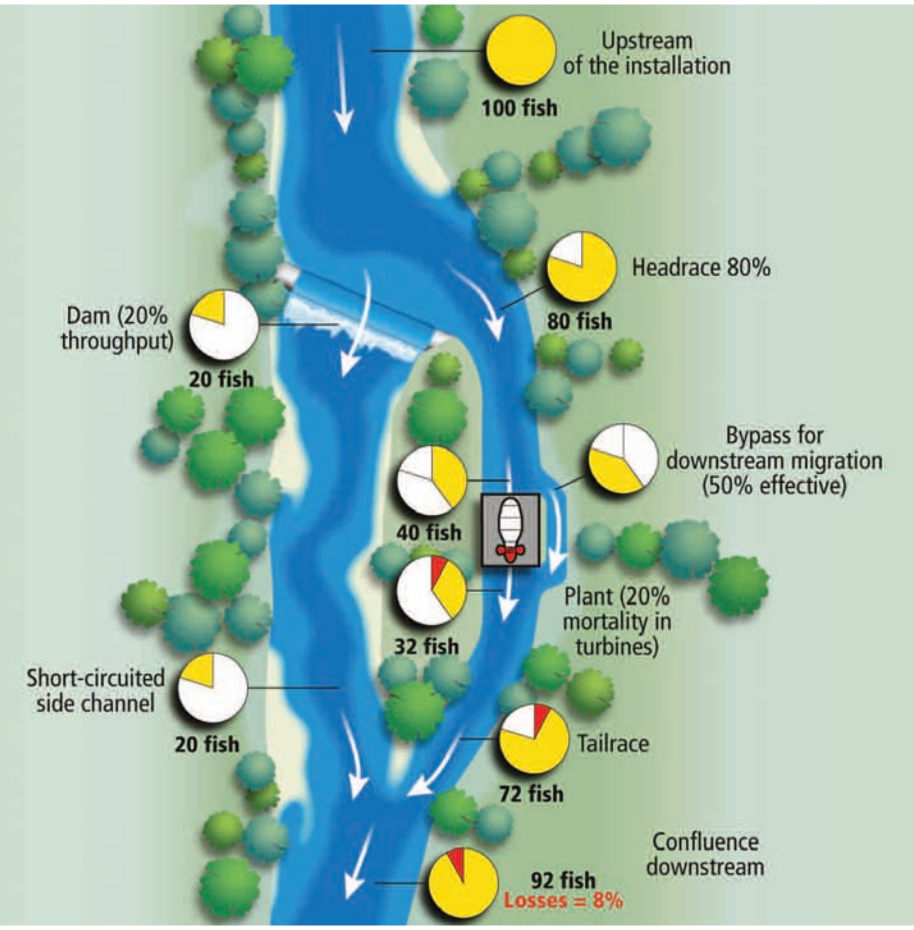


Diagram of a typical installation and basis for modelling the downstream migration. According to Voetgle and Larinier, 2004.

When a bypass for the downstream migration of fish exists at the water intake of the plant, a certain percentage transit the bypass and return without injury to the tailrace, while the remainder transit the turbines. Depending on the characteristics of the turbines, mortality rates are more or less high.

The survivors then join the fish that travelled (generally without injuries) via the diversion system (dam) and/or the bypass, and continue their migration downstream.

Assessment of the potential impact of a water intake on downstream migration requires a certain level of expertise based not only on the various on-site studies carried out, but also on in-depth knowledge of the functioning of installations, the hydrology of the river and the distribution of discharges at the site.

An assessment of the potential impact of a structure on downstream migration must generally determine the site parameters presented below.

■ **The percentage of fish effectively entering the water intake,** which is a function of discharges during the migratory period, the discharge entering the water intake and the configuration of the installation (dam, water intake). Experiments have been carried out on numerous sites, often using radio-monitoring techniques, and produced valuable information on the behaviour of fish, particularly smolts and silver eels migrating downstream, and notably on encountering dams and water-intake screens (Croze & Larinier, 1999; Croze *et al.*, 1999 and 2001; Chanseau *et al.*, 1999 and 2002; Travade *et al.*, 1999 and 2010; Bau *et al.*, 2008 and 2013).

■ **The potential injuries suffered depending on the type and the characteristics of the hydromechanical devices equipping the installation** (turbines, pumps, etc.). Experiments have been carried out in various countries (United States, Canada, Sweden, Scotland, Germany, France) on different species (primarily the salmonid juveniles and eels) to assess the injuries (percentage of deaths and types of injuries) sustained when transiting different types of turbines. The experiments produced fairly similar results and a number of general conclusions may be drawn on the potential injuries suffered by fish. Equations indicating approximate mortality levels of fish as a function of the type of turbine and its hydromechanical characteristics (number of blades, rotational speed, runner diameter), the head-drop and the size of the fish have been proposed, particularly for salmonid juveniles and silver eels (Larinier and Dartiguelongue, 1989; Gomes and Larinier, 2008).

■ **The permeability of water-intake screens** which depends essentially on the spacing between the bars and the effectiveness of the bypasses for downstream migration (when they exist and are open).

Assessment of the potential injuries in a river or river basin

In addition to estimating potential mortalities caused by a single structure, it is important, particularly for diadromous fish, to calculate potential mortalities along the entire migratory path taking into account the position of each structure and the habitats located upstream.

Studies to determine the cumulative losses along an entire migratory path have been carried out for smolts and eels, notably in the Adour-Garonne basin (SW France) (Bosc and Larinier, 2000; Pallo and Larinier, 2002; Voegtlé and Larinier, 2004, 2008; Voegtlé, 2010).

It should be noted that a basic premise in all these studies is that the distribution of fish in an area depends directly on the quantities of available habitat. In most cases, the existing obstacles also influence upstream migrations, thus modifying the "theoretical" distribution of fish.

The RefMADI reference dataset developed by Onema in conjunction with the Ecology ministry proposes a set of data sheets presenting the assessment method for upstream and downstream migration at a hydroelectric plant. Data sheets specifically addressing the downstream migration of eels along entire migratory paths and for individual structures may be consulted and downloaded at **http://www.onema.fr/refmadi**.

Caution. For the ICE protocol, given the complexity of the mechanisms involved in downstream migration and the in-depth knowledge required on the local hydrology, on draw-off conditions and on the hydromechanical characteristics of each structure, it was decided not to propose an assessment procedure based on simple criteria. To determine the downstream passability of structures, a specific study carried out by highly specialised technicians remains indispensable.

Definition of species groups

Presentation of the species groups

To meet the objectives of the ICE protocol, the various species were grouped according to their swimming capabilities, i.e. essentially their maximum speeds and the minimum water depths required for swimming, and their jumping capabilities. These characteristics are the two main biological traits influencing their capacity to overcome physical barriers (see the section on the passage capabilities of fish). This is, however, a rather simplified approach that occasionally groups species having considerably different eco-ethologies and/or morphologies.

Only upstream migration for reproductive purposes (with the exception of eels) was taken into account given that this type of movement is particularly impacted by fragmented environments. In terms of passage capabilities, the **study focused on adult fish or those approaching their sexual maturity** (except for eels which are present in French waters during their juvenile stages).

The distribution of fish into different ICE species groups is discussed below and presented in table form at the end of this section (see Tables 3 and 4). **A total of eleven species groups were established**, where some are divided into subgroups.

NB Eels constitute a separate group given that their passage capabilities differ significantly from those of other species.

For each ICE species group or subgroup, the swimming speeds set for U_{max} were determined using notably the Videler (1993) equations as well as experimental studies focusing on the passage of obstacles and visual observations of fish clearing obstacles.

The minimum depths required for a group of species to swim were determined based on the form factors and by adopting as a general guideline a minimum depth (h_{min}) of approximately 1.5 times the body depth of the fish (see the section on the passage capabilities of fish in the first chapter titled Ecological continuity and fish).

NB An effort was made not to exaggerate the number of groups for the ICE protocol. However, in special cases requiring more precise study of a particular species, a more in-depth analysis is possible using more sophisticated tools.

Many of the species mentioned are likely to move about and clear obstacles at younger ages (ontogenetic movements). Assessments on juvenile fish of the various species are also possible. In this case, it is necessary to reduce the maximum swimming speeds U_{max} and the minimum water depths h_{min} mentioned below. Practically speaking, it may be easier to use the values supplied for a smaller species having a comparable morphology, for example, an Atlantic salmon smolt will generally have swimming capabilities relatively similar to those of a brown trout of equivalent size.

■ Group one

This group comprises anadromous salmonids, namely the Atlantic salmon (*Salmo salar*) (see Figure 29a) and sea trout (*Salmo trutta*) (see Figure 29b).

Figure 29

a © Onema
b © Fagard - Onema

Examples of species in the first group. (a) Atlantic salmon, (b) sea trout.

These two species, in the adult stage, have the greatest passage capabilities in terms of swimming and/or jumping.

Migrating fish are generally very large, ranging from 50 to 100 cm, depending on the number of years spent in the ocean. For smaller sea trout, see Group 4a (brown trout measuring between 25 and 55 cm).

On the other hand, for lake trout reaching large sizes in the adult stage, it is advised to consult the data for this first group rather than Group four.

For Group 1, **a maximum speed U_{max} of approximately 4.5 to 6.5 m/s** was selected (average speed approximately 5.5 m/s). This is in line with numerous reference data on these species (Kreitmann, 1932; Stuart, 1962; Bell, 1986; Booth *et al.*, 1997; Colavecchia *et al.*, 1998; Beach, 1984; Lauritzen *et al.* 2010).

Atlantic salmon and sea trout are excellent jumpers. The maximum head-drop that they can overcome by jumping is approximately 1 to 2.5 metres depending on the size of the fish and if the conditions just below the obstacle are conducive to jumping (see Figure 30).

The minimum water depth h_{min} selected to ensure passage is approximately 20 cm.

Figure 30

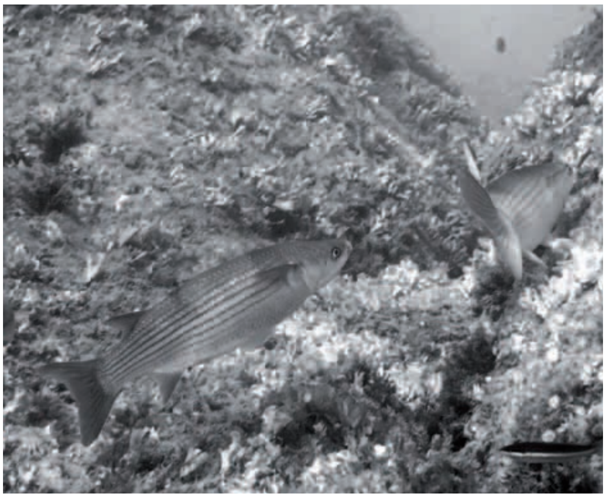
a, b © Chanseau - Onema

Examples of obstacles cleared by Atlantic salmon in the Gave de Pau River.

■ **Group two**

This group is made up of the thicklip grey mullet (*Chelon labrosus*) and the thinlip mullet (*Liza ramada*), two catadromous fish (see Figure 31). Following the migration of the juveniles from the sea (the reproduction site) to brackish or fresh waters, the fish spend most of their trophic period in estuaries and rivers, before migrating downstream as adults to reproduce in the sea (Liao, 1981, in Gautier and Hussenot, 2005).

Figure 31



© Daufresne - Irstea

Examples of species in Group two. Thinlip mullet.

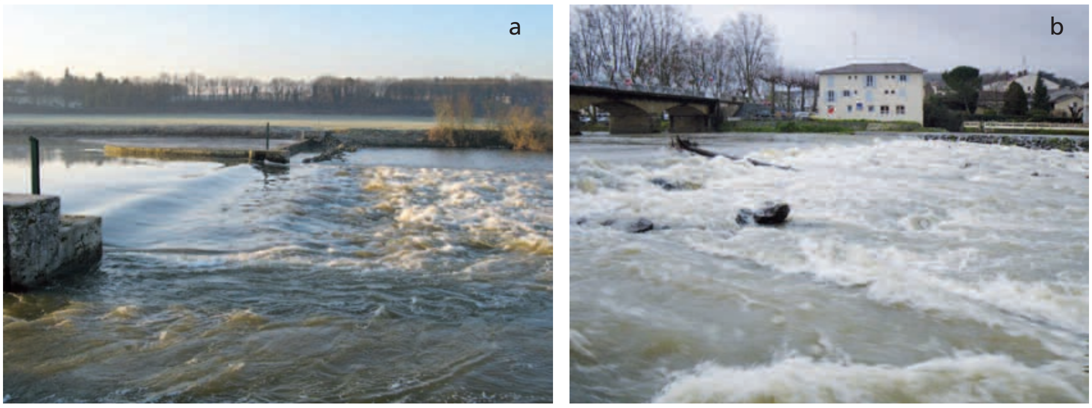
During their upstream migration, mullets are often caught in migratory fish passes located in the lower and middle sections of rivers (Briand and Boussion, 1998). Current knowledge on these species in terms of obstacle passage is, however, rather limited. A few observations have been made on French rivers (Garonne, Dordogne, Loire, Seine, Vilaine, etc.) that confirm the high migratory potential of this group of species.

At the time of the upstream migration, mullets are generally between 30 and 70 cm long. On the whole, they are good swimmers and jumpers, capable, in certain configurations, of overcoming head-drops exceeding 1.5 metres (see Figure 32).

A **maximum speed U_{max} of approximately 4.0 to 5.5 m/s (average speed approximately 4.75 m/s)** was selected for this group, which corresponds to the maximum speeds of the flathead mullet (Mugil cephalus), i.e. approximately 4 m/s for fish around 20 cm long, according to FishBase.

The minimum water depth h_{min} selected to ensure passage is approximately 10 cm.

Figure 32



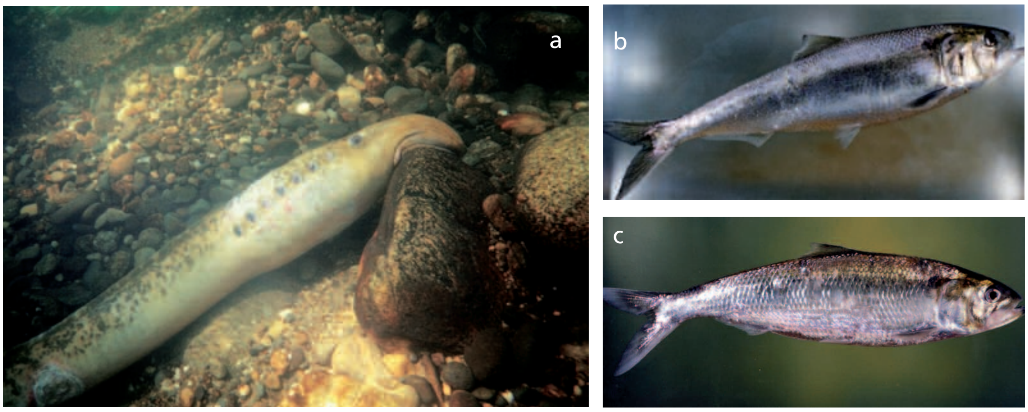
a © Steinbach - Onema
b © Voegtlé - Ecogea

Examples of obstacles cleared by mullets. Mullets are capable of overcoming (a) this weir on the Cher River and (b) the weir in the town of Aire-sur-Adour (Adour River).

■ **Group three**

This group is made up of Allis shad (*Alosa alosa*, see Figure 33b), Twaite shad (*Alosa fallax fallax*, see Figure 33c) and sea lamprey (*Petromyzon marinus*, see Figure 33a), which are anadromous fish from the Clupeidae and Petromyzontidae families respectively.

Figure 33



a © Ecogea
b, c © Vigneux - Onema

Examples of species in Group three. (a) Sea lamprey, (b) Allis shad, (c) Twaite shad.

Shad and lampreys were divided into three subgroups (3a for Allis shad, 3b for Twaite shad and 3c for sea lampreys) due to their very different morphologies in terms of their lengths and particularly the **minimum water depths h_{min}** required to overcome an obstacle while swimming (**15 cm for Allis shad, 10 cm for Twaite shad and sea lampreys**).

The shad frequently caught in migratory fish passes and radio-monitoring studies, notably in the Rhône River (Roche and Broche, 2005), provided evidence of their capabilities in swimming over obstacles (see Figure 34).

At the time of migration, Twaite shad are approximately 30 to 50 cm long and Allis shad from 45 to 70 cm long.

The **maximum speeds U_{max}** selected for the two species are fairly similar, though slightly lower for Twaite shad given its smaller size. The speeds are 3.5 to 5.0 m/s (average speed approximately 4.25 m/s) for Allis shad and 3.0 to 4.5 m/s (average speed approximately 3.75 m/s) for Twaite shad, which corresponds to the reference data for the species (Larinier and Travade, 2002).

Shad cannot jump and rapidly encounter difficulties in overcoming obstacles where there are plunging jets.

Figure 34

a, b © Roche - Onema

Examples of passable and impassable obstacles for shad. (a) Weir on the Ardèche River that shad can clear. The photo shows hydrological conditions enabling passage. (b) Weir on the Cèze River that shad cannot pass, except when discharges are very high, which is rare during the migratory period.

The swimming technique of sea lamprey differs significantly from that of shad. According to the scientific literature, its swimming capabilities are not as good (Almeida *et al.*, 2007; Mesa *et al.*, 2003), but lampreys have a particular means of overcoming obstacles called "burst and attach" (Quintella *et al.*, 2004) which consists of a rapid succession of sprints at maximum speed (bursts), followed by the fish holding on to the substrate with its sucker mouth (attach). Using this technique, sea lampreys have better passage capabilities than if their maximum swimming speeds alone are taken into account. This explains why they were placed in Group three.

For sea lampreys, **a maximum speed U_{max} similar to that of Twaite shad, i.e. approximately 3.0 to 4.5 m/s** was selected (average speed approximately 3.75 m/s).

Migrating lampreys are generally 60 to 90 cm long.

Similar to shad, sea lampreys cannot jump, which means they cannot easily overcome vertical obstacles where the jet is not in contact with the structure and there are no contact points for its sucker (Kemp *et al.*, 2008) (see Figure 35).

Figure 35

© Ovidio - Université of Liège-LDPH

Example of a vertical obstacle that blocks lampreys during their upstream migration.

■ Group four

The fourth group comprises the holobiotic subgroup of brown trout (*Salmo trutta*) in the Salmonidae family (see Figure 36). In terms of their systematic biology, it is the same species as sea trout, however the fish are often smaller and have lesser swimming capabilities.

Figure 36

© Ecogea

A species in Group four. Brown trout.

Group four is divided into two subgroups according to size (15 to 30 cm and 25 to 55 cm). This distinction is due to the great variations in the size of migrating adults depending on the type of river and the thermal regime (streams at the head of river basins, small and larger rivers, rivers flowing to the sea).

NB As noted above, smaller sea trout (< 50 cm) fall into Group four (Subgroup 4a for brown trout measuring between 25 and 55 cm). On the other hand, for lake trout reaching large sizes in the adult stage (> 50 to 60 cm), it is advised to consult the data for Group one.

The swimming capabilities of trout are well documented in the scientific literature (Kreitman, 1933; Hertel, 1966; Beach, 1984; Bell, 1986) and the maximum speed of the largest specimens can reach 5 m/s. Visual observations (Stuart, 1962) and radio monitoring (Ovidio and Philippart, 2002; Ovidio *et al.*, 2007) have revealed that trout are capable of overcoming different types of small obstacles (falls, slopes, combinations of the two) by jumping and/or by swimming (see Figure 37).

Subgroup 4a

For this group made up of the largest fish (25 to 55 cm), a **maximum speed U_{max} of between 3.0 and 5.0 m/s** (average 4 m/s) was selected. For this size class, the **minimum water depth h_{min} selected to ensure passage is approximately 10 cm.**

Subgroup 4b

For this group made up of the smaller adults (15 to 30 cm), a **maximum speed U_{max} of between 2.5 and 3.5 m/s** (average 3 m/s) was selected. For this size class, the **minimum water depth h_{min} selected to ensure passage is approximately 5 cm.**

Figure 37

a, b, c © Ovidio - University of Liège-LDPH

Examples of obstacles cleared by radio-monitored brown trout in Southern Belgium. (a) Aisne River, (b) Lhomme River, (c) Ourthe River, (d) Vesdre River. Photos a and b show low-flow levels. Photos c and d show hydrological conditions conducive to passage.

■ **Group five**

This group is made up of pike (*Esox lucius*) from the Esocidae family and asp (*Aspius aspius*) from the cyprinids, two carnivorous, holobiotic species (see Figure 38).

Figure 38

© Ecogea

Examples of a species in Group five. Pike.

Studies on the migration and passage of obstacles by pike in rivers have been carried out in France (Dubost and Vauclin, 2004) and in Belgium (Ovidio and Philippart, 2002 and 2005). Movements upstream are frequently observed, with maximum distances of approximately 16 km (Belgium, Ourthe-Amblève Rivers) and 20 km (France, Ill River), occasionally including passage of dams, both equipped and not equipped with migratory fish passes (see Figure 39).

Figure 39

a, b © Ovidio - University of Liège-LDPH

Examples of obstacles cleared by radio-monitored pike in the Amblève River (Southern Belgium). The photos show hydrological conditions lower than the optimum passage discharge. (a) General view of the obstacle, (b) zoom on the passage zone.

The swimming capabilities of pike are relatively well known (Harper and Blake, 1991; Frith and Blake, 1991; Meixer *et al.*, 2010).

Concerning asp, the spring migrations of thousands of fish may be observed each year at the fish passes in Iffezheim and Gambsheim on the Rhine. Their rapid expansion since 2001 to the main rivers in the Rhine-Meuse basin is a clear sign of their migratory capabilities (Burgun, 2005).

The scientific literature contains little information on this species. Friedrich (2003) measured in the Elbe River swimming speeds greater than 2 m/s during the migration before and after reproduction. However, given the large size and the morphology of the fish similar to pike, the maximum speed is probably fairly high.

For the two species, the size of adult fish commonly exceeds 50 cm and can reach 75 cm for asp, and even exceed 100 cm for pike, which means that, in light of their morphology, a **minimum water depth h_{min} of approximately 15 cm should be selected to ensure passage** of both species.

Pike and asp are not thought to have a true jumping capability and generally use their swimming capabilities to overcome physical obstacles.

A **maximum speed U_{max} of approximately 3.5 to 5.0 m/s** (average speed approximately 4.25 m/s) was selected, which corresponds to the maximum speeds mentioned in the scientific literature.

■ Group six

The only fish in this group is the grayling (*Thymallus thymallus*), a holobiotic species from the Salmonidae family (see Figure 40).

Figure 40

a © Onema

The species in Group six.
Grayling.

Grayling can cover several kilometres during their reproduction migration that takes place at precise times (Parkinson *et al.*, 1999; Meyer, 2001; Ovidio *et al.*, 2004; Lucas and Bubb, 2005) and is often followed by a rapid return to their home base.

The scientific literature contains little information on the capabilities of grayling to overcome obstacles. However, research done using radio-monitoring techniques in the Belgian Ardennes by Ovidio *et al.* (2007) revealed that grayling do have a certain capability to clear obstacles of up to one metre by swimming or jumping (see Figure 41).

Figure 41

a

b

a, b © Ovidio - University of Liège-LDPH

Examples of obstacles cleared by radio-monitored grayling in Southern Belgium. Obstacles in the Aisne River. The photos show hydrological conditions lower than the optimum passage discharge.

Its jumping capabilities would appear to be slightly inferior to those of brown trout. For example, Lucas and Bubb (2005), using pit tags, showed that grayling had more difficulty than trout in clearing a V-shaped obstacle with a head-drop of 0.4 metre (a success rate of 36% for grayling and 84% for brown trout).

Maximum swimming speeds are fairly similar, but slightly inferior to those of brown trout. A **maximum speed U_{max} of approximately 3.0 to 4.5 m/s** (average speed 3.75 m/s) was selected.

At the time of the reproduction migration, grayling are generally between 25 and 50 cm long.

Similar to Group 4a, which corresponds to the larger brown trout, given the morphology of grayling, a **minimum water depth h_{min} of approximately 10 cm should be selected to ensure passage.**

■ Group seven

Group seven is made up of rheophilic cyprinids that are generally large in size (barbel *Barbus barbus*, nase *Chondrostoma* nasus and chub *Squalius cephalus*, see Figure 42a) and river lamprey (*Lampetra fluviatilis*, see Figure 42b) from the Petromyzontidae family.

Figure 42

a © Vigneux - Onema
b © Ecogea

Examples of species in Group seven. (a) Chub, (b) river lamprey.

Similar to Group three, this group was divided into two subgroups (7a for the rheophilic cyprinids and 7b for river lampreys) due to their very different morphologies in terms of the **minimum water depths h_{min} required to overcome an obstacle while swimming (10 cm for the rheophilic cyprinids, 5 cm for river lampreys).**

Subgroup 7a

Large rheophilic cyprinids have vital needs and the physical means for migrations over several kilometres and even dozens of kilometres in unfragmented rivers (Baras, 1992; Fredrich, 2003; Fredrich *et al.*, 2003; Lucas and Batley, 1996; De Leeuw and Winter, 2008; Ovidio *et al.*, 2007; Ovidio and Philippart, 2008).

They are also found in abundant numbers in different types of fish passes (Lucas, 2000; Slavik *et al.*, 2009; Larinier, 2002; Ovidio *et al.*, 2007).

Given the size of the migrating fish, generally between 25 and 80 cm, a **maximum speed U_{max} of 2.5 to 4.0 m/s** (average speed 3.25 m/s) was selected for Group 7a, which is in line with the swimming speeds mentioned in the scientific literature (Kreitmann, 1933; Lucas and Fear, 1997; Environmental Agency, 2007). Rheophilic cyprinids have no true jumping capabilities.

A number of biotelemetric studies have revealed that rheophilic cyprinids have little motivation and/or aptitude to overcome physical barriers (see Figure 43ab). It is not rare to see fish accumulating at the foot of obstacles in fragmented rivers (Lucas and Fear, 1997; Hubert and Kirchofer, 1998; Ovidio and Philippart, 2002; Horky *et al.*, 2007; Ovidio and Philippart, 2008).

Figure 43

a, b © Ovidio - University of Liège-LDPH
c © Capra - Irstea

Examples of obstacles not overcome and of an obstacle overcome by species in Group seven. (a and b) Obstacles not overcome by radio-monitored barbel and nase during their upstream migration in the Ourthe (a) and the Vesdre (b) Rivers, (c) obstacle overcome by nase and chub monitored using acoustic telemetric techniques in the Rhône River. The photo shows hydrological conditions close to the optimum passage discharge.

However, a recent study carried out in the Rhône River (Capra *et al.*, not published) revealed that nase, chub and barbel are capable of overcoming a rock chute (see Figure 43c, above).

Subgroup 7b

Similar to the sea lamprey, the river lamprey is capable of clearing obstacles using the "burst and attach" technique (Quintella *et al.*, 2004), however its capabilities are more limited given its smaller size (Kemp *et al.*, 2008).

Using this technique, river lampreys have better passage capabilities than if their maximum swimming speeds alone are taken into account, which explains their presence in Group seven. They are also capable of using the deepest layers in water flows.

To account for this particular feature, an **equivalent maximum speed U_{max} close to that of rheophilic cyprinids, i.e. approximately 2.0 to 3.5 m/s** (average speed 2.75 m/s) was selected for river lampreys.

Migrating lampreys are generally 30 to 45 cm long.

Similar to rheophilic cyprinids, river lampreys cannot jump, which means they cannot easily overcome vertical obstacles where the jet is not in contact with the structure and there are no contact points for its sucker (Kemp *et al.*, 2008).

■ Group eight

This group comprises nine holobiotic species, namely four ubiquitous Cyprinidae (common bream *Abramis brama*, white bream *Blicca bjoerkna*, ide *Leuciscus idus*, daces *Leuciscus* spp. except *idus*) , two limnophilic Cyprinidae (common carp *Cyprinus carpio* and tench *Tinca tinca*), one Lotinae (burbot *Lota lota*) and two Percidae (pikeperch *Sander luciperca* and perch *Perca fluviatilis*).

The group was divided into four subgroups based essentially on the differences in size between the species.

Subgroup 8a comprises only common carp because its size and morphology require a considerable minimum water depth h_{min} of approximately 25 cm.

Subgroup 8b comprises pikeperch and common bream because, in spite of the difference in size, their morphologies require a fairly significant minimum water depth h_{min} of approximately 15 cm.

Subgroup 8c includes smaller species (white bream, ide, river burbot, perch, tench), generally between 20 and 50 cm in size (see Figure 44). Given their physical characteristics, these five species require a minimum water depth h_{min} of approximately 10 cm.

Subgroup 8d groups the dace species (except the ide), whose morphologies (length, body depth) require a slightly smaller water depth of approximately 5 cm.

Figure 44

a, b © Daufresne - Irstea

Examples of species in Group eight. (a) Tench, (b) perch.

Subgroups 8a and 8b

The scientific literature is not abundant, however it is known that common bream and common carp have the potential to cover several kilometres (even several dozen kilometres) during their biological cycle (Molls, 1997; Hladík and Kubecka, 2003; Jellyman, 2009; Jones and Stuart, 2009; Paragamian *et al.*, 2005). These species may be found abundantly in fish passes (Horky *et al.*, 2007; Ovidio *et al.*, 2007; Stuart *et al.*, 2008) and bream are occasionally mentioned as one of the most abundant species in migratory passes on large European rivers (Ovidio *et al.*, 2013; Chanseau *et al.*, 2000).

Very little bibliographic data on swimming speeds is available and generally concerns carp and, to a lesser degree, common bream. The data indicate maximum speeds of approximately 0.6 to 3 m/s (Kreitmann, 1933; Komarow, 1971; Zerrath, 1996; Tudorache *et al.*, 2008).

In spite of its morphology fairly similar to that of pike, pikeperch have significantly inferior swimming capabilities and the maximum speed does not exceed 3 m/s (Peake *et al.*, 2000 in Stizostedion vitreum; Koed and Thorstad, 2001). To our knowledge, no *in situ* observations of weir passages have been mentioned in the scientific literature. On the other hand, fish overcoming dams via fish passes have been regularly observed.

Subgroups 8c and 8d

The species in these subgroups (white bream, ide, burbot, perch, tench, daces) are biologically very different, but have all been observed in migratory fish passes or swimming over weirs (see Figure 45) (Prchalova *et al.*, 2006; Hladık and Kubecka, 2007; Slavik *et al.*, 2009; Ovidio et al., 2013; data from various control stations for fish passes in France), which clearly shows that part of the population migrates upstream during certain periods of the year.

Figure 45

© Voegtlé - Ecogea

Example of an obstacle overcome by young perch during their upstream migration. The Hardy stream with hydrological conditions conducive to passage.

Migrations of several kilometres up to several dozen kilometres have been mentioned in the scientific literature for some of these species. This information is based on telemetric studies (Baade and Fredrich, 1998; Winter and Fredrich 2003; Geeraerts *et al.*, 2007; De Leeuw and Winter, 2008; Kuliskova *et al.*, 2009; Paragamian *et al.*, 2005).

Data on their capabilities in terms of overcoming obstacles are very rare and would seem to indicate a low aptitude for clearing physical barriers. Some of the more ubiquitous of these species have demonstrated a clear preference for reproduction downstream of weirs rather than attempting to overcome the obstacle (Geeraerts *et al.*, 2007; Horky *et al.*, 2007).

For the entire Group eight (8a to 8d), a **maximum speed U_{max} of approximately 2.0 to 3.5 m/s** (average speed 2.75 m/s) was selected. **This group is unable to jump**.

■ Group nine

This group comprises ten **Cyprinidae** (common bleak *Alburnus alburnus*, see Figure 46a, schneider *Alburnoides bipunctatus*, Mediterranean barbel *Barbus meridionalis*, blageon *Telestes souffia*, Crucian carp *Carassius carassius*, Prussian carp *Carassius gibelio*, roach *Rutilus rutilus*, gudgeons *Gobio spp*., rudd *Scardinius erythrophtalmus* and South-west European nase *Parachondrostoma toxostoma*), two Percidae (Rhône streber *Zingel asper* and ruffe *Gymnocephalus cernuus*), the Cottidae (bullheads *Cottus spp*., several species are present in France, see Figure 46b), two Cobitidae (spined loach *Cobitis taenia* and stone loach *Barbatula barbatula*, see Figure 46c) and finally one Petromyzontidae (brook lamprey *Lampetra planeri*, see Figure 46d).

Figure 46

a

b

a, b © Daufresne - Irstea

Examples of species in Group nine. (a) Bleak, (b) bullhead.

Suite Figure 46

c © Daufresne - Irstea
d © Kardacz - Ecogea

(c) Stone loach, (d) brook lampreys.

The group was divided into two subgroups based essentially on the differences in size between the species and on the benthic behaviour of certain species.

Subgroup 9a comprises the larger species, generally between 10 and 30 cm in length (common bleak, schneider, Mediterranean barbel, blageon, Crucian carp, Prussian carp, roach, rudd and nase).

Subgroup 9b comprises the Rhône streber, bullheads, gudgeons, ruffe, brook lamprey, stone loach and spined loach. These small, fairly benthic species can swim very close to the bottom and take advantage of the low water velocities. They are somewhat smaller than the fish in Group 9a and generally range from 5 to 15 cm in length. To take into account the benthic behaviour of the species in Group 9b and in spite of their smaller size compared to Group 9a, a **minimum water depth h_{min} of approximately 5 cm and similar swimming speeds** were selected for Group 9 as a whole.

None of the species in either subgroup have true jumping capabilities.

Subgroup 9a

Among these species on which very little is known concerning their migratory behaviour, it should be noted that common bleak, schneider, roach and rudd have been caught and observed, often in abundance, in certain migratory passes in France, notably in fish passes originally designed for shad. This indicates that these species, in spite of their small size, are capable of finding passageways by swimming in the deepest layers of water flows (see Figure 47).

For this group, a **maximum speed U_{max} of approximately 1.5 to 3.0 m/s** was selected (average speed approximately 2.25 m/s).

Figure 47

© Ovidio - University of Liège-LDPH

Example of an obstacle not overcome by radio-monitored roach during their upstream migration in the Vesdre River in Belgium. The photo shows low-flow conditions.

Subgroup 9b

Very few data on the mobility and the range of their habitat are available for these small species. They are very rarely caught in migratory fish passes because their small size enables them to slip through the bars of the cages. However, gudgeon, minnows, brook lamprey, stone loach and bullheads have been observed in migratory passes in Southern Belgium (Ovidio *et al.*, 2005, 2007).

Special passes for Rhône streber have also been created in the Rhône basin (Gomes *et al.*, 2005) and are used by the species. Among the 12 species in this group, bullheads have been the most extensively studied in terms of their mobility. They were long thought to be extremely sedentary, however recent use of more suitable techniques on individual fish (dyes, pit tags, microtelemetry) have revealed habitats ranging up to several hundred metres (Knaepkens *et al.*, 2004; Breeder *et al.*, 2009; Ovidio *et al.*, 2009).

Limited data are available in the scientific literature on swimming speeds. Gaudin and Pradelle (2001) have suggested a maximum speed for Rhône streber of approximately 1.3 to 1.4 m/s. De Boeck *et al.* (2006) indicated a maximum speed of approximately 1.1 m/s for stone loach and Zerrath (1996) proposed 2.1 m/s for gudgeon. The maximum speed of the threespine stickleback is thought to be approximately 1.5 m/s (Law and Blake 1995; Whoriskey and Wooton, 1987). Ovidio *et al.* (2007b) showed that bullheads are capable of clearing small weirs (30 to 40 cm high), both natural and man-made having fairly different configurations, but generally having slight slopes (up to 12°) and rough substrates with stones or riprap (see Figure 48). A vertical (straight drop) or subvertical weir 20 to 25 cm high is impassable for the species, which confirms the hypotheses put forward by Utzinger *et al.* (1998).

However, similar to the bullheads, all the other species in Group 9b can take advantage of the deepest layers in the water flow where the velocities are the lowest. To account for this particular feature, a **maximum speed U_{max} was selected for Group 9b that is close to that of Group 9a, i.e. 1.5 to 3.0 m/s** (average speed 2.25 m/s).

Figure 48

a, b, c, d © Ovidio - University of Liège-LDPH

Examples of obstacles cleared by bullheads monitored using pit tags in the Falogne stream in Belgium. The photos show hydrological conditions conducive to passage.

■ Group ten

This group is made up of five small species from three families, namely three Cyprinidae (sunbleak *Leucaspius delineatus*, bitterling *Rhodeus amarus* (see Figure 49a) and minnows *Phoxinus spp.* (see Figure 49b, several species are present in France, see the Atlas on freshwater fish in France, Keith *et al.*, 2011)) and two Gasterosteidae (threespine stickleback *Gasterosteus gymnurus* and smoothtail ninespine stickleback *Pungitius laevis*).

Figure 49

a, b © Daufresne - Irstea

Examples of species in Group ten. (a) Bitterling, (b) minnow.

Very few data on the mobility and the range of their habitat are available for these small species.

These species are significantly smaller than those in Group nine and range from 5 to 10 cm in length. **Similar to Group 9, a minimum water depth hmin of approximately 5 cm was selected to ensure passage for the entire Group 10.**

Very few data are available on the capabilities of these species to overcome weirs. Holthe *et al.* (2005) demonstrated in laboratory experiments that minnows are not capable of overcoming a head-drop of more than 27 cm.

For Group 10, a **maximum speed Umax of approximately 1 to 2 m/s** was selected (average speed approximately 1.5 m/s).

None of the species listed in this group have jumping capabilities.

■ Group eleven

This group is made up of a single species, the European eel (*Anguilla anguilla*), a catadromous species in the Anguillidae family (see Figure 50).

Figure 50

a © Marty - Onema
b © Daufresne - Irstea

Examples of fish in Group eleven. (a) Glass eel and elver, (b) yellow eel.

As noted in the section on passage capabilities, eels cannot be analysed in the same manner as other fish species due to their technique of overcoming physical barriers by crawling up wet surfaces.

Their swimming capabilities are much lower than their size would suggest. For glass eels, the maximum speed is approximately 30 to 50 cm/s. The distance covered in water flowing at 0.30 m/s is approximately 3 metres and that distance drops to approximately 30 cm in water flowing a 0.5 m/s (Mc Cleave, 1980). For elvers and yellow eels, the maximum swimming speeds are in the 1.0 to 1.5 m/s range (Blaxter and Dixon, 1959).

On the other hand, their ability to crawl enables them to overcome physical barriers with high head-drops and low overflow heights (Steinbach, 2006) (see Figure 51). The smallest eels can climb vertical walls thanks to the surface tension between their bodies and the wet wall (the force is proportional to the length of the fish). However, in growing, the weight to surface tension ratio increases in proportion to their length, which explains why only the smallest eels (less than approximately 12 cm in length) can effectively use this technique.

Finally, eels are not capable of jumping.

Figure 51

a, b © Steinbach - Onema

Examples of obstacles that a certain percentage of yellow eels can overcome by crawling. These structures nonetheless hinder the free movement of the species.

Given the differences in passage capabilities (crawling or swimming) depending on the size of the fish, it was decided to split Group 11 into two subgroups:

- Subgroup 11a comprising elvers and yellow eels, i.e. the larger fish generally between 12 and 40 cm in length;
- Subgroup 11b comprising the younger fish less than 12 cm in length, corresponding to the glass-eel stage.

A maximum speed Umax of approximately 1.5 m/s was selected for Subgroup 11a and 0.5 m/s for Subgroup 11b.

Given that eels generally make use of their ability to crawl over obstacles and, where necessary, to breathe through their skin, **a water depth of approximately 2 cm is thought to be the maximum for their crawling technique to be fully effective. At greater water depths, the forces exerted on the fish hinder effective use of this very particular technique and the sheet of water is sufficient for elvers to swim** (Subgroup 11a).

Species not mentioned in the groups

The Atlas of freshwater fish in France (Keith *et al.*, 2011) lists approximately one hundred fish species for continental France and Corsica.

In view of simplifying the presentation of this protocol, it was decided to discuss only the most common taxa.

The list of selected species is presented in alphabetical order below (see Table 3) and in the ICE species groups according to their swimming and jumping capabilities (see Table 4).

Tableau 3 *Alphabetical list of the main fish species presented in the ICE protocol and the corresponding ICE species group.*

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

Tableau 4 *Table listing the ICE species groups and the corresponding swimming and jumping capabilities.*

ICE species group	Species	Jumping species	Swimming speed (m/s)			Height of jump (m)		
			Min.	*Avg.*	Max.	Min.	*Avg.*	Max.
1	Atlantic salmon (*Salmo salar*) Brown or sea trout [50-100] (*Salmo trutta*)	Yes	**4.5**	*5.5*	**6.5**	**1**	*1.5*	**2.5**
2	Mullets (*Chelon labrosus, Liza ramada*)	Yes	**4**	*4.75*	**5.5**	**0.8**	*1.1*	**1.8**
3a	Allis shad (*Alosa alosa*)	No	**3.5**	*4.25*	**5**	-	-	-
3b	Twaite shad (*Alosa fallax fallax*)		**3**	*3.75*	**4.5**			
3c	Sea lamprey (*Petromyzon marinus*)							
4a	Brown or sea trout [25-55] (*Salmo trutta*)	Yes	**3**	*4*	**5**	**0.5**	*0.9*	**1.4**
4b	Brown trout [15-30] (*Salmo trutta*)		**2.5**	*3*	**3.5**	**0.3**	*0.5*	**0.8**
5	Asp (*Aspius aspius*) Pike (*Esox lucius*)	No	**3.5**	*4.25*	**5**	-	-	-
6	Grayling (*Thymallus thymallus*)	Yes	**3**	*3.75*	**4.5**	**0.4**	*0.75*	**1.2**
7a	Barbel (*Barbus barbus*) Chub (*Squalius cephalus*) Nase (*Chondrostoma nasus*)	No	**2.5**	*3.25*	**4**	-	-	-
7b	River lamprey (*Lampetra fluviatilis*)		**2**	*2.75*	**3.5**			
8a	Common carp (*Cyprinus carpio*)	No	**2**	*2.75*	**3.5**	-	-	-
8b	Common bream (*Abramis brama*) Pikeperch (*Sander lucioperca*)							
8c	White bream (*Blicca bjoerkna*) Ide (*Leuciscus idus*) Burbot (*Lota lota*) Perch (*Perca fluviatilis*) Tench (*Tinca tinca*)							
8d	Daces (*Leuciscus spp.* except *Idus*)							
9a	Bleak (*Alburnus alburnus*) Schneider (*Alburnoides bipunctatus*) Mediterranean barbel (*Barbus meridionalis*) Blageon (*Telestes souffia*) Crucian carp (*Carassius carassius*) Prussian carp (*Carassius gibelio*) Roach (*Rutilus rutilus*) Rudd (*Scardinius erythrophthalmus*) South-west European nase (*Parachondrostoma toxostoma*)	No	**1.5**	*2.25*	**3**	-	-	-
9b	Streber (*Zingel asper*) Bullheads (*Cottus spp.*) Gudgeons (*Gobio spp.*) Ruffe (*Gymnocephalus cernuus*) Brook lamprey (*Lampetra planeri*) Stone loach (*Barbatula barbatula*) Spined loach (*Cobitis taenia*)							
10	Sunbleak (*Leucaspius delineatus*) Bitterling (*Rhodeus amarus*) Threespine stickleback (*Gasterosteus gymnurus*) Smoothtail ninespine stickleback (*Pungitius laevis*) Minnows (*Phoxinus spp.*)	No	**1**	*1.5*	**2**	-	-	-
11a	European eel [yellow eel] (*Anguilla anguilla*)	No	**< 1.5**			-	-	-
11b	European eel [glass eel] (*Anguilla anguilla*)		**< 0.5**					

The species not listed in the tables above can, however, be assigned to one of the groups based on the available biological knowledge and their morphological characteristics (minimum and maximum sizes, form factors, etc.).

Below are brief presentations of current knowledge on sturgeon, flounder and Wels catfish.

Sturgeon (*Acipenser sturio*, see Figure 52b) are anadromous amphibiotic migrators in the Acipenseridae family. Few studies have been made on their swimming capabilities. Lake sturgeon (*Acipenser fulvescens*) are present in North America and adults (approximately 130 cm long) are thought to be capable of maintaining a cruising speed of approximately 1 m/s and reaching speeds of approximately 1.8 m/s for very short periods (Peake *et al.*, 1996).

The scientific literature does not mention any capability to jump over obstacles. Given their morphology, no true jumping capability would seem likely (Lepage, personal paper).

Flounder (*Platichthys flesus*, see Figure 52c) are catadromous amphibiotic migrators in the Pleuronectidae family. Adults spend most of their lives in estuaries and the fresh waters of rivers and may be found up to several hundred kilometres from the sea. When it is time to reproduce, they migrate downstream to the sea to spawn between January and April. After hatching, some of the young fish head for the estuaries of rivers to continue their development. In years past, they travelled fairly far up rivers, for example to Mainz on the Rhine, Metz on the Moselle, Orléans on the Loire, Paris on the Seine, etc.

Adults vary in size between 20 and 50 cm. Their morphology and special swimming technique mean they have very limited swimming capabilities compared to fish of similar size, but with more "standard" morphologies. Duthie (1982) mentioned maximum swimming speeds of less than 1.5 m/s, which is comparable to the species in Group ten. In addition, they have absolutely no jumping capabilities. Another particular feature of flounder is the use of an anaerobic metabolism, even when swimming at limited speeds (Duthie, 1982).

Wels catfish (*Silurus glanis*, see Figure 52a) is a potamodromous species in the Siluridae family that is found increasingly frequently in large European rivers (Copp *et al.*, 2009). Very few data are available in the scientific literature, however it is known that the Wels catfish can undertake movements often mirroring those of its prey (Carol *et al.*, 2007; Pohlmann *et al.*, 2001).

It is found in migratory fish passes increasingly frequently. Studies of Wels catfish carried out at certain fish passes, notably those equipped with control stations and located on large rivers (Garonne, Dordogne Rivers, etc.), have revealed the passage of fish of widely varying sizes (from a few dozen centimetres to over two metres).

Little is known about the swimming capabilities of the Wels catfish. However, a recent study on juvenile *S. meridionalis* (Zeng *et al.*, 2009), a species similar to *S. glanis*, indicated a maximum critical speed of 3.4 body lengths per second at 28°C. In addition, adults are very powerful and capable of brief accelerations to capture prey.

To date, there is no available information on the ability of Wels catfish to jump over physical obstacles. However, the morphology of the fish is certainly a major disadvantage.

Figure 52

Examples of species. (a) Wels catfish, (b) sturgeon, (c) flounder.

a, b, c © E. Vigneux - Onema

Definition of passability classes

The objective of the ICE protocol is to put users in a position to determine the potential impact of an obstacle on the movement of fish, based on simple criteria and easily implemented human and material resources.

The protocol is structured around a comparison of the geometric and hydraulic characteristics of obstacles with the physical swimming and jumping capabilities of the fish species analysed.

Caution. The approach proposed here is designed to be as logical and rigorous as possible, however, it is still a simplification given current knowledge on the passage capabilities of certain species, the highly variable swimming capabilities within a species or group of species, the geometric complexity of certain obstacles causing significant differences in hydrological conditions for a given discharge and the variability of hydrological and thermal conditions during migratory periods.

Given the above, it was deemed preferable to use passability classes, similar to projects comparable to the ICE protocol carried out in other countries (see Table 5).

Tableau 5 *Summary of the main methods developed worldwide to assess the passability of a structure.*

Country	Organisation and/or references	Species	Type of structure	Number of classes	Main criteria
United States	Washington Department of Fish and Wildlife (WDFD, 2000)	Salmonids	Various, essentially road and tidal structures	4 classes: 0%, 33%, 66%, 100%	Level A: slope, head-drop, depth Level B: length, velocity, depth, head-drop, type of structure
	U.S. Department of Agriculture (USDA) (Clarkin *et al.*, 2005)	All species, but particularly salmonids	Road structures	3 classes: green, grey and red	Slope, downstream fall, length, velocity
	Coffman (2005)	3 species groups: salmonids, cyprinids, percids and cottids	Road structures	3 classes: green, red and indeterminate	Slope, downstream fall, length, velocity
New Zealand	James and Joy (2008)	All species	All structures	4 classes	Expert knowledge
Germany	DWA (2005)	All species	All structures	4 classes	The criteria used for fish passes (essentially head-drop)
Belgium (Wallonia)	Wallonia Public Service and University of Liège (2013)	All species	All structures	4 classes	Expert knowledge
United Kingdom	Kemp *et al.* (2008) Kemp and O'Hanley (2010)	Species groups: salmon, trout, lamprey, cyprinids, juvenile salmonids, juvenile eels, smolts, juvenile lampreys, silver eels	All structures	4 classes: 0%, 33%, 66%, 100%	Head-drop, velocity, depth, hydraulic jump
Spain (Catalonia)	Solà *et al.* (2011)	4 species groups: marine/estuarine species, eels, cyprinids, salmonids	All structures	5 classes: ranging from bad to high	Head-drop, plunge pool, water depth, slope, velocity

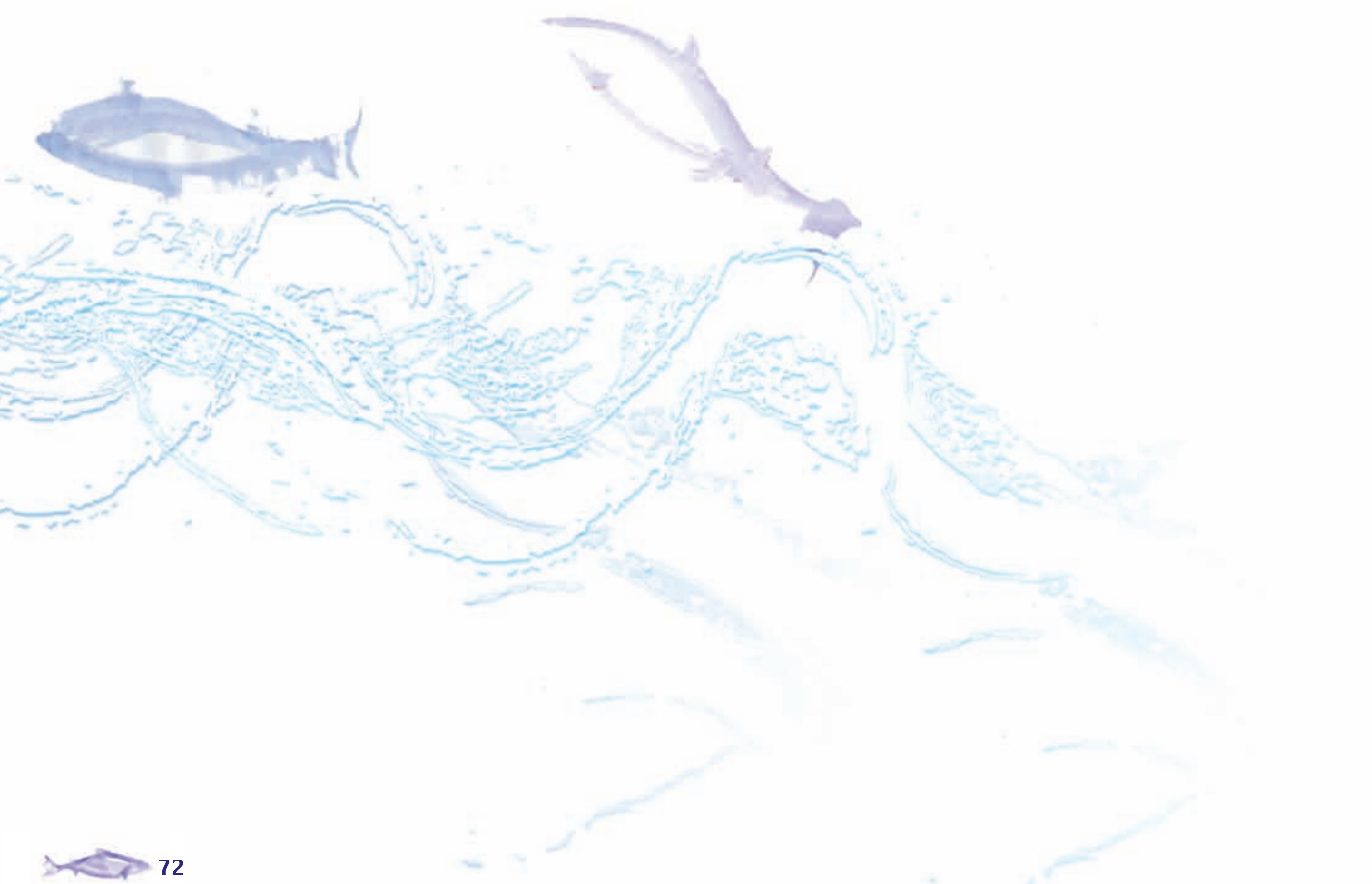
Five passability classes were selected for the ICE protocol. The definitions for each class are, on the whole, in line with those proposed by Kemp *et al.* (2008) and Kemp and O'Hanley (2010).

A colour code is assigned to each class (0, 0.33, 0.66 and 1) to facilitate implementation and enhance understanding.

Caution. The four passability classes (0, 0.33, 0.66 and 1) should not be understood as passage rates for a species or group of species. They are rather indicators of the need to undertake restoration work on the structure. In this sense, each number is not a percentage, but an indicator of environmental degradation and of the need for an intervention (the closer the indicator is to zero, the greater the need for an intervention).

An indeterminate class (NC) was created for more complex situations where in-depth analysis is required to determine the passability class (complex structures, etc.). This class may be assigned while waiting for a later assessment.

The definitions of the passability classes are presented below. The criteria and the procedure used to determine the passability class(es) of an obstacle as a function of its characteristics and a given group of species will be presented later.



Total barrier (ICE class = 0)

The barrier cannot be overcome by the species/stages of a given species group and constitutes a complete obstacle to their migration.

However, under exceptional conditions, the obstacle may become momentarily passable for a fraction of the population.

High-impact partial barrier (ICE class = 0.33)

The barrier is a major obstacle to the migration of the species/stages of the given species group.

The obstacle cannot be overcome most of the time and/or by a high percentage of the population. Upstream migration is possible only during a limited part of the migratory period or for a limited part of the population in the given group. The obstacle incurs delays in migration that are detrimental to the biological cycles of the species.

Medium-impact partial barrier (ICE class = 0.66)

The barrier is a significant obstacle to the migration of the species/stages of the given species group.

Passage of the obstacle during upstream migration is possible most of the time and for a high percentage of the population. But the obstacle can nonetheless cause non-negligible delays in migration.

Consequently, the obstacle cannot be overcome during part of the migratory period by a significant part of the population in the given group.

Low-impact passable barrier (ICE class = 1)

The barrier is not a significant obstacle to the migration of the species/stages of the given species group.

Most of the population can overcome the obstacle within a short time span and without injury. However, that does not mean that the obstacle does not cause any delays in migration or that all fish in the given group can overcome it without injury.

Barrier having indeterminate impact (ICE class = NC)

Obstacle passability cannot be determined solely on the basis of ICE data. An assessment of the impact requires additional investigations and/or more in-depth analysis.

NB This approach may also be applied to assessments of downstream migration. However, as noted in the section on the protocol objectives and limits, given the complexity of downstream-migration parameters and situations, it was decided not to establish assessment criteria for the passability of structures during downstream migration. A specific study carried out by highly specialised technicians remains indispensable.

c

Assessment of passability during upstream migration

Fixed elements of weirs and dams

Configurations frequently encountered

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

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

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

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

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

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

■ Inclined faces that fish can overcome by swimming

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

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

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

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

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

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

where α *= elevation angle expressed in decimal degrees and* p *= slope expressed in percentage.*

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

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

Figure 53

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

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

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

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

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

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

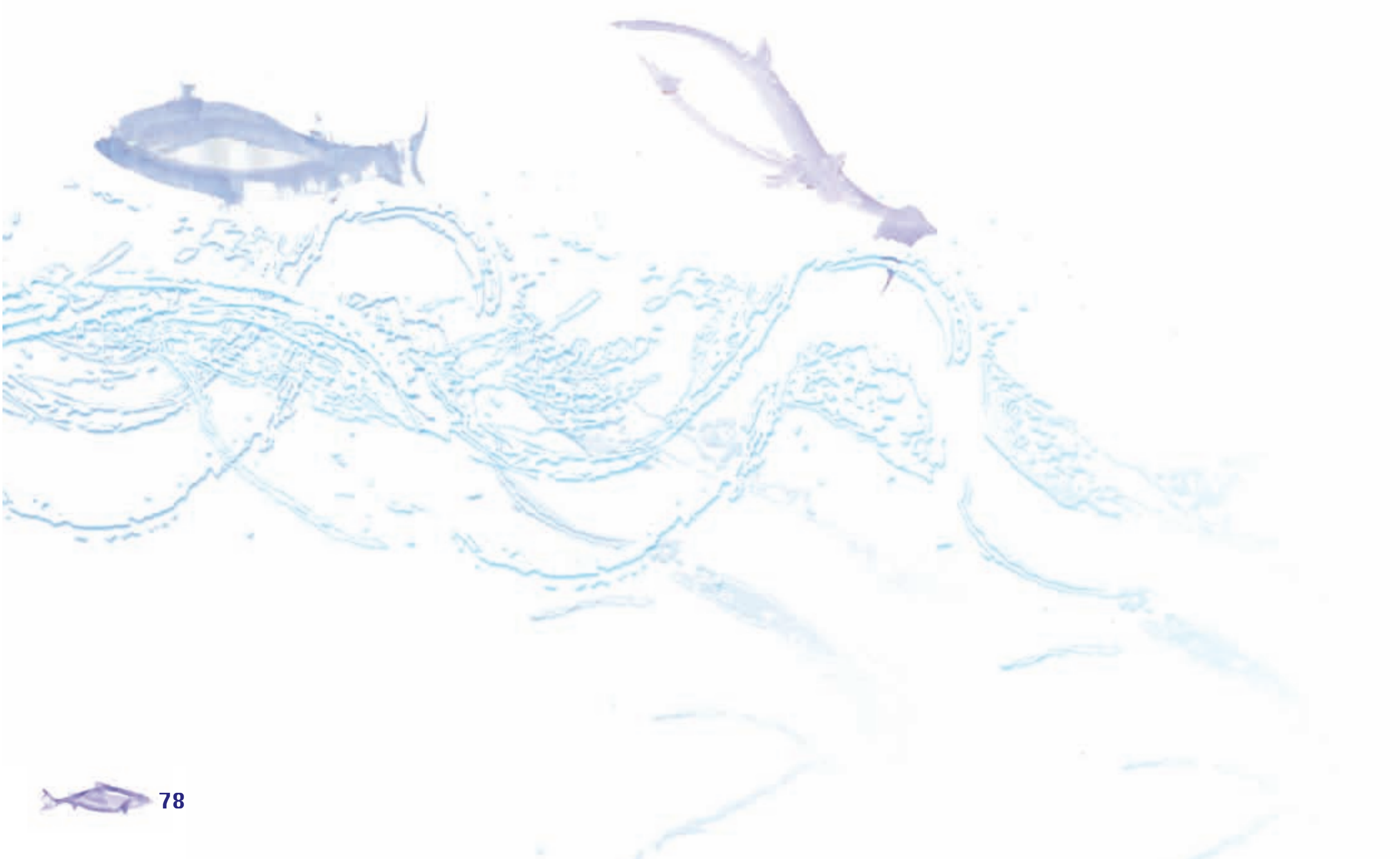
In this chapter, the method used to determine the passability class is presented for:

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

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

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

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



Vertical and subvertical obstacles

(slope >150% (56°))

Passability criteria for jumping species

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

■ Definition of passability classes

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

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

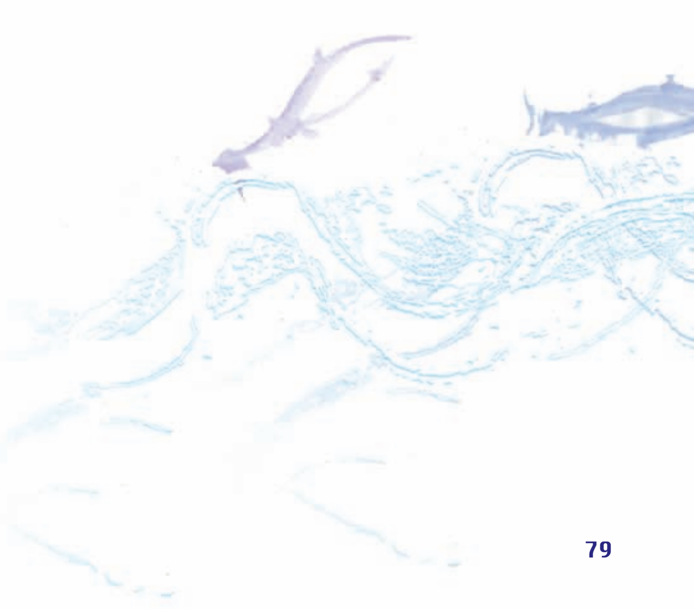
If the head-drop DH is between the theoretical jumping height of the minimum size of fish Lp_{min} (DH_{min}) and the average size of fish Lp_{avg} (DH_{avg}) in the given species, the obstacle is considered a **medium-impact partial barrier (ICE class = 0.66)**.

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

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

■ Extreme head-drop $DH_{extreme}$

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



Non-jumping species

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

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

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

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

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

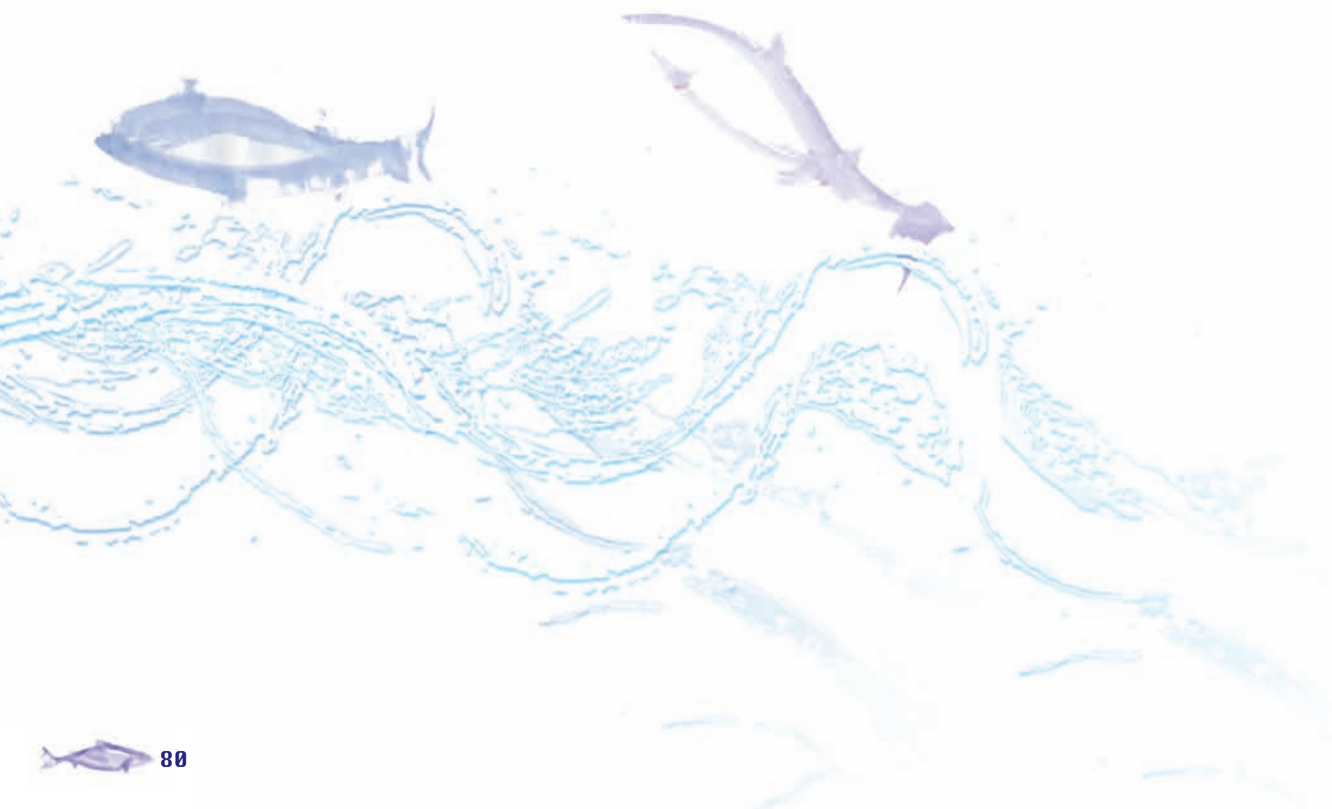
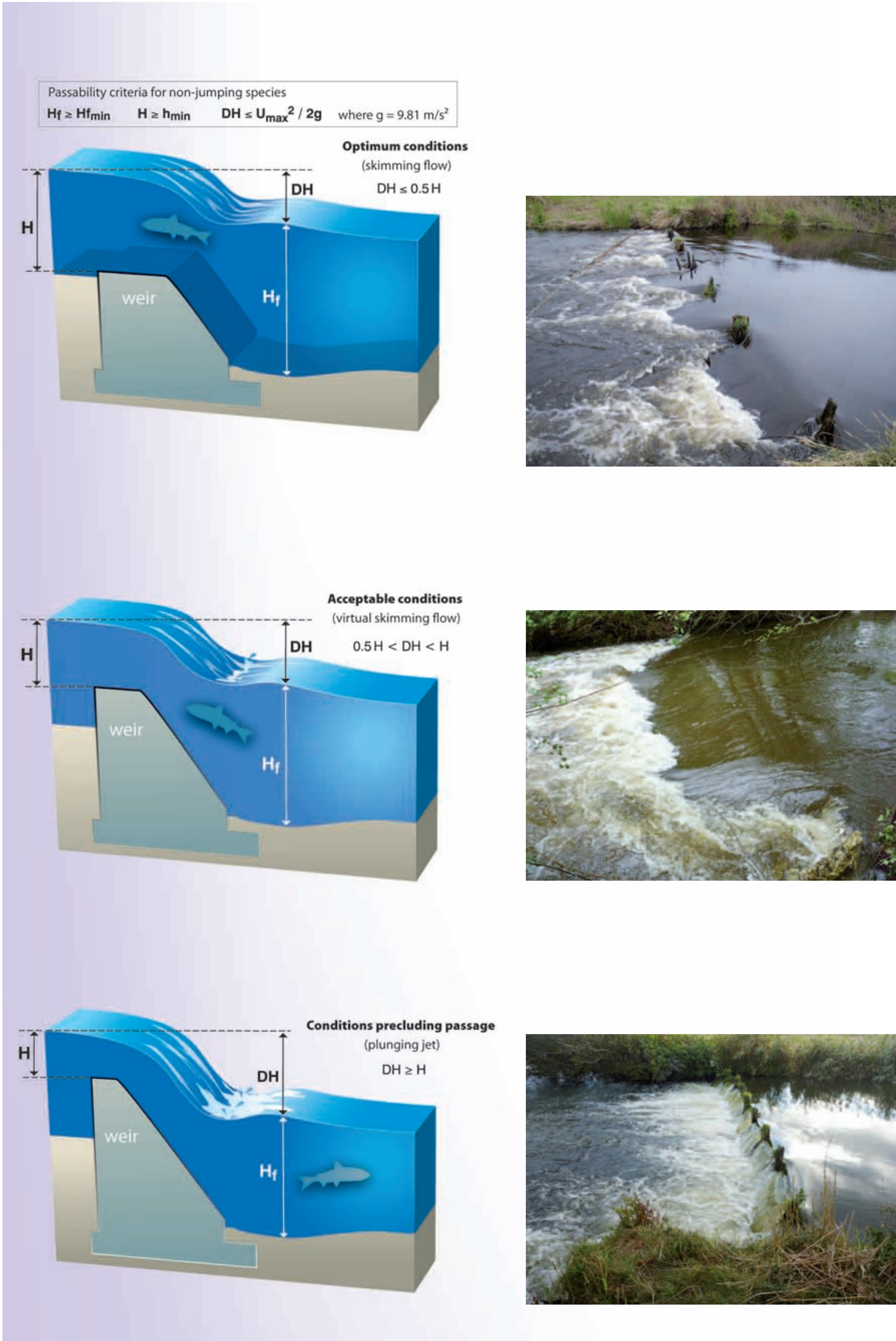


Figure 54



a, b, c © Voegtlé - Ecogea

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

Determining passability classes

■ Threshold values used for the decision tree

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

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

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

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

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

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

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

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

■ Decision tree

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

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

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

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

2. Analysis of the overflow height at the obstacle

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

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

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

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

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

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

4. Jumping species

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

5. Skimming flows

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

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

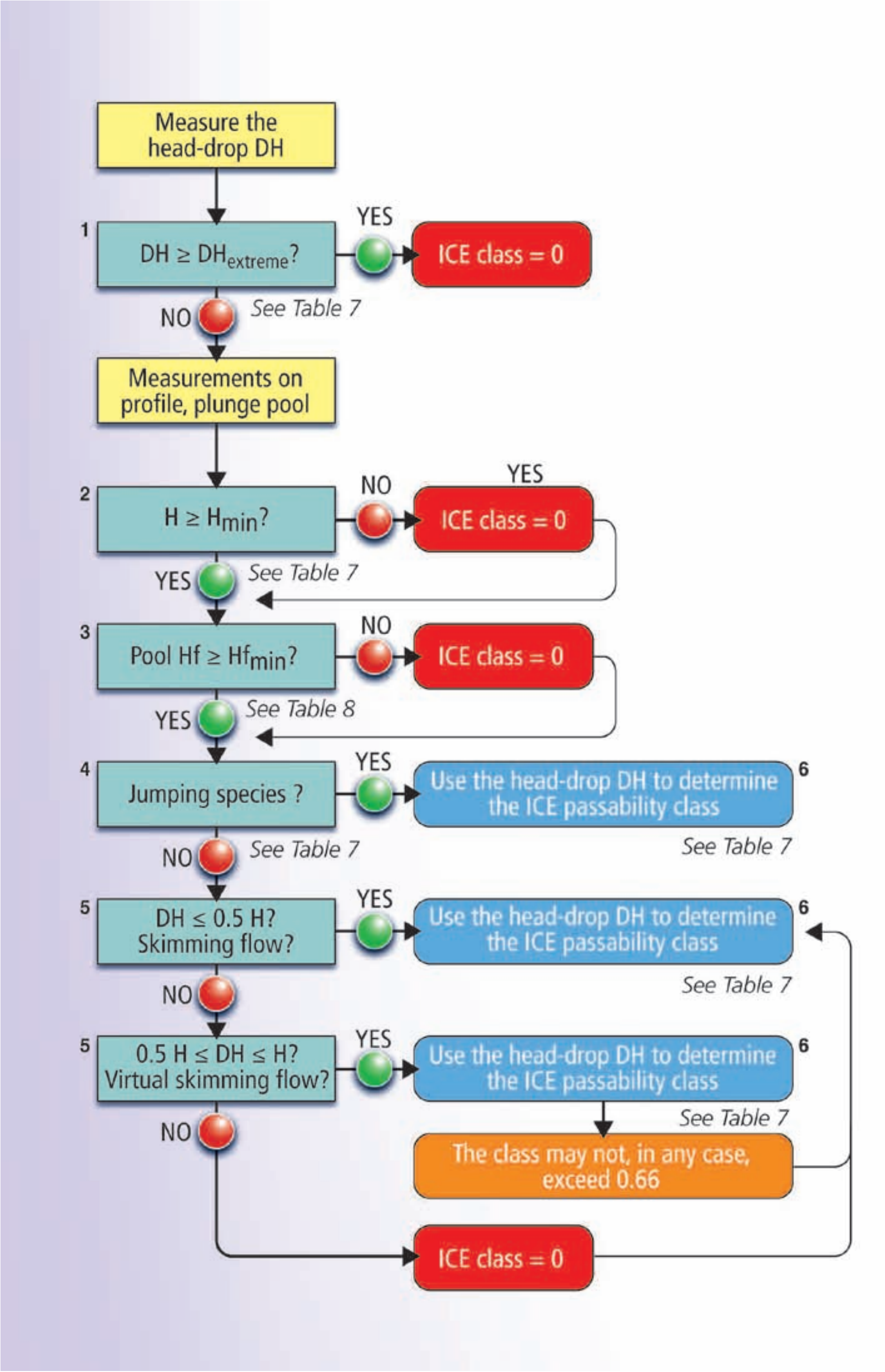
If DH > H, the flow is a plunging jet and the obstacle may be considered a total barrier in the sense of the ICE protocol (ICE class = 0).

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

6. Analysis of the head-drop

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

Figure 55



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

Weirs with inclined downstream faces (slope ≤150%)

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

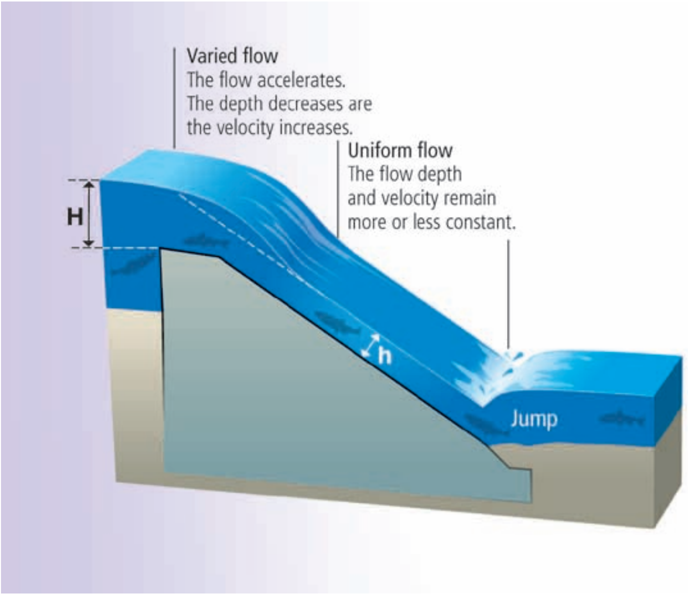
Passability criteria on a uniform inclined glacis

■ Flow conditions

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

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

Figure 56



Changes in flow conditions along an inclined glacis.

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

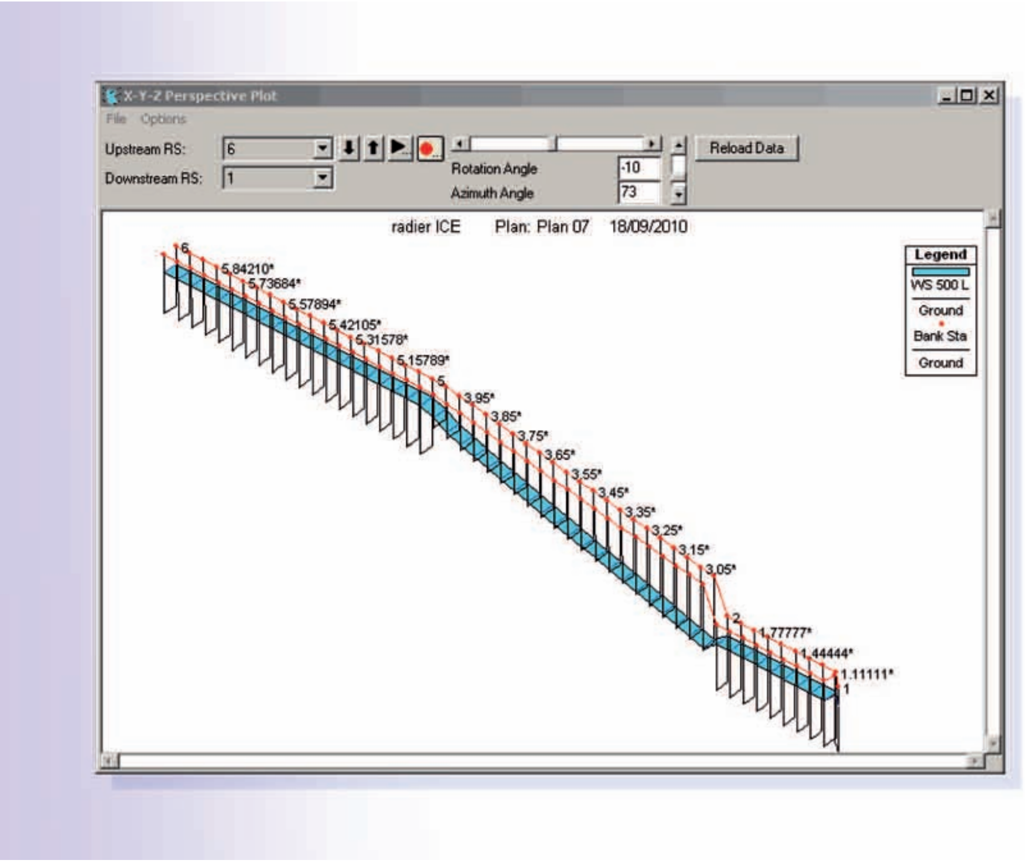
The modelling was carried out for a weir with a total head-drop of five metres (see Figure 57), by varying the different physical and hydraulic parameters influencing the flow conditions, namely:

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

■ the roughness of the glacis. To model the effects of roughness, seven Manning-Strikler (n) coefficients were tested, 0.01 (very smooth substrate equivalent to floated concrete); 0.015, 0.02, 0.03, 0.04, 0.05 and 0.06 (very rough, equivalent to coarse masonry);

■ unit discharge (the discharge per meter width). Seven unit discharges were tested, 125, 250, 500, 750, 1000, 1500 and 2000 L/s/m.

Figure 57



Graphic presentation of hydraulic modelling using the HEC RAS software.

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

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

The graphs reveal:

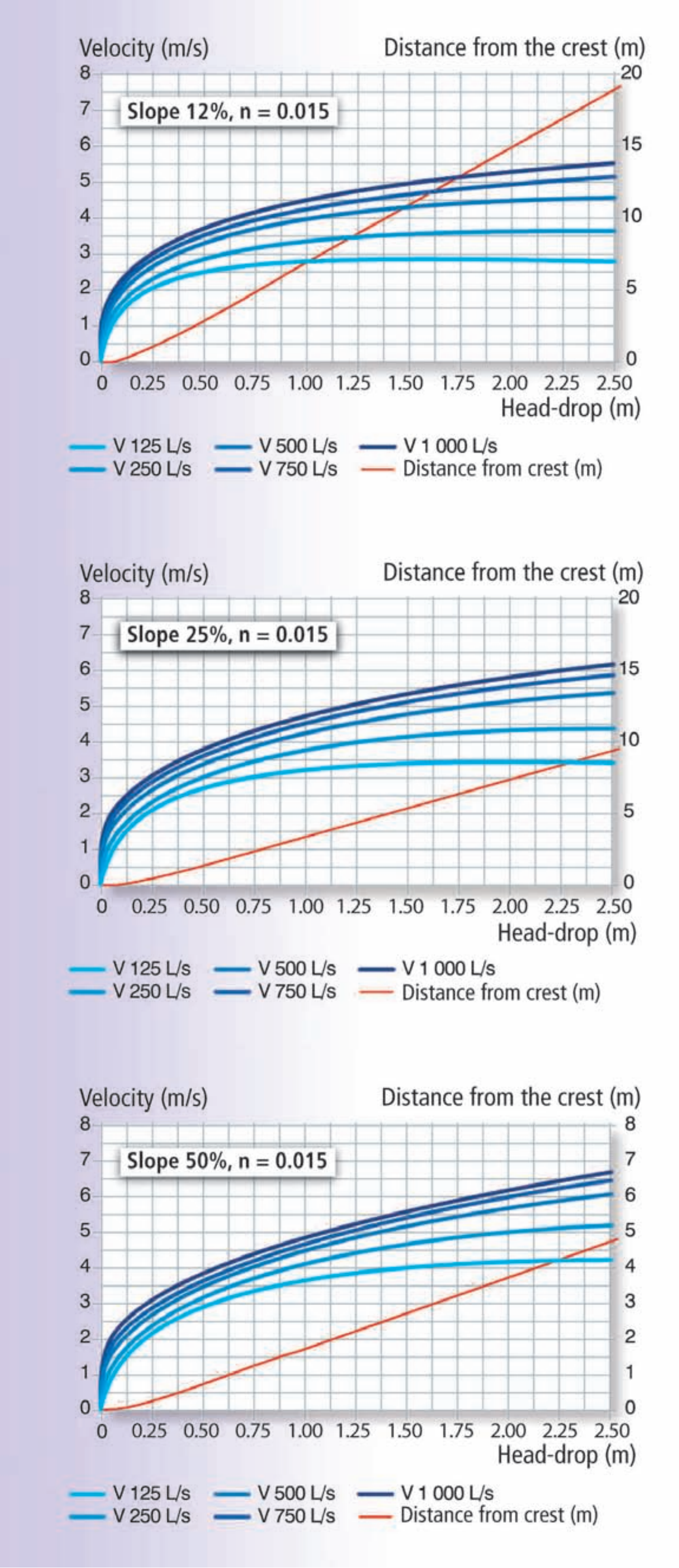
■ an acceleration in the velocity starting at the crest until a certain distance at which the flow becomes uniform (constant velocity and depth);

■ that velocities increase with the unit discharge;

■ the distance at which the flow becomes uniform increases with the unit discharge and decreases with the roughness.

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

Figure 58



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

■ Modelling fish passability

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

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

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

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

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

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

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

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

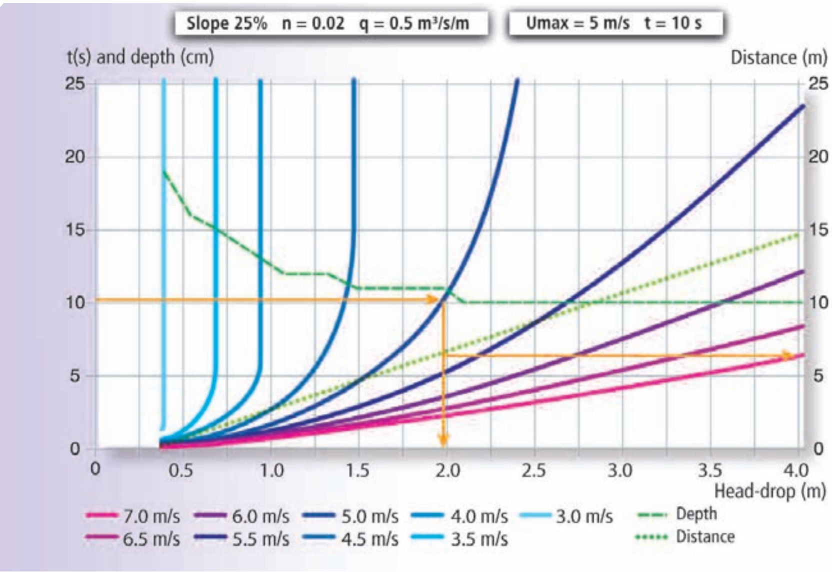
Graphs were produced for six slopes (3% to 100%), seven unit discharges (0.125 m³/s/m to 2 m³/s/m), seven roughness values (Manning n 0.01 to 0.06), representing a total of approximately 300 graphs similar to that in Figure 59 and 3 000 endurance/head-drop combinations that fish can overcome.

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

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

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

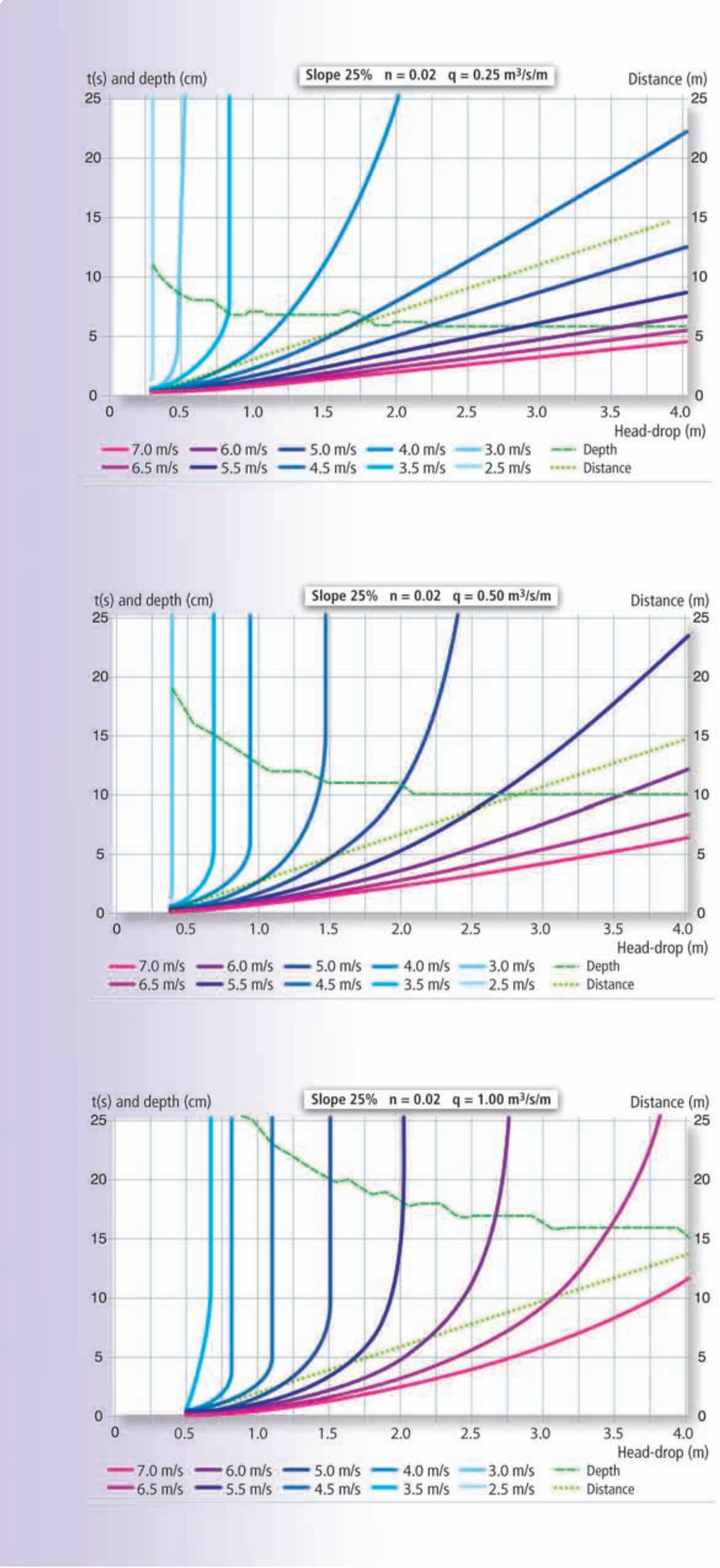
Figure 59



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

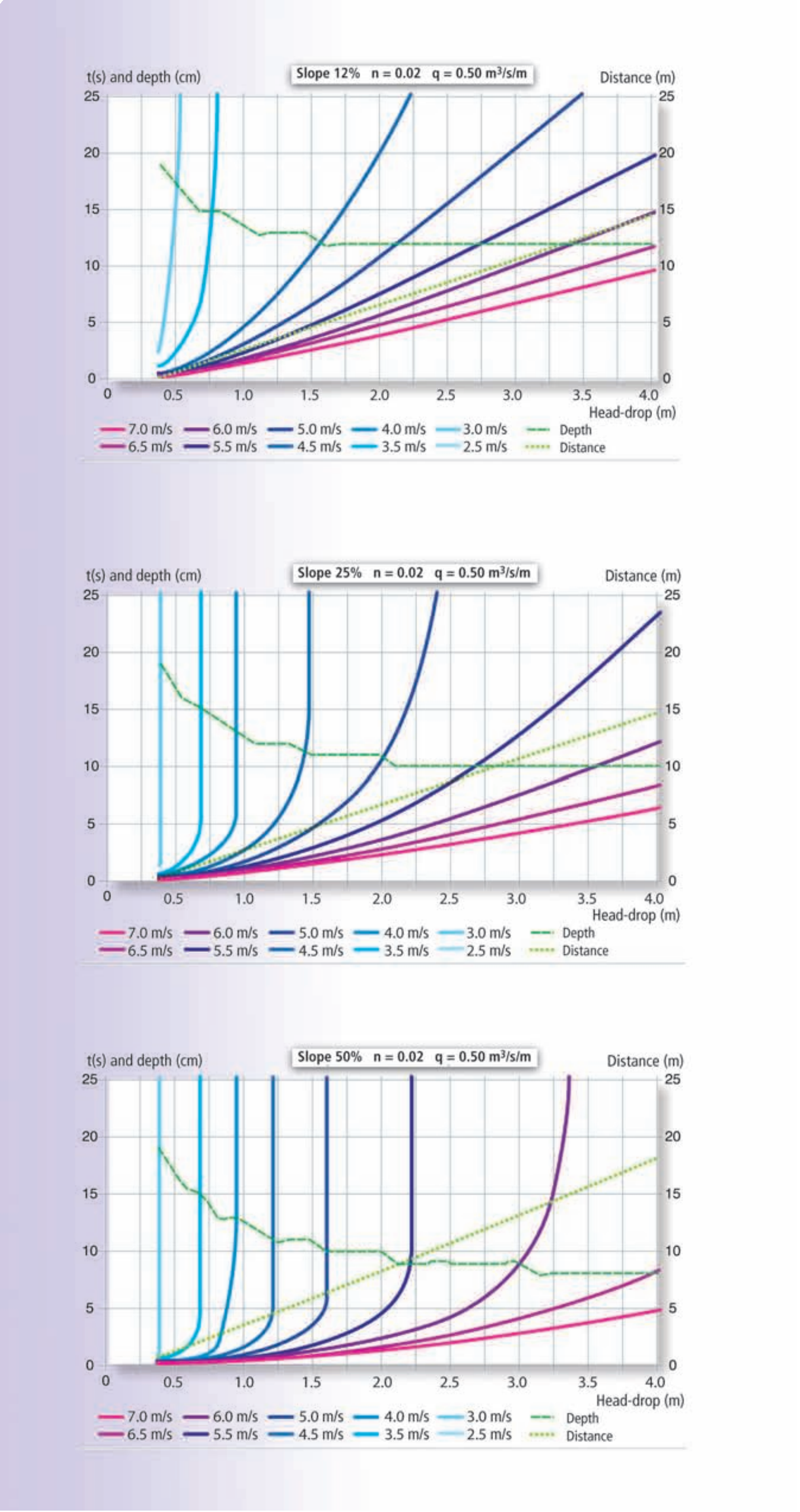
The graphs shown in Figures 60, 61 and 62 show the influence of the unit discharge as well as that of the slope and roughness of the glacis.

Figure 60



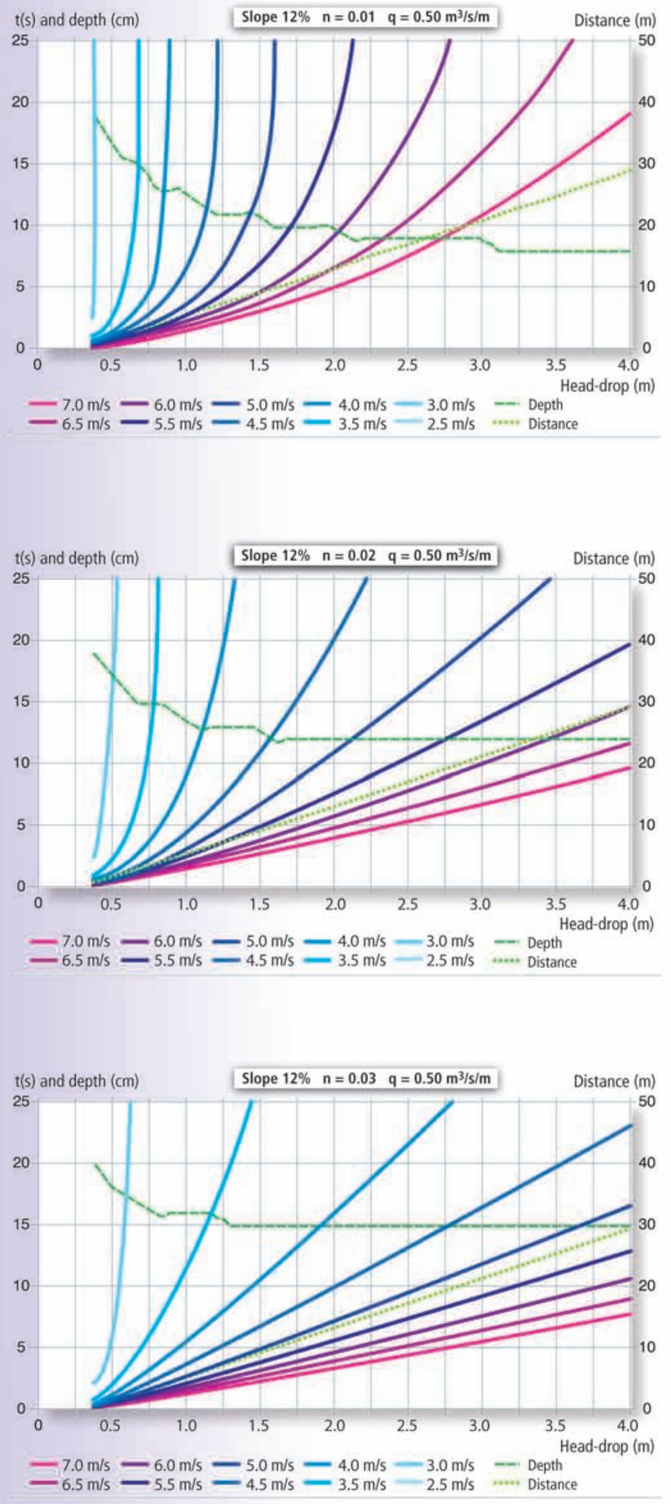
Passable head-drop as a function of the maximum swimming speed U_{max} and the endurance t on a glacis having a slope of 25% and roughness n = 0.02. The three graphs correspond to three different unit discharges (q = 0.25 m³/s/m, 0.5 m³/s/m and 1.0 m³/s/m).

Figure 61



Passable head-drop as a function of the maximum swimming speed U_{max} and the endurance t on a glacis where the unit discharge q = 0.5 m³/s/m. The three graphs correspond to three different slopes (12%, 25% and 50%) having a constant roughness n = 0.02.

Figure 62



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

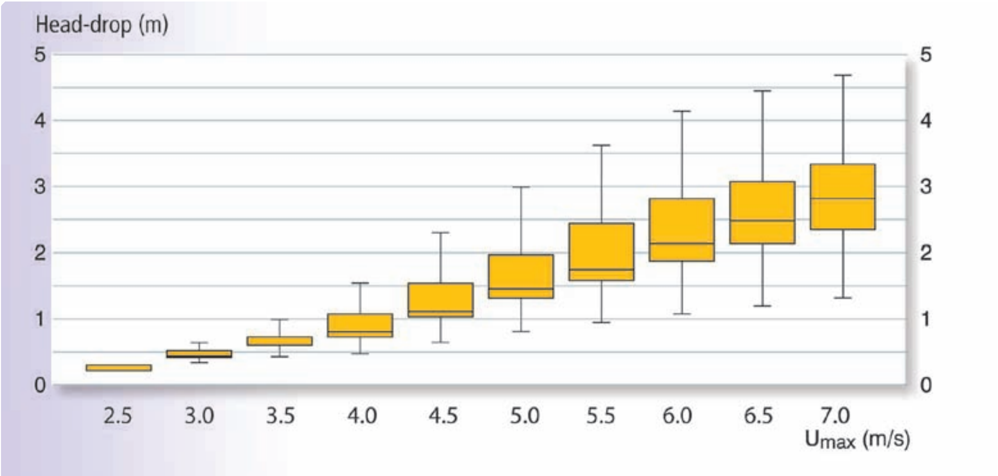
■ Statistical analysis of results

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

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

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

Figure 63



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

■ Definition of passability classes

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

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

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

■ if the head-drop DH is passable for fish of minimum size Lp_{min} in the given species, the obstacle is considered a low-impact passable barrier **(ICE class = 1)**;

■ if the head-drop DH is between the passable heights for fish of minimum Lp_{min} and average Lp_{avg} sizes in the given species, the obstacle is considered a medium-impact partial barrier **(ICE class = 0.66)**;

■ if the head-drop DH is between the passable heights for fish of average Lp_{avg} and maximum Lp_{max} sizes in the given species, the obstacle is considered a high-impact partial barrier **(ICE class = 0.33)**;

■ if the head-drop DH is not passable for fish of maximum size Lp_{max} in the given species, the obstacle is considered a total barrier **(ICE class = 0)**.

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

Steps in the weir profile

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

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

Figure 64

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

A step can cause two types of flow (see Figure 65):

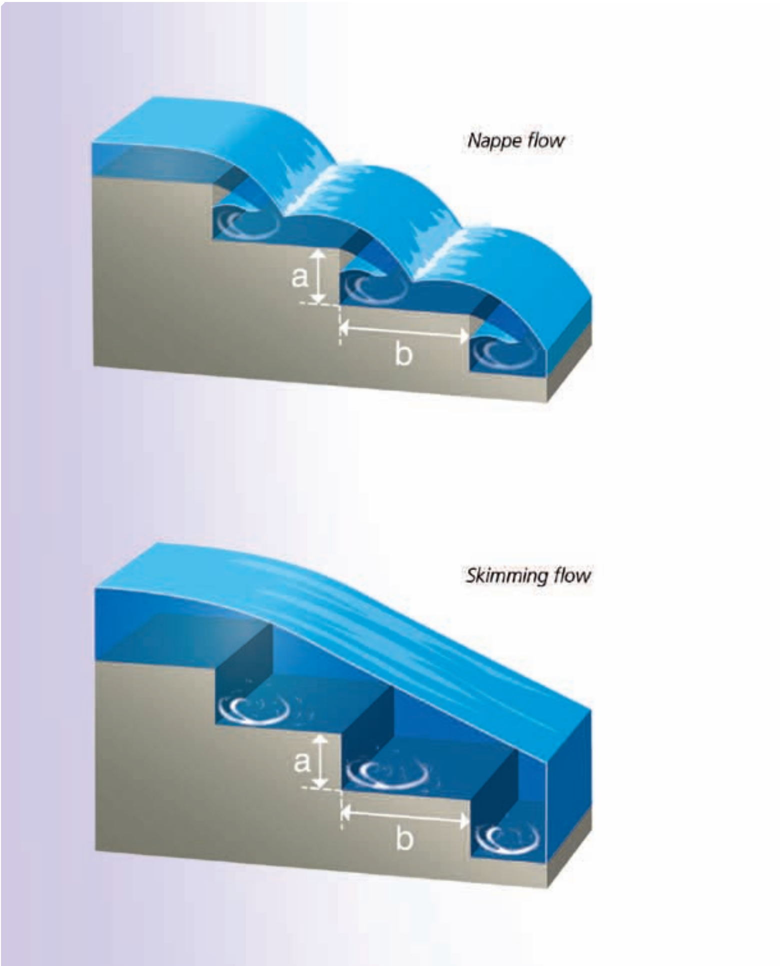
■ nappe flow, where the sheet of water falls over the crest of the step, resulting in a hydraulic jump

■ skimming flow, where the discharge is sufficient to "erase" the step.

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

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

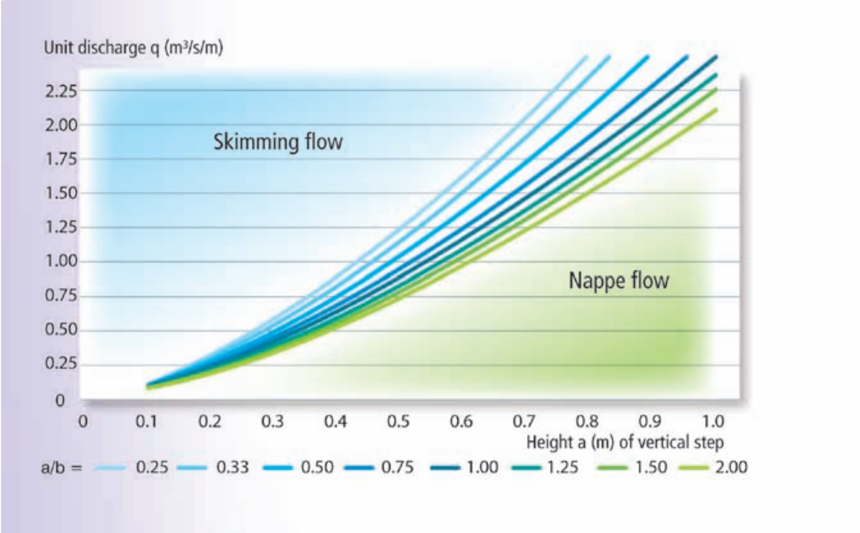
Figure 65



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

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

Figure 66



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

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

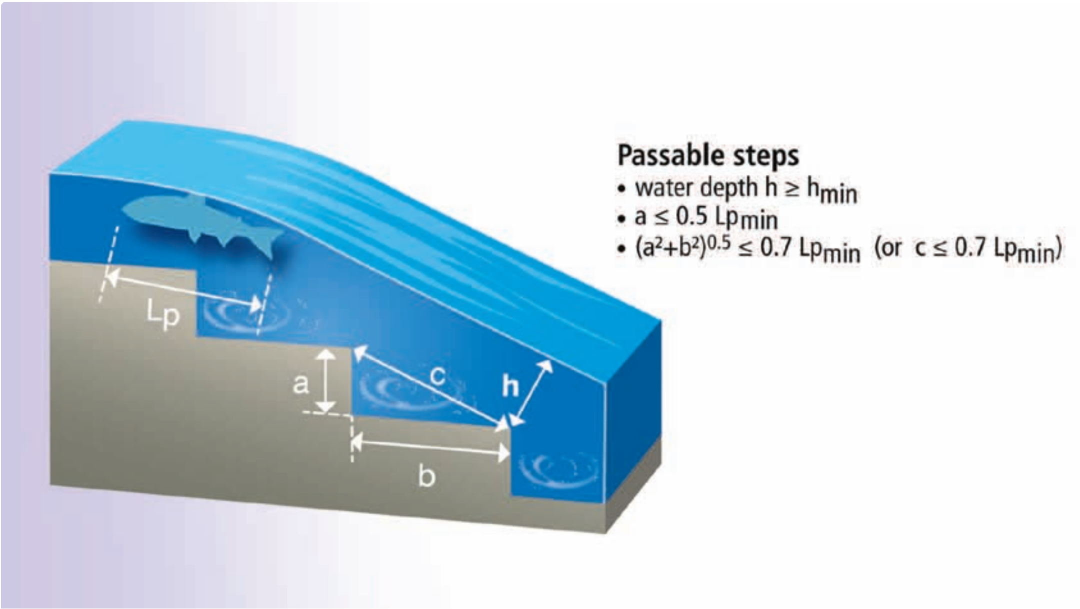
Consequently, it is thought that fish can clear a step only if the following conditions are met (see Figure 67):

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

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

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

Figure 67



Necessary conditions for fish to overcome a step.

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

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

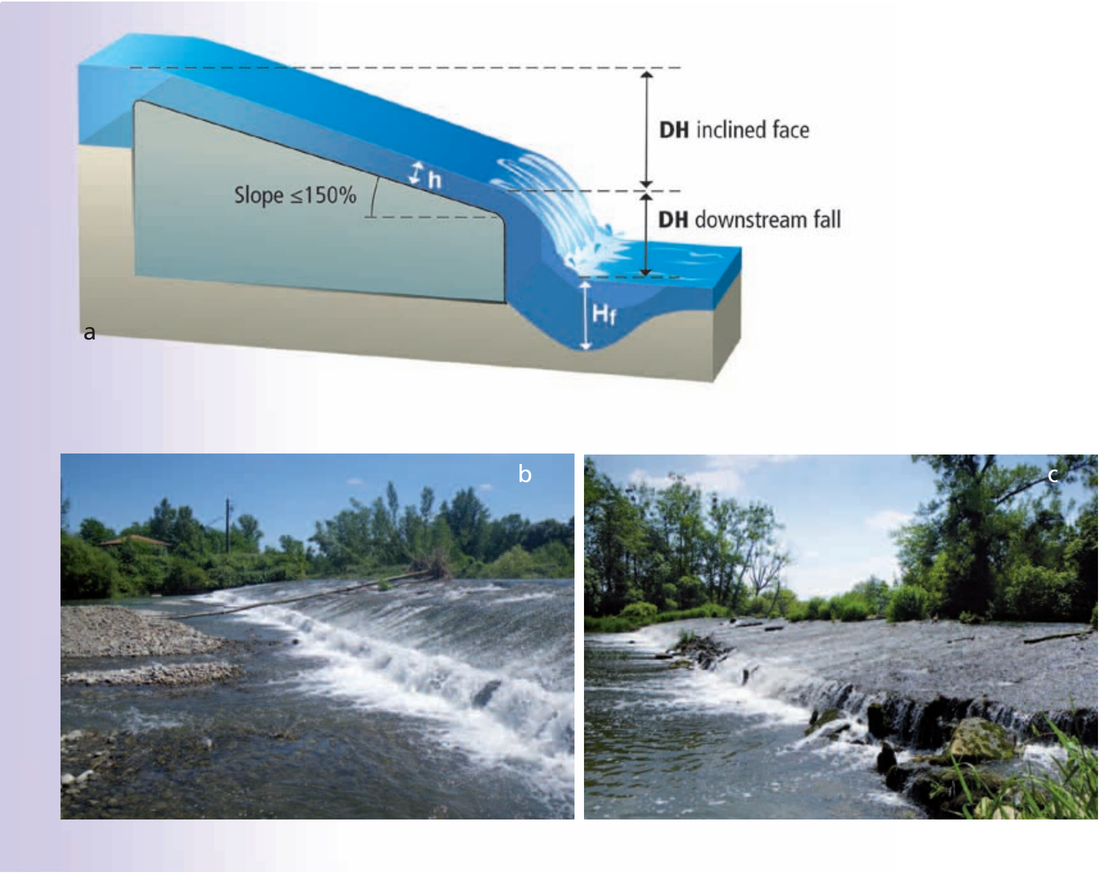
Downstream fall

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

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

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

Figure 68



a © Chanseau - Onema
b © Burgun - Onema

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

Tableau 9

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

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

Determining passability classes

■ Threshold values used for the decision tree

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

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

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

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

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

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

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

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

■ Decision tree

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

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

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

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

2. Analysis of the downstream fall, if it exists

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

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

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

Otherwise, go to Step 3b.

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

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

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

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

4. Analysis of the water depth on the glacis

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

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

5. Analysis of steps on the inclined downstream face

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

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

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

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

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

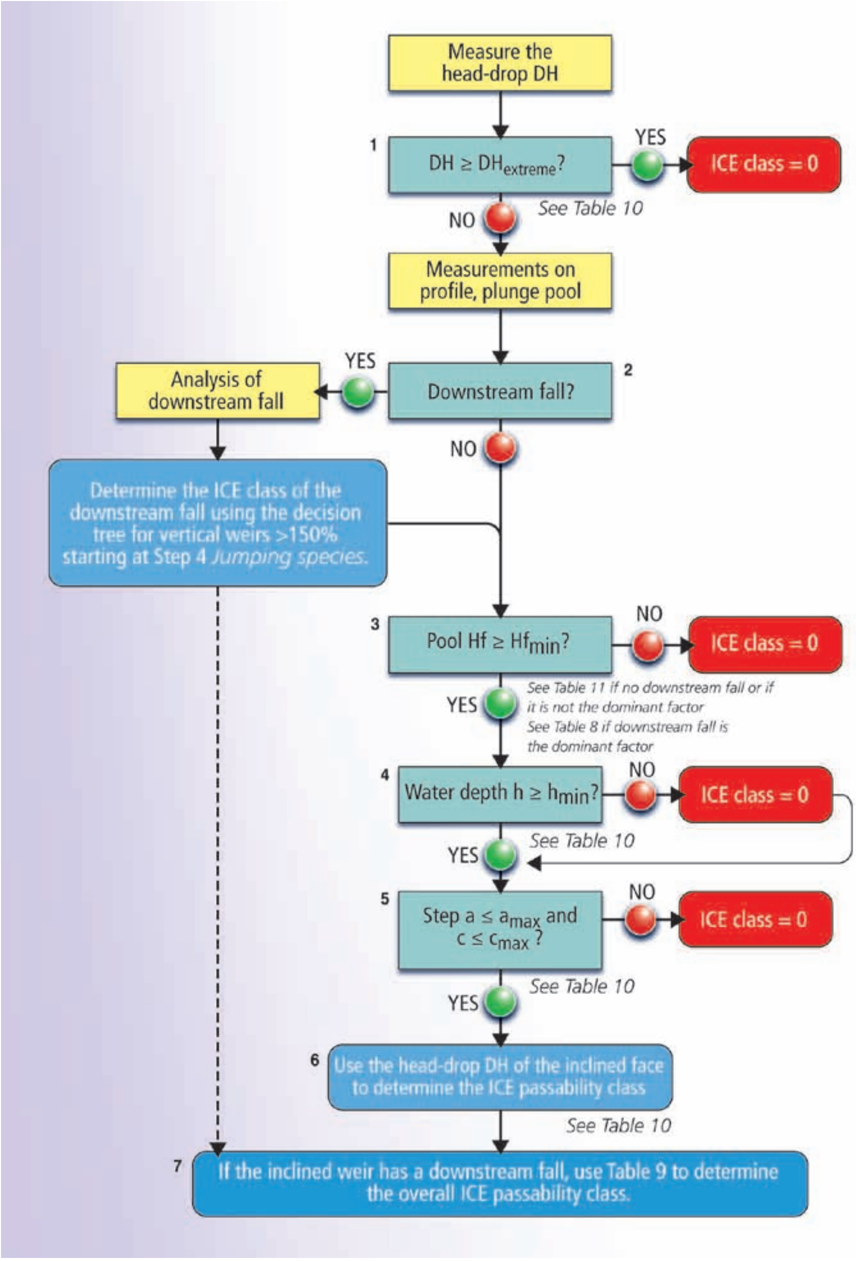
Then go to Step 7.

7. Analysis of the overall passability of the structure

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

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

Figure 69



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

Rock weirs, a special case

General

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

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

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

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

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

Figure 70

a, b © Larinier - Ecohydraulic centre

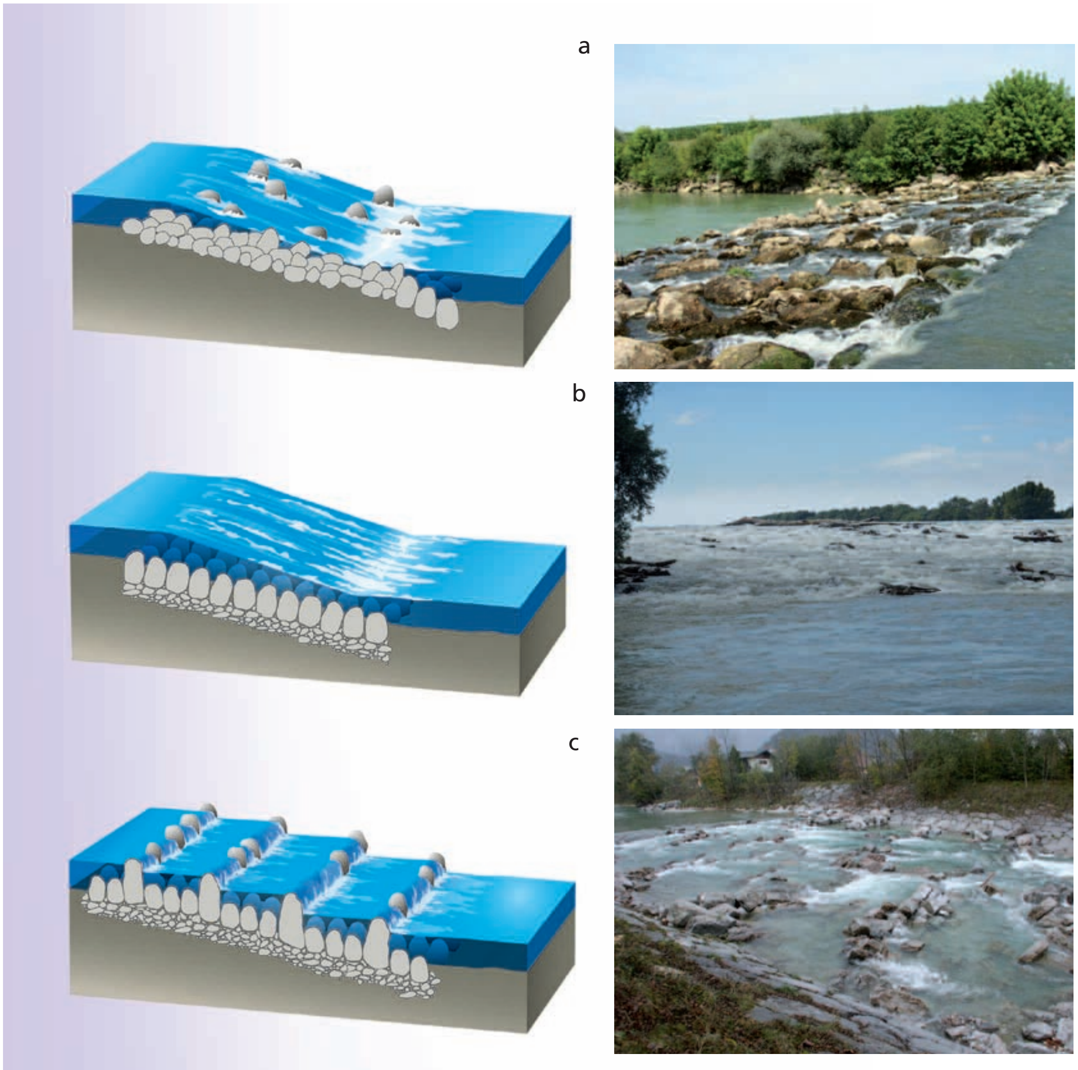
Examples of rock weirs.

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

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

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

Figure 71



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

Examples of various rock-weir layouts.

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

72

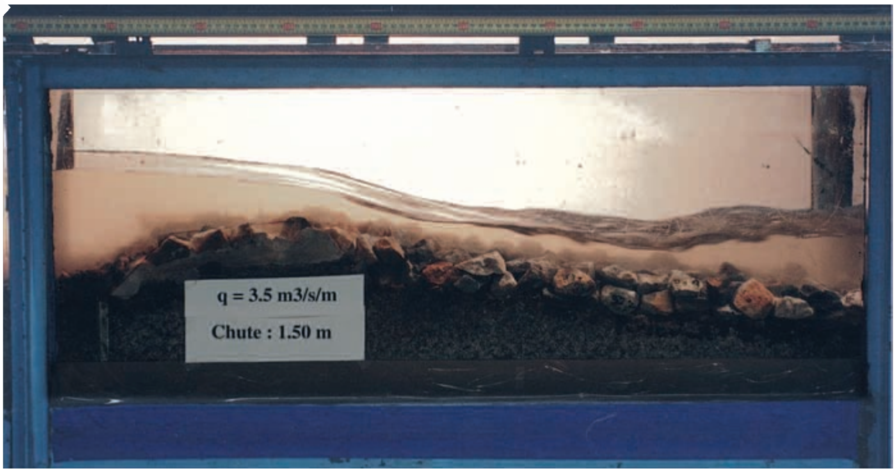
a © Voegtle - Ecogea
b © Larinier - Ecohydraulic centre

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

Fish and hydraulic problems

Similar to an inclined weir (see the section on weirs with inclined downstream faces (slope ≤150%)), the flow velocity increases progressively from the crest downstream until the flow becomes uniform, at which point the average water depth remains approximately constant along the rest of the glacis (see Figure 73). The rougher the surface and the lower the unit discharge, the shorter the distance to create uniform conditions. The distance is approximately 3 to 4 metres for unit discharges of 1 to 2 m³/s/m.

Figure 73



© drawn from *Larinier* et al. (2006)

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

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

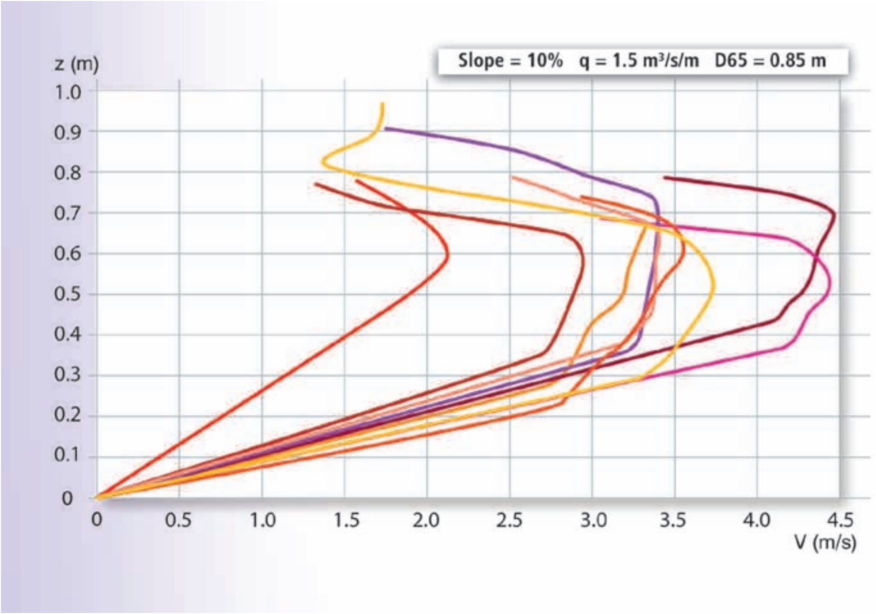
The flow conditions (water depth, velocity, type of flow) are determined by the slope of the glacis, the length of the glacis (or the head-drop), the unit discharge and the surface roughness, which itself depends on the size and shape of the rocks, their layout and whether or not they are joined.

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

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

Figure 74 illustrates this by showing the velocity profiles measured for a 1.5 m³/s/m unit discharge on a rock chute (slope 10%) where the size of the rocks was D65 = 0.85 m. The measurements for several points in the water column in uniform sections reveal the high spatial variability of the velocity profiles (maximum values ranging from 2.1 m/s to 3.7 m/s) and a very strong velocity gradient in the column.

Figure 74



© drawn from Larinier et al. (2006)

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

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

Two factors limit passability:

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

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

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

Figure 75

a © Voegtlé - Ecogea
b © Chanseau - Onema

Examples of flows over rock weirs.

Figure 76

a © Voegtlé - Ecogea
b © Larinier - Onema

Flows over rock weirs vary in quality.

A difficult assessment

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

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

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

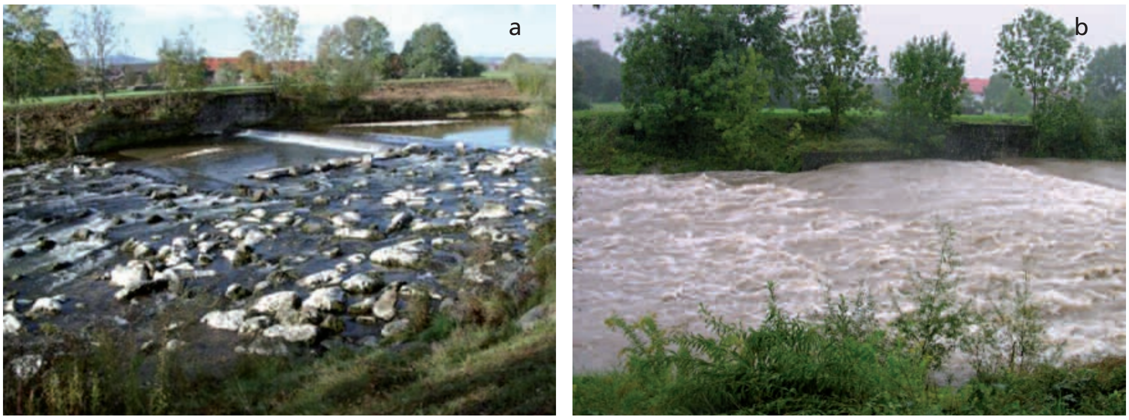
Similarly, **in situ biological assessments using capture-mark-recapture (CMR) or telemetric techniques are complex, require extensive resources** and are limited to a few species (generally large in size). It is also difficult to transfer them to other sites.

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

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

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

Figure 77



© Wang

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

Passability criteria and classes

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

where:

Vm: average flow velocity (m/s)

hm: water depth (m)

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

I: slope of the weir (m/m)

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

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

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

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

Steps

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

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

Figure 78

© Larinier - Ecohydraulic centre

Examples of rock weirs with steps.

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

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

Plunge pool

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

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

Determining passability classes

■ Threshold values used for the decision tree

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

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

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

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

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

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

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

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

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

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

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

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

■ Decision tree

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

1. Analysis of the minimum water depth in the passageway

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

2. Analysis of steps

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

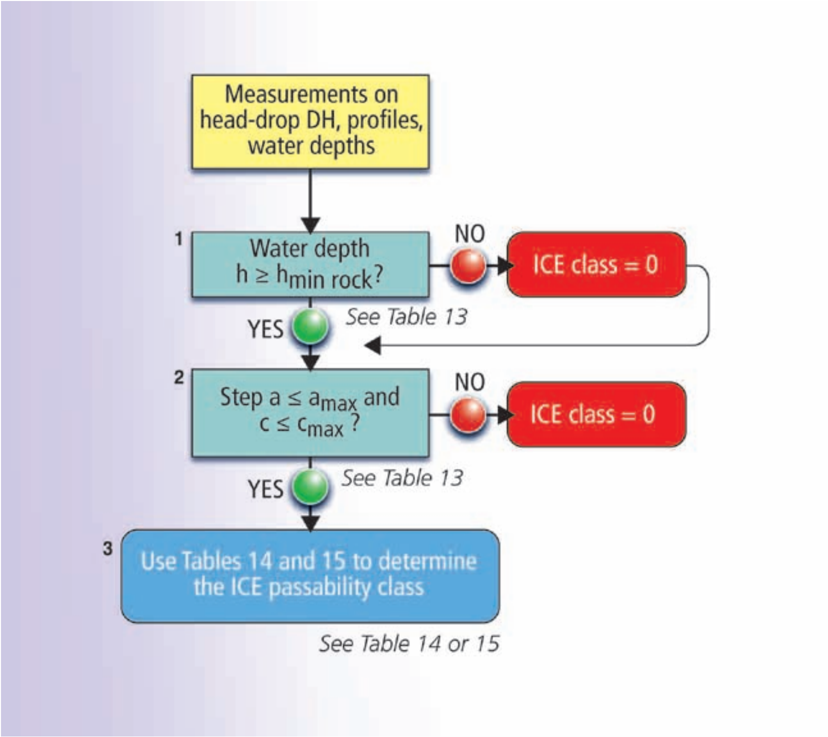
If the dimensions (a and c) of a single step exceed the maximum values a_{max} and c_{max} listed in Table 13, the obstacle may be considered a total barrier (ICE class = 0).

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

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

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

Figure 79



Decision tree to determine ICE passability classes for rock weirs.

Moving parts of an obstacle

Overflows

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

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

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

Figure 80

a © Burgun - Onema
b © Richard - Onema

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

Underflows

Passability criteria

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

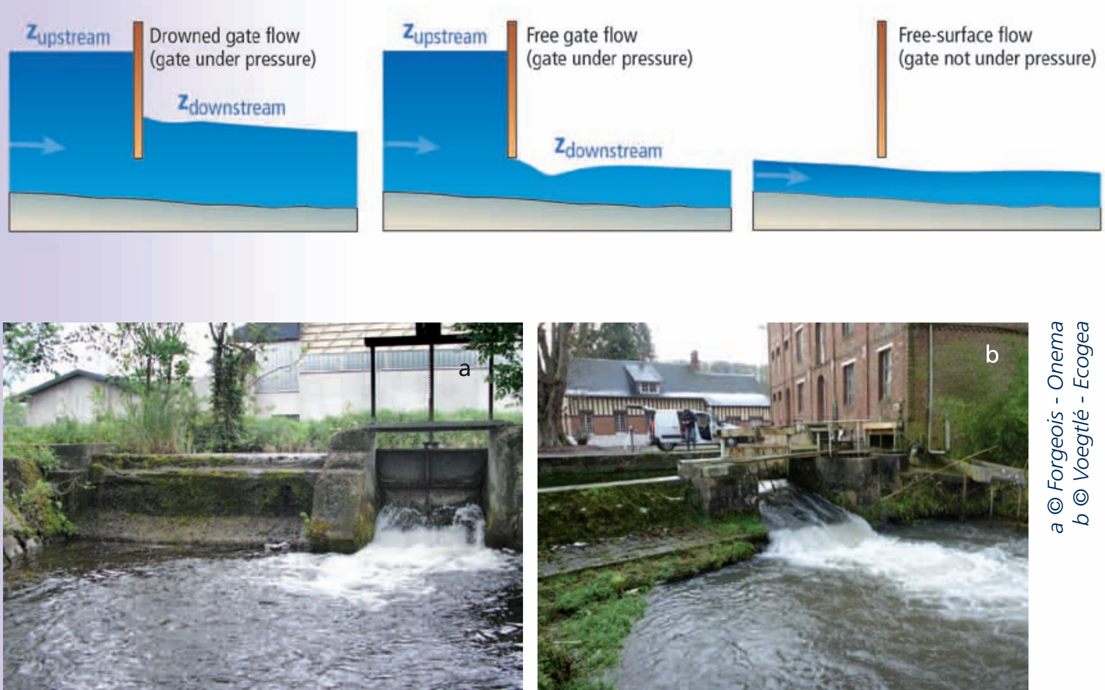
Even though the flow velocities are very often far greater than the swimming capabilities of fish, it is nonetheless worthwhile to acquire the data required to determine the passability of these gates by the various groups of species. This information is even more important when a structure is made up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

■ The different types of flows under gates

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

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

Figure 81



a © Forgeois - Onema
b © Voegtlé - Ecogea

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

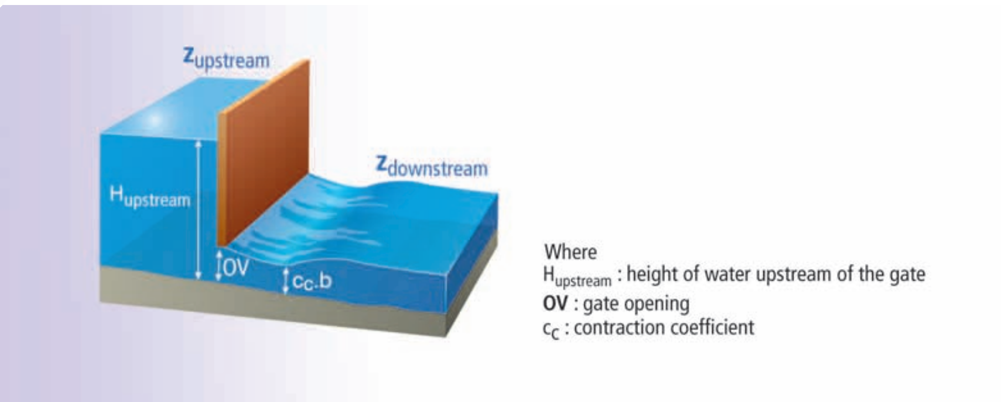
■ Drowned and free gate flows

Free gate flow

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

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

Figure 82



Parameters used to calculate a free gate flow.

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

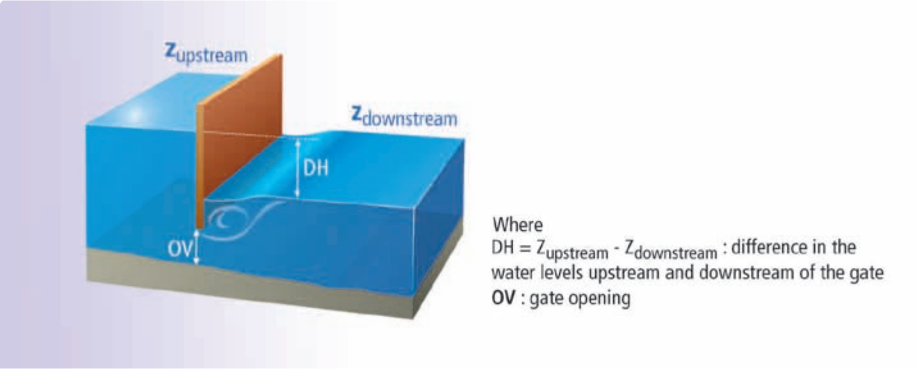
Drowned gate flow

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

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

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

Figure 83



Parameters used to calculate a drowned gate flow.

■ **Definition of passability classes**

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

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

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

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

Size of opening

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

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

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

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

Determining passability classes

■ Threshold values used for the decision tree

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

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

■ Decision tree

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

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

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

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

2. Analysis of the gate opening

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

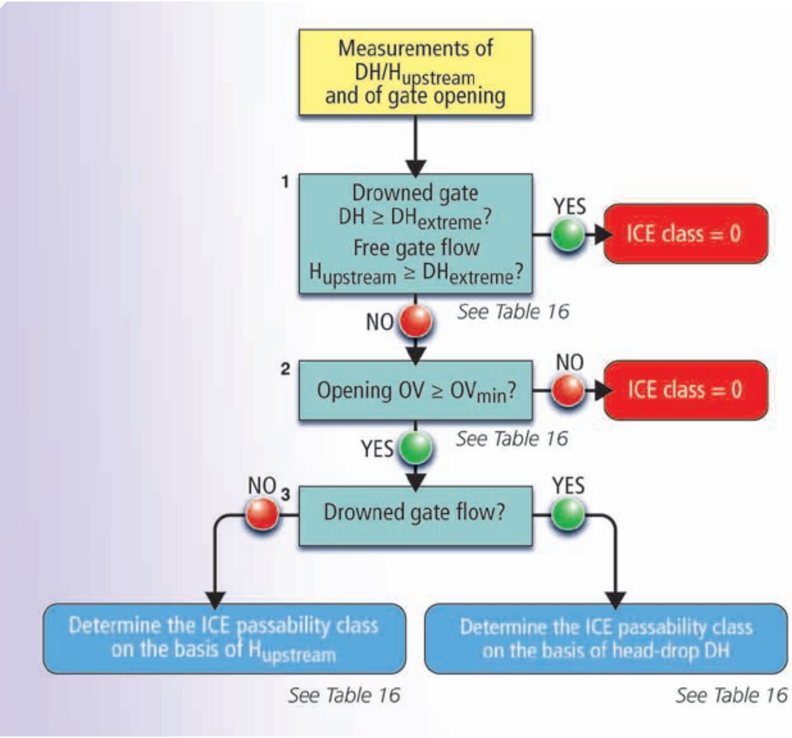
If $OV < OV_{min}$, the obstacle may be considered a total barrier under the current configuration and the current hydrological conditions (ICE class = 0).

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

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

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

Figure 84



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

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

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

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

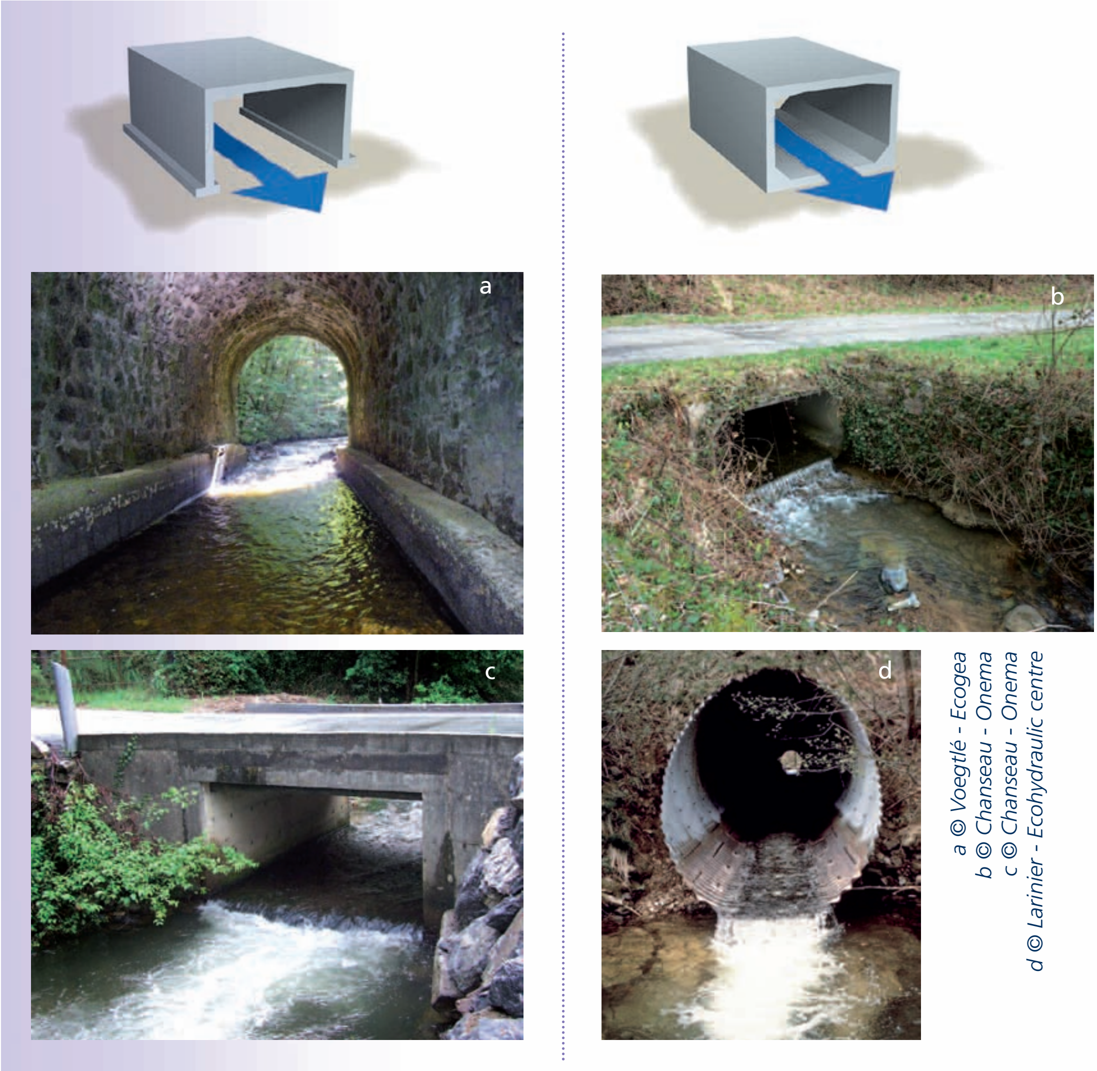
Road/rail structures

The different types of structures

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

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

Figure 85



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

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

The main causes limiting passage

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

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

■ Excessive flow velocities inside structures

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

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

Figure 86

a © Voegtlé - Ecogea
b © Baudoin - Onema

Examples of high flow velocities in culverts.

■ Insufficient water depths

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

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

Figure 87

a © Voegtlé - Ecogea
b © Onema

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

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

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

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

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

Figure 88

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

Examples of falls downstream of road structures.

■ Poor positioning at the head of the structure

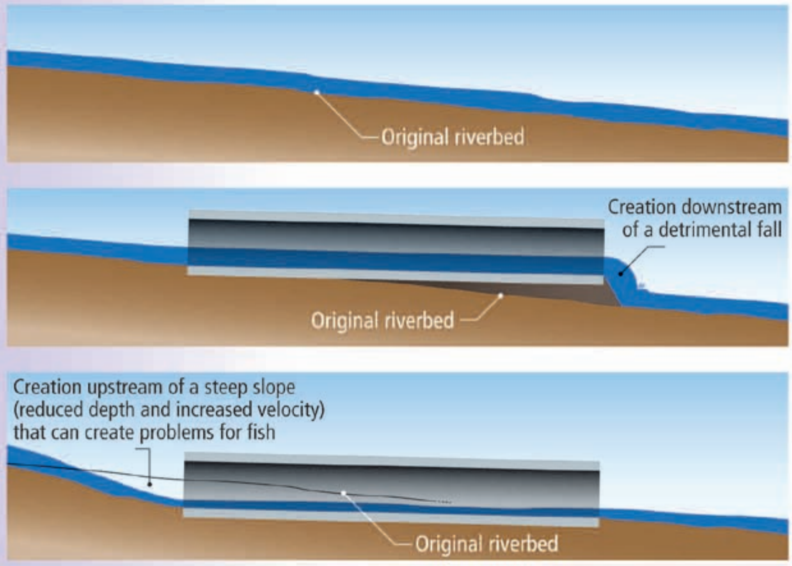
Poor positioning at the head of the structure may, in some cases, result in the creation just upstream in the riverbed of a zone characterised by high velocities and low depths that is difficult for fish to overcome (see Figures 89a and 89b).

Figure 89a

© Voegtlé - Ecogea

Example of high flow velocities created upstream of culverts.

Figure 89 b



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

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

Figure 90

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

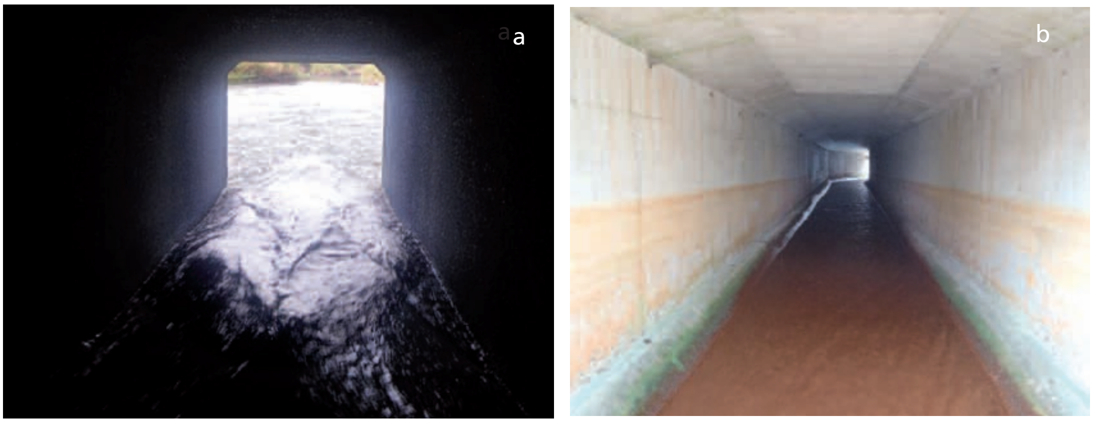
Diagrams and photos of structures with sufficient and insufficient air passage.

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

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

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

Figure 91



a © Voegtlé - Ecogea
b © Chanseau - Onema

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

Assessment procedure

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

The expended anaerobic power can therefore be written as:

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

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

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

As a result:

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

And:

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

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

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

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

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

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

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

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

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

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

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

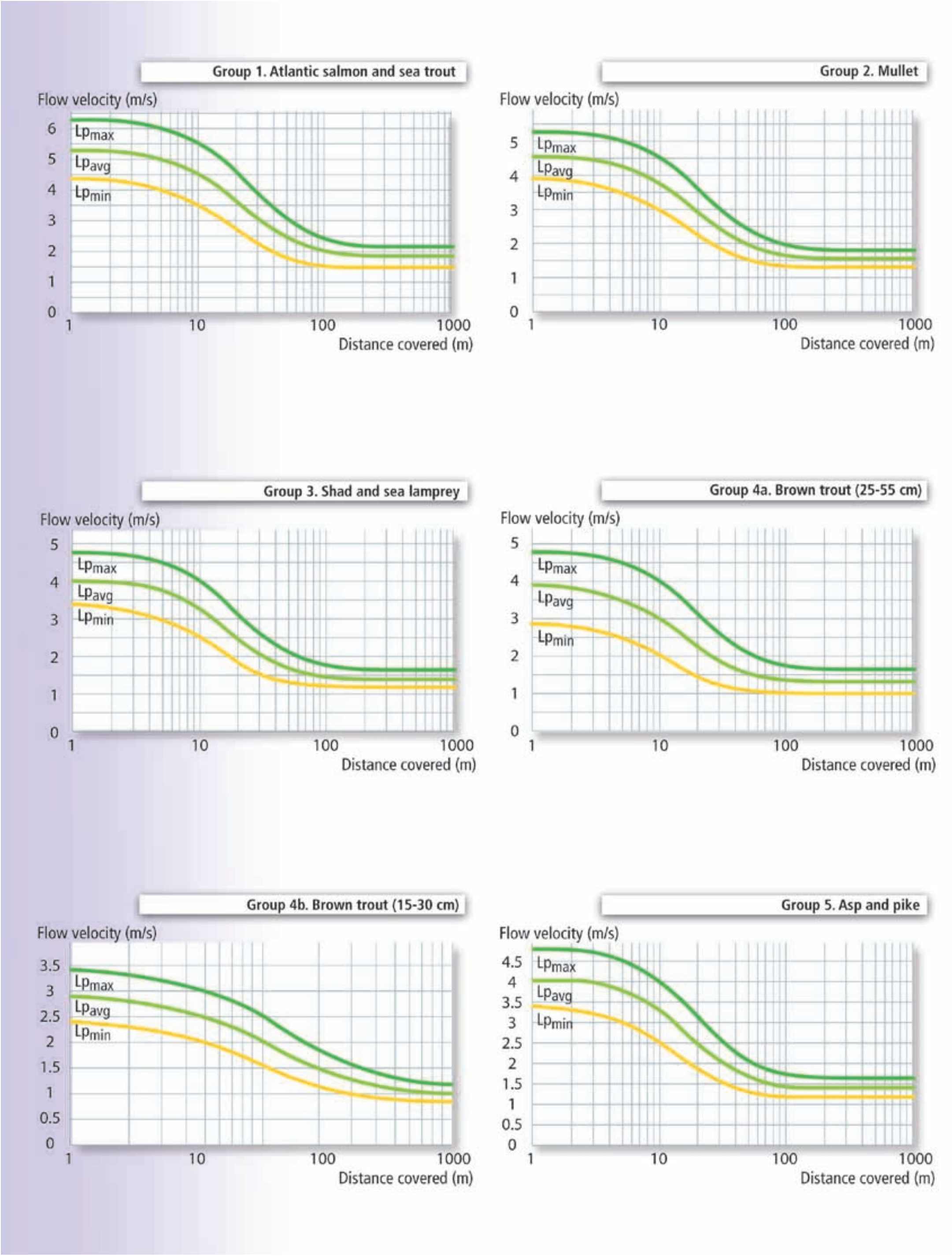
When the flow velocity exceeds two-thirds of the maximum swimming speed, the distance covered is greatest when the fish swims at its maximum speed.

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

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

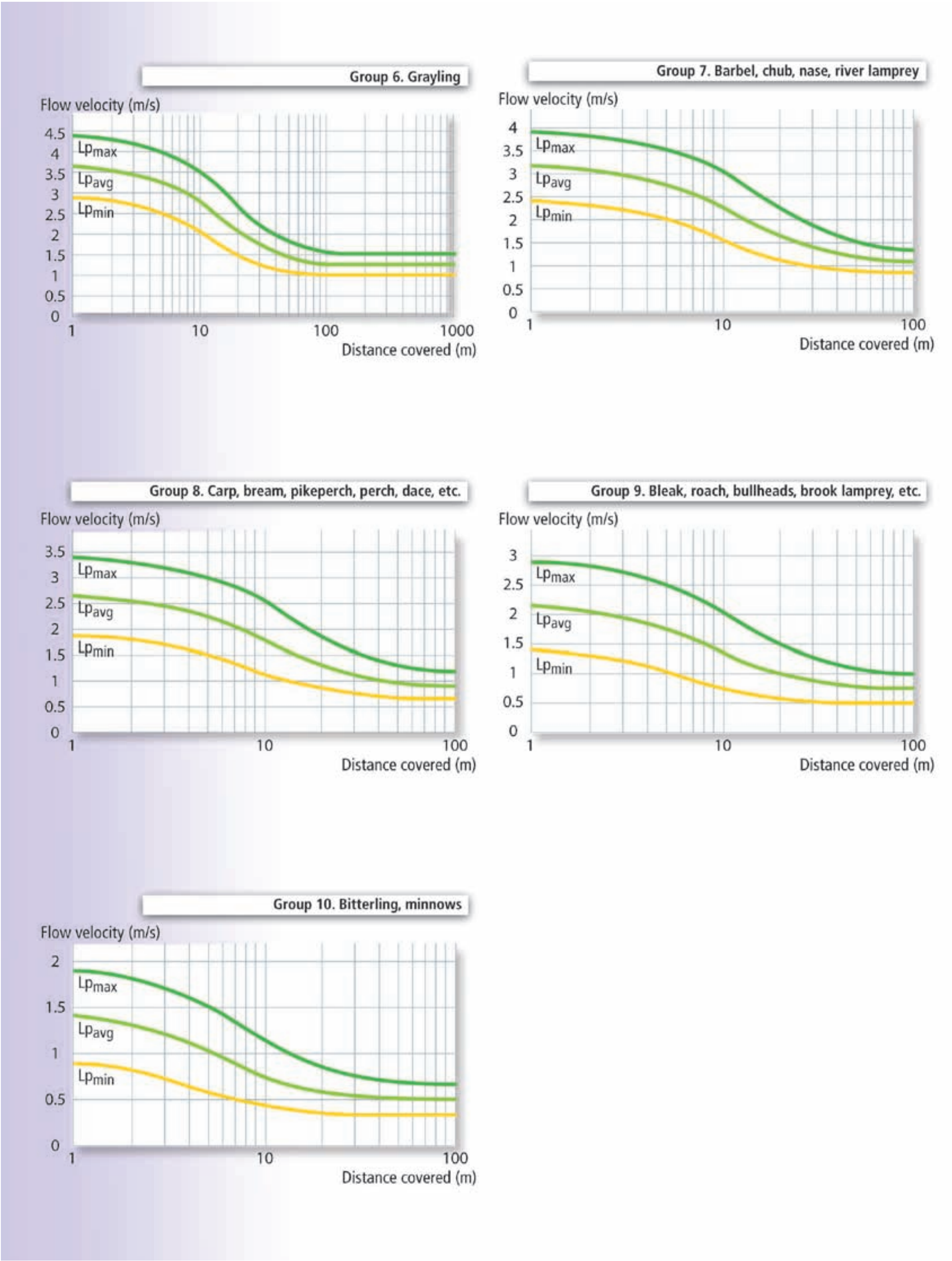
For each species or group of species, the dark green, light green and yellow lines correspond to the largest (Lp_{max}), average (Lp_{avg}) and smallest (Lp_{min}) fish, respectively.

Figure 92



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

Figure 93



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

Definition of passability classes

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

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

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

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

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

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

Downstream fall

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

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

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

Figure 94

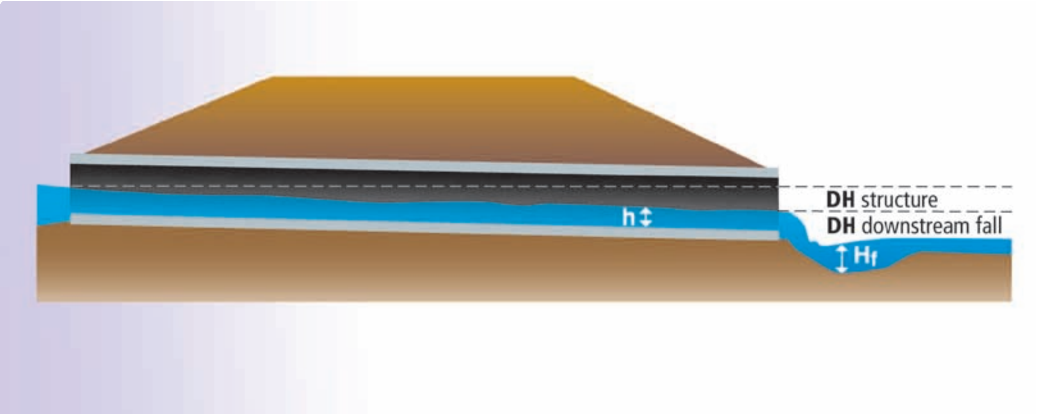


Diagram showing a road structure with a downstream fall.

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

Tableau 17

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

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

Step in the structure

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

Figure 95

© Baudoin - Onema

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

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

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

Structures submerged upstream and/or downstream

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

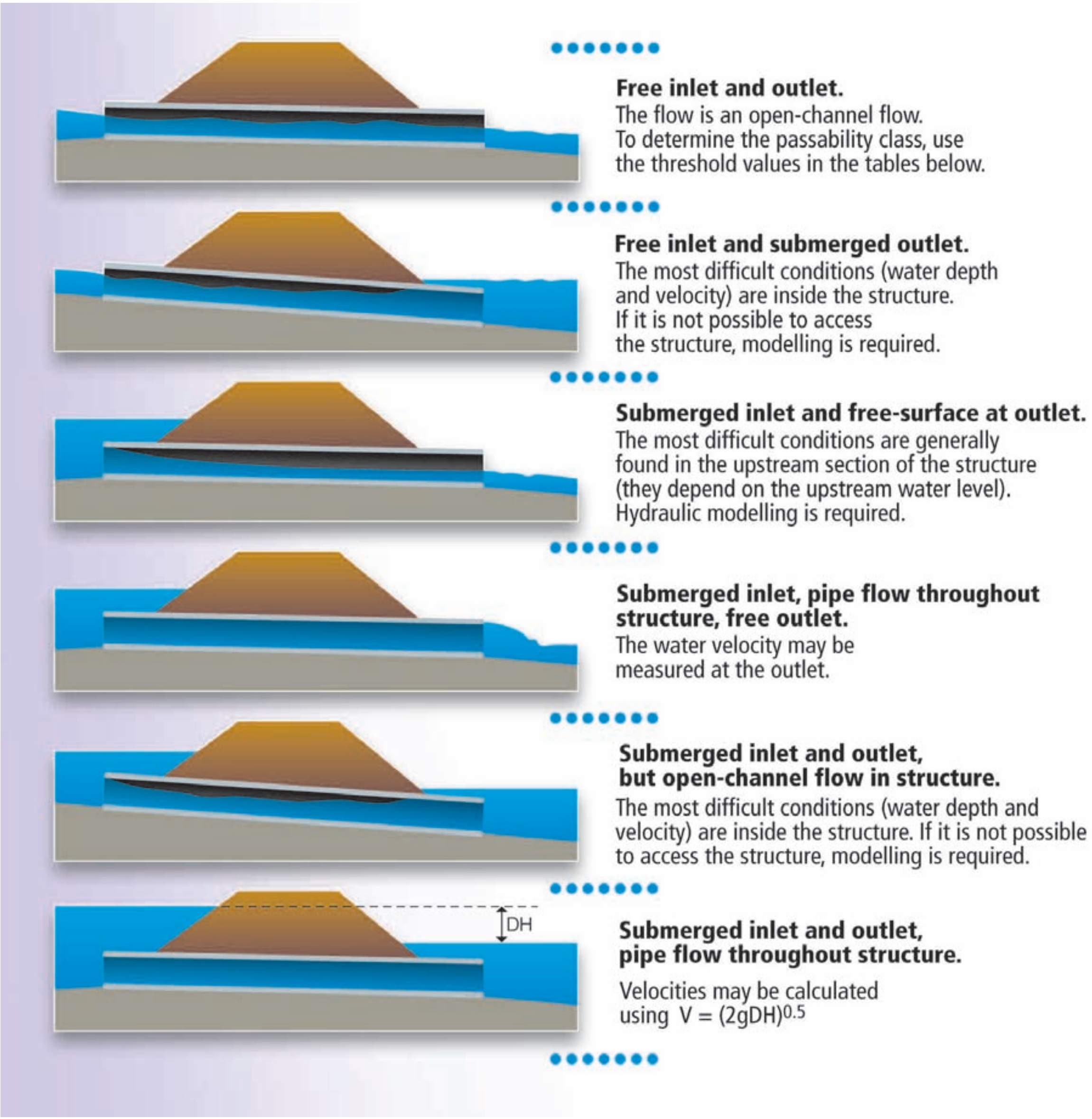
When the structure is submerged upstream, the hydraulic passageways are generally fairly small (round or box culvert) and it is difficult to measure the water velocities and depths. **Determination of structure passability will require an assessment of the maximum velocity using orifice calculations**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

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

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

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

Figure 96



Various flow configurations in culverts.

Determining passability classes

■ Threshold values used for the decision tree

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

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

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

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

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

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

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

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

■ Decision tree

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

1. Analysis of the downstream fall, if it exists

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

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

2. Analysis of the water depth in the structure

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

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

3. Analysis of steps in the structure

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

4. Analysis of the slope

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

5. Analysis of flow velocities

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

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

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

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

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

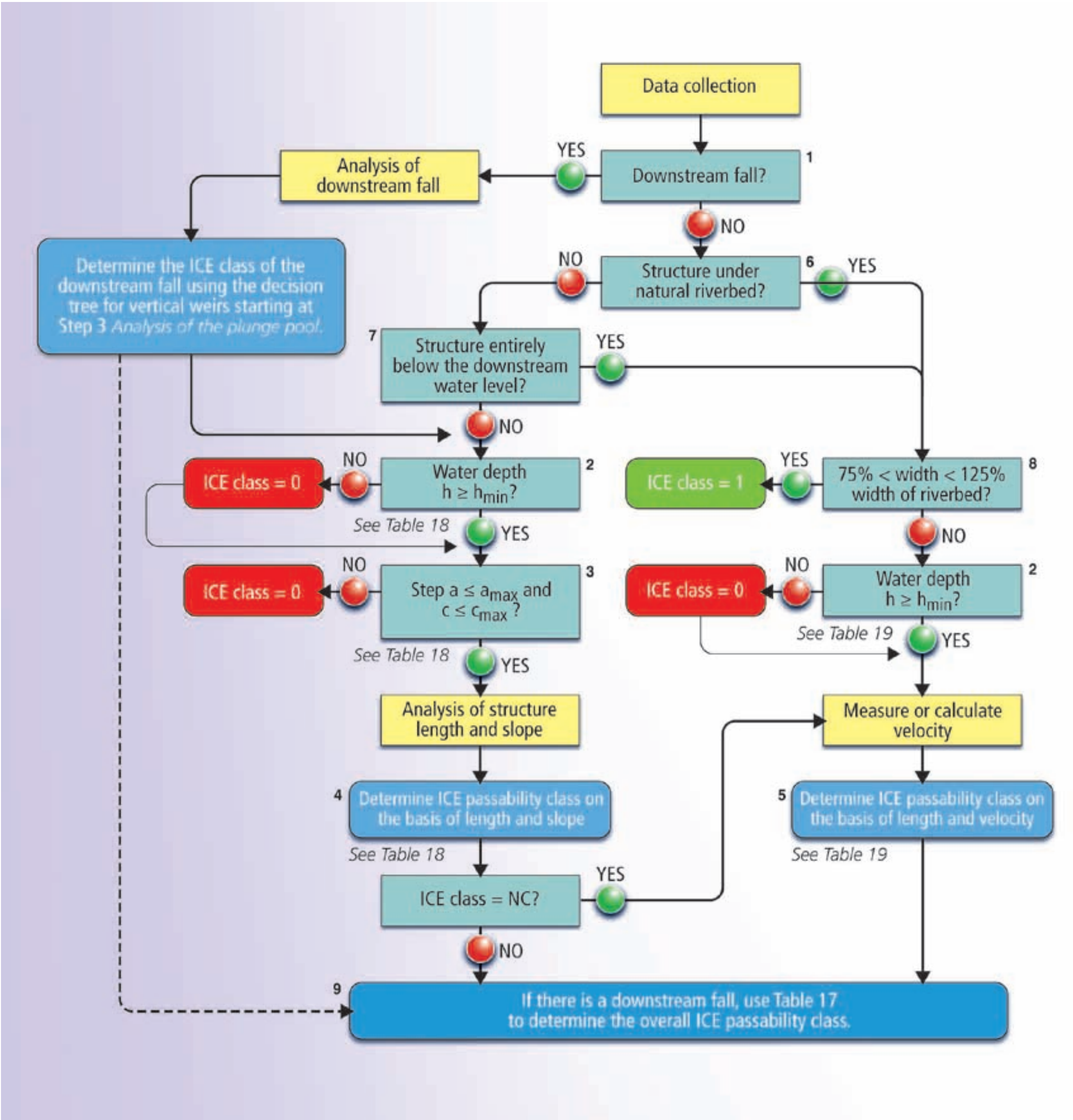
8. Analysis of the structure width

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

9. Analysis of structure passability

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

Figure 97



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

Tidal structures

General

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

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

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

Figure 98

a, b © Voegtlé - Ecogea

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

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

Figure 99

a, b © Voegtlé - Ecogea

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

The different types of structures

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

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

Figure 100

a © Voegtlé - Ecogea
b © Chanseau - Onema

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

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

Figure 101

a © Voegtlé - Ecogea

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

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

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

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

Figure 102

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

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

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

Assessment of passability

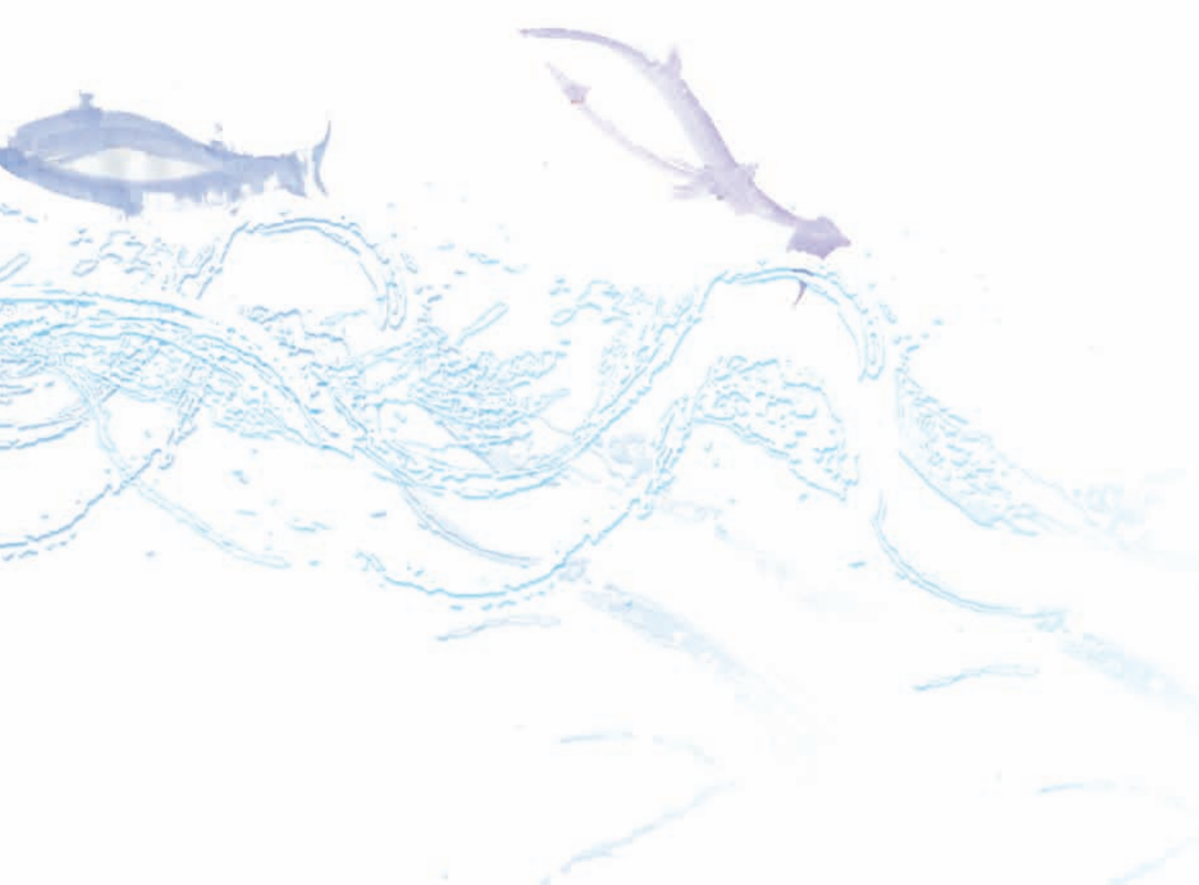
Knowledge on the behaviour of fish at tidal structures and on the influence of tides is still very limited, due notably to the complexity of the necessary experiments. It is nonetheless possible to say that a majority of the concerned species take advantage of the high tides to colonise the areas upstream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

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

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

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

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



Complex and mixed structures

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

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

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

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

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

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

Figure 103

a © Onema
b © Voegtlé - Ecogea

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

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

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

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

Figure 104

a © Voegtlé Ecogea
b © Richard - Onema

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

Determining the passability class for each part of a structure

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

Determining the passability class for the structure as a whole

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

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

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

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

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

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

Below are a number of examples.

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

Eels, a special case

Specific approach

■ General

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

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

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

■ Size of eels

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

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

Older fish, namely elvers and yellow eels, have greater swimming capabilities than glass eels. They can swim over some obstacles having low head-drops when crawling is not possible.
To take into account the specific aspects of each age, two distinct groups were created:

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

■ Passability criteria and integration of crawling capabilities

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

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

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

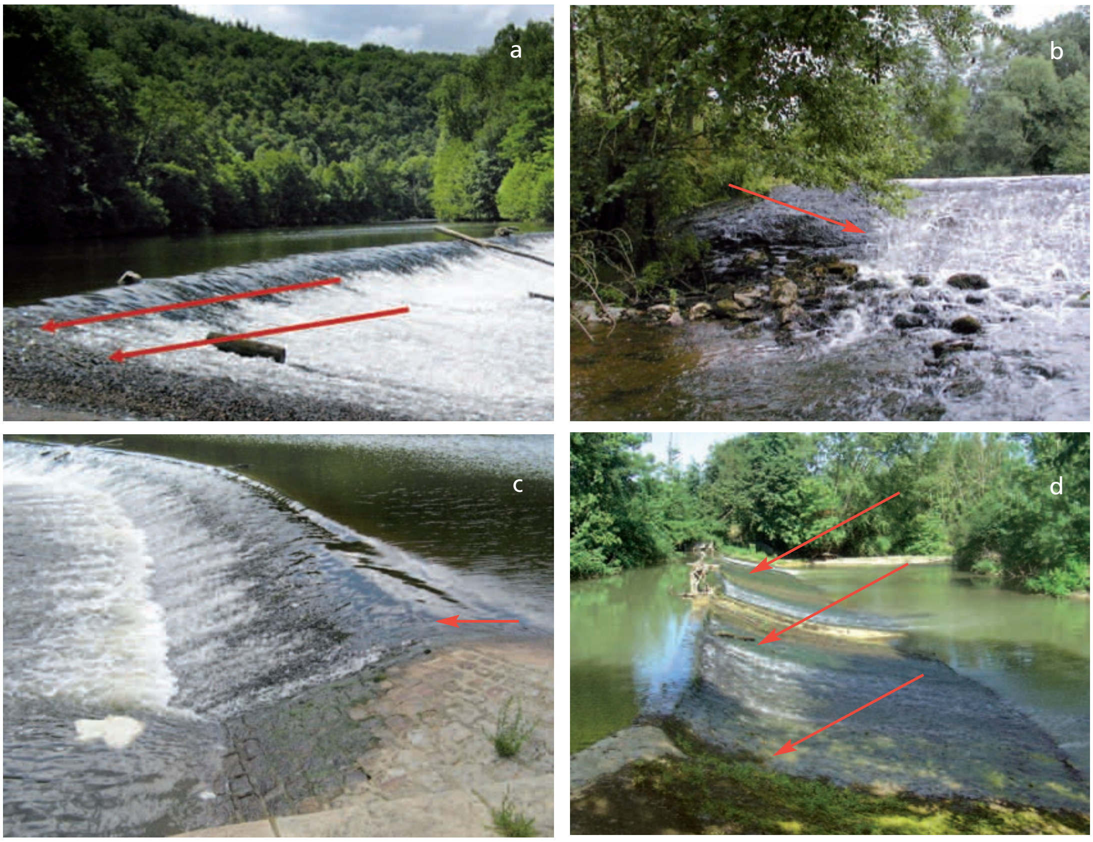
Does a crawl way exist?

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

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

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

Figure 105



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

Examples of crawl ways.

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

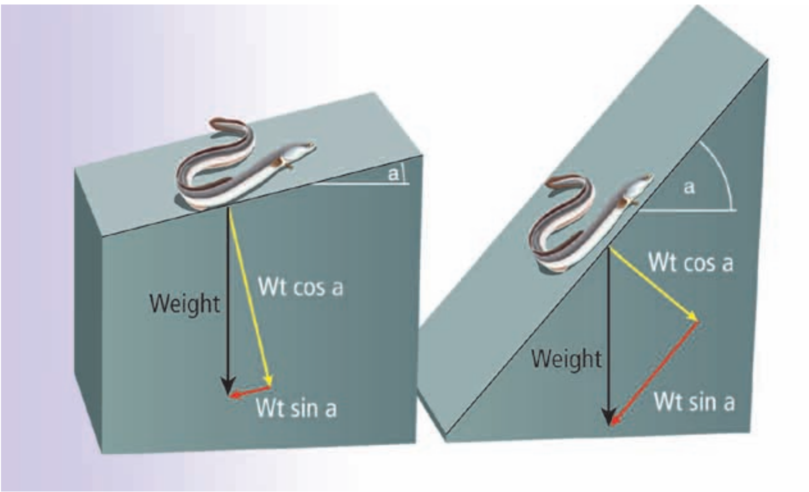
For glass eels, which have no real swimming capability, the obstacle may be considered a total barrier (ICE class = 0).

Slope

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

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

Figure 106



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

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

Tableau 21 *Breakdown of weight into two components.*

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

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

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

Distance to be overcome

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

Determining passability classes

■ Threshold values used for the decision tree

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

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

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

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

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

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

■ Decision tree

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

1. Does a crawl way exist?

If a continuous passageway exists with a very low flow depth (< 20 mm for elvers and < 10 mm for glass eels), then draft the long profile of the potential crawl way and go to Step 3.
If not, eels are required to use their swimming capabilities. Go to Step 2.
However, if a crawl way is not manifest, it may nonetheless be worthwhile to determine the passability class for more favourable hydrological conditions under which a crawl way may appear. Depending on the score of the subsequent analysis (Step 3), it will be possible to decide whether or not to return to the obstacle for measurements under other discharge conditions.

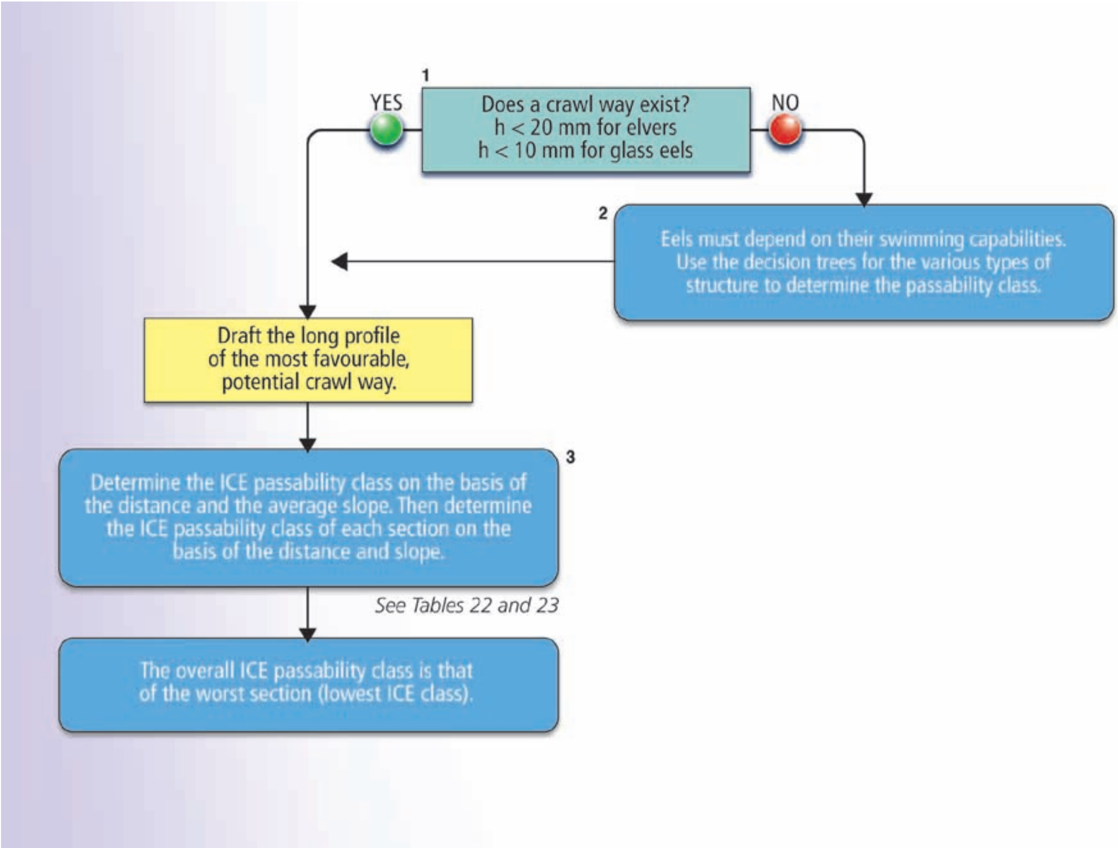
2. Determining the overall passability class of the obstacle if a crawl way does not exist

For elvers, use the various tables for the different types of structures in the same manner as for the other fish species.
For glass eels, the obstacle may be considered a total barrier (ICE class = 0).

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

Determine the ICE passability class using Tables 22 and 23, taking into account the total distance and the average slope of the crawl way.
If the crawl way was broken down into different sections, determine the passability class of each section using the same tables. If one or more of the sections are assigned a passability class lower than the class for the crawl way as a whole, the lowest class determines the result for the entire crawl way.

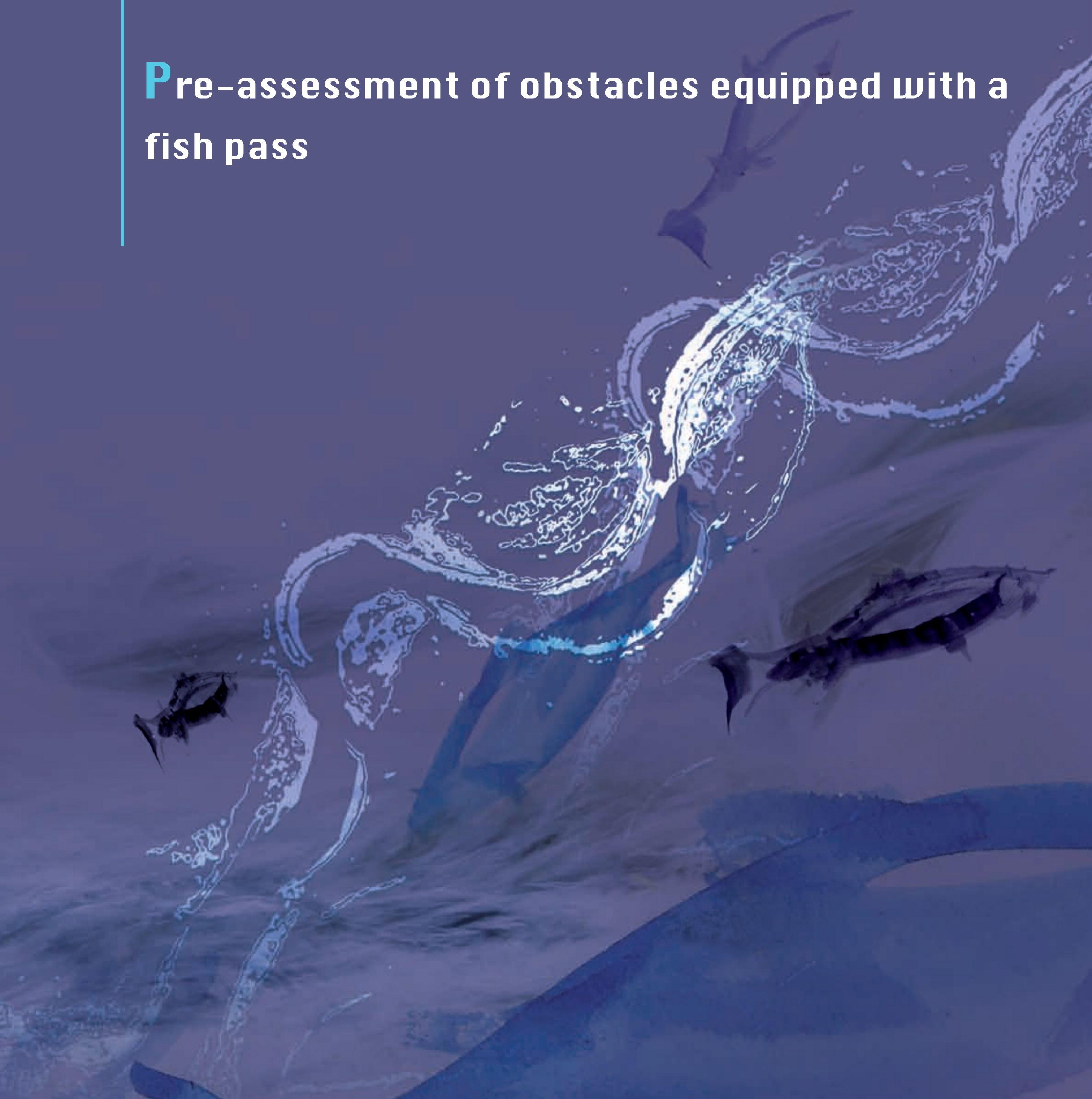
Figure 107



Decision tree to determine ICE passability classes for eels.

D

Pre-assessment of obstacles equipped with a fish pass



The different types of fish pass

This chapter presents the main types of fish pass likely to be encountered at structures and explains the general operating principles.

For more information, a number of technical guides on system sizing may be consulted, notably those listed below:

- *Larinier M., Porcher J.P., Travade F., Gosset C. (1994). Passes à poissons. Expertise, Conception des ouvrages de franchissement. Conseil Supérieur de la Pêche. Collection Mise au point.*
- *Larinier M., Courret D., Gomes P. (2006). Guide technique pour la conception des passes « naturelles ». Rapport Ghaappe RA.06.05-V1.*

Most of the information below is drawn from the two guides listed above. They may be consulted on the EauFrance portal (www.documentation.eaufrance.fr).

Pool-type fish passes

Basic idea behind pool-type fish passes

The basic idea is to divide the total height that the fish must overcome into a series of pools. The water can flow from one pool to the next by overflowing each partition, by flowing through one or more orifices in the partitions separating the pools or by flowing through one or more slots or notches. There are also hybrid fish passes where the water flows both over the partitions and through a submerged orifice.

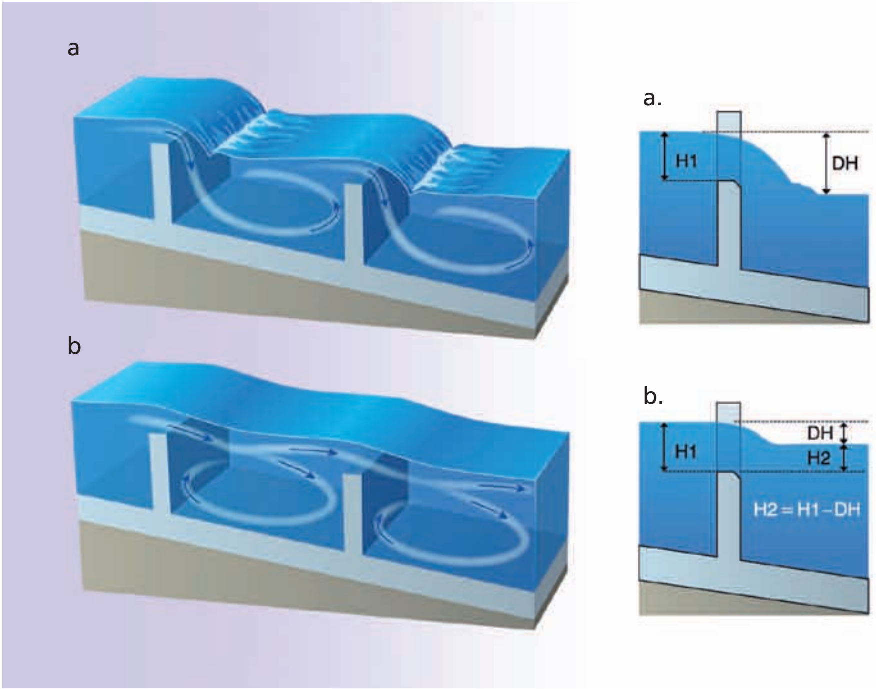
The main parameters of a fish pass are the size of the pools and the geometric characteristics of the partitions which, depending on the water level upstream and downstream of the fish pass, determine the hydraulic characteristics of the fish pass (discharge, water flow between pools, flow characteristics in each pool).

Head-drop between each pool and type of flow

The head-drop DH between each pool depends on the swimming and jumping capabilities of the species in question.
The flow may be a plunging jet (see Figure 108a) or a skimming flow (see Figure 108b). In the first type, the jet that forms over each partition plunges to the bottom of the pool. The energy is dissipated in the turbulent mixing and dispersed in the hydraulic jump at the foot of the fall. The fish must jump through the sheet of water flowing over the partition to reach the next pool. Plunging jets must imperatively be avoided for species that cannot jump.

When a skimming flow exists, the energy is dissipated in the lower pool through the creation of large recirculation currents. This type of flow occurs when the downstream water level is higher than the top of the partition and the depth of water higher than the partition is equal to approximately one-half of the overflow height.

Figure 108



Types of flow over partitions in pool-type fish passes. (a) Plunging jet, (b) skimming flow.

■ Size of pools

The minimum length of pools is primarily a function of the size of the fish using the fish pass. A minimum length of approximately 2.5 to 3 times the length of the largest fish is generally recommended.

Similarly, the minimum depth of the pools is also a function of the species in question. For large migratory salmonids, the minimum depth should be around one metre. For trout, lesser depths of approximately 0.75 metre are possible.

In fish passes with plunging jets, the depth of water immediately below the jet must be at least double the head-drop between pools to enable fish to prepare the jump.

Practically speaking, it is generally the hydrodynamic conditions (discharge, head-drop between pools, jet characteristics) that determine the minimum dimensions of the pools.

Difficulties for fish increase with the degree of turbulence and aeration in the pools. A simple indicator of the agitation in the pools of a fish pass is the dissipated power density (expressed in Watts/m^3).

■ Minimum dimensions of notches, orifices and slots

For skimming flows, notches and slots must generally be at least 30 to 40 cm wide for large migratory salmonids, 40 to 50 cm for shad, 25 cm for rheophilic cyprinids and 15 cm for very small species.

For plunging jets, much larger widths are required, particularly if fish must make a considerable effort to jump to the upper pool.

For all species, even the smallest, passageways should be wide enough (greater than 15 to 20 cm) to avoid making the pass excessively vulnerable to clogging by debris.

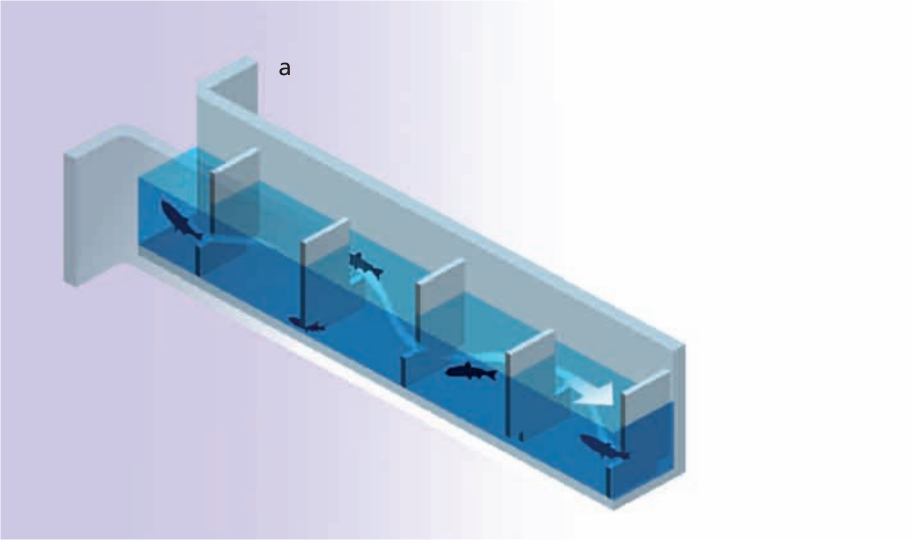
For orifices at the bottom of the pool intended for the passage of fish, the minimum surface area is approximately 0.1 square metre for large fish and 0.03 square metre for trout and most cyprinids.

■ The main forms of pool-type fish passes

Passes with deep, lateral notches and submerged orifices

Travel between pools takes place via lateral notches and bottom orifices located on opposite sides of each partition and changing sides from one partition to the next. A deflector on the upstream face of each partition stabilises the flow and reduces the "curl" of the water around the end of the partition (see Figure 109).

Figure 109



b © Mayeras - Ecogea
c © Voegtlé - Ecogea

Diagram and examples of fish passes with lateral notches and bottom orifices. (a) Diagram, (b) fish pass with lateral notches at the Las Rives weir on the Ariège River, (c) fish pass with lateral notches at the Eygun draw-off on the Gave d'Aspe River.

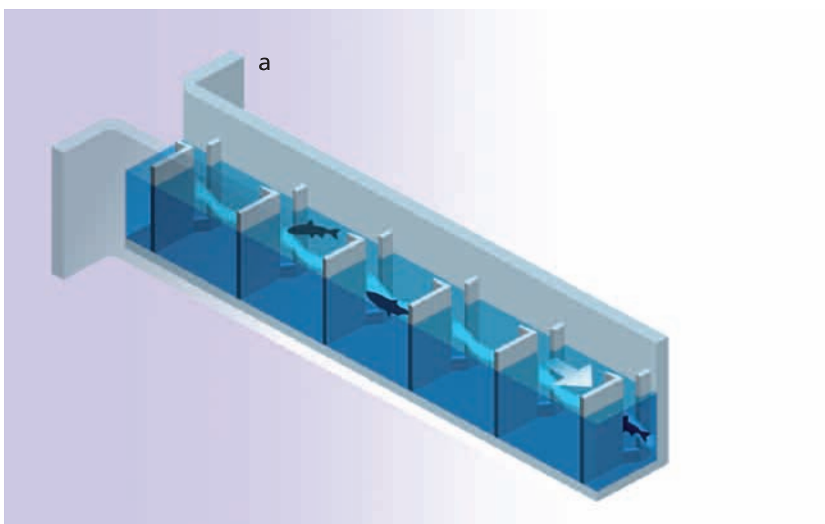
Fish passes with vertical slots

The currents passing through the slots (when two slots exist) converge and meet in the central section of the downstream pool, effectively dissipating the flow energy and creating calm zones on each side of the pool and in the area immediately downstream of the partition (see Figure 110).

The major advantage of fish passes with vertical slots is that they can handle significant variations in the upstream water level, on the condition that similar variations occur on the downstream level.

In addition, if the slots extend to the bottom of the pool, this type of pass is suitable for both benthic and open-water species due to the velocity gradient.

Figure 110



b, c © Voegtlé - Ecogea

Diagram and examples of fish passes with vertical slots. (a) Diagram, (b) fish pass with two slots for each pool at the Coy dam on the Gave de Pau River, (c) fish pass with a single slot for each pool at the Susmiou factory on the Gave d'Oloron River.

Fish passes with triangular notches

Fish passes with triangular notches were designed to create a type of pass capable of operating under a wide range of upstream discharge and water-level conditions without requiring added discharge in the downstream section or a device regulating the upstream discharge. In this type of pass, the water flows over each partition into the next pool. The profile of each partition is triangular or semi-triangular. The result is generally a mixed form of operation, with a skimming flow over the lower part of the partition and a plunging jet on the sides (see Figure 111).

Under high-water conditions, a fast skimming flow forms in the centre of the pass whereas the lateral flows remain manageable for the fish. Fish passes with triangular notches function as pool-type passes under low-flow conditions and as a rough channel under high-water conditions. There is consequently no point in attempting to reason in terms of the maximum dissipated power density in a given pool.

Figure 111

a © Larinier - Ecohydraulic centre
b © Voegtle - Ecogea

Examples of fish passes with triangular notches. (a) The Sarrancolin fish pass with triangular notches on the Neste River, (b) the Jaulnes fish pass with triangular notches on the Seine River.

Pre-barrages

Pre-barrages often represent an elegant solution to assist fish in overcoming relatively low obstacles. The system consists of several walls or weirs creating large pools downstream of the obstacle, thus splitting the total height that must be overcome (see Figure 112). They are generally located near one of the river banks to facilitate their maintenance. On small rivers, they can span the entire riverbed without causing any problems.

Given that the flow between two pools is generally a plunging jet and that the fall is greater than 40 to 50 cm, this type of fish pass is suitable for jumping species and specifically salmonids. However, particularly for low obstacles, this type of fish pass can be adapted to the needs of less agile species by reducing the height between pools and ensuring a skimming flow between pools.

Figure 112

b, c © Voegtlé - Ecogea

Examples of pre-barrages. (a) Pre-barrages at the Guilhot dam on the Ariège River, (b) pre-barrages at the Gurmençon dam on the Gave d'Aspe River.

Rock-chute fish passes

Rock-chute fish passes consist of a channel linking the upstream and downstream reaches in which the flow energy is dissipated by roughness along the bottom and sides and/or a succession of obstacles (rocks, groynes, weirs, etc.) positioned more or less regularly in order to create a passageway for the fish.

This type of pass represents a rough equivalent to a natural river with a high slope. They generally require the installation of large rocks to dissipate the energy, reduce flow velocities and increase the water depth.

The slope is fairly low compared to other fish passes and varies from 1% to a maximum of 10%, depending on the species in question.

The pass can be installed across part or the entire width of the obstacle or to the side (bypass branch).

Two main types of rustic rock-chute fish passes exist. They differ on how the energy is dissipated by the elements disrupting the flow:

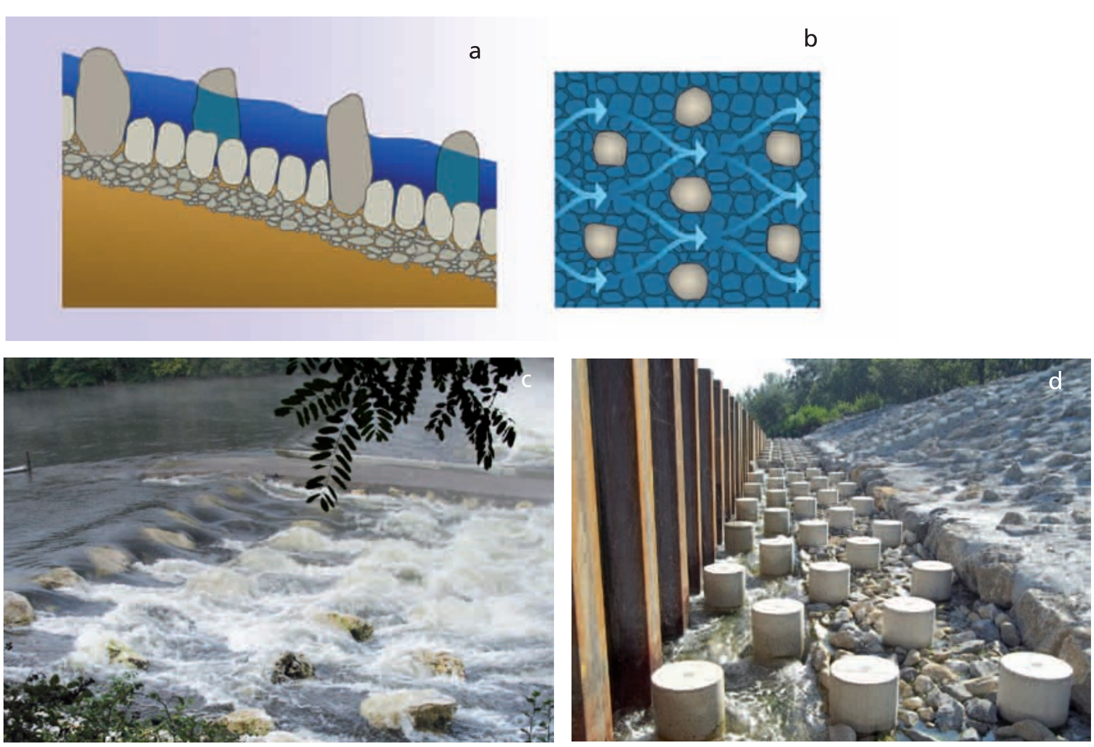
- **fish passes with staggered arrays of elements;**
- **fish passes with successive rows of elements.**

Rock chutes made up of joined riprap, in a compact layout forming a continuous rough surface, pose problems for many fish species. **They cannot be considered true fish passes unless the longitudinal slope remains very slight (less than 3%).**

Fish passes with staggered arrays of elements

In this configuration, the flow energy is dissipated by the more or less regularly distributed large elements spread separately over the rock chute (see Figure 113).

Figure 113



a, b © according to Larinier et al, 2006
c © Chanseau - Onema
d © Roche - Onema

Diagrams and examples of rock chutes with staggered arrays of elements.
(a) and (b) Diagrams of rock chutes with staggered arrays of elements, (c) rock chute at the Carennac weir on the Dordogne River, (d) fish pass at the weir for the ASF A7 highway over the Rubion River.

Each area immediately downstream of the large elements is a shelter and rest zone for migrating fish.

The spaces between elements (lateral and longitudinal distances) are generally regular and depend on the slope of the chute, the discharge transiting the pass and the passage capabilities of the given species.

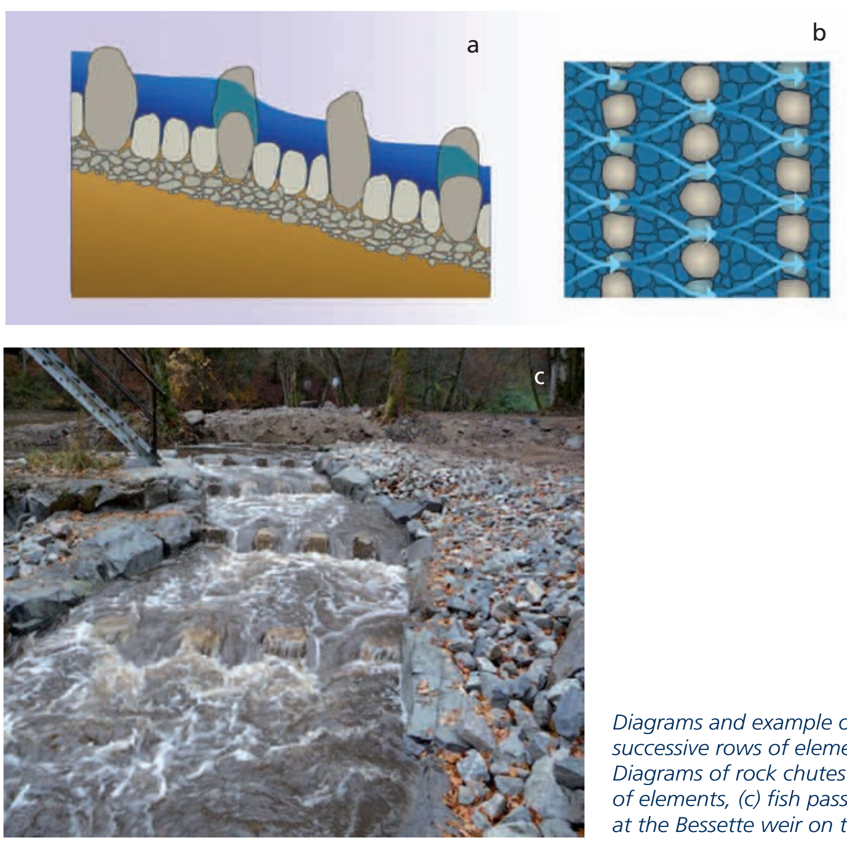
The surface roughness reduces the flow velocity near the bottom, which facilitates passage for smaller species.

Fish passes with successive rows of elements

One means to maintain sufficient water depths while limiting the discharge is to arrange the rocks in rows at regular intervals. The result is a set of virtual pools where fish are likely to find rest zones (see Figure 114).

This type of pass is very similar to "standard" pool-type fish passes and the sizing criteria are fairly comparable.

Figure 114



a, b © according to Larinier et al, 2006
c © Courret - Onema

Diagrams and example of rock chutes with successive rows of elements. (a) and (b) Diagrams of rock chutes with successive rows of elements, (c) fish pass at the Bessette weir on the Diège River.

Denil fish passes

The general idea is to install in a straight, rectangular channel, with a relatively steep slope, baffles on the bottom and/or the sides to reduce the average flow velocities.

The baffles may be more or less complex in shape. They cause helical, secondary currents that significantly dissipate the flow energy.

Each section of a Denil fish pass does not provide rest zones and fish must transit without stopping. When the head-drop between upstream and downstream is significant, the fish must make an intense effort over a time span that can easily exceed their endurance. For this reason, it may be necessary to break the fish pass into sections with rest basins between each section.

■ Pros and cons of Denil fish passes

Flow velocities and aeration in Denil fish passes tend to be very high. This type of pass should be used for large fish having good swimming capabilities, such as salmonids migrating over long distances, lampreys and certain large holobiotic species (trout, barbel, etc.).

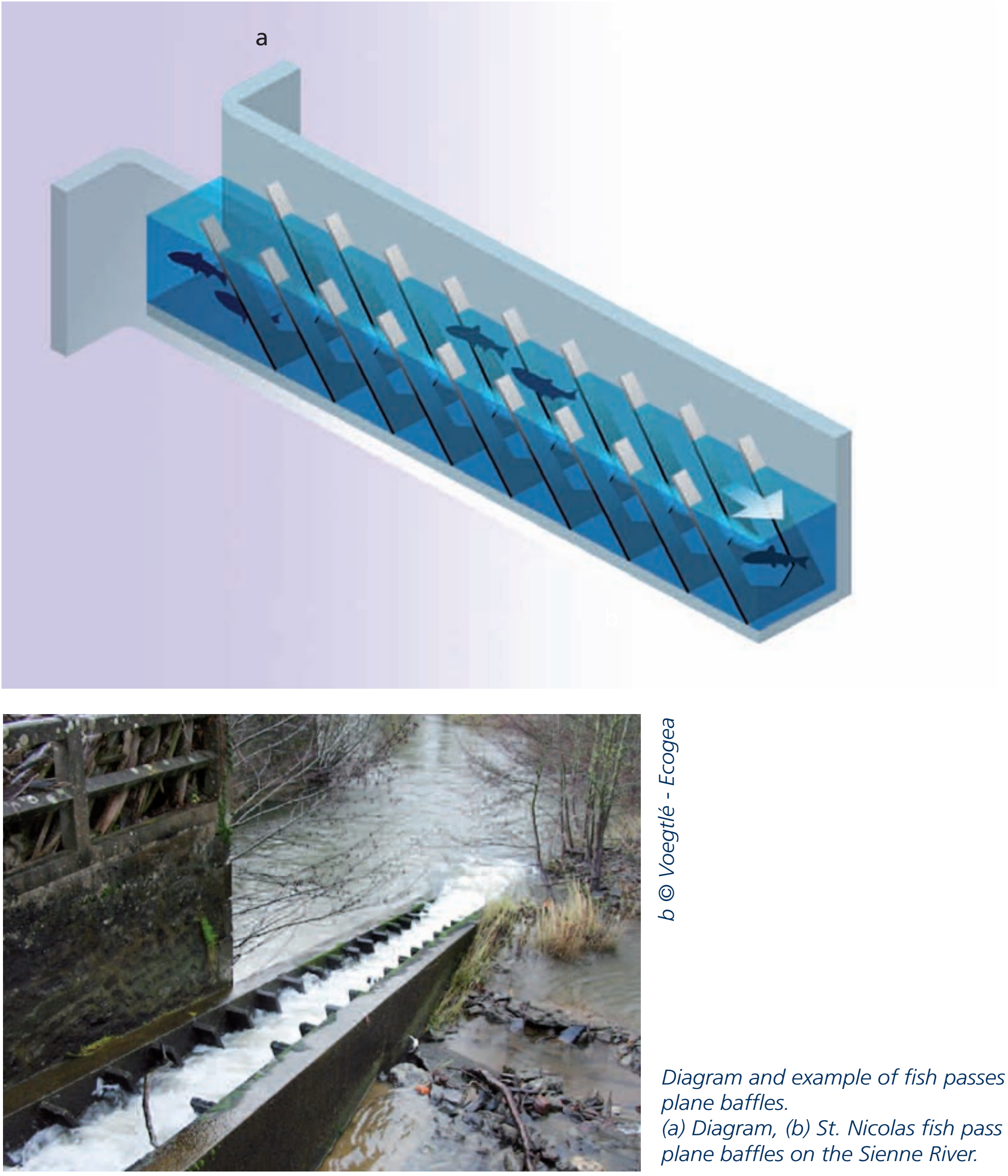
Generally speaking, Denil fish passes are intended for fish more than 30 cm long. They may be used for smaller species if the baffles are significantly reduced in size.

■ The different types of Denil fish passes

Fish passes with plane baffles

This is a commonly used type of fish pass. The main advantage is that the plane baffles, installed at a 45° angle to the slope of the channel, are very easy to manufacture (see Figure 115). The width of the channel can vary between 60 cm and one metre, and the slope can vary between 12 and 20%.

Figure 115



b © Voegtlé - Ecogea

Diagram and example of fish passes with plane baffles.
(a) Diagram, (b) St. Nicolas fish pass with plane baffles on the Sienne River.

Fish passes with Fatou baffles

Fish passes with Fatou baffles (see Figure 116) are highly effective hydraulically speaking. However, they have two major disadvantages, namely the baffles are difficult to manufacture due to their shape and the passes are vulnerable to clogging by branches and other floating debris. In as much as their intended use is very similar to that of fish passes with plane baffles, the latter are generally preferred. The operational conditions under which they are used are identical to those of fish passes with plane baffles.

Figure 116

a, b © Larinier - Ecohydraulic centre

Examples of fish passes with Fatou baffles. (a) Fish pass with Fatou baffles at Halsou on the Nive River, (b) idem at the Claies de Vire site on the Vire River.

Fish passes with floor baffles

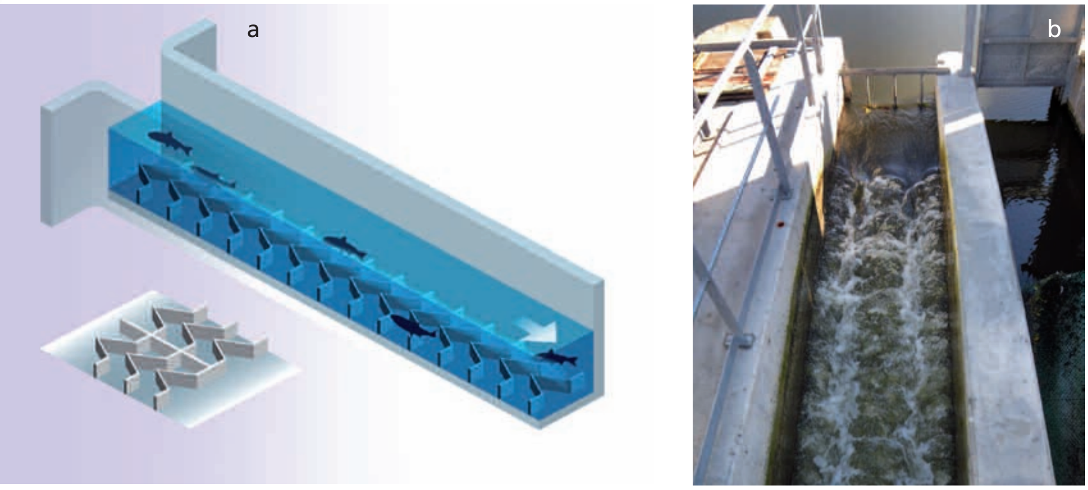
This type of fish pass is used primarily in France.

The baffles are positioned along the bottom of the pass. They are made of sheet metal 8 to 10 mm thick and the height varies from 8 to 20 cm depending on the given species (see Figure 117).

For large migratory salmonids, a maximum slope of 15 to 16% is recommended with baffles between 10 and 20 cm high.

In passes designed specifically for trout, the size of the baffles (8 to 10 cm high) and the lengths of each straight section of pass must be reduced.

Figure 117



b © Mayeras - Ecogea

Diagram and example of fish passes with floor baffles.
(a) Diagram, (b) fish pass with floor baffles at the Soustons dam.

Fish passes with thick chevron baffles and "combined" fish passes

The basic idea is essentially the same as that for floor baffles. However, the baffles are much thicker and are generally made of wood in order to hurt fish less and to enable the passage of boats, e.g. canoes and kayaks (see Figure 118).

Unfortunately, they are less effective hydraulically speaking and are suitable only for large migratory salmonids. They are also highly sensitive to variations in the upstream water level. In that they are suitable for a very limited number of fish, this type of system is almost never used any more in France for fish passes.

Figure 118

Examples of fish passes with thick chevron baffles.
(a) Fish pass with chevron baffles at the Moulin Neuf dam on the Trieux River, (b) Fish pass with chevron baffles combined with a pass for eels in the Haute-Normandie department.

a © Larinier - Ecohydraulic centre
b © Fagard - Onema

Fish passes designed specifically for eels

■ Design principle

For adult and nearly adult fish, it is often possible to design a "standard" fish pass adapted to the needs of eels or to optimise existing installations by adding roughness along the bottom, reducing head-drops, etc.

For younger eels, on the other hand, given their limited swimming capabilities, special systems are generally proposed, targeting the crawling technique used by the fish.

Fish passes specifically designed for glass eels and elvers comprise two parts.

- **A ramp,** the lower part of which is submerged below the downstream water level. The ramp is covered with a "substrate", a surface designed to facilitate the upward progression of the fish. Different types of surface may be used, depending on the region or country. The surface is always kept wet, either by water flowing from upstream or using a pump. The width of ramps can vary, but they generally have a longitudinal slope of 10 to 100%, which varies depending on the type of crawl surface used.
- **An upstream section,** designed to facilitate access to the upstream waters. The objective is to ensure that this section constitutes a transition so that the eels are not blocked by either a discontinuity in the supply of water or zones with excessively high flow velocities. The main problem encountered has to do with fluctuations in the upstream water level.

A drop in the level can lead to the fish pass running dry. On the other hand, an increase can rapidly result in excess quantities of water in the fish pass. This problem can be handled in two ways:

- create a latitudinal slope in the ramp to mitigate the variations in the upstream water level and maintain a zone with a low water depth and moderate flow velocity to assist the fish (see Figure 119). The latitudinal slope is generally in the 20 to 100% range, with lower values below 50% when the crawl way comprises studs;
- extend the top end of the ramp to a level higher than the maximum upstream water level and use a pump to ensure the flow of water on the ramp. The fish arriving at the top of the ramp slide down a chute and fall into the upstream water or into a holding tank where they can be caught for transport or counting purposes.

The substrate type, slope and discharge are essential factors that determine obstacle passability for eels. The interaction between these different factors is generally very clear (Voegtlé and Larinier, 2000).

Figure 119

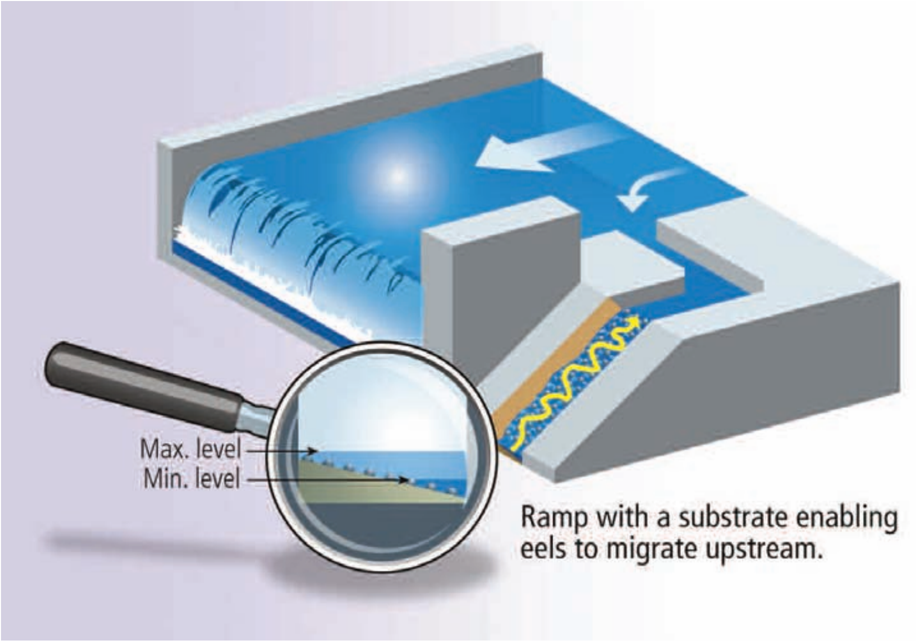


Diagram of a fish pass for eels supplied directly with upstream water.

■ The main substrates for eels available in France

The surfaces used for eel ramps are generally of the brush or stud type. The size and the spacing between each element in the surface depend on the size of the transiting fish. Spacing of approximately 14 mm between elements supporting the progression is the most common and useful for different fish sizes.

Brush-type substrates (see Figure 120a). These mats consist of synthetic fibres arranged in clumps on a PVC base. Different spacing (7 to 21 mm) between clumps is available depending on the biological stage of the given fish. This type of substrate is commonly used in France, notably for very young fish (glass eels).

Stud-type substrates (see Figure 120b). These concrete or polyurethane tiles have an array of studs. The technical characteristics (density and size of studs) of the tiles are such that they may be used exclusively for elvers and larger eels. A further consequence of these characteristics is that the latitudinal slope should be less steep than for brush substrates.

Figure 120


Examples of fish passes for eels.
(a) Fish pass for eels on the Soustons River. Ramp equipped with a brush-type substrate.
(b) Fish pass for eels at the Bergerac dam on the Dordogne River. Ramp equipped with a substrate comprising polyurethane studs.

a © Voegtlé - Ecogea
b © Lagarrigue - Ecogea

Locks and elevators

■ Fish locks

The idea behind fish locks (see Figure 121) is very similar to locks for boats. The fish are drawn into a downstream chamber and then floated up to the upstream section. They are encouraged to leave the lock by creating a downward current via a bypass.

The lock procedure may be summed up in three phases.

- **Entry phase.** The downstream gate is open. The fish are attracted to the downstream chamber by the water flowing from upstream.
- **Filling and exit phase.** Following a certain duration of the entry phase, the downstream gate closes and the lock fills with water. The fish follow the free surface up the conduit and enter the upstream chamber when the lock is full. A current is created to encourage the fish to exit the lock.
- **Emptying phase.** After a given amount of time, the upstream gate closes. The lock is gradually emptied via a bypass. When the lock is almost completely empty and the pressure on the downstream gate is low enough, the gate opens again.

A complete cycle may last between one and several hours.

Figure 121

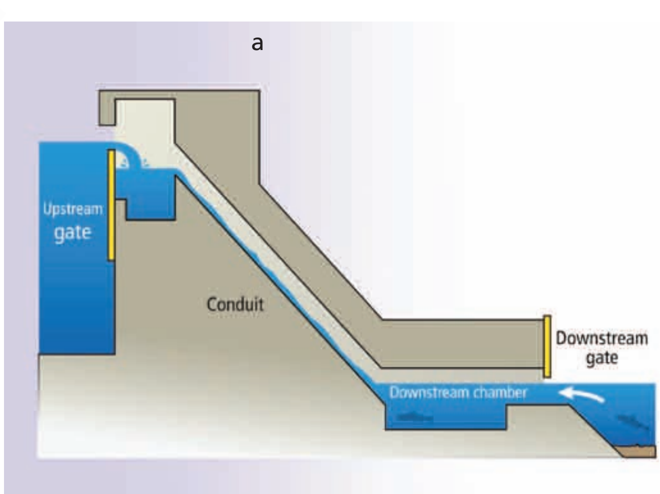


Diagram and example of a fish lock. (a) Diagram, (b) Saint-Maurice fish lock on the Adour River.

b © Chanseau - Onema

The effectiveness of a fish lock depends on the behaviour of the fish which must remain in the downstream chamber during the entire entry phase, then proceed up with the water level during the filling phase and exit the lock before the emptying phase.

Many locks have turned out to be not very effective or totally ineffective. As a result, they are now rarely used in France and abroad.

■ Fish elevators

Generally speaking, a fish elevator (see Figure 122) is a mechanical system that catches fish at the foot of an obstacle in a tank holding enough water for the given number of fish, then lifts the tank and empties it into the upstream reach.

The fish are first drawn into a holding basin by a discharge sufficient to attract them. They are caught in a wire cage equipped with a device to avoid travel back downstream. The lifting tank is located at the bottom of the cage. Immediately downstream of the cage is a mechanised, vertical screen that blocks access while the cage and tank are lifted to avoid crushing any fish when the cage and tank come back down.

An electric winch located at the top of the metallic or concrete structure lifts the cage and tank. The tank then tips or a gate is opened to allow the fish to transit to the upstream reach.

The procedure for this type of elevator may be summed up as follows.

■ **Trapping phase.** The tank is at the bottom of the shaft, the protective screen providing access to the cage is open. Attracted by the flow of water, fish enter the cage and are trapped by the anti-return device.

■ **Lifting and release phase.** The protective screen drops, blocking access, the cage and tank are lifted and the tank then releases the fish to the upstream reach.

■ **Descent phase.** After releasing the fish, the cage and tank travel back down to the bottom. The protective screen then opens and fish may again access the cage.

The main advantages of fish elevators compared to other types of fish passes lie in their construction costs, which do not depend significantly on the height of the obstacle, in their small footprint and in their lesser sensitivity to variations in the upstream water level.

The main disadvantages have to do with operating difficulties, higher operating costs and longer down times than for "static" fish passes due to the higher potential for breakdowns. In addition, the effectiveness of elevators for small species is relatively limited due to the impossibility of using, for operational reasons, screens with a sufficiently fine mesh.

Given the advantages and disadvantages of these systems, they are generally used when the head-drop between the upstream and downstream reaches is close to or exceeds ten metres. For smaller head-drops, it is often better to use standard fish passes.

Figure 122

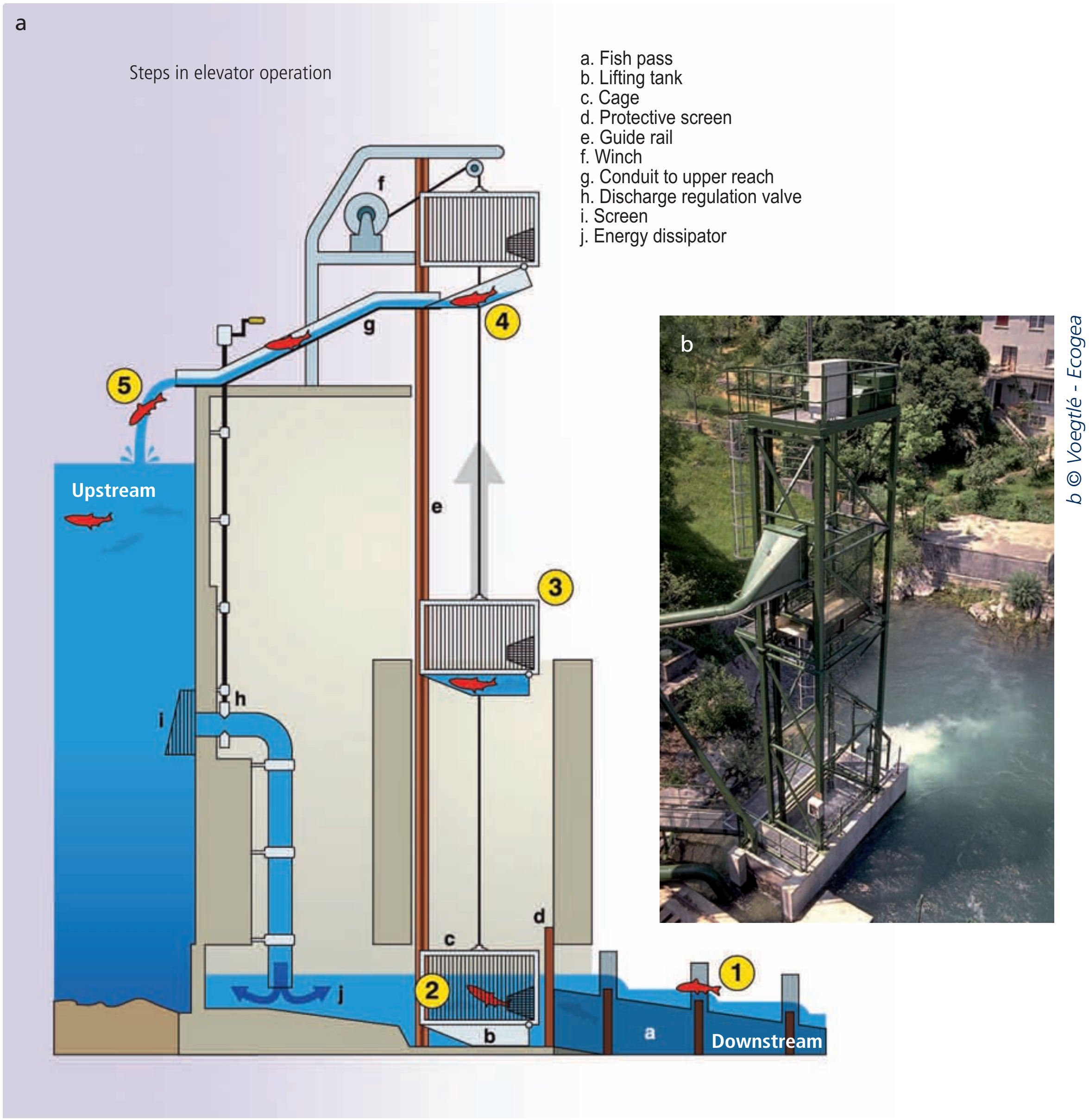


Diagram and example of a fish elevator. (a) Diagram of a fish elevator with a built-in lifting tank, (b) Castet elevator on the Ossau River.

Tidal structures

In most cases, particularly when estuarine structures are designed to avoid or limit the entry of water further upstream, they create major problems for the passage of the fish species that use the tidal currents to travel upstream.

When the purpose of estuarine structures is the opposite, i.e. when they are used to prevent the outflow of high-tide waters during low tide, there are generally far fewer problems because upstream migration generally occurs during the rising tide.

To facilitate the upstream passage of fish, there are two main possibilities for structures (not including automated management systems):

■ let water penetrate upstream in one of three ways, namely by maintaining one or more gates open or slightly open, by creating one or more orifices in the structures or by delaying the closing of gates;
■ implement the same solution as for other types of structures, i.e. create a fish pass.

■ Solutions letting sea or brackish water penetrate upstream

Maintain one or more gates open or slightly open

This solution consists of leaving the system (gates, doors, flaps) open or slightly open during the rising tide (see Figure 123). The volume of water penetrating upstream depends on the strength of the tide and the size of the opening.

This very simple and inexpensive solution generally makes it possible, particularly for tide gates, to allow a continuous inflow during (virtually) the entire rising tide and from top to bottom of the water column.

Figure 123

a © Chanseau - Onema
b © Voegtlé - Ecogea

Examples of tidal structures left partially open or chocked open to enable passage upstream. (a) Gates held open at the Saubusse structure on the Adour River, (b) tide gates chocked open in the Arcins marshes.

The devices used to maintain the gates open are generally permanent and difficult to remove, which may cause problems in the case of particularly high tides.

The openings, which span the entire height of the gate, theoretically allow the entry of greater volumes of water with high levels of suspended matter and salt, which may, in certain cases, be a problem for the upstream environment.

In addition, if the water volumes that the upstream environment can accept are limited, which is often the case, that reduces the permissible input volumes during the slack period around high tide, considered a strategic moment at least for glass eels (Lafaille *et al.*, 2007).

Finally, particularly before installing chocks, it is necessary to check that the gate/flap and the support structure can handle the hydraulic pressures, which can be considerable. There is a non-negligible risk of deforming the moving parts or the structure.

Create one or more orifices in the structure

This solution consists of creating one or more orifices in the gate (tide gate, flap, lift gate) or in the structure itself.

The orifices (see Figure 124) are themselves generally equipped with a lift gate used to adjust the throughput. Depending on the situation upstream, this system can be used to easily adapt the throughput to seasonal limitations upstream and to the strength of tides.

Figure 124

a © Chanseau - Onema
b © Voegtlé - Ecogea

Examples of orifices created to allow the passage of fish.
(a) and (b) Orifices positioned in the lower section of tide gates to allow the passage of fish when open, at Jalles in South-West France.

Depending on the size of the orifice and its position (height) in the gate, more or less water will penetrate upstream.

The lower the position of the orifice in the gate, the more water will penetrate upstream and the earlier the water will enter during the rising tide. On the other hand, a low position in the gate is likely to result in more suspended matter arriving upstream, which may be a negative factor in some cases.

In that the fish are required to pass through a precisely identified and relatively small orifice, there is a risk of poaching and simple measures should be foreseen, if necessary, to limit the risks.

Delay closing of the gates

Systems designed to delay the closing of gates (floats, counter-weights, springs, etc.) are occasionally used on certain sites in France and abroad (see Figure 125, Environment Agency, 2011). The general idea is to ensure the passage of water upstream at a particular time during the rising tide.

The systems are more or less effective depending on the volume of water penetrating upstream and on the time when the gates fully close. Their effectiveness drops sharply in particular if the gates close (or the volume of incoming water is severely limited) at the time when a maximum number of fish arrive at the foot of the obstacle, i.e. a few hours before the slack period around high tide.

Figure 125

The SRT system developed by the U.K. Environment Agency (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/291577/scho0811buay-e-e.pdf). (a) and (b) SRT system in the closed position, (c) system partially open, depending on the water level caused by tides.

a, b, c © Williams - UK Environment Agency (2011)

■ Creation of "standard" fish passes

For certain estuarine structures where it is not possible to manage or modify the system to allow the passage of water upstream, "standard" fish passes (pool-type passes, eel passes, etc.) may be installed (see Figure 126).

Figure 126

a, b © Voegtlé - Ecogea
c, d © IAV

Examples of fish passes in estuaries. (a) and (b) Fish pass inside the Durdent estuarine structure, (c) and (d) fish pass for eels at the Arzal dam on the Vilaine River.

Pre-assessment of the different types of fish pass

Method used for the ICE protocol

■ An assessment prior to in-depth study of fish-pass hydraulic operation and attractiveness

The general strategy for a fish pass is to attract the migratory fish and to encourage them (or oblige them in the case of an elevator) to transit upstream via the structure.

An effective fish pass is one where the fish can find the entry rapidly and transit upstream without difficulty, delay, stress or injury detrimental to further migration. Consequently, **a fish pass must be attractive and functional.**

The attractiveness of a fish pass depends on how it is installed with respect to the obstacle and in particular on the characteristics of the entry, the discharge flowing through the pass, the geometry of the bed and the nearby hydraulic conditions. The current flowing out at the foot of the pass must be sufficient and must not be masked by flows from the turbines and spillways, or by backflows.

The effectiveness of a fish pass, i.e. the compatibility of the hydraulic conditions in the pass with the behaviour and swimming capabilities of the targeted species, is determined by the internal hydraulic conditions which depend on the pass geometry (type of pass, size, slope, etc.) and on the hydrological conditions during migratory periods, as well as, in some cases, on the management of the gates in the overall structure. The variability of the hydrological conditions and of gate management generally produce fluctuations in the water levels upstream and downstream of the obstacle and consequently some variability in the hydraulic conditions inside the fish pass.

Though it is possible to roughly gauge the suitability of the overall physical characteristics of a fish pass (the type of pass and its geometry) for the given species, **it is impossible to rapidly set simple and relevant criteria (the objective of the ICE protocol) in view of assessing pass attractiveness and its adaptability to variations in the hydrological conditions.**

This type of assessment requires a high level of technical know-how in sizing hydraulic systems and in the behaviour of fish. Further prerequisites include in-depth knowledge on the hydrology of the given river, the breakdown of discharges on the site depending on the hydrological conditions and the upstream and downstream water levels and their variations during the migratory periods of the given species.

For the ICE protocol, the first step is to make sure that the type and characteristics of the fish pass are suitable for the given species.

Caution. The pre-assessment procedures presented below for the various types of fish pass are simply the preliminary studies undertaken prior to a complete analysis of the fish pass. In a context of surveillance monitoring of the ecological status of aquatic environments, the purpose of the pre-assessments is to rapidly identify, using simple criteria based on easily measured parameters, fish passes that are clearly not well suited or not at all suited to the given fish species. In the framework of projects to restore ecological continuity and particularly for the assessment of obstacles subject to legal requirements, a complete study must subsequently be carried out, taking into account other criteria of pass effectiveness (attractiveness, other functional hydraulic factors pertaining to the fish pass itself and to the overall obstacle, etc.) and targeting all the necessary assessment parameters, in order to identify the causes of the malfunction and to determine the extent of the corrective measures.

■ Pre-assessment method

The method indicates for the main sizing parameters, for each species group and for each type of fish pass suited to a given group of species:

- **minimum values,** corresponding to the size and morphology of the fish (minimum size of pools and of slots/notches, minimum water depths, minimum discharge for given slots/notches);
- **maximum recommended values** or value ranges, corresponding to the swimming/jumping capabilities of a species or group of species (flow velocities, head-drops between pools, etc.).

Certain results proposed for fish passes will not appear to be consistent with the values indicated previously for the assessment of obstacle passability.

This is particularly true for the recommended head-drops between pools in fish passes, which do not correspond to the threshold values for the ICE protocol 1 and 0.66 passability classes.

These differences in values or value ranges take into account factors other than those strictly related to the given species or group of species, in particular factors having to do with:

- the hydrodynamic conditions in the fish pass, which is a confined environment where discharges and head-drops are limited and depend on the volume of the pool;
- pass construction and maintenance;
- the fact that, for the least agile species, the hydraulic conditions in the pass can be much more rigorously controlled than those for a weir, in particular by installing rough surfaces (having precise sizes and layout) on the bottom of the pass that benefit small, benthic species.

Sizing criteria other than those used for the ICE protocol may also be important, depending on the type of fish pass (size of deflectors, baffles and/or orifices, width of pools, length of straight sections, etc.). They are not covered during the pre-assessment and must be checked during the subsequent in-depth study, using in particular the technical sizing guides.

Pool-type fish passes

Pool-type fish passes can be adapted to all fish species if the head-drops between pools and at the pass outlet, the types of flow and the pool dimensions (width, length and depth) are compatible with the behaviour and passage capabilities of all the fish.

■ ***Fish passes with skimming flows (vertical slots, deep lateral notches or triangular notches)***

The following points must be analysed during the pre-assessment.

1. Type of flow

It is necessary to check that the flow in a pool-type fish pass is effectively a skimming flow.

If the flow over the slots or notches is a skimming flow ($H \geq 2$ DH or DH ≤ 0.5 H), proceed with the analysis of the main dimensions indicated in Table 24, starting with Step 2.

If the flow is a plunging jet ($H < 2$ DH), it is clear that the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose. However, for the jumping species, it is nonetheless worthwhile to check the main dimensions using the pre-assessment procedure for passes with plunging jets (see the next section).

2. Analysis of head-drops

If the head-drops DH between pools and at the pass outlet are greater than the values (maximum head-drop) indicated in Table 24, the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 3.

3. Analysis of the widths of passageways (slots, notches)

If the widths of the slots or notches are less than the minimum values indicated in Table 24, the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 4.

4. Analysis of pool depths

If the pool depths are less than the minimum values indicated in Table 24, the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 5.

5. Analysis of pool lengths

If the pool lengths are less than the minimum values indicated in Table 24, the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, the pre-assessment result is positive, however **it is necessary to proceed with the in-depth study of the hydraulic conditions in the fish pass and of its attractiveness.**

Tableau 24 *Threshold values for pre-assessment of pool-type fish passes with skimming flows.*

ICE species group	Species	Maximum head-drop (m) *	Recommended head-drop (m) *	Minimum width of slots and lateral notches (m) *	Minimum depth of pools (m) *	Minimum length of pools (m) *
1	Atlantic salmon (*Salmo salar*) Brown or sea trout [50-100] (*Salmo trutta*)	0.35	0.30	0.30	1.00	2.50
2	Mullets (*Chelon labrosus, Liza ramada*)	0.35	0.30	0.20	1.00	1.75
3a	Allis shad (*Alosa alosa*)	0.30	0.25	0.40	1.00	3.50
3b	Twaite shad (*Alosa fallax fallax*)					
3c	Sea lamprey (*Petromyzon marinus*)			0.15		1.25
4a	Brown or sea trout [25-55] (*Salmo trutta*)	0.35	0.30	0.20	1.00	1.75
4b	Brown trout [15-30] (*Salmo trutta*)	0.30	0.25	0.15	0.75	1.25
5	Asp (*Aspius aspius*) Pike (*Esox lucius*)	0.30	0.25	0.30	0.75	2.50
6	Grayling (*Thymallus thymallus*)	0.30	0.25	0.20	0.75	1.75
7a	Barbel (*Barbus barbus*) Chub (*Squalius cephalus*) Nase (*Chondrostoma nasus*)	0.30	0.25	0.25	0.75	2.00
7b	River lamprey (*Lampetra fluviatilis*)			0.15		1.25
8a	Common carp (*Cyprinus carpio*)	0.25	0.20	0.30	0.75	2.50
8b	Common bream (*Abramis brama*) Pikeperch (*Sander lucioperca*)					
8c	White bream (*Blicca bjoerkna*) Ide (*Leuciscus idus*) Burbot (*Lota lota*) Perch (*Perca fluviatilis*) Tench (*Tinca tinca*)					
8d	Daces (*Leuciscus spp.* except *Idus*)					
9a	Bleak (*Alburnus alburnus*) Schneider (*Alburnoides bipunctatus*) Mediterranean barbel (*Barbus meridionalis*) Blageon (*Telestes souffia*) Crucian carp (*Carassius carassius*) Prussian carp (*Carassius gibelio*) Roach (*Rutilus rutilus*) Rudd (*Scardinius erythrophthalmus*) SW European nase (*Parachondrostoma toxostoma*)	0.25	0.20	0.25	0.75	2.00
9b	Streber (*Zingel asper*) Bullheads (*Cottus spp.*) Gudgeons (*Gobio spp.*) Ruffe (*Gymnocephalus cernuus*) Brook lamprey (*Lampetra planeri*) Stone loach (*Barbatula barbatula*) Spined loach (*Cobitis taenia*)	0.20	0.15	0.15	0.50	1.25
10	Sunbleak (*Leucaspius delineatus*) Bitterling (*Rhodeus amarus*) Threespine stickleback (*Gasterosteus gymnurus*) Smoothtail ninespine stickleback (*Pungitius laevis*) Minnows (*Phoxinus spp.*)	0.20	0.15	0.15	0.50	1.25
11a	European eel [yellow eel] *(Anguilla anguilla)*	0.25	0.20	0.15	0.50	1.25
11b	European eel [glass eel] *(Anguilla anguilla)*	-	-		-	-

(*) The values shown above are recommended values. Under certain conditions (discharge, available space, etc.), it may be necessary to select slightly different values. The greater the overrun of the threshold values by the measured values, the greater the non-suitability of the fish pass.

■ Fish passes with plunging jets (rectangular notches, pre-barrages, triangular notches)

The following points must be analysed during the pre-assessment.

1. Type of flow

It is necessary to check that the flow in the pool-type fish pass is effectively a plunging jet.

If the flow over the notches is a skimming flow ($H \geq 2$ DH or DH ≤ 0.5 H), proceed with the analysis of the main dimensions indicated in Table 24 (see the previous section on fish passes with skimming flows).

If the flow is a plunging jet ($H < 2$ DH), it is clear that the fish pass is suitable only for jumping species. Go to Step 2.

2. Analysis of head-drops

If the head-drops DH between pools and at the pass outlet are greater than the values (maximum head-drop) indicated in Table 25, the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 3.

3. Analysis of pool depths

If the pool depths are less than the minimum values indicated in Table 25 or if the pool depths are less than twice the head-drop upstream of the pool, the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 4.

4. Analysis of the overflow height over the notches

If the overflow height over the notches is less than the minimum values indicated in Table 25, the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 5.

5. Analysis of pool lengths

If the pool lengths are less than the minimum values indicated in Table 25, the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, the pre-assessment result is positive, however **it is necessary to proceed with the in-depth study of the hydraulic conditions in the fish pass and of its attractiveness.**

Tableau 25 *Threshold values for pre-assessment of pool-type fish passes with plunging jets.*

ICE species group	Species	Maximum head-drop (m)*	Recommended head-drop (m)*	Minimum depth of pools (m)*	Minimum overflow height over notches (m)*	Minimum length of pools (m)*
1	Atlantic salmon (*Salmo salar*) Brown or sea trout [50-100] (*Salmo trutta*)	0.75	0.30	1.00	0.30	2.00
2	Mullets (*Chelon labrosus*, *Liza ramada*)	0.60	0.30	0.75	0.20	1.25
3a	Allis shad (*Alosa alosa*)	-	-	-	-	-
3b	Twaite shad (*Alosa fallax fallax*)					
3c	Sea lamprey (*Petromyzon marinus*)					
4a	Brown or sea trout [25-55] (*Salmo trutta*)	0.40	0.30	0.75	0.20	1.25
4b	Brown trout [15-30] (*Salmo trutta*)	0.30	0.25	0.75		1.00
5	Asp (*Aspius aspius*) Pike (*Esox lucius*)	-	-	-	-	-
6	Grayling (*Thymallus thymallus*)	0.30	0.25	0.75	0.20	1.00
7a	Barbel (*Barbus barbus*) Chub (*Squalius cephalus*) Nase (*Chondrostoma nasus*)	-	-	-	-	-
7b	River lamprey (*Lampetra fluviatilis*)					
8a	Common carp (*Cyprinus carpio*)	-	-	-	-	-
8b	Common bream (*Abramis brama*) Pikeperch (*Sander lucioperca*)					
8c	White bream (*Blicca bjoerkna*) Ide (*Leuciscus idus*) Burbot (*Lota lota*) Perch (*Perca fluviatilis*) Tench (*Tinca tinca*)					
8d	Daces (*Leuciscus spp.* except *Idus*)					
9a	Bleak (*Alburnus alburnus*) Schneider (*Alburnoides bipunctatus*) Mediterranean barbel (*Barbus meridionalis*) Blageon (*Telestes souffia*) Crucian carp (*Carassius carassius*) Prussian carp (*Carassius gibelio*) Roach (*Rutilus rutilus*) Rudd (*Scardinius erythrophthalmus*) SW European nase (*Parachondrostoma toxostoma*)	-	-	-	-	-
9b	Streber (*Zingel asper*) Bullheads (*Cottus spp.*) Gudgeons (*Gobio spp.*) Ruffe (*Gymnocephalus cernuus*) Brook lamprey (*Lampetra planeri*) Stone loach (*Barbatula barbatula*) Spined loach (*Cobitis taenia*)					
10	Sunbleak (*Leucaspius delineatus*) Bitterling (*Rhodeus amarus*) Threespine stickleback (*Gasterosteus gymnurus*) Smoothtail ninespine stickleback (*Pungitius laevis*) Minnows (*Phoxinus spp.*)	-	-	-	-	-
11a	European eel [yellow eel] *(Anguilla anguilla)*	-	-	-	-	-
11b	European eel [glass eel] *(Anguilla anguilla)*	-	-	-	-	-

(*) The values shown above are recommended values. Under certain conditions (discharge, available space, etc.), it may be necessary to select slightly different values. The greater the overrun of the threshold values by the measured values, the greater the non-suitability of the fish pass.

Rock-chute fish passes

■ Fish passes with successive rows of elements

The following points must be analysed during the pre-assessment.

1. Type of flow

It is necessary to check that the flow is effectively a skimming flow over the successive rows of elements (riprap, concrete blocks, separate sheet piles, etc.).

If the flow over the rows is a skimming flow ($H \geq 2$ DH or DH ≤ 0.5 H), proceed with the analysis of the main dimensions indicated in Table 26, starting with Step 2.

If 0.5 H ≤ DH ≤ H, the flow is almost a plunging jet and the pass may be considered not well suited to the given purpose.

If the flow is a plunging jet (DH > H), it is clear that the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not at all suited to the given purpose.

2. Analysis of head-drops between pools

If the head-drops over the rows of elements are greater than the values (maximum head-drop) indicated in Table 26, the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 3.

3. Analysis of the overflow height over the rows

If the overflow height over the rows is less than the minimum values indicated in Table 26, the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 4.

4. Analysis of pool depths

If the pool depths are less than the minimum values indicated in Table 26, the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, the pre-assessment result is positive, however **it is necessary to proceed with the in-depth study of the hydraulic conditions in the fish pass and of its attractiveness.**

Special analysis for eels

If a crawl way exists in the fish pass (notably one with a suitable latitudinal slope), a pre-assessment may be run using the procedure presented in the section of Chapter C on eels.

If the fish pass with a crawl way is not a low-impact passable barrier (ICE class ≠ 1), the pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, if the fish pass with a crawl way is a low-impact passable barrier (ICE class = 1), the pre-assessment result is positive, however **it is necessary to proceed with the in-depth study** (hydraulic conditions, attractiveness, presence of a suitable crawl way under all hydrological conditions, etc.).

Tableau 26 *Threshold values for pre-assessment of rock-chute fish passes with successive rows of elements.*

<table>
<tr><th>ICE species group</th><th>Species</th><th>Maximum head-drop (m)*</th><th>Recommended head-drop (m)*</th><th>Minimum overflow height over the rows (m)*</th><th>Minimum depth of pools (m)*</th></tr>
<tr><td>1</td><td>Atlantic salmon (Salmo salar)
Brown or sea trout [50-100] (Salmo trutta)</td><td>0.30</td><td>0.25</td><td>0.30</td><td>0.50</td></tr>
<tr><td>2</td><td>Mullets (Chelon labrosus, Liza ramada)</td><td>0.30</td><td>0.25</td><td>0.20</td><td>0.50</td></tr>
<tr><td>3a</td><td>Allis shad (Alosa alosa)</td><td rowspan="3">0.25</td><td rowspan="3">0.20</td><td rowspan="2">0.40</td><td rowspan="3">0.40</td></tr>
<tr><td>3b</td><td>Twaite shad (Alosa fallax fallax)</td></tr>
<tr><td>3c</td><td>Sea lamprey (Petromyzon marinus)</td><td>0.15</td></tr>
<tr><td>4a</td><td>Brown or sea trout [25-55] (Salmo trutta)</td><td>0.30</td><td>0.25</td><td rowspan="2">0.20</td><td>0.50</td></tr>
<tr><td>4b</td><td>Brown trout [15-30] (Salmo trutta)</td><td>0.25</td><td>0.20</td><td>0.40</td></tr>
<tr><td>5</td><td>Asp (Aspius aspius)
Pike (Esox lucius)</td><td>0.25</td><td>0.20</td><td>0.20</td><td>0.40</td></tr>
<tr><td>6</td><td>Grayling (Thymallus thymallus)</td><td>0.25</td><td>0.20</td><td>0.20</td><td>0.40</td></tr>
<tr><td>7a</td><td>Barbel (Barbus barbus)
Chub (Squalius cephalus)
Nase (Chondrostoma nasus)</td><td rowspan="2">0.25</td><td rowspan="2">0.20</td><td>0.20</td><td rowspan="2">0.40</td></tr>
<tr><td>7b</td><td>River lamprey (Lampetra fluviatilis)</td><td>0.15</td></tr>
<tr><td>8a</td><td>Common carp (Cyprinus carpio)</td><td rowspan="4">0.20</td><td rowspan="4">0.15</td><td rowspan="4">0.20</td><td rowspan="4">0.30</td></tr>
<tr><td>8b</td><td>Common bream (Abramis brama)
Pikeperch (Sander lucioperca)</td></tr>
<tr><td>8c</td><td>White bream (Blicca bjoerkna)
Ide (Leuciscus idus)
Burbot (Lota lota)
Perch (Perca fluviatilis)
Tench (Tinca tinca)</td></tr>
<tr><td>8d</td><td>Daces (Leuciscus spp. except Idus)</td></tr>
<tr><td>9a</td><td>Bleak (Alburnus alburnus)
Schneider (Alburnoides bipunctatus)
Mediterranean barbel (Barbus meridionalis)
Blageon (Telestes souffia)
Crucian carp (Carassius carassius)
Prussian carp (Carassius gibelio)
Roach (Rutilus rutilus)
Rudd (Scardinius erythrophthalmus)
SW European nase (Parachondrostoma toxostoma)</td><td>0.20</td><td>0.15</td><td>0.20</td><td>3.00</td></tr>
<tr><td>9b</td><td>Streber (Zingel asper)
Bullheads (Cottus spp.)
Gudgeons (Gobio spp.)
Ruffe (Gymnocephalus cernuus)
Brook lamprey (Lampetra planeri)
Stone loach (Barbatula barbatula)
Spined loach (Cobitis taenia)</td><td>0.15</td><td>0.10</td><td>0.20</td><td>0.20</td></tr>
<tr><td>10</td><td>Sunbleak (Leucaspius delineatus)
Bitterling (Rhodeus amarus)
Threespine stickleback (Gasterosteus gymnurus)
Smoothtail ninespine stickleback (Pungitius laevis)
Minnows (Phoxinus spp.)</td><td>0.15</td><td>0.10</td><td>0.20</td><td>0.20</td></tr>
<tr><td>11a</td><td>European eel [yellow eel] (Anguilla anguilla)</td><td>0.20</td><td>0.15</td><td>0.05</td><td>0.20</td></tr>
<tr><td>11b</td><td>European eel [glass eel] (Anguilla anguilla)</td><td>-</td><td>-</td><td>-</td><td>-</td></tr>
</table>

(*) The values shown above are recommended values. Under certain conditions (discharge, available space, etc.), it may be necessary to select slightly different values. The greater the overrun of the threshold values by the measured values, the greater the non-suitability of the fish pass.

■ Rock-chute fish passes with staggered arrays of elements

The following points must be analysed during the pre-assessment.

1. Analysis of the minimum water depth

If the water depth is less than the minimum values indicated in Table 27, the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 2.

2. Analysis of flow velocities

It is necessary to determine the maximum flow velocity.

If the maximum velocity is greater than the maximum values indicated in Table 27, the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, the pre-assessment result is positive, however **it is necessary to proceed with the in-depth study of the hydraulic conditions in the fish pass and of its attractiveness.**

Special analysis for eels

If a crawl way exists in the fish pass (notably one with a suitable latitudinal slope), a pre-assessment may also be run using the procedure presented in the section of Chapter C on eels.

If the fish pass with a crawl way is not a low-impact passable barrier (ICE class ≠ 1), the pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, if the fish pass with a crawl way is a low-impact passable barrier (ICE class = 1), the pre-assessment result is positive, however **it is necessary to proceed with the in-depth study** (hydraulic conditions, attractiveness, presence of a suitable crawl way under all hydrological conditions, etc.).

Tableau 27 *Threshold values for pre-assessment of rock-chute fish passes with staggered arrays of elements.*

ICE species group	Species	Minimum water depth (m)*	Maximum flow velocity (m/s)*
1	Atlantic salmon (*Salmo salar*) Brown or sea trout [50-100] (*Salmo trutta*)	0.40	2.50
2	Mullets (*Chelon labrosus, Liza ramada*)	0.30	2.50
3a	Allis shad (*Alosa alosa*)	0.40	2.00
3b	Twaite shad (*Alosa fallax fallax*)		
3c	Sea lamprey (*Petromyzon marinus*)	0.15	
4a	Brown or sea trout [25-55] (*Salmo trutta*)	0.30	2.00
4b	Brown trout [15-30] (*Salmo trutta*)	0.20	
5	Asp (*Aspius aspius*) Pike (*Esox lucius*)	0.30	2.00
6	Grayling (*Thymallus thymallus*)	0.30	2.00
7a	Barbel (*Barbus barbus*) Chub (*Squalius cephalus*) Nase (*Chondrostoma nasus*)	0.30	2.00
7b	River lamprey (*Lampetra fluviatilis*)	0.15	
8a	Common carp (*Cyprinus carpio*)	0.3	1.50
8b	Common bream (*Abramis brama*) Pikeperch (*Sander lucioperca*)		
8c	White bream (*Blicca bjoerkna*) Ide (*Leuciscus idus*) Burbot (*Lota lota*) Perch (*Perca fluviatilis*) Tench (*Tinca tinca*)		
8d	Daces (*Leuciscus spp.* except *Idus*)		
9a	Bleak (*Alburnus alburnus*) Schneider (*Alburnoides bipunctatus*) Mediterranean barbel (*Barbus meridionalis*) Blageon (*Telestes souffia*) Crucian carp (*Carassius carassius*) Prussian carp (*Carassius gibelio*) Roach (*Rutilus rutilus*) Rudd (*Scardinius erythrophthalmus*) SW European nase (*Parachondrostoma toxostoma*)	0.20	1.50
9b	Streber (*Zingel asper*) Bullheads (*Cottus spp.*) Gudgeons (*Gobio spp.*) Ruffe (*Gymnocephalus cernuus*) Brook lamprey (*Lampetra planeri*) Stone loach (*Barbatula barbatula*) Spined loach (*Cobitis taenia*)		
10	Sunbleak (*Leucaspius delineatus*) Bitterling (*Rhodeus amarus*) Threespine stickleback (*Gasterosteus gymnurus*) Smoothtail ninespine stickleback (*Pungitius laevis*) Minnows (*Phoxinus spp.*)	0.20	1.50
11a	European eel [yellow eel] *(Anguilla anguilla)*	0.05	1.50
11b	European eel [glass eel] *(Anguilla anguilla)*	-	-

(*) The values shown above are recommended values. Under certain conditions (discharge, available space, etc.), it may be necessary to select slightly different values. The greater the overrun of the threshold values by the measured values, the greater the non-suitability of the fish pass.

Denil fish passes

Denil fish passes are not suitable for all species. They should be used only for fish with good swimming capabilities.

The following points must be analysed during the pre-assessment.

1. Check that a downstream fall does not exist

If there is a fall at the downstream end, the fish pass does not comply with the minimum general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 2.

2. Check on the species

Check that the species or group of species is capable of using this type of fish pass (i.e. that the species belongs to an ICE species group ≤ 7a). If OK, go to Step 3.

Shad prefer regular flows in parallel streamlines and avoid wherever possible whirlpools and highly turbulent zones. For the two shad subgroups 3a and 3b, in the context of the ICE pre-assessment, Denil fish passes may be considered not well suited or not at all suited to the given purpose.

The river lamprey (group 7b) should have passage capabilities theoretically sufficient to swim up Denil fish passes without any great difficulties. However, given the limited current knowledge and as a precautionary measure, river lampreys should not be included in the pre-assessment.

Denil fish passes are not suitable for the species groups numbered 8 and higher.

3. Analysis of the water depth

If the water depth over the baffles is less than the threshold values indicated in Table 28, the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 4.

4. Analysis of the slope

If the slope is greater than 16% (floor baffles) or 20% (plane baffles), the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, **it is necessary to proceed with the in-depth study** (hydraulic conditions in the fish pass as a function of hydrology during the migratory period, analysis of the length of straight sections and of the dimensions of rest pools, attractiveness, etc.).

Tableau 28 *Threshold values for pre-assessment of Denil fish passes.*

ICE species group	Species	Minimum water depth for floor baffles (m)	Minimum water depth for plane baffles (m)
1	Atlantic salmon (*Salmo salar*) Brown or sea trout [50-100] (*Salmo trutta*)	0.20	0.30
2	Mullets (*Chelon labrosus, Liza ramada*)	0.15	0.25
3a	Allis shad (*Alosa alosa*)	0.20	0.30
3b	Twaite shad (*Alosa fallax fallax*)	0.15	0.25
3c	Sea lamprey (*Petromyzon marinus*)	0.10	0.10
4a	Brown or sea trout [25-55] (*Salmo trutta*)	0.15	0.25
4b	Brown trout [15-30] (*Salmo trutta*)	0.10	0.20
5	Asp (*Aspius aspius*) Pike (*Esox lucius*)	0.20	0.30
6	Grayling (*Thymallus thymallus*)	0.15	0.25
7a	Barbel (*Barbus barbus*) Chub (*Squalius cephalus*) Nase (*Chondrostoma nasus*)	0.15	0.25
7b	River lamprey (*Lampetra fluviatilis*)	0.10	0.10

The values shown above are recommended values. Under certain conditions (discharge, available space, etc.), it may be necessary to select slightly different values. The greater the overrun of the threshold values by the measured values, the greater the non-suitability of the fish pass.

Fish passes designed specifically for eels

The following points must be analysed during the pre-assessment.

1. Check that a downstream fall does not exist

If there is a fall at the downstream end, the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, go to Step 2.

2. Check that a continuous crawl way exists

Inspect the entire height and distance that the fish must overcome to ensure that a passageway suitable for crawling exists for eels (wettened zone, but where the depth is less than 10 mm for elvers and 5 mm for glass eels). If OK, go to Step 3.

Otherwise, the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

NB A maximum depth of 20 mm is tolerable for slight longitudinal slopes in the 15 to 20% range or for brush-type substrates, which are less sensitive to water depths than stud-type substrates. For glass eels, the water depth must always be less than 5 mm, whatever the longitudinal slope.

In light of these threshold values, it is best to create a latitudinal slope even if the fish pass is supplied with pumped water.

3. Analysis of the longitudinal slope

Check that the longitudinal slope of the crawl way is less than the recommended maximum of 100% for brush-type substrates and 70% for stud-type substrates. If OK, go to Step 4.

Otherwise, the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

NB The value for the longitudinal slope of stud-type substrates is a recommended value. Under certain conditions (discharge, available space, slight latitudinal slope, head-drop, etc.), it may be necessary to select a slightly higher value. The greater the overrun of the threshold values by the measured values, the greater the non-suitability of the fish pass.

4. Analysis of the latitudinal slope

If the fish pass has a latitudinal slope (supplied directly with upstream water), check that the latitudinal slope of the crawl way is less than the recommended maximum of 50% for brush-type substrates and 25% for stud-type substrates. If OK, go to Step 5.

Otherwise, the slope is too steep, the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

NB The values indicated for latitudinal slopes are recommended values. Under certain conditions (discharge, available space, slight longitudinal slope, head-drop, etc.), it may be necessary to select a slightly higher value. The greater the overrun of the threshold values by the measured values, the greater the non-suitability of the fish pass.

5. Type of substrate

If very young eels (glass eels in particular) are likely to use the fish pass and the substrate is not of the brush type (or similar), the substrate is not suitable and the fish pass does not comply with the general sizing criteria, i.e. the pass is not well suited or not at all suited to the given purpose.

Otherwise, the pre-assessment result is positive, however **it is necessary to proceed with the in-depth study of the hydraulic conditions in the fish pass and of its attractiveness.**

Bypass channels

In a bypass channel, linking the upstream and downstream reaches, the flow energy is dissipated and flow velocities are reduced. These characteristics are due to the roughness of the bed and banks, and a succession of elements (rocks, groynes, weirs, etc.) positioned more or less regularly. The objective is to create a flow similar to that of a natural river. The slope can vary somewhat, from 1 to over 6%. It depends on the given species and on the discharges in the channel.

In general, bypass channels are not easy to create given the slight slope (which often makes considerable lengths necessary) and the difficulty in adapting them to the often considerable variations in water levels without special systems (gates, flaps, pool-type fish passes).

There are two main types of bypass channel.

- **Channels in which energy dissipation is achieved primarily by regularly spaced weirs.** These weirs create a series of pools whose length is calculated to dissipate the energy before the next weir. In this case, a pre-assessment can be carried out by analysing each weir using the criteria proposed for pool-type fish passes.
- **Channels in which energy dissipation takes place more or less regularly along the entire channel due to bed/bank roughness and individual elements (rocks, groynes, etc.).** For this type of bypass channel, an in-depth study of the operating conditions and the hydraulic conditions in the channel is required.

Figure 127

(a) Bypass channel for the Graves lake on the Gave de Pau River, (b) Biron bypass channel on the Gave de Pau River, (c) Vilette bypass channel on the Eure River, (d) Hamet bypass channel on the Eure River.

Locks, elevators and tidal structures

It is difficult to provide simple and easily measurable criteria in order to determine rapidly whether a given system is not well suited or not at all suited for the given species.

For this type of structure, an in-depth study of the operating conditions and the hydraulic conditions in the structure is required.

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Main symbols and abbreviations

■ **a, b, c:** Height (a), length (b) and diagonal (c) of a step (expressed in metres). The value of c is equal to $\sqrt{(a^2+b^2)}$. The parameters amax and cmax correspond to the maximum height and diagonal of a step up to which a fish can overcome the obstacle, on the condition that the flow be a skimming flow. The values of amax and cmax depend on the length of the fish.

a_{max}: Maximum height of a step that can still be cleared by fish. This value must be less than 0.5 Lp.

c_{max}: Maximum diagonal of a step that can still be cleared by fish. This value must be less than 0.7 Lp.

■ **α:** Angle of incidence of the water jet, which corresponds to the slope of the glacis (expressed in degrees).

■ **β:** Angle of incidence of the jump of a fish (expressed in degrees).

■ **DH**: Head-drop, which corresponds to the difference between the water levels upstream and downstream of the fall. This is the same as the difference between $Z_{upstream}$ and $Z_{downstream}$ (expressed in metres).

DH_{max}: Corresponds to the maximum theoretical head-drop that can be overcome by a fish of size Lp_{max}

DH_{min}: Corresponds to the maximum theoretical head-drop that can be overcome by a fish of size Lp_{min}

DH_{avg}: Corresponds to the maximum theoretical head-drop that can be overcome by a fish of size Lp_{avg}

$DH_{extreme}$: Corresponds (for vertical weirs, inclined faces and flows under gates) to the head-drop that cannot be overcome by a species or group of species and for which ICE analysis is not necessary. The value corresponds to the head-drop DHmax to which is added a safety margin of approximately 0.5 to 1 metre, depending on the species. When the head-drop created by an obstacle is greater than DHextreme, the structure necessarily constitutes a total barrier.

■ **g**: The acceleration of gravity (9.81 m/s²).

■ **h**: The depth of a flow of water (in metres).

h_{min}: Absolute minimum depth (or minimum thickness of a sheet of water) required for a fish to swim (expressed in metres). The value is a function of the species' size and morphology. In the ICE protocol, the value of h_{min} is indicated for each species or group of species. It corresponds roughly to the average body depth (hp) of the species or group of species under consideration. This parameter is used in assessing inclined weirs.

$h_{min\ roch}$: Absolute minimum depth (or minimum thickness of a sheet of water) in metres, required for a fish to swim and to provide smooth flow over a rock weir. The value is a function of the species' morphology and of the slope of the glacis. In the ICE protocol, the value of $h_{min\ rock}$ is indicated for each species or group of species. This parameter is used notably to assess rock weirs or for a pre-assessment of rustic fish passes comprising riprap.

■ **H**: Overflow height for an overflow chute, a notch or a gate. The value of this parameter is expressed in metres.

$H_{upstream}$: Corresponds to the depth of water behind a gate. This parameter is used for ICE assessments of flows under gates or through orifices, but where the downstream outflow is free.

H_{min}: Absolute minimum overflow height enabling the passage of a species (expressed in metres). The value, corresponding to $Z_{upstream}$ minus Z_{weir}, is a function of the species' size and morphology. An H_{min} value is indicated for each jumping species or group of jumping species. This parameter is used notably in assessing vertical falls and fish passes.

■ **Hf**: Depth of the water in the plunge pool at the foot of an obstacle (expressed in metres).

Hf_{min}: Absolute minimum depth required by the fish to overcome the obstacle. It depends on the head drop and the angle of incidence α of the jet. This parameter is used in assessing vertical and subvertical falls and for inclined weirs.

■ **hp:** Body depth of the fish (in metres). This value is a function of the morphology of each fish and corresponds to the form factor (k) divided by the length of the fish.

hp_{min} : Minimum body depth of a given species taking into account the biological stage considered for the ICE protocol. This body depth corresponds to a fish of size Lp_{min}.

hp_{max} : Maximum body depth of a given species taking into account the biological stage considered for the ICE protocol. This body depth corresponds to a fish of size Lp_{max}.

hp_{avg} : Body depth corresponding to the average between hpmin and hpmax. This body depth corresponds to a fish of size Lp_{avg}.

■ **L**: Length of a structure that a fish must overcome (expressed in metres). This parameter is used when assessing road and rail structures and in special cases for eels when the fish pass includes a crawl way.

Lp: Total length of a fish (expressed in metres).

Lp_{min}: Minimum length of a given species taking into account the biological stage considered for the ICE protocol.

Lp_{max}: Maximum length of a given species taking into account the biological stage considered for the ICE protocol.

Lp_{avg}: Length corresponding to the average between Lp_{min} and Lp_{max}.

■ **n**: Manning coefficient. This coefficient represents the roughness of the river bed and banks affecting a flow.

■ **OV**: Opening of a gate (expressed in metres).

OV_{min}: Absolute minimum opening (in metres) of a gate required for the passage of the given fish species. In the ICE protocol, the value of h_{min} is indicated for each species or group of species. This value is used in assessing gates.

■ **P_{aer}**: Maximum muscular power developed during aerobic glycolysis. It corresponds to the maximum cruising speed U_{cr} prior to the shift to anaerobic conditions.

■ **P_{ana}**: Maximum muscular power developed during anaerobic glycolysis. It is proportional to the maximum speed U_{max}.

■ **Pv**: Dissipated power density. This parameter is a simple indicator of the agitation in the basins of a fish pass (expressed in Watts/m^3).

■ **q**: Unit discharge, i.e. the discharge per meter width (expressed in m^3/s/m or m^2/s).

■ **t or tu**: Time (or endurance) during which a fish can swim at speed U. The endurance of a fish tu_{max} at its top speed U_{max} is generally between 10 and 20 seconds.

■ **U**: Swimming speed of a fish (expressed in metres per second).

$\mathbf{U_{max}}$: Maximum (also top or sprint) swimming speed of a fish.
$\mathbf{U_{cr}}$: Cruising speed, i.e. the speed that a fish can maintain for hours.

■ **V**: Flow velocity of water (expressed in metres per second).

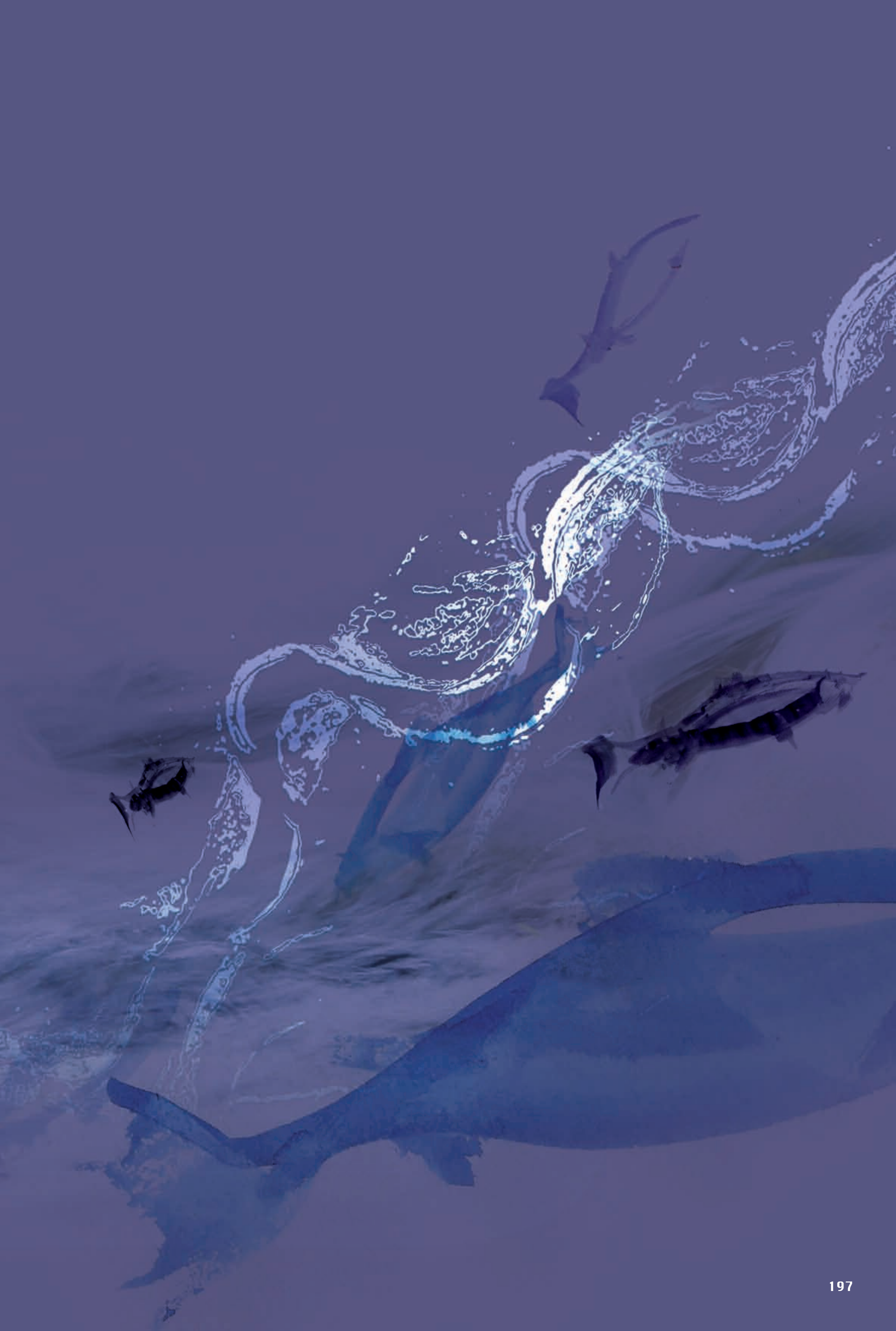
■ $\mathbf{X_{max}}$: Theoretical maximum jumping length of a given fish (expressed in metres), calculated as a function of its maximum speed U_{max} and the angle of incidence β of the jump.

■ $\mathbf{Y_{max}}$: Theoretical maximum jumping height of a given fish (expressed in metres), calculated as a function of its maximum speed U_{max} and the angle of incidence β of the jump. Practically speaking, part of the length of the fish is added.

■ $\mathbf{Z_{upstream}}$: Elevation of the water line upstream of an obstacle (expressed in metres or metres asl).

■ $\mathbf{Z_{downstream}}$: Elevation of the water line downstream of an obstacle (expressed in metres or metres asl).

■ $\mathbf{Z_{weir}}$: Elevation of a weir (expressed in metres or metres asl).



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AFAQ
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The international community has progressively acknowledged the issues raised by the fragmentation of habitats and responded with a number of legal texts. In the European Union, the Water framework directive is a prime example in the field of aquatic environments. The objective of the texts is generally to preserve or to restore the ecological continuity of hydrosystems and their riparian corridors in order to slow or to stop the loss of biodiversity now taking place.

In aquatic ecosystems, the massive (yet often unsuspected) numbers of transverse obstacles on rivers (over 70 000 obstacles have already been inventoried in France) are one of the main causes of degraded ecological continuity, particularly for fish whose survival depends on their freedom of movement. An evaluation of the degradations to ecological continuity is a prerequisite to assessing the seriousness of problems in the field and identifying the priorities for action.

The need for a simple, reliable and standardised assessment method for use by a wide range of environmental stakeholders rapidly became evident. Onema responded to the challenge and coordinated the development of the ICE protocol as the basis for the required ecological-continuity assessment method.

This richly illustrated book in the *Knowledge for action* series presents the results of the development work and particularly the concepts, design methods and detailed application procedures for the ICE protocol. It also presents succinctly the main scientific and technical knowledge available internationally on the issues involved in ecological continuity for fish, the physical capabilities of various fish species in continental France, the different types of obstacles and their impact, and the main types of fish passes now used.

This book should enable readers to understand in detail the methods implemented, to apply them locally and, in general, to use the information presented here for an array of other specific needs.

Jean-Marc BAUDOIN, PhD in functional ecology, director of the Onema-Irstea centre for study and research on the hydroecology of lakes, coordinated over a period of five years numerous national projects concerning hydromorphology and the ecological continuity of continental aquatic environments as a member of the Onema general management.

Vincent BURGUN, engineer (AgroParisTech-Engref) at the technical-support department for water policy at the Onema North-East regional office, works primarily in the field of assessing and restoring ecological continuity.

Matthieu CHANSEAU, PhD in biology, expert consultant for the Ecology ministry, in charge of the Ecological-continuity project and Programmes and networks for migratory animals at the Onema South-West regional office, has worked for many years on the impact of various obstacles in rivers on the behaviour of fish.

Michel LARINIER, PhD and engineer in hydraulics, scientific expert, served as director of the GHAAPPE, of the Onema Ecohydraulic centre and of the River installations for migratory fish research team, and invested thirty years into researching, experimenting and providing technical assistance in the field of ecohydraulics.

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Bruno VOEGTLE, civil engineer (ENSIP), hydraulics engineer (ENSEEIHT) and co-director of ECOGEA (engineering firm for the management of the aquatic environment), headquartered in Pins-Justaret (Haute-Garonne department), has specialised in ecohydraulics and particularly in the ecological continuity of fish.

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