Assessing the passage of obstacles by fish and macro-crustaceans in the French tropical islands of the Atlantic and Indian Oceans. Concepts and design

Karl Kreutzenberger, Pierre Sagnes, Pierre Valade, Bruno Voegtlé

OFB
OFFICE FRANÇAIS DE LA BIODIVERSITÉ

Knowledge for action

The ICE method for ecological continuity

Assessing the passage of obstacles by fish and macro-crustaceans in the French tropical islands of the Atlantic and Indian Oceans

Concepts and design

Karl Kreutzenberger, Pierre Sagnes,
Pierre Valade and Bruno Voegtlé

N°34

RÉPUBLIQUE FRANÇAISE
Liberté
Égalité
Fraternité

This book continues the ***" Knowledge for action "*** series that makes new research findings and science-advice work available to professionals in the water and aquatic-environment sector (scientists, engineers, managers, instructors, students, etc.).

It is available on the OFB site (https://professionnels.ofb.fr/en/node/1170) and at the French partnership portal for "Water and biodiversity documents" (www.documentation.eauetbiodiversite.fr).

The ICE method for ecological continuity

Assessing the passage of obstacles by fish and macro-crustaceans in the French tropical islands of the Atlantic and Indian Oceans

Concepts and design

Karl Kreutzenberger, Pierre Sagnes,
Pierre Valade and Bruno Voegtlé

N°34

Preface

Fragmentation of natural habitats is one of the main causes of biodiversity loss (*European Environment Agency*, 2011). Obstacles to flow in rivers have negative impacts, namely:

- a "barrier" effect that can block certain species from reaching habitats needed to achieve their life cycles under good conditions;
- degradation of aquatic environments and consequently of the living communities and the ecological processes in those environments.

In light of the legal requirements (EU Water framework directive - WFD, Law on water and aquatic environments - LEMA, Grenelle environmental agreements, etc.) and the vast array of environmental issues surrounding the restoration of ecological continuity in aquatic environments, the former National Agency for Water and Aquatic Environments (Onema), which integrated the French Biodiversity Agency between 2017 and 2020, launched and coordinated the development of a method to assess the passage of river obstacles by fish in continental France. That work produced the ICE method for ecological continuity. The method was presented in a document published in 2014 (Baudoin *et al.*, 2014) and an operational version, the ICE protocol designed for work in the field, was subsequently published (Burgun *et al.*, 2015).

The method and the field protocol are based on a wide-ranging study of the international scientific literature, on the scientific and technical results of a work group comprising French (Onema and the Ecogea consulting firm) and Belgian (Liège University) experts, and on the experience gained in the field by technical personnel in charge of restoring ecological continuity in rivers. The goal was to create an operational analysis tool that was simple, robust, objective and consistent, in order to assess the degree to which transverse obstacles (weirs, dams) in rivers block the movement of fish.

Given their tropical characteristics, the hydrological functioning and the aquatic fauna of rivers in the French overseas territories under consideration differ widely from those of rivers in continental France. The characteristics of the hydraulic structures in the overseas rivers can also differ significantly. For these reasons, the assessment method for the passage of obstacles by fish developed and used in continental France could not be used without modifications in the overseas territories.

On the basis of the general principles of the method developed for continental France, the objective of this document is to adapt that method to the physical (types of obstacles) and biological (fish and macro-crustaceans) context of the French tropical islands of the Atlantic and Indian Oceans (Guadeloupe, Martinique, Mayotte and Réunion). Similar to the method for continental France, the overseas method has produced a reliable and standardised tool based on scientific principles and observations. It can be used to assess the difficulties created by obstacles by comparing their characteristics (typology, geometry, hydraulics) to the passage capabilities of the given species of fish and macro-crustaceans.

IMPORTANT NOTE

This document does not address fish passes installed next to obstacles in rivers. Fish passes are still relatively rare in the overseas territories and the assessment of their effectiveness requires specific methods.

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

Finally, this document presents the overseas method. The field protocol, designed to ensure correct sizing and the safety of operations in the field, as well as a standardised procedure, is available in a separate document (Burgun *et al.*, 2015).

Abstract

Fragmentation of natural habitats is one of the main causes of biodiversity loss. The international community decided to act and created legal obligations in view of maintaining sufficiently diversified and interconnected habitats so that animal and plant species can satisfy their vital needs and, where possible, adapt to environmental changes. For example, the EU Water framework directive (WFD, 2000) highlighted the value of gaining knowledge, preserving and restoring ecological continuity in hydrosystems and riparian corridors.

Many transverse obstacles in rivers (over 100 000 have already been inventoried in France) can degrade ecological continuity in aquatic ecosystems.

This situation made it necessary to develop new, standardised tools to diagnose the risks, in a given area, of damage to ecological continuity (notably in terms of the movement of aquatic fauna) caused by obstacles to flow. It was in this context, shortly before 2010, that the National Agency for Water and Aquatic Environments (Onema), which later integrated the French Biodiversity Agency (OFB), decided to address the problem and coordinate the development of the ICE (Information on the Continuity of Ecosystems) method, designed to assess the severity of the impacts of obstacles on the movement of the main species of fish in continental France (Baudoin *et al.*, 2014).

In the French tropical islands of the Atlantic and Indian Oceans (Guadeloupe, Martinique, Mayotte and Réunion), a survey still under way has already revealed the existence of over one thousand obstacles in rivers. Many of these structures can limit and even completely block the movements, vital to the achievement of their life cycles, of fish and macro-crustaceans, virtually all of which are diadromous.

To date, the assessment of the potential impacts on ecological continuity was generally undertaken by a small number of experts in the field. However, a series of issues, ranging from the number of obstacles requiring assessment to the need for a simplified means of sharing knowledge and common concepts among highly diverse stakeholders (project owners, consulting firms, site managers, civil servants, etc.), made it necessary to offer a simple method that is scientifically sound, objective, understandable and implementable in a minimum amount of time. Calling on the experience gained in deploying the method in continental France and in a partnership with all the overseas Environmental Directorates and Water Offices, and with the Écogea and Ocea consulting firms, OFB coordinated and facilitated the adaptation of the method to the tropical islands of Guadeloupe, Martinique, Mayotte and Réunion.

This book in the ***Knowledge for action*** series is organised in three chapters. It summarises the main scientific and technical knowledge available internationally and presents the method as follows:

- **chapter one** presents the issues surrounding ecological continuity for fish and crustaceans in tropical islands of the Atlantic and Indian Oceans. It discusses the types of obstacles encountered, the ecological and functional issues concerning the movement of the species of fish and macro-crustaceans in question, and describes for each species the main environmental, ethological and physical factors determining the possibility and their capability of overcoming obstacles;
- **chapter two** elaborates on the fundamental concepts of the ICE method adapted to tropical islands of the Atlantic and Indian Oceans, the scope of its applicability, the groups of species under consideration, their characteristics and the five passability classes ranking the impacts of obstacles on the upstream migration of the species;
- **chapter three** examines in detail the proposed method and looks at each step in the diagnostic procedure to determine the passability of obstacles to upstream migration using decision trees and explanatory text. In the process, the criteria used to define the passability classes for commonly encountered types of obstacles are presented. By comparing the hydraulic and physical characteristics of the assessed obstacle with the physical capabilities of the species, the method makes possible a scientifically sound, step-by-step analysis of the degree to which a given obstacle is passable by the species in question. The method expands its scope by including an analysis of specific taxa and proposes an assessment and diagnostic procedure for the crawling capabilities of eels, the suction and climbing capabilities of *Sicydiinae* and the post-larvae/juveniles of small, benthic species, as well as the walking capabilities of macro-crustaceans.

This detailed and richly illustrated book in the ***Knowledge for action*** series clearly explains the method developed, the fundamental concepts and issues involved, and puts readers in a position to effectively implement the method in the field.

Keywords:

Species, fish, macro-crustaceans, obstacles, method, analysis, capability, passability, tropical islands

Contents

Introduction

Origin and definition of the concept of ecological continuity

Ecological continuity is a recent concept that was first introduced by the British botanist Francis Rose (Rose, 1974). The term is particularly evident when discussing continental aquatic ecosystems, which by their very nature are organised in a continuum of flowing water, however the initial research on the topic targeted terrestrial ecology, in particular landscape ecology and the study of forest systems. The terms “landscape continuity”, “biological continuity” and “connectivity” are also frequently used and associated with the concepts of ecological corridors and ecological networks, for example the French TVB (Trame Verte et Bleue) system of ecological networks.

Though several definitions of ecological continuity exist, the most commonly used today 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. "*habitat [that] 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).

Regulatory aspects and the French context

The Water framework directive (WFD, 2000) generalised the use of this neologism within the water 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 rivers. It is in this sense that it constitutes a full-fledged quality element, called “*river continuity*”, in assessments of ecological status.

In France, the 2006 law on water and aquatic environments (LEMA, 2006) 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).

The presence and increasing numbers of transverse structures created by humans in rivers (for power generation, drinking water, irrigation, navigation, bed-stabilisation systems, aquaculture, recreational activities, etc.) have significantly modified ecosystem structures and functioning. By blocking the flow of water, they may hinder the movement of living communities, modify and degrade the quality of aquatic environments, reduce the diversity of habitats available for the various species and alter the physical-chemical quality of water. The consequences for biological communities can be drastic. The most emblematic example is that of diadromous (migratory) fish whose spawning grounds may be submerged deep under water and their access limited or totally blocked by transversal structures.

For over 50% of surface water bodies (WFD report, 2016), hydromorphological alterations and notably degraded ecological continuity have been designated as responsible factors in the risks of not achieving good ecological status. This fragmentation runs directly counter to maintaining the correct functioning of rivers and, consequently, to preserving the quality of aquatic environments and biodiversity.

In France in 2018, over 100 000 obstacles (dams, weirs, etc.) had been inventoried in the national database on obstacles to river flow (ROE). This situation made it necessary to develop new, standardised tools to diagnose the risks, in a given area, of damage to ecological continuity (notably in terms of the movement of aquatic fauna) caused by obstacles to flow.

A method to assess obstacle passability

Onema (integrated into OFB between 2017 and 2020) responded to the challenge and coordinated the development of the ICE (Information on the Continuity of Ecosystems) method, designed to assess the severity of the impacts of obstacles on the movement of the main species of fish in continental France (Baudoin *et al.*, 2014). A second document, the protocol, outlining the effective implementation of the method in the field, was also produced (Burgun *et al.*, 2015).

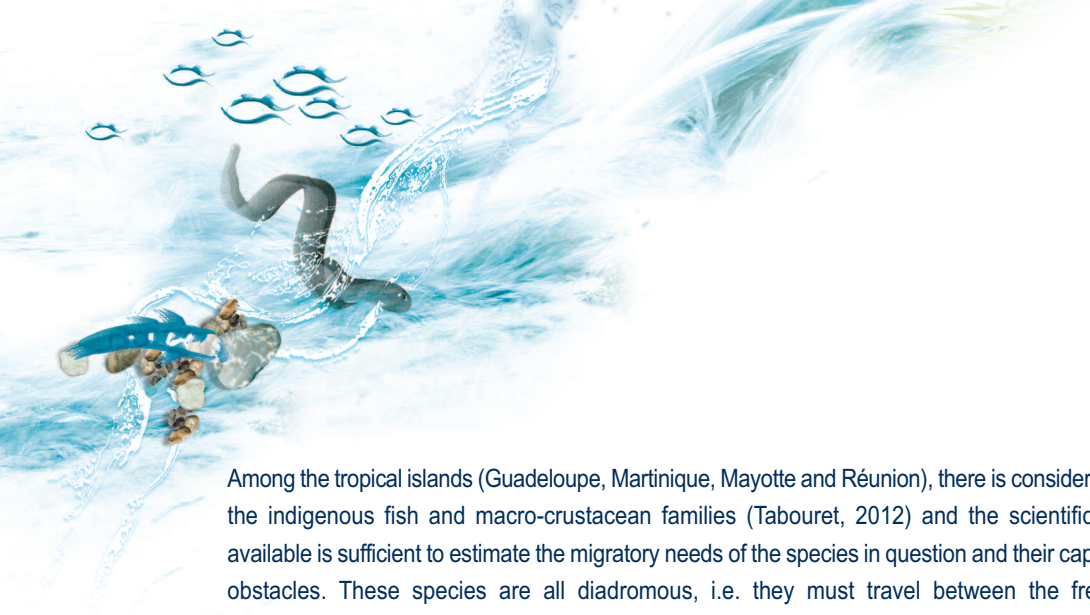
Barriers to the free movement of aquatic fauna may be either physical-chemical (temperature, oxygen levels, pollution, etc.) or physical (waterfalls, flow velocity, turbulence, dry periods, low water levels, etc.). Given the available scientific knowledge, the method presented here addresses solely the **physical effects of transverse structures on the movement of fish.**

The knowledge acquired in continental France has been stored in a database (https://geobs.eaufrance.fr/).

Adaptation to the overseas context

A large number of transverse obstacles exist in the hydrographic networks of the French tropical islands of the Atlantic and Indian Oceans, hereinafter called the French overseas territories (FOT). In 2018, the ROE database had already listed over one thousand obstacles.

The obvious next step was for OFB, in conjunction with the overseas Environmental Directorates and Water Offices, to adapt the ICE assessment method to all the French overseas territories. The basic concepts of the method for continental France, i.e. a comparison of the topographical and hydraulic characteristics of structures with the physical capabilities of the species analysed, remained the same for the overseas territories.



Among the tropical islands (Guadeloupe, Martinique, Mayotte and Réunion), there is considerable similarity between the indigenous fish and macro-crustacean families (Tabouret, 2012) and the scientific knowledge currently available is sufficient to estimate the migratory needs of the species in question and their capabilities in overcoming obstacles. These species are all diadromous, i.e. they must travel between the freshwater and marine environments in order to achieve their life cycle and are consequently highly affected by physical barriers installed in rivers (Tabouret, 2013).

For French Guiana, the severe lack of knowledge on the biology and migratory capabilities of many fish species made it necessary, as a precautionary measure, not to include the territory in the method. **For that reason, in this document, only the insular territories of the Atlantic and Indian Oceans are included (Guadeloupe, Martinique, Mayotte and Réunion).**

The islands of Martinique, Guadeloupe, Réunion and Mayotte all boast considerable diversity of freshwater decapod crustaceans. On the islands, strong local and culinary traditions have developed around these species. Very large in some cases, they are regularly captured during campaigns to collect fish samples (electrofishing and trapping). Decapod crustaceans are frequently the only diadromous species present in the upper sections of river basins and are consequently of major importance for the biodiversity of aquatic macrofauna on tropical islands. **For this reason, macro-crustaceans had to be included in the ICE method.**

To facilitate the understanding and learning of the method, this document reuses many components and excerpts from the document presenting the method for continental France (Baudoin *et al.*, 2014), notably concerning the fundamental scientific and technical aspects that it adapts to the specificities of the tropical, insular environments and species.

For that reason, this ***Knowledge for action*** document is divided into three chapters:

- **chapter one** discusses the importance of ecological continuity for fish and macro-crustaceans, based on a review of the current scientific knowledge. It also summarises the physical capabilities to overcome obstacles of different species found in the rivers of the French tropical islands of the Atlantic and Indian Oceans, indicating the parameters used to assess those capabilities and the main factors on which passage depends;
- **chapter two** presents the general principles underlying the method adapted to the French insular, overseas territories. It defines the scope of the method and the main types of obstacle analysed. In addition, it lists species' groups according to their capabilities in overcoming obstacles and defines the passability classes selected for the method;
- **chapter three** goes into the details of the diagnostic procedure to determine the passability of various types of obstacles during upstream migration.

This detailed and richly illustrated book in the **Knowledge for action** series clearly explains the method developed, the fundamental concepts and issues involved, and puts readers in a position to effectively implement the method in the field. The knowledge collected and presented here may also serve for many other applications in related fields.

A

Ecological continuity, fish and crustaceans

The importance of free movement for fish and crustaceans

The biological context, mobility and migration

Similar to many other free (non-attached) animals, fish and crustaceans must move continuously between different habitats and over a range of spatial scales 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 maximise progeny and to perpetuate the species.

Movements between the various habitats take place in a temporal sequence depending on the changing needs in the biological stages of individual animals, for example the larval, fry, juvenile and adult stages of fish. The spatial structure of a population is thus the result of the behaviour of the individual animals that constitute the population and that move in pursuit of the available resources in the various, accessible habitats in the river.

Depending on the objective, these movements take place over highly variable time scales (days, seasons or even years), distances (from a few centimetres to several thousand kilometres) and in different directions (longitudinally either upstream or downstream, laterally between the main river and floodplain habitats, vertically in the case of deep rivers).

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 animal to increase its chances to transmit its genes to future generations (Lucas and Baras, 2001).

■ The main movements of fish and decapod crustaceans

Fish and decapod crustaceans move within the river continuum. They shift regularly between different habitats, depending on their biological stage and activities, for example they make daily round trips between feeding and rest areas. These regular movements are generally limited to distances ranging from a few metres to a few dozen metres within a series of habitats and depend on the needs and behaviour of the individual animal (feeding regime, time spans between activities, etc.).

Other movements, over larger time scales and distances, are required to achieve the life cycle of species. Ontogenic movements respond to the habitat requirements of the different development stages and depend on the movement capabilities of species, but also on environmental factors such as the availability of food. Concerning the species in the rivers of the insular, overseas territories, a majority of migrations take place along

the longitudinal axis of the river, however relatively little information on these migrations is available. Migrations within rivers are also caused by the strong floods prevalent in these tropical environments (tropical storms). Numerous monitoring programmes (Smith and Kwak, 2014a, 2014b; Lagarde *et al.*, 2016) revealed that adult mullets, *Eleotridae* and *Sicydiinae* (a sub-family of *Gobiidae*) moved in conjunction with one or more tropical floods. The fish migrated downstream during the flood, then swam back up the river to progressively recolonise the habitats that they had previously occupied.

Finally, there are also migrations between freshwater and marine environments that are necessary parts of the life cycle of diadromous species, which are by far the majority of the species of freshwater fish and crustaceans on tropical islands (McDowall, 1988, 2007; Keith, 2003; Bauer, 2013). The composition and abundance of these migrations can vary significantly depending on the season. For example, this seasonal variability was demonstrated on Réunion during monitoring programmes on upstream migrations in the mouths of three rivers from 2007 to 2012 (Arda, 2012).

In order to fully gauge the free movement of fish and crustaceans over and through structures in aquatic environments, **it is very important to have precise information on the migratory behaviour of the different species** in both natural and regulated water courses, notably during the critical periods, i.e. during migrations required to achieve their life cycle.

■ The different types of migratory fish and crustaceans

Indigenous communities of fish and decapod crustaceans in the French insular, overseas territories (Martinique, Guadeloupe, Réunion and Mayotte) consist of diadromous, vicariant, complementary and sporadic species. The primary or secondary species found in the freshwaters of these islands were all introduced by humans (Lim *et al.*, 2002; Keith *et al.*, 2006; Monti *et al.*, 2010).

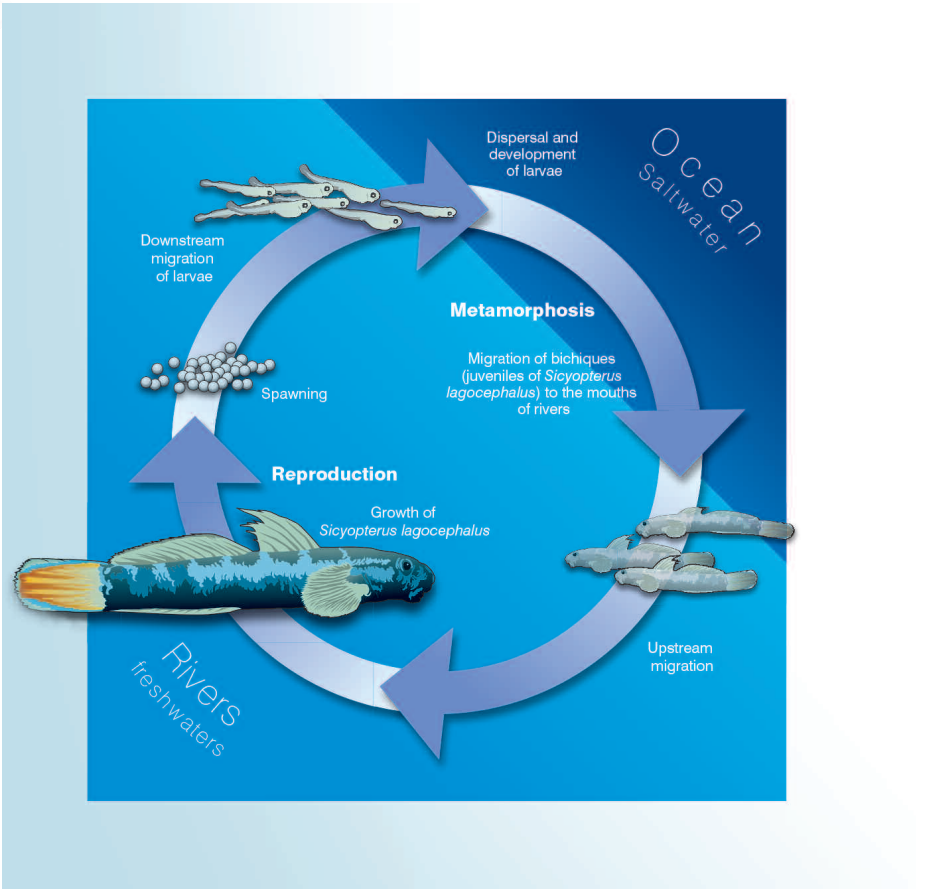
The diadromous fish and crustaceans (amphidromous and catadromous) are the most frequently found in rivers, from the mouth to the source, and upstream of natural waterfalls that can be several dozen metres high (e.g. *Atyidae*, *Anguillidae* and *Sicydiinae* on Réunion). The vicariant and sporadic species colonise lentic areas in the downstream sections of rivers.

Type 1. Amphidromous species

Amphidromy, as defined by Myers (1949), is the most common type of migration observed in the fish and crustaceans of tropical islands (McDowall, 2010). The main characteristics of amphidromy (McDowall, 2007, 2010) include 1) reproduction in freshwaters, 2) immediate transfer of the larvae (or free embryos) to marine waters following hatching, 3) a growth period in the sea of up to several months, 4) a return to freshwaters during the juvenile (or post-larval) stage, 5) a growth period in freshwaters to maturity, 6) reproduction in freshwaters (Figure 1, page 14; Tables 1 and 2, pages 15 and 16). Adults may spend several years in the freshwater environment and reproduce a number of times.

In some cases, the adults of amphidromous fish can migrate downstream during reproduction, but they do not reach the sea.

Figure 1



*Migratory cycle of an amphidromous migratory species (*Gobiidae*). Modified after Tabouret, 2012.*

In fish, this life cycle is valid for freshwater *Gobiidae* species (Keith, 2003), as well as for *Eleotridae* (Maeda *et al.*, 2008) and, *a priori*, for freshwater *Agonostomus* mullets (Smith and Kwak, 2014b). For *Gobiidae* and *Eleotridae*, a number of studies and research projects have described, on the one hand, the characteristics of the larvae during downstream migration (Delacroix and Champeau, 1992; Bell and Brown, 1995; Maeda *et al.*, 2008; Valade *et al.*, 2009; Yamasaki *et al.*, 2011; Zydlewski and Wilkie, 2012; Ellien *et al.*, 2014) and, on the other, the stages and speeds of colonisation in river mouths (Bell, 1997; Fièvet and Le Guennec, 1998; Keith, 2003; Hoarau, 2005; Maeda *et al.*, 2007; Arda, 2012; Teichert, 2012; Teichert *et al.*, 2014). However, the migratory phases of freshwater *Agonostomus* mullets are less well researched and researchers do not always agree (Cruz, 1987; Phillip, 1993; Marcy *et al.*, 2005; McDowall, 2007), with the exception of a few isolated observations concerning the migration phases of young *Agonostomus monticola* in rivers (Voegtlé and Valade, *obs. in situ*).

The life cycle of freshwater shrimp (*Atyidae*, *Palaemonidae*) in the insular FOTs (French overseas territories) is also amphidromous. Two main behaviours may be observed in these species during the downstream-migration phase (Bauer, 2013). In species that colonise only small hydrographic systems (insular context) and the *Atyidae* in particular, the females release the larvae into the current. But studies have shown that in several *Macrobrachium* species living in large, continental hydrosystems, berried (gravid) females can migrate several hundred kilometres downstream before releasing the larvae (Bauer and Delahoussaye, 2008; Olivier, 2013). The berried females that migrated downstream then migrate back up the river to recolonise the upstream habitats.

It should be noted that many gasteropod molluscs on tropical islands also have an amphidromous life cycle (McDowall, 2007). In some cases, molluscs and particularly *Neritininae* species may migrate in massive numbers (Pyron and Covich, 2003; Blanco and Scatena, 2007).

Table 1 *List of amphidromous fish in the insular FOTs and their biological stages during migration.*

Family	Species	Name in English (E) and in Creole (C)	FOT				Stage for upstream migration	Stage for downstream migration
			Guadeloupe	Martinique	Mayotte	Réunion		
Eleotridae	*Butis butis*	Crazy fish, crimson-tipped flathead-sleeper, duckbill sleeper (E)			X	X	Post-larval / Juvenile	Larval
	Dormitator maculatus	Fat sleeper (E) / ti-nèg, dormeur (C)	X	X			Post-larval / Juvenile	Egg / Larval
	Eleotris amblyopsis	Large-scaled spiny-cheek sleeper (E) / pitit dormè (C)	X				Post-larval / Juvenile	Larval
	Eleotris klunzingerii *	Brown sleeper, dusky sleeper (E) / cabot noir (C)			X	X	Post-larval / Juvenile	Larval
	Eleotris mauritiana	Widehead sleeper (E) / cabot noir (C)			X	X	Post-larval / Juvenile	Larval
	Eleotris perniger	Small-scaled spiny-cheek sleeper (E) / pitit dormè, flèche (C)	X	X			Post-larval / Juvenile	Larval
	Gobiomorus dormitor	Bigmouth sleeper (E) / grand dormeur, dormeur (C)	X	X			Post-larval / Juvenile	Larval
	Guavina guavina	Guavina (E) / dormeur (C)		X			Post-larval / Juvenile	Larval
	Hypseleotris cyprinoides	Tropical carp-gudgeon (E)			X	X	Post-larval / Juvenile	Larval
	Ophieleotris cf *aporos*	Snakehead gudgeon (E)			X		Post-larval / Juvenile	Larval
	Ophiocara porocephala	Northern mud gudgeon, spangled sleeper (E) / makanbale latet ron (C)			X		Post-larval / Juvenile	Larval
Gobiesocidae	*Gobiesox nudus*	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	X	X			Post-larval / Juvenile	Egg / Larval
Gobiidae	*Awaous banana*	River goby (E) / jolpot, loche (C)	X	X			Post-larval / Juvenile / Adult?	Larval / Adult?
	Awaous commersoni	Commerson's freshwater goby, river goby (E) / loche, cabot (C)			X	X	Post-larval / Juvenile / Adult?	Larval / Adult?
	Cotylopus acutipinnis	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)				X	Post-larval / Juvenile	Larval
	Cotylopus rubripinnis	Goby (E)			X		Post-larval / Juvenile	Larval
	Ctenogobius pseudofasciatus	Slashcheek goby (E)		X			Post-larval / Juvenile	Larval
	Glossogobius callidus	Tank goby (E)			X		Post-larval / Juvenile	Larval
	Glossogobius giurus	Tank goby (E) / loche (C)			X	X	Post-larval / Juvenile	Larval
	Glossogobius kokius	- (E) / loche, cabot (C)				X	Post-larval / Juvenile	Larval
	Mugilogobius mertoni	Chequered mangrove goby, Merton's mangrove goby, meander goby (E) / gobi milet (C)			X		Post-larval / Juvenile	Larval
	Redigobius balteatus	Rhinohorn goby (E)			X		Post-larval / Juvenile	Larval
	Redigobius bikolanus	Bigmouth goby, speckled goby (E) / gobi tase (C)			X		Post-larval / Juvenile	Larval
	Sicydium plumieri	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)	X	X			Post-larval / Juvenile	Larval
	Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)	X	X			Post-larval / Juvenile	Larval
	Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)			X	X	Post-larval / Juvenile	Larval
	Stenogobius polyzona	Chinestripe goby (E) / cabot rayé (C)			X	X	Post-larval / Juvenile	Larval
Mugilidae	*Agonostomus catalai*	Comoro mullet (E)			X		Post-larval / Juvenile	Egg / Larval
	Agonostomus monticola	Mountain mullet (E) / milet (C)	X	X			Post-larval / Juvenile	Egg / Larval
	Agonostomus telfairii	Fairy mullet (E) / chitte (C)			X	X	Post-larval / Juvenile	Egg / Larval

** Name of E. fusca after Mennesson and Keith (2017).*
** FOT = French overseas territory.*

Table 2 *List of amphidromous decapod crustaceans in the insular FOTs and their biological stages during migration.*

Family	Species	Name in English (E) and in Creole (C)	FOT				Stage for upstream migration	Stage for downstream migration
			Guadeloupe	Martinique	Mayotte	Réunion		
Atyidae	*Atya innocous*	Basket shrimp (E) / cacador, bouc, grand bouc (C)	X	X			Juvenile / Adult	Larval
	Atya scabra	Camacuto shrimp (E) / cacador, bouc, grand bouc (C)	X	X			Juvenile / Adult	Larval
	Atyoida serrata	- (E) / crevette bouledogue (C)			X	X	Juvenile / Adult	Larval
	Caridina longirostris	Long-nosed shrimp (E) / chevaquine (C)			X		Juvenile / Adult	NI
	Caridina serratirostris	Ninja shrimp (E) / chevaquine (C)			X	X	Juvenile / Adult	Larval
	Caridina typus	Typical caridina shrimp (E) / chevaquine (C)			X	X	Juvenile / Adult	Larval
	Jonga serrei	Jonga (E) / petit bouc (C)	X				Juvenile / Adult	Larval
	Micratya poeyi	Tiny basket shrimp (E) / petit bouc (C)	X	X			Juvenile / Adult	Larval
	Potimirim glabra	Smooth potimirim (E) / petit bouc (C)	X				Juvenile / Adult	Larval
	Potimirim potimirim	Potimirim (E) / petit bouc (C)	X	X			Juvenile / Adult	Larval
Grapsidae	*Sesarmops impressum*	- (E) / crabe de rivière (C)			X		Juvenile	Larval / Adult?
	Varuna litterata	Peregrine crab, river swimming crab (E) / crabe de rivière (C)			X	X	Juvenile	Larval / Adult?
Palaemonidae	*Macrobrachium acanthurus*	Cinnamon river shrimp (E) / chevrette, bouquet cannelle (C)	X	X			Juvenile / Adult	Larval / Adult?
	Macrobrachium australe	Koua river prawn (E) / chevrette grand bras (C)			X	X	Juvenile / Adult	Larval / Adult?
	Macrobrachium carcinus	Bigclaw river shrimp (E) / ouassou, z'habitant, écrevisse, bouquet pintade (C)	X	X			Juvenile / Adult	Larval / Adult?
	Macrobrachium crenulatum	Striped river shrimp (E) / queue rouge, écrevisse, queue de madras (C)	X	X			Juvenile / Adult	Larval / Adult?
	Macrobrachium equidens	Rough river prawn (E) / camaron tacheté, kanmaron (C)			X		Juvenile / Adult	Larval / Adult?
	Macrobrachium faustinum	Bigarm river shrimp, Caribbean longarm shrimp (E) / alexis, gros mordant, écrevisse (C)	X	X			Juvenile / Adult	Larval
	Macrobrachium heterochirus	Cascade river prawn (E) / grand bras, écrevisse (C)	X	X			Juvenile / Adult	Larval / Adult?
	Macrobrachium hirtimanus	- (E) / écrevisse, chevrette lecroc (C) (no longer present?)				?	Juvenile / Adult	Larval / Adult?
	Macrobrachium lar	Monkey river prawn (E) / chevrette, camaron, kanmaron gran lebra (C)			X	X	Juvenile / Adult	Larval / Adult?
	Macrobrachium lepidactylus	Madagascar scale prawn (E) / écrevisse, bétangue (C)			X	X	Juvenile / Adult	Larval / Adult?
	Palaemon pandaliformis	American grass shrimp (E) / bouquet potitinga (C)	X	X			Juvenile / Adult	NI
Xiphocaridae	*Xiphocaris elongata*	Cricket shrimp, yellow-nosed shrimp (E) / pissette (C)	X	X			Juvenile / Adult	Larval

NI: not indicated
* FOT = French overseas territory.

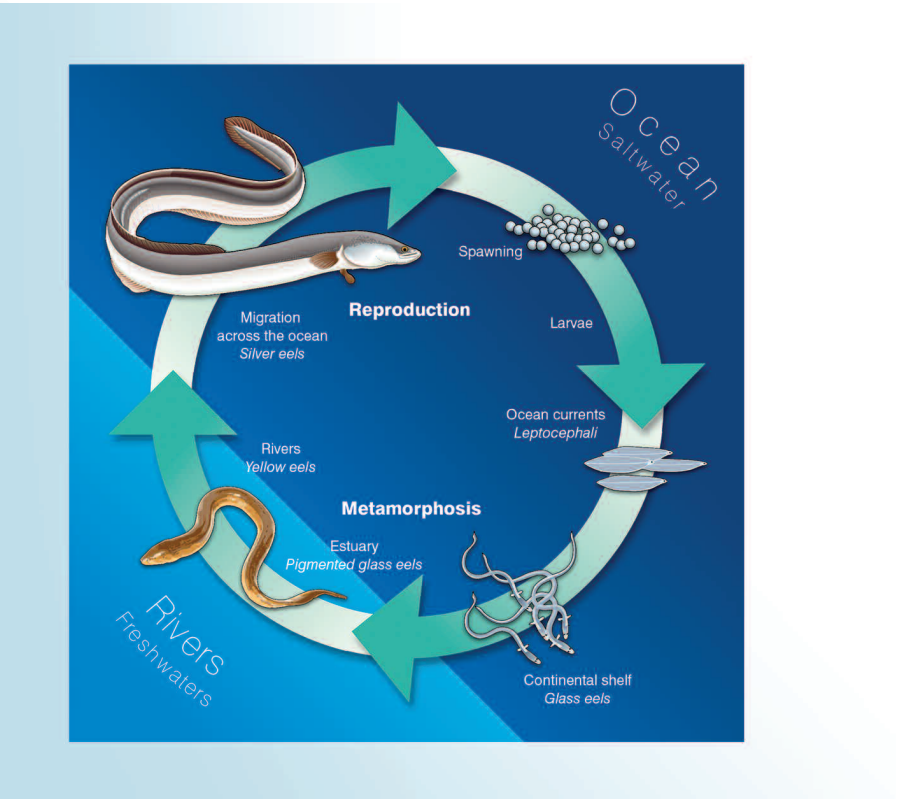
Type 2. Catadromous species

Catadromous species are also long-distance migrators and must travel between the sea and freshwaters in the course of their biological cycle. They migrate up rivers during the juvenile stage and colonise entire river systems, whereas the adults migrate downstream to the sea in order to spawn (Figure 2; Table 3).

The most emblematic species in this group are the eels. Five species of eels are found in the French insular, overseas territories, namely *Anguilla rostrata* in Martinique and Guadeloupe, *Anguilla marmorata*, *Anguilla mossambica*, *Anguilla bicolor bicolor* and *Anguilla bengalis* in Réunion and Mayotte. Eels spend most of their life cycle in freshwaters. They migrate to the ocean to reproduce. Several months after hatching and floating in the ocean, the larvae (leptocephali) metamorphose into post-larvae (glass eels) and colonise freshwaters. The glass eels migrate up rivers and later become elvers and then yellow eels. On becoming sexually mature,

the eels again metamorphose into silver eels. During this latter stage, the eels progressively adapt to renewed life in deep marine environments. In the south-western section of the Indian Ocean, the periods during which glass eels colonise freshwaters and their size vary depending on the species and the site (Robinet *et al.*, 2003; Reveillac, 2008). Not a great deal is known about the periods during which silver eels undertake their downstream migration in the studied French insular, overseas territories (Robinet and Feunteun, 2002). Wouthuyzen *et al.* (2009) have suggested that tropical eels can migrate over most of the year to the ocean in view of reproducing, except during the driest months.

Figure 2



Migratory cycle of a catadromous migratory species.

Table 3 *List of catadromous fish in the insular FOTs and their biological stages during migration.*

Family	Species	Name in English (E) and in Creole (C)	FOT				Stage for upstream migration	Stage for downstream migration
			Guadeloupe	Martinique	Mayotte	Réunion		
Anguillidae	*Anguilla bengalensis*	Indian mottled eel (E) / z'amab, z'anguille (C)			X	X	Glass eel / Elver	Adult (silver eel)
	Anguilla bicolor bicolor	Indonesian shortfin eel (E) / z'amab, z'anguille (C)			X	X	Glass eel / Elver	Adult (silver eel)
	Anguilla marmorata	Giant mottled eel, marbled eel (E) / z'amab, z'anguille (C)			X	X	Glass eel / Elver	Adult (silver eel)
	Anguilla mossambica	African longfin eel (E) / z'amab, z'anguille (C)			X	X	Glass eel / Elver	Adult (silver eel)
	Anguilla rostrata	American eel (E) / z'anguille (C)	X	X			Glass eel / Elver	Adult (silver eel)
Kuhliidae	*Kuhlia rupestris*	Jungle perch, rock flagtail (E) / doule de roche, carpe (C)			X	X	Juvenile / Adult	Adult
	Kuhlia sauvagii	Rock flagtail (E) / doule de roche, carpe (C)			X	X	Juvenile / Adult	Adult

* FOT = French overseas territory.

Two other fish species are catadromous, namely the rock flagtails *Kuhlia rupestris* and *Kuhlia sauvagii* (Feutry *et al.*, 2012b, 2013). Among the overseas territories, these species may be found in Mayotte and Réunion (Keith *et al.*, 2006; Feutry *et al.*, 2012a). Observations by Lewis and Hogan (1987) suggest that downstream migration and reproduction take place during the austral summer, which has been confirmed for Réunion, where it has been shown that the effective reproductive period of *Kuhlia rupestris* runs from October to August, with the main period running from November to January (Arda, 2012). Juveniles of the *Kuhlia rupestris* and *Kuhlia sauvagii* species colonise rivers after spending 30 to 40 days as larvae in the marine environment (Feutry *et al.*, 2012c), a relatively short period in comparison with the amphidromous species in the insular, overseas territories. On Réunion, recruitment in rivers spans a large part of the year, with a peak in January and February.

Type 3. Vicariant and sporadic species

Vicariant and sporadic fish (Table 4) are held not to be diadromous, but they live indifferently in freshwaters or saltwater. They colonise the lower sections of river basins and do not extend beyond the first rapids.

Due to a lack of knowledge on their biology, several species (*Agonostomus*, *Kuhlia*, etc.) were for years classified as vicariant or sporadic given that they belong to families of marine species (Lim *et al.*, 2002; Keith *et al.*, 2006; Monti *et al.*, 2010), but were later classified as diadromous (amphidromous or catadromous) following more in-depth study (Feutry *et al.*, 2012b; Smith and Kwak, 2014b). For example, pipefish are currently classified as vicariant, but it is now thought that they spawn in freshwaters and that the larvae migrate downstream and develop in the ocean. On Réunion, brooding males from the *M. brachyurus* species have been observed over two kilometres upstream of the river mouth (Marsouins River, Valade, personal observation). The species could be amphidromous or semi-amphidromous (i.e. a marine/brackish cycle).

The same is true for certain decapod-crustacean species that live exclusively in lentic habitats in the lower sections of rivers or in coastal water bodies. An example is *Palaemon concinnus* on Réunion and Mayotte. For these species, upstream migration generally takes place during the juvenile stage, but the stage for downstream migration is unknown (adults or larvae). Little is known about these species and a precise diagnosis of their capacity to overcome obstacles is not possible, however they should be taken into account on a case by case basis in the context of the studied structure.

Table 4 *List of vicariant and sporadic fish in the insular FOTs and their biological stages during migration.*

Family	Species	Name in English (E) and in Creole (C)	FOT				Stage for upstream migration	Stage for downstream migration
			Guadeloupe	Martinique	Mayotte	Réunion		
Ambassidae	*Ambassis ambassis*	Longspine glassy, Commerson's glassy perchlet (E) / ambache (C)			X	X	Post-larval / Juvenile	NI
	Ambassis natalensis	Slender glassy (E) / ambache (C)			X	X	Post-larval / Juvenile	NI
Megalopidae	*Megalops atlanticus*	Tarpon (E) / palika (C)	X	X			NI	NI
	Megalops cyprinoides	Indo-Pacific tarpon (E)			X	X	NI	
Syngnathidae	*Microphis argulus*	Flat-nosed pipefish (E)			X	X	NI	NI
	Microphis brachyurus	Short-tailed pipefish (E)		X		X	NI	Larval
	Microphis lineatus	Opossum pipefish (E) / poisson brindille (C)	X				NI	NI

NI: not indicated
* FOT = French overseas territory.

The different types of obstacles

The obstacles to the migration of diadromous species can be natural (waterfalls, rivers running dry) or caused by man-made modifications in the river.

Among the latter, there are physical barriers created by structures built across the river (roads, weirs, fisheries, etc.) and hydraulic installations where large quantities of water are commonly drawn off, which can result in river sections with very low water depths or even dry sections when the draw-off occurs in conjunction with areas with high levels of infiltration.

Many transverse structures created by humans in rivers are likely to reduce longitudinal connectivity and have a more or less negative impact on populations of fish and/or crustaceans (in 2018, the ROE database had already listed over one thousand structures in the studied French overseas territories).

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 animals 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 (e.g. following repeated, unsuccessful attempts to pass, a concentration of predators, etc.).

Obstacles can create problems for both:
- **upstream migration**, i.e. when the fish are heading upstream. This type of migration may involve:
- post-larvae and juveniles of amphidromous species (*Gobiidae*, *Eleotridae*, etc.) prior to reproduction, those of catadromous species (*Anguillidae* in the glass-eel or elver stages) or those of holobiotic species (river crabs),
- adults of amphidromous or catadromous species following a downstream migration caused by flooding or reproductive processes (e.g. *Macrobrachium*) or adults of holobiotic species (river crabs);
- **downstream migration**, i.e. when the fish are heading downstream (to the sea or to lower elevations). This type of migration may involve 1) the larvae of amphidromous species on their way to the ocean to grow up to the post-larval or juvenile stages (e.g. *Gobiidae*), or 2) the adults of catadromous species prior to reproduction, for example eels.

■ Barriers hindering upstream migration

Natural waterfalls and dry periods

The rivers in the French insular, overseas territories commonly have waterfalls measuring several meters and even tens of metres (Figure 3, page 20). The most striking examples are on Réunion and Guadeloupe, where several rivers have waterfalls over ten metres high even in the lower and mid sections (the Langevin, Sainte-Suzanne, Roches, Saint-Jean Rivers, etc., on Réunion, and the Lézarde, Bois Malaisé, Grand Carbet, Petit Carbet, Moreau, Galion, Tambour Rivers, etc., on Guadeloupe). The most spectacular waterfalls are over 100 metres high (Trou de Fer and Bras Magasin Falls on Réunion, and the Grand Carbet and Petit Carbet Falls on Guadeloupe). On Mayotte, waterfalls are not as high, for example on the Coconi River (Hapandzo Falls), the Bouyouni River and the Chiconi River (Soulou Falls). On Martinique, waterfalls are less common (Argis, Gendarme and Saint-Didier Falls).

Figure 3

a, b, d © B. Voegtlé (Ecogea)
c © P. Valade (Ocea Consult')

Examples of natural waterfalls.
(a) Niagara Falls (Réunion), (b) Paradis Falls (Guadeloupe), (c) Natural waterfall (Martinique), (d) Boungoumouhé Falls (Mayotte).

By limiting certain migrations (notably upstream), these obstacles affect the distribution of fish and crustaceans, however to a lesser degree for the latter given their walking capabilities (Fièvet, 1998; Fièvet *et al.*, 2001). Certain *Atyidae* species, such as basket shrimp and camacuto shrimp (*Atya innocous* and *Atya scabra*), cricket shrimp (*Xiphocaris elongata*) and *Atyoida serrata* would appear to derive advantages from developing upstream of certain natural waterfalls, probably due to a lower risk of predation, as has been documented for *Atya lanipes* and *Xiphocaris elongata* (Covich *et al.*, 2009).

Given the high degree of infiltration of rivers and occasionally severe low-flow levels on coasts exposed to the winds, many rivers in insular, overseas environments can have very low discharges during low-flow periods. In certain rivers on Réunion, these conditions can result in dry river reaches several hundred metres in permanent rivers (Bras de Sainte-Suzanne River, Langevin River, etc.) (Figure 4a). In some rivers (Saint-Étienne River, Galets River, etc.), these dry conditions can be worsened by drawoffs for irrigation and the production of drinking water (Figure 4b).

Figure 4

© P. Valade (Ocea Consult')

Examples of dry conditions on Réunion that may be natural in origin, but are amplified by upstream drawoffs.
(a) Bras de Sainte-Suzanne River, (b) Mouth of the Galets River.

Similar phenomena have been observed in Mayotte (Rouaka and Mroni bé Rivers, etc.), but not studied in depth. On the other hand, they would appear to be much less frequent in the Caribbean. These natural dry periods create total barriers when they occur, but cease to be barriers for migration (upstream and downstream) as soon as sufficient discharge is restored. Consequently, they are generally temporary barriers.

N.B. In the French insular, overseas territories, the main rivers are used as sources for irrigation and drinking water, and hydroelectric installations often exist in the upstream sections, given the potential for power generation due to the steep topography. In the insular context where water is not spread equally over space and time, conflicts concerning the quantities of the resource used are sharpened. The legal minimum discharges (French water law, LEMA 2006) are a priority in the 2016-2021 RBMPs of the territories, however actual implementation is often difficult in that it impacts other uses at least part of the year. In such cases, it is important to determine the effects of hydraulic discontinuities on the pertinent fish and macro-crustacean populations (recruitment, reproduction and/or downstream-migration phases), depending on the ecological issues specific to the habitats in the river, and to attempt to reduce the impacts by assessing scenarios comprising different periods and time spans during which continuity is ensured.

N.B. Given the number of natural obstacles encountered in rivers in the studied insular, overseas territories and in view of restoring continuity, these obstacles must be examined in order to determine their impact on the biological situation of upstream installations. For this reason, even though the main objective of the ICE method is to diagnose the passability of man-made obstacles, it is important to take into account natural obstacles when applying the method in the overseas territories in order to determine the issues involved in restoring continuities.

In determining the passability of natural obstacles, it is preferable to refer whenever possible to observations made in the field (local knowledge) and to inventory data acquired upstream and downstream of the natural obstacles. For the above reasons, the ICE method is not used to assess the passability of natural obstacles.

Weirs and dams

A majority of the weirs and dams in the studied French insular, overseas territories were built during the 1900s to draw water for irrigation, distribution of drinking water and/or hydroelectric generation.

Massive extractions of alluvial matter from river beds and the impoundment of rivers had a considerable impact on their ecological equilibrium. To limit down-cutting and to consolidate existing structures (bridges, weirs, etc.), a large number of rock weirs were built to stabilise river beds. That is notably the case for the Capot River on Martinique and the Herbes River on Guadeloupe, where they travel through urban areas, and the auxiliary dam on the Bras de la Plaine River on Réunion.

There are three main types of structures:

- **small to mid-sized weirs** (lower than 5 metres in general, but potentially up to a dozen metres), characterised by a more or less inclined downstream glacis. In this type of structure, the water flows consistently in contact with the structure (no curl or air gaps);
- **vertical weirs or arch dams**, where the crest is generally shaped to allow the flow of water. In these structures, the downstream face of the weir is vertical and a gap often occurs between the sheet of water and the structure. These structures are larger than the previous, up to 30 metres high, for example the Takamaka II dam on the Marsouins River on Réunion;
- **gravity dams made of earth or concrete**, that can reach heights of 20 to 25 metres. They are equipped with a spillway sized for the installation. These structures are strategic components for the supply of drinking water and irrigation on islands or parts of islands where water resources are rare or the terrain is steep, e.g.

Grande-Terre in Guadeloupe, the southern section of Martinique and Mayotte. In some cases, these structures can also be used for power generation. They may be built on permanent rivers (e.g. the reservoir on the Manzo River in Ducos on Martinique, the Combani and Dzoumogné reservoirs on Mayotte), or in ravines without permanently flowing water (e.g. the Ravine Dumanoir River on Guadeloupe, supplied by the Carbet, Moreau and Pérou Rivers).

In addition, some weirs are built and equipped to measure discharges. The flow meters may be automatic recording devices or simply rods or planks indicating the water level. Given the high levels of sediment transport and the width of river beds on Guadeloupe, Réunion and Martinique, metering weirs are positioned on small rivers and/or in the upper sections of river basins. On Mayotte, on the other hand, these weirs could be built on the downstream and mid-sections of some rivers (Dembéni, Koualé, Boungoumouhé, etc.). Metering weirs are not very high (less than one metre), but they can, in certain cases, represent partial barriers for diadromous fauna (obstacles for certain species depending on the hydrological conditions).

Depending on the conditions specific to each island (geology, river slope, hydrology, sediment transport, etc.), the types of structure differ between regions. For example, numerous structures in the Caribbean (Guadeloupe and Martinique) are highly similar, whereas those on Réunion and Mayotte are very different.

Similar to continental France, depending on the physical characteristics of each structure (height, profile, slope, length of the glacis, etc. for the geometry, and concrete, rock-fill, etc. for the construction materials) and the river hydrology, the hydraulic conditions (flow velocities, water depths, head-drop, etc.) upstream, downstream and at the structure can make it totally impossible for fish to overcome the obstacle.

Depending on the design of the downstream face, the obstacles to upstream migration may be:

- **vertical or subvertical waterfalls that species can overcome only by jumping or using specific capabilities (walking, suction, crawling).** 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, or if they do not have any specific capabilities in overcoming obstacles (walking, suction, crawling);
- **inclined faces.** The degree of passability of an inclined downstream face depends on the flow characteristics on the glacis (water depths, flow velocities) and the distance to be overcome, which in turn must be compared with the capabilities of the species in question (swimming, endurance, suction, crawling, walking) and their physical characteristics (body depth);
- **mixed designs comprising a succession of inclined sections and other, more or less vertical sections (steps, etc.).** 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.

The specific conditions prevalent in the rivers, particularly the violence of floods and the corresponding transport of impressive quantities of sediment and debris, notably during tropical storms, explain why few structures are equipped with moving parts (gates, flaps). Some rivers less subject to strong flooding may have weirs equipped with moving parts, however this type of structure is extremely rare in the studied French overseas territories (Figure 6).

Flows over flaps generally result in vertical or subvertical waterfalls.

In other types of structures, for example those with gate systems, the water can flow over the gate or under if the gate is partially lifted. Flow velocities under the gate may exceed the swimming capabilities of species.

Figure 5

a, d, e, f © B. Voegtlé (Ecogea)
b © P. Valade (Ocea Consult')
c © A. Dayde (Hydrétudes)

Examples of weirs and dams on rivers in the French insular, overseas territories.
(a) Dzoumogné reservoir for drinking water (Mayotte), (b) Bengalis weir for irrigation on the Mât River (Réunion), (c) ILO weir for irrigation on the Mât River (Réunion), (d) Stabilisation weir on the Grande River (Martinique), (e) EDF weir (drawoff for hydropower) on the Bananier River (Guadeloupe), (f) Hydrometric weir (Martinique).

Figure 6

© B. Voegtlé (Ecogea)

Example of a weir comprising moving parts (gates).

Flap gates on the Kwalé River (Mayotte).

Road structures

Road structures are the most commonly encountered obstacles in rivers in the studied French insular, overseas territories. They are most frequent in the lower sections of rivers, in more developed areas with larger populations.

In most cases (the Caribbean, Mayotte), the road structures are simply **fords**, i.e. the rivers are crossed via a submerged road. The river bed may be natural or have a man-made apron (rocks, concrete, etc.). When the downstream section of a ford lies underwater, this type of structure generally does not constitute an obstacle for diadromous species. However, in most cases, **the apron is voluntarily positioned higher than the natural river bed, in which case it essentially produces the same effect as a weir** and may represent a significant obstacle for aquatic fauna (Figure 7).

Figure 7

a, d © P. Valade (Ocea Consult')
b, c © B. Voegtlé (Ecogea)

Examples of weir-like fords.
(a) Ford on the Saint-Denis River (Réunion), (b) Ford on the Case Navire River (Martinique), (c) Ford on a tributary to the Ourovéni River (Mayotte), (d) Ford with a step on the Blanche River (Martinique).

Roads across rivers may also run over culverts or rigid-frame bridges (Figure 8). Similar to fords, they may constitute major obstacles to the upstream migration of species.

Figure 8

b, c, d © B. Voegtlé (Ecogea)
a © P. Valade (Ocea Consult')

Examples of roads over rivers.
(a) Road over the Saint-Louis River (Guadeloupe), (b) Road over the Écrevisses River (Martinique), (c) Road over the Remparts River (Réunion), (d) Road over the Beja River (Mayotte).

The main causes limiting the movement of fish and macro-crustacean species through the hydraulic passages (culverts, box culverts) are the following:

- excessive flow velocities inside the passages;
- uniform water velocities with no rest areas, i.e. the fauna must clear the obstacle in a single shot;
- insufficient water depths;
- waterfalls at the downstream end of structures;
- an absence of areas conducive to climbing by *Gobiidae*, crawling by eels or walking by macro-crustaceans.

These different problems are generally caused by poor positioning (height, slope, etc.) or by poor sizing of the passages. If the cross-section of the hydraulic passage(s) has been under-sized with respect to the transiting discharge, the structure may find itself under pressure with, as a result, high flow velocities that are difficult to overcome. Conversely, if the structure has been over-sized, the water depth may be insufficient and make it difficult for species to cross through the structure.

In addition, if the air passage of the hydraulic installations (culverts, box culverts) is insufficient, debris may block the entry or become stuck inside the structure, thus constituting a physical barrier and/or causing increased flow velocities.

Finally, the darkness inside the structures, notably the sudden change in luminosity during the day can also make certain species reticent to enter the structure.

Gobiidae *post-larvae fisheries*

Fishing of young gobies is a widespread activity throughout the Indopacific tropical zone (Bell, 1999). On Martinique, Guadeloupe and particularly Réunion, *Gobiidae Sicydiinae* post-larvae have traditionally been fished in the mouths of rivers. The local names for the post-larvae are “pissettes” or “Titiris” in the Caribbean and “bichiques” on Réunion (Aboussouan, 1969; Schübel, 1998; Bell, 1999). The intent is to catch *Gobiidae* for the most part, however *Eleotridae* are also found among the captured fish (Arda, 2012). These fisheries are seasonal and follow the moon phases, i.e. they take place between the last quarter and two to three days after the new moon.

On Réunion, a majority of captures during the hot season concern the bichique *Sicyopterus lagocephalus* and, to a lesser degree (and more commonly in the cooler season), *Cotylopus acutipinnis*. The captures take place in the ocean and in rivers. This fishery is a major element in the cultural heritage on Réunion and also has high socio-economic value that draws in participants (a sales price of between 30 and 70 euros per kilogramme to end consumers over the last few years), in spite of the fact that the results are highly uncertain.

In the ocean, nomadic fishermen track developing schools of post-larvae along the coast. When a school is found, the fish are caught using mosquito nets. This fishing technique is used just before new moons during the last months of the year (October to December) and targets *Sicyopterus lagocephalus*. It developed during the last half of the 1900s.

In rivers, bichiques are captured using fish traps positioned in channels (Figure 9). In rivers with large deltas, the water is diverted from the natural river bed into channels, whereas in rivers where the mouth forms a wide, shallow opening, rows of stones divide the mouth into a number of channels. Fishing in rivers takes place the entire year, except for the new moon in March (Préfet de La Réunion, 2008a, 2008b). Management of these fisheries is a priority in the 2016-2021 RBMP for Réunion with the double objective of restoring the quality of fish communities in rivers while maintaining and organising this traditional and novel activity by setting up pilot projects to regulate the fishing effort, organising the fishers throughout the island, etc.

Figure 9

a © P. Valade (Ocea Consult')
b © B. Voegtlé (Ecogea)

Examples of systems used to fish Gobiidae *on Réunion.*
(a) The mouth of a river divided into channels used to catch bichiques (Roches River), (b) Example of a channel equipped with nets made of natural materials in a river with a large delta (Saint-Étienne River).

In the Caribbean, this fishery has been less studied, but is nonetheless traditional with a high cultural value (Morandi *et al.*, 2015). It targets the post-larvae and juveniles of Plumier’s stone-biting goby and the spotted algae-eating goby (*Sicydium punctatum* and *Sicydium plumieri* / *antillarum*). The fish are caught using mosquito

or cloth nets in the mouths of rivers from July to December. No particular structures or other systems are used. This is a part-time activity used to complement revenues. On Martinique, it continues even though fishing in rivers has been prohibited (Préfet de la Martinique, 2014).

■ Barriers hindering downstream migration

Structures (with or without abstractions) **may constitute serious obstacles to the downstream migration of eggs, larvae, juveniles and adults.** The main causes of delays, injuries or mortalities are the arrival time and more or less long blockage in a reservoir, transit via spillways and hydroelectric turbines, and being drawn into water intakes.

For the anadromous species (indigenous macro-crustaceans, *Gobiidae*, *Eleotridae* fish, etc.), downstream migration takes place during the larval stage called the free-embryo stage (Delacroix and Champeau, 1992; McDowall, 2007; Maeda *et al.*, 2008; Bell, 2009; Valade *et al.*, 2009; Teichert *et al.*, 2013; Ellien *et al.*, 2014). It should be noted, however, that both the adults and larvae of certain macro-crustaceans (*Macrobrachium spp.*) may migrate downstream, but this behaviour would appear to be limited to large, continental rivers in which the species may be found up to several hundred kilometres from the ocean (Bauer and Delahoussaye, 2008; Bauer, 2011).

For catadromous species (*Anguillidae*, *Kuhliidae*), it is the mature adults that migrate downstream to the ocean in order to reproduce (Hogan and Nicholson, 1987; Robinet and Feunteun, 2002; Sugeha *et al.*, 2006; Wouthuyzen *et al.*, 2009; Feutry *et al.*, 2012b).

Passage via spillways, flood gates and natural waterfalls

Passage via spillways, flood gates and natural waterfalls (see Figure 10) can result in direct deaths (injuries, shocks, etc.) or indirect deaths (vulnerability to predation by shocked or disoriented fish on arriving downstream).

Figure 10

a, d © P. Valade (Ocea Consult')
b, c © B. Voegtlé (Ecogea)

Examples of spillways and natural waterfalls that fish must overcome when migrating downstream.
(a) Natural waterfall (Réunion), (b) Vertical waterfall over a dam spillway (Réunion), (c) Water flowing over the glacis of a dam (Mayotte), (d) Water flowing over a glacis (Martinique).

The available studies, notably on salmon, would seem to indicate that mortality levels vary widely from one site to another depending on the height of the waterfall, the presence of a sufficiently deep stilling basin at the foot of the obstacle, possible shocks against aprons, rocks, etc. (Bell and Delacy, 1972; Ruggles, 1980; Ruggles and Murray, 1983).

When passing over a spillway or a natural waterfall, depending on the discharge and the flow configuration, downstream migrators are likely to:

- **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, i.e. the jet does not make the fish hit the substrate. The impact velocity V (in metres per second) may be roughly calculated using the following equation: $V = (2 \times 9.81 \times DH)^{0.5}$ where DH (in metres) is the height of waterfall. 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 waterfalls of approximately 50 metres (i.e. an impact velocity of some 30 m/s) (Voegtlé, personal publication). Consequently, free fall is better for smaller fish (fry and fish less than 15 to 20 cm long). For larger fish, the effects are very similar whether the fall takes place inside or outside the nappe, i.e. injuries become serious starting at approximately 12 to 13 metres of fall.

Fish drawn into water intakes

Water intakes may be used for a number of purposes including the abstraction of drinking water, irrigation, fish farming (ponds, tanks) and electrical generation (hydroelectric plants).

Aquatic fauna 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 (Figure 11).

Frequently in the studied French overseas territories, the water drawn off is not returned to the river (notably irrigation and drinking water) and the damage done to fauna migrating downstream can vary widely depending on the quantities of water abstracted and on the possibilities for the fauna to return to the river.

In hydroelectric plants, the water is run through turbines and then returned to the river. Unfortunately, passage through the turbines subjects downstream migrators 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 migrators (Larinier and Dartiguelongue, 1989; Gomes and Larinier, 2008). In the overseas territories, hydroelectric installations often have high head drops and mortality rates may be quite high, however they will depend on

the characteristics of the installation and on how it is managed (Lagarde, 2016). The mortality of larvae passing through a hydroelectric installation can be estimated, on a case by case basis, by comparing the escapement rate of larvae on exiting the installation and that of larvae migrating downstream under natural conditions.

Figure 11

a, b, d © B. Voegtlé (Ecogea)
c © P. Valade (Ocea Consult')

Examples of water intakes for different purposes: (a) Intake for electrical generation on the Langevin River (Réunion), (b) Intake for drinking water on the Moustique River (Guadeloupe), (c) Intake for drinking water (Guadeloupe), (d) Intake for irrigation (Réunion).

Sedimentation in reservoirs or in settling basins

The presence of a dam or of a settling basin for a water intake results in a reduction in the flow velocity (Figure 12) and blocks part of the sediment load. This slowing of the flow may hinder and even block fauna that use the flow for their downstream migration. In some cases, notably for species that must reach the ocean quickly, their survival is at risk.

For example, the larvae of amphidromous fish and crustaceans (less than two millimetres in size) can only swim upwards (they cannot swim horizontally), i.e. they can maintain their position in the water column and avoid falling to the bottom (Balon and Bruton, 1994; Valade *et al.*, 2009). In some reservoirs and particularly in the settling basins for water intakes, the absence of a longitudinal current results, at some point in time, in the larvae falling to the bottom and dying (Valade *et al.*, 2004; Antea *et al.*, 2011).

Figure 12

a © P. Valade (Ocea Consult')
b © B. Voegtlé (Ecogea)

Examples of installations slowing flows and potentially hindering downstream migration of fauna that require a longitudinal flow.
(a) Settling basin for a water intake (Réunion), (b) Dzoumogné reservoir (Mayotte).

Main impacts of an obstacle on the movements of fish and macro-crustacean communities

Physical obstacles (waterfalls, dams, hydroelectric turbines, excessive flow currents or slowing currents due to increasing water depths, insufficient water levels or dry sections) in rivers can disturb more or less seriously the movements of aquatic species and limit the colonisation of favourable habitats for their growth or their access to reproduction zones. These situations have been extensively described for river systems in temperate zones. Given that all indigenous fish and decapod-crustacean species in the French insular, overseas territories are diadromous, barriers have an even greater impact in these territories than in temperate zones (March *et al.*, 2003; McDowall, 2007; Bell, 2009; Bauer, 2011).

■ Direct effects on populations

Obstacles produce direct effects on the populations of species by modifying favourable habitats (e.g. drowned habitats) and by limiting access to zones required for reproduction, growth and feeding. Blocking migrators downstream of barriers can create excessive population densities, resulting in greater predation, lower growth and less favourable conditions generally, which in turn reduces the overall reproduction capacities of the populations in question. Barriers with water intakes produce particularly harsh effects in that the diversity and quantity of the available habitats downstream are reduced.

There may be positive effects (e.g. a limited number of predators) upstream of barriers for certain species having particularly effective upstream-migration capabilities, notably crustaceans (Covich *et al.*, 2009). However, this aspect must be taken with caution because in the case of water intakes, the loss of life during downstream migration may be considerable and result for a given population in a very low and even no net gain in fitness.

■ Phenotypic effects

Forced halts or even delays during the migration of species to their reproduction zones can have consequences on the individual level. For example, it has been shown that a weir ten metres high can result in morphological selection of *Cotylopus acutipinnis* juveniles, whereas the same weir did not have the same effect on the other goby species *Sicyopterus lagocephalus* (Lagarde, 2018).

Obstacles hindering both upstream and downstream migrations can therefore operate a double selection:

- an initial selection during upstream migration, allowing through only those individual animals having the greatest passage capabilities (good physiological condition, best size and morphology, etc.);
- a second selection (reduction) in the progeny of these that succeeded in the upstream migration, due to losses during the downstream migration.

Over the river basin as a whole, the quality and functionality of habitats downstream of an obstacle will also affect the reproductive success of those that could not overcome the obstacle (the minimum discharge rate is of particular importance).

Over time, the presence of obstacle(s) can create an imbalance within a population of fish or macro-crustaceans by favouring certain phenotypes over others.

■ Delayed migration and mortalities due to fatigue

For species in temperate environments, the cumulative impact of a large number of structures on highly fragmented rivers may be very high, even if no major obstacles have been detected (Chanseau *et al.*, 1999; Ovidio and Philippart, 2002; Thorstad *et al.*, 2005).

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

Unfortunately, these specific points have not been studied extensively for species in tropical, insular environments.

■ Injuries and mortalities in structures

Injuries or mortalities of fish may occur at structures during upstream migration (knocks following jumps, etc.), but this type of impact is more frequent during downstream migration, notably at structures incorporating a water intake.

When a structure comprises an intake, some of the downstream migrators 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 migrators through spillways rarely causes injuries, particularly if the dam is not very high (less than ten metres) and the stilling basin is deep enough that the migrators do not hit the bottom.

Concerning water intakes, 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 migrators 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 migrator (Larinier and Dartiguelongue, 1989; Larinier and Travade, 2002; Gomes and Larinier, 2008; Voegtlé and Larinier, 2008; Voegtlé, 2010a, 2010b, 2014; Thinus and Guillot, 2016) and particularly on turbine flow rates, configuration and characteristics.

■ Increased risk of predation and disease

By concentrating and increasing the residence time of fish and macro-crustaceans in certain areas and/or causing fatigue due to successive passage attempts, obstacles are likely to increase predation by birds, ichtyophagous fish and poachers.

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

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

■ Other effects

Problems in passing obstacles may also cause biological imbalances and affect the general functioning of ecosystems.

On the whole, rivers on volcanic, tropical islands have a low level of species richness. For example, browsing fish such as the *Gobiidae Sicydiinae* are largely responsible for the transformation of the available energy by eating the periphyton. These species, arriving in massive numbers in the mouths of rivers, provide significant amounts of organic matter that is important for the ecological functioning of the rivers. They make possible the development of carnivorous/opportunistic fish (*Eleotridae*, *Anguillidae*, *Kuhliidae*), as well as the development of detritivore species (macro-crustaceans) on the other end of the food chain. In light of the above, obstacles to river continuity for these species and in particular for the fisheries can cause a more general imbalance in the river communities.

The absence of or a reduction in the densities of browsing fish such as the *Gobiidae Sicydiinae* can also lead to proliferation of filamentous algae. A proliferation of filamentous algae reduces the overall carrying capacity for aquatic fauna (fish, invertebrates) and can locally cause problems for water uses, e.g. organic matter in abstracted water, the quality of bathing waters, etc. (Valade, personal observation).

The capabilities of fish and macro-crustaceans to overcome obstacles

The different types of passage

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

- the migratory behaviour and passage capabilities of the given species;
- the configuration of the obstacle and the pertaining hydraulic characteristics.

Passage capabilities of species are tied directly to their morphology and biomechanical characteristics, which in turn are largely determined by the ecology of the given species (e.g. benthic vs. pelagic species) and by the types of environments in which they live and/or transit during their biological cycle (e.g. rheophilic vs. limnophilic species and stages). Other factors, such as the water temperature and the physiological condition of migrators also influence the passage capabilities of a given animal, but will not be taken into consideration here in the interest of simplicity.

In the French tropical, insular environments, few fish species have highly developed jumping or sprinting capabilities that would potentially allow them to overcome certain obstacles. The fish and macro-crustaceans in these environments are above all known for other passage techniques, on the condition, however, that travel surfaces are wet, examples being walking by decapod crustaceans, crawling by eels and "climbing" by *Gobiidae Sicydiinae* using their pelvic fins joined to form suction cups (see the sections on the suction capabilities of these latter species).

It is using these special techniques that certain species can, in certain cases, colonise river basins in spite of numerous structures and river reaches upstream of natural waterfalls measuring several metres in height and even, in exceptional cases, several hundred metres.

Swimming capabilities of fish

■ Activity levels 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 fish;

- **maximum-speed swimming or sprinting**, an activity that requires an intense effort and can be maintained for a very short time only, ranging from a few seconds to a few dozen seconds depending on the species and the size of each fish;
- the **sustained-swimming** level, i.e. a level between cruising and sprinting, which can be maintained for a few minutes and even up to dozens of 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. . **According to various authors, fish are able to maintain maximum speed for periods of approximately 10 to 20 seconds** (Beach, 1984; Zhou, 1982; Wardle, 1980; Videler, 1993; Castro-Santos, 2006).

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).

The **length of the fish (Lp)** is the main factor determining the swimming speed. Videler (1993) proposed an equation, based on experimental results, estimating the maximum swimming speed as a function of the length of the fish. This equation has the advantage of taking into account the results of studies carried out on various species under different experimental conditions. For this reason, it provides a reliable value for swimming speeds based on objective factors.

$$U_{max} = 0.4 + 7.4\ Lp$$ *The equation proposed by Videler (1993).*

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:

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

N.B. **For the ICE method adapted to the French insular, overseas territories, given the lack of experimental studies focusing on the passability of obstacles, the maximum swimming speeds U_{max} of the species in question were set using the equation above proposed by Videler (1993) and adjusted taking into account *in situ* visual observations of fish clearing obstacles.**

Table 5 presents the size classes selected for the different ontogenetic stages of the fish species addressed in this book (adults / subadults, juveniles, stages specific to the eel species).

The range of lengths (Lp_{min} - Lp_{max}, i.e. the minimum and maximum lengths selected) was determined based notably on the data available in the atlases for freshwater fish in Martinique (Lim *et al.*, 2002), Guadeloupe (Monti *et al.*, 2010), Réunion (Keith *et al.*, 2006), the Comoros, Mascarenhas and Seychelles (Keith *et al.*, 2006), and on the review of the data on diadromous fish published by the National Museum of Natural History (Tabouret, 2012).

Lp_{avg} is the average value of the minimum and maximum values Lp_{min} and Lp_{max}.

Table 5 *Size criteria selected for the different species under consideration.*

Family	Species	Name in English (E) and in Creole (C)	FOT				Biological stage	Length of fish (mm)		
			Guadeloupe	Martinique	Mayotte	Réunion		Lp min	*Lp avg*	Lp max
Anguillidae	*Anguilla bengalensis*	Indian mottled eel (E) / z'amab, z'anguille (C)			X	X				
	Anguilla bicolor bicolor	Indonesian shortfin eel (E) / z'amab, z'anguille (C)			X	X	Glass eel	50	*75*	100
	Anguilla marmorata	Giant mottled eel, marbled eel (E) / z'amab, z'anguille (C)			X	X				
	Anguilla mossambica	African longfin eel (E) / z'amab, z'anguille (C)			X	X	Yellow to adult eel	100	*1000* (A. marmorata) *500 (other species)*	**2000 (A. marmorata) 1000 (other species)**
	Anguilla rostrata	American eel (E) / z'anguille (C)	X	X						
Eleotridae	*Butis butis*	Crazy fish, crimson-tipped flathead-sleeper, duckbill sleeper (E)			X	X				
	Dormitator maculatus	Fat sleeper (E) / ti-nèg, dormeur (C)	X	X						
	Eleotris amblyopsis	Large-scaled spiny-cheek sleeper (E) / pitit dormè (C)	X							
	Eleotris klunzingerii	Brown sleeper, dusky sleeper (E) / cabot noir (C)			X	X	Juvenile	15	*30*	40
	Eleotris mauritiana	Widehead sleeper (E) / cabot noir (C)			X	X				
	Eleotris perniger	Small-scaled spiny-cheek sleeper (E) / pitit dormè, flèche (C)	X	X						
	Gobiomorus dormitor	Bigmouth sleeper (E) / grand dormeur, dormeur (C)	X	X						
	Guavina guavina	Guavina (E) / dormeur (C)		X						
	Hypseleotris cyprinoides	Tropical carp-gudgeon (E)			X	X	Subadult / Adult	40	*100*	150
	Ophieleotris cf *aporos*	Snakehead gudgeon (E)			X					
	Ophiocara porocephala	Northern mud gudgeon, spangled sleeper (E) / makanbale latet ron (C)			X					
Gobiesocidae	*Gobiesox nudus*	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	X	X			Juvenile Subadult / Adult	15 40	*30* *100*	40 150
Gobiidae	*Awaous banana*	River goby (E) / jolpot, loche (C)	X	X						
	Awaous commersoni	Commerson's freshwater goby, river goby (E) / loche, cabot (C)			X	X				
	Cotylopus acutipinnis	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)				X				
	Cotylopus rubripinnis	Goby (E)			X					
	Ctenogobius pseudofasciatus	Slashcheek goby (E)		X						
	Glossogobius callidus	Tank goby (E)			X		Juvenile	15	*30*	40
	Glossogobius giurus	Tank goby (E) / loche (C)			X	X				
	Glossogobius kokius	- (E) / loche, cabot (C)				X				
	Mugilogobius mertoni	Chequered mangrove goby, Merton's mangrove goby, meander goby (E) / gobi milet (C)			X					
	Redigobius balteatus	Rhinohorn goby (E)			X					
	Redigobius bikolanus	Bigmouth goby, speckled goby (E) / gobi tase (C)			X		Subadult / Adult	40	*100*	150
	Sicydium plumieri	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)	X	X						
	Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)	X	X						
	Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)			X	X				
	Stenogobius polyzona	Chinestripe goby (E) / cabot rayé (C)			X	X				
Kuhliidae	*Kuhlia rupestris*	Jungle perch, rock flagtail (E) / doule de roche, carpe (C)			X	X	Juvenile	20	*60*	100
	Kuhlia sauvagii	Rock flagtail (E) / doule de roche, carpe (C)			X	X	Subadult / Adult	100	*300*	400
Mugilidae	*Agonostomus catalai*	Comoro mullet (E)			X					
	Agonostomus monticola	Mountain mullet (E) / milet (C)	X	X			Juvenile Subadult / Adult	25 100	*65* *200*	100 300
	Agonostomus telfairii	Fairy mullet (E) / chitte (C)			X	X				

NI: not indicated
* FOT = French overseas territory.

■ Minimum water depth

The water must be deep enough to enable a fish to use its full swimming capabilities, i.e. such that it can propel its way forward by undulating its body and using its caudal (tail) fin. 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, vary from approximately 0.10 (*Gobiidae*) to almost 0.30 (*Kuhliidae*).

The scientific literature (Larinier *et al.*, 1994; FAO and DVWK, 2002; DWA, 2006) often mentions a minimum depth required for swimming of 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.

N.B. For the ICE method adapted to the insular, overseas territories, the minimum water depth 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 (or group of species) and at the given development stage. Body depths were determined using a form factor estimated for each species (Figure 13).

Figure 13

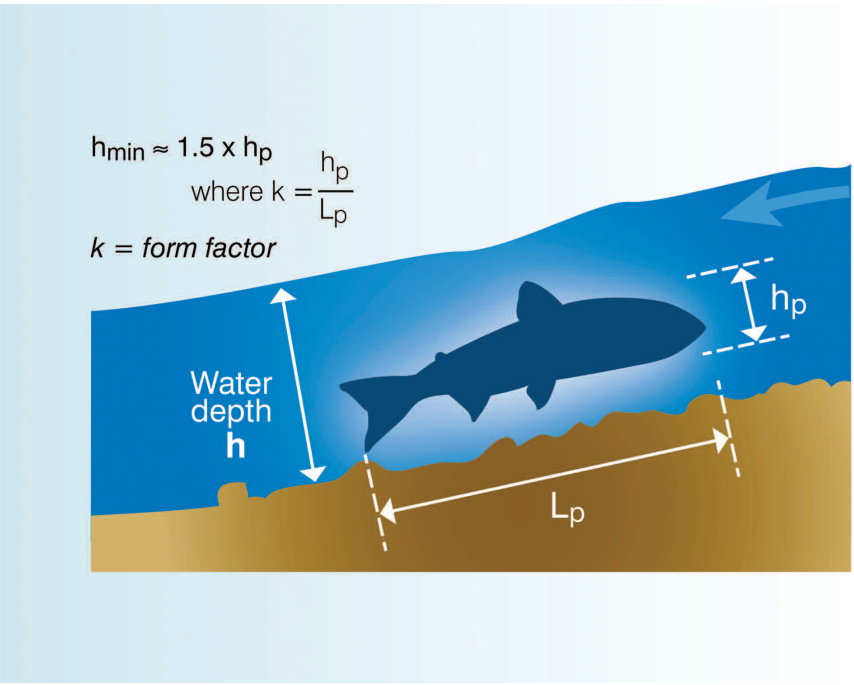


Diagram showing the water depth seen as the minimum (h_{min}) required for fish to swim adequately. Adapted from Baudoin et al.*, 2014.*

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

Passage of fish by jumping

■ Jumping capabilities

Mugilidae (*Agonostomus monticola*, *Agonostomus telfairii*, *Agonostomus catalai*) often attempt to jump over an obstacle (Figure 14).
Other species, for example those in the *Kuhliidae* family, are capable of jumping, however this behaviour is theoretical and they have never been observed jumping over an obstacle.

Figure 14

a © P. Valade (Ocea Consult')
b © B. Voegtlé (Ecogea)

*Juvenile mullets (*Agonostomus*) attempting to jump over a ford in the Ravine Chaude along the Goyaves Grande River (Guadeloupe).*
(a) Juveniles at the foot of the obstacle, (b) Fish attempting to jump over the obstacle.

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 the horizontal and vertical distances travelled by the projectile (i.e. the fish) at time t;
U_{max} is the initial speed, taken here as the sprinting speed of the fish;
β is the angle of incidence with respect to the horizontal;
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:

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

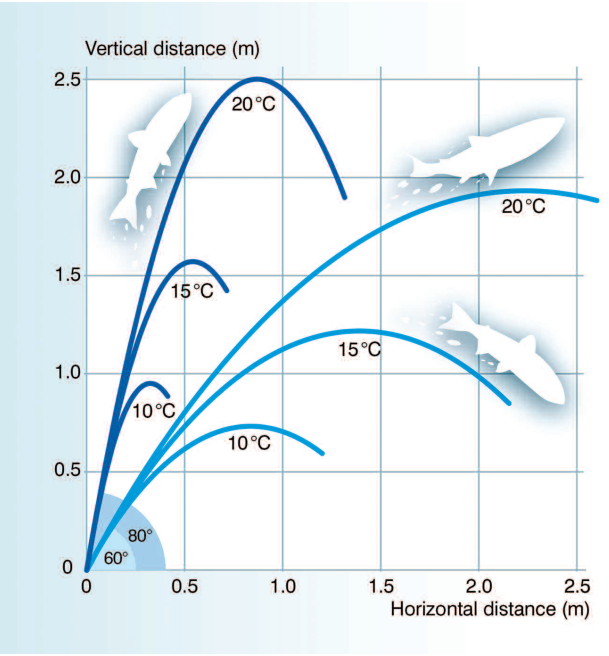
The theoretical trajectories of a salmon 0.8 metres long are shown as a function of the water temperature and the angle of incidence of the jump (Figure 15). The graph makes clear the key importance of the water temperature and the angle of incidence for the height attained by a jumping fish.

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 fin clears the water surface (Powers and Osborne, 1985).

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

Table 6 indicates the theoretical jumping heights of a fish as a function of its length and other parameters.

Figure 15



The theoretical trajectories of a salmon 0.8 metres long as a function of the water temperature and the angle of incidence (from the horizontal) at the start of the jump. After Larinier et al.*, 2002, modified by Baudoin* et al.*, 2014.*

Table 6

Theoretical jumping height that can be achieved by a fish as a function of its length, its initial speed U_{max}, the angle of incidence of the jump and the fraction of the length Lp added to the maximum height Y_{max} of the jump.

Maximum speed U_{max} (m/s)	Corresponding length of fish (Lp), after 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°
7.00	0.90	2.4	1.9	1.0	2.9	2.3	1.5	3.3	2.8	1.9
6.50	0.80	2.1	1.6	0.9	2.5	2.0	1.3	2.9	2.4	1.7
6.00	0.75	1.8	1.4	0.8	2.2	1.8	1.1	2.5	2.1	1.5
5.50	0.70	1.5	1.2	0.6	1.8	1.5	1.0	2.2	1.8	1.3
5.00	0.60	1.2	1.0	0.5	1.5	1.3	0.8	1.9	1.6	1.1
4.50	0.55	1.0	0.8	0.4	1.3	1.1	0.7	1.6	1.3	1.0
4.00	0.50	0.8	0.6	0.3	1.0	0.9	0.6	1.3	1.1	0.8
3.50	0.40	0.6	0.5	0.3	0.8	0.7	0.5	1.0	0.9	0.7
3.00	0.35	0.4	0.3	0.2	0.6	0.5	0.4	0.8	0.7	0.5
2.50	0.30	0.3	0.2	0.1	0.5	0.4	0.3	0.6	0.5	0.4
2.00	0.20	0.2	0.2	0.1	0.3	0.3	0.2	0.4	0.4	0.3
1.50	0.15	0.1	0.1	0.0	0.2	0.2	0.1	0.3	0.2	0.2
1.00	0.10	0.1	0.1	0.0	0.1	0.1	0.1	0.2	0.2	0.1
0.75	0.05	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.1	0.1

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

N.B. For the ICE method adapted to the insular, overseas territories, general jumping parameters for fish were set, including an angle of incidence of 60° and a height equivalent to Y_{max} + Lp / 2. The Y_{max} value was derived from data and observations collected *in situ* or, failing that, the value was calculated using the Videler (1993) equation based on the size of fish.

■ Minimum hydraulic head

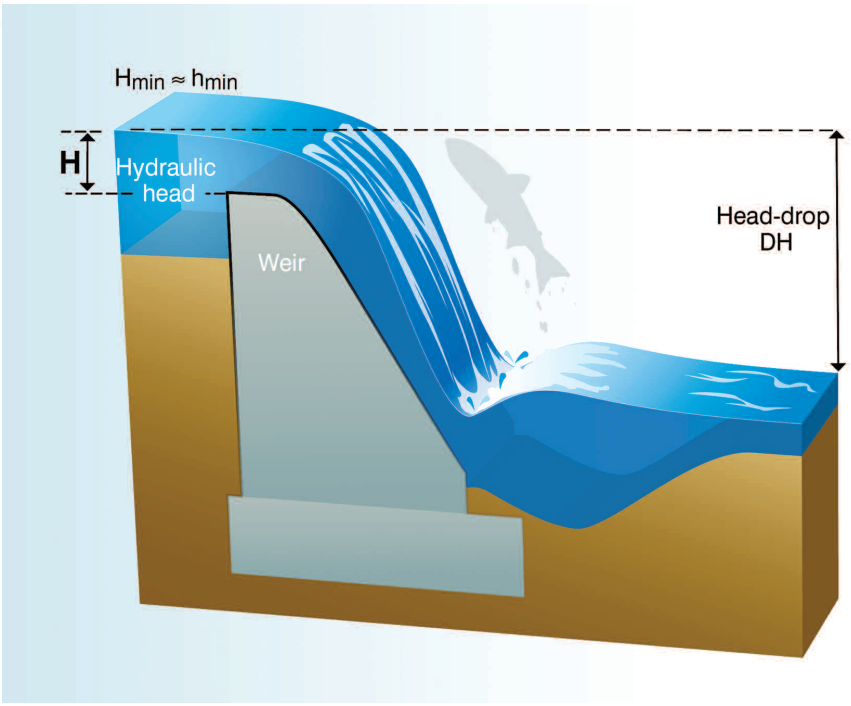
For a fish to overcome an obstacle by jumping, the hydraulic head at the obstacle (weir, natural waterfall) must be sufficient to enable the fish to restart effective swimming immediately on striking the water. This is particularly important for high waterfalls when the fish risks landing on the crest of the structure.

For smaller waterfalls significantly lower than the jumping capability of the fish, the horizontal distance covered during the jump 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.

N.B. For the ICE method adapted to the insular, overseas territories, the minimum hydraulic head H_{min} required to jump over an obstacle is considered equal to the minimum water depth h_{min} required for a fish to effectively swim (Figure 16).

Caution. The values calculated for hydraulic heads are absolute minimum values required for the passage of obstacles. In fish passes, where the objective is to maximise passage, much higher values are systematically used.

Figure 16



The minimum hydraulic head (H_{min}) required for fish to plunge back into the water and start swimming after jumping over an obstacle is approximately equal to h_{min}, the minimum water depth required for fish to swim adequately (see Figure 13). After Baudoin et al.*, 2014.*

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 (Figure 17b, d).

If the substrate at the foot of the waterfall is sufficiently soft, the jet of water scours out a plunge pool in which the energy of the fall dissipates. The level of energy depends on the river discharge.

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 of incidence and reaches its maximum value for vertical or subvertical waterfalls.

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 (Figure 17a, c).

Figure 17

a, c © P. Valade (Ocea Consult')
b, d © B. Voegtlé (Ecogea)

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

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

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, whatever the head-drop, the required minimum depth of the plunge pool is the same. This criterion tends to result in minimum depth values for the pool that are far too great for small head-drops. For example, if the criterion for the pool depth is 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 (Stuart, 1962; Lauritzen *et al.*, 2010). 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 (for example, depths of between 1.5 metres and 3 metres for a head-drop of 1.5 metres).

N.B. For the ICE method, 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 (Figure 18), 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 this approach:

$$Hf \geq \sqrt{DH \sin \alpha}$$

Figure 18

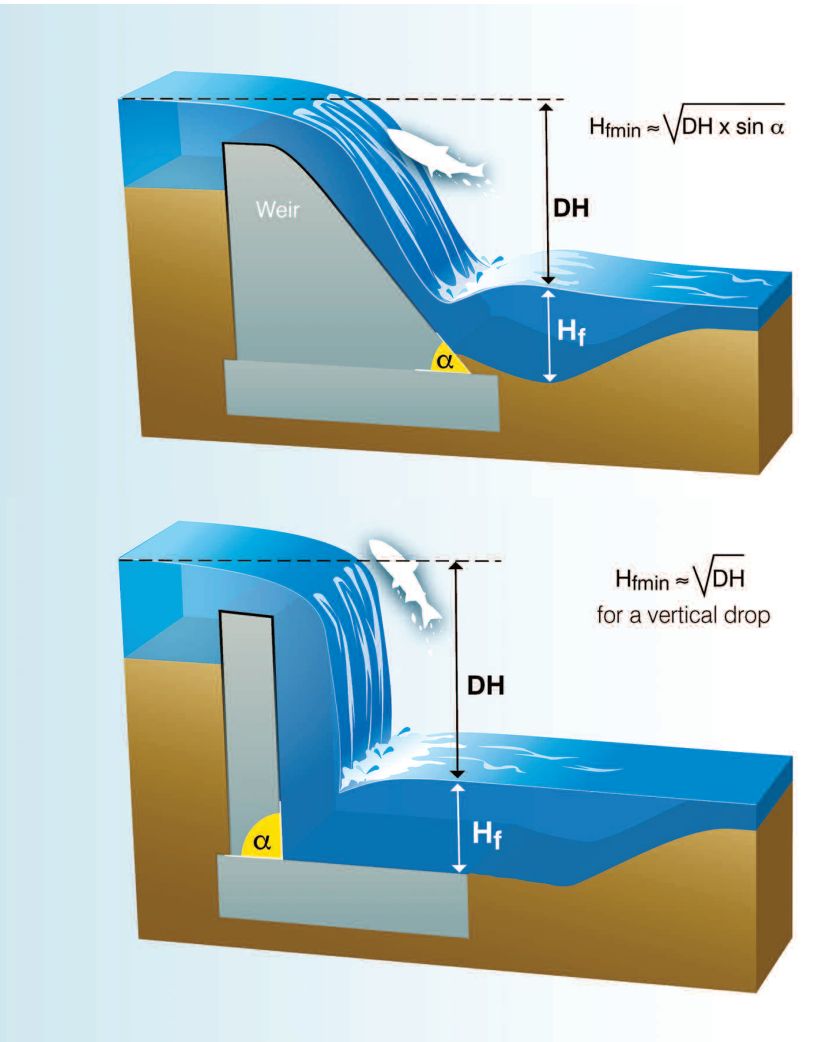


Diagram showing the approximate, minimum depth of a plunge pool (Hf_{min}) required for fish to overcome an obstacle (swimming or jumping) under satisfactory conditions. After Baudoin et al.*, 2014.*

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 that would enable it to jump or swim successfully over the obstacle.

In addition, the usable depth of the pool should be 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 have generally shown that a majority of attempts by fish to jump over an obstacle originate relatively close to the point where the falling water strikes the downstream surface.

N.B. **For the ICE method, 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 of the falling water**, which corresponds to the observations and work carried out by Lauritzen *et al.* (2005).

The crawling capabilities specific to eels

Given their morphology and swimming technique, eels have limited swimming capabilities compared to other species of similar size, notably in terms of their maximum speeds.

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 (Tsukamoto *et al.*, 1975; Clough and Turnpenny, 2001). For elvers (approximately 20 cm long) and yellow eels, the maximum swimming speeds are in the 1 to 1.5 m/s range (Sörenson, 1951; Blaxter and Dixon, 1959; Clough *et al.*, 2002).

Mc Leave (1980) studied the performance of European glass eels (*Anguilla anguilla*). The distance covered swimming against water flowing at 0.3 m/s is approximately 3 metres and that distance drops to less than 50 cm in water flowing at 0.5 m/s.

However, due to their special morphology and capacity to breathe through their skin, eels can also crawl (Figure 19), if the underlying surface is wet. It is this particular type of movement that enables eel species to circumvent certain natural and man-made obstacles and to colonise some reservoirs.

Very small eels can climb up vertical walls without requiring any notable “support points”. They use the surface tension created by the contact between their bodies and the wet wall to adhere to the surface (Legault, 1986, 1987; Lagarde *et al.*, 2016). 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 (Figure 19a).

The type and slope of the crawling substrate, and the depth/velocity of water flowing over it, in conjunction with the size of the eels, are the main and often related factors determining whether eel species can overcome obstacles. To effectively crawl up an obstacle, the water depth/velocity must be limited and an eel must be able to support itself at several points (Figure 19b). 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; Lagarde *et al.*, 2016).

Figure 19

a © P. Valade (Ocea Consult')
b © R. Lagarde (Hydrô Réunion)

Crawling eels. (a) Very young eels (slightly pigmented glass eels) climbing a vertical wall. It is essentially the surface tension that enables them not to slip down the substrate. (b) A eel migrating up a special crawl substrate offering enough support points.

The suction capabilities specific to *Gobiidae Sicydiinae*

The *Sicydiinae* are a subfamily of the *Gobiidae*. Given their morphology and small size, their swimming capabilities are limited. However, **the *Sicydiinae* have a subdiscoidal suction cup**, formed by the coalescence of their pelvic fins (Figure 20a), that provides them with exceptional capabilities in climbing and overcoming wet walls. Thanks to this special morphological trait and the capacity to breathe through their skin, the *Sicydiinae* can "suction cup" their way up (Figure 20b), if the underlying surface is wet. Even high obstacles, both natural and man-made, can be overcome by the fish using this particular technique. For example, *Sicydium punctatum*, *Sicydium plumieri*, *Sicyopterus lagocephalus* and *Cotylopus acutipinnis* are present over large sections of rivers, ranging from the mouth to elevations of over 600 metres and even over 1 000 metres on Réunion.

In addition, particularly in the case of small fish, **the surface tension between their body and the wet surface improves their progress up steep surfaces**. Similar to eels however, when the fish grow in size, the weight to surface tension ratio, which is proportional to their length, increases, which explains why the smaller fish are better at overcoming obstacles than the larger fish (Voegtlé *et al.*, 2002; Lagarde *et al.*, 2016).

Figure 20

a © A. Collet (Ocea Consult')
b © R. Lagarde (Hydrô Réunion)

The suction capabilities of Gobiidae Sicydiinae. *(a) The subdiscoidal suction cup formed by the coalescence of the pelvic fins in* Cotylopus rubripinnis*, (b)* Sicyopterus lagocephalus *climbing a wet wall.*

The passage capabilities have been studied in particular for *Sicyopterus lagocephalus* and *Cotylopus acutipinnis* (Voegtlé *et al.*, 2002; Lagarde *et al.*, 2016) and *Sicyopterus lagocephalus* has been tested on different surfaces (ranging from smooth to rough) and on different slopes (up to 90°). The slope of the substrate and the depth/velocity of water flowing over it are the main and often related factors determining whether *Sicydiinae* can overcome obstacles. To ensure optimum progression using their suction cup, the substrate should be somewhat humid.

It should be noted that very young *Eleotridae* juveniles, for example the sleepers *Eleotris klunzingerii* and *Eleotris mauritiana*, and certain *Gobiidae*, such as *Awaous commersoni* (Blob *et al.*, 2006) or *Stenogobius polyzona*, would appear to be capable of colonising sections upstream of natural waterfalls by using their pelvic fins and the surface tension to climb obstacles, similar to glass eels. However, these passage capabilities would also appear to be limited to the post-larval and juvenile stages and are not as exceptional as those of the *Sicydiinae*.

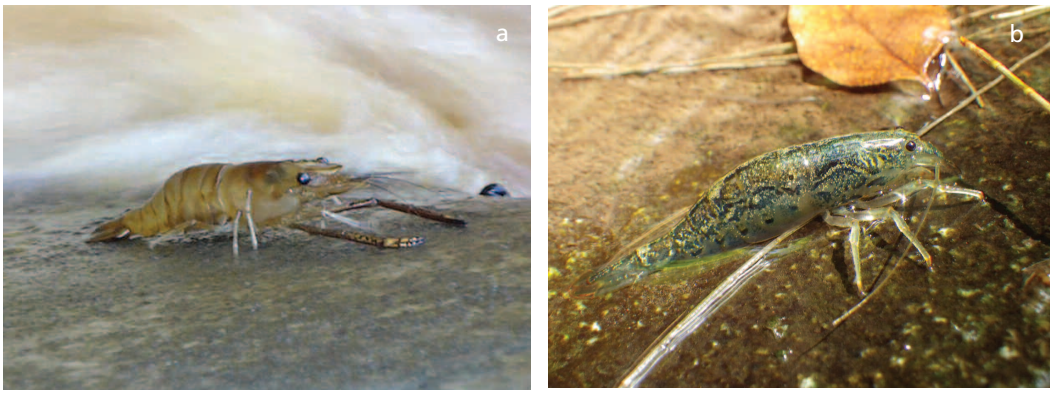
The walking capabilities specific to macro-crustaceans

By the end of their larval stage in the ocean, macro-crustaceans can walk (Figure 21). When confronted with a waterfall or a zone with high flow velocities, migrators (similar to eels and *Sicydiinae*) attempt to overcome the obstacle along the edges of the flow, i.e. where very little water flows or where the substrate is barely wetted by the spray.

Passage takes place in three phases (Fièvet *et al.*, 1998):

- **phase 1, exiting the water.** The animals halt for a moment on exiting the water. The halt is shorter if other crustaceans are coming up from behind;
- **phase 2, forward progression (walking).** The animals use the pereiopods P3, P4 and P5 to walk on the wetted substrate in parallel with the flowing water. They make stops along the way (Voegtlé and Valade, personal observation);
- **phase 3, the return to the water.** To cross through the strong current just upstream of a waterfall, the animals enter the water and continue walking on the substrate. In addition to walking, *Xiphocaris elongata* (*Xiphocarididae*) is capable of making three or four small jumps on the water surface, thus enabling it to clear the zone with a strong current (Fièvet *et al.*, 1998; Fièvet, 1999a).

Figure 21



a © P. Valade (Ocea Consult')
b © B. Voegtlé (Ecogea)

The walking capabilities of macro-crustaceans. (a) Camaron Macrobrachium lar *overcoming an obstacle by walking next to the flow of water (in the background) on a weir used to abstract drinking water on the Ourovéni River on Mayotte, (b)* Atyoida serrata *walking in a very shallow flow of water (millimetric) at a high elevation on Réunion.*

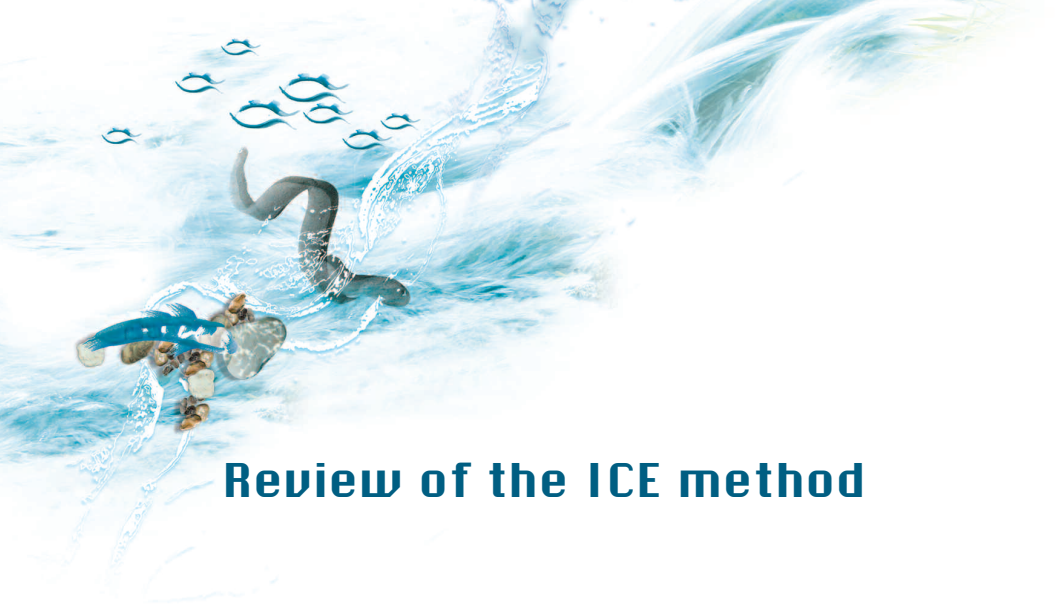
The slope of the substrate and the depth/velocity of water flowing over it are also essential factors determining whether the crustaceans can overcome an obstacle (Hamano *et al.*, 1995; Olivier *et al.*, 2013). For reasons having to do with the size to weight ratio and for a given species, it would appear that passage capabilities decrease with the increase in size.

Species in the *Atyidae* and *Xiphocarididae* families have greater passage capabilities than the other macro-crustaceans, a fact demonstrated by their longitudinal distribution in the various rivers in the insular, overseas territories (Fièvet *et al.*, 2001; Olivier *et al.*, 2012; Ocea Consult', 2014).

Variations in the immediate environment of *Xiphocarididae*, e.g. changes in luminosity, shadows, sudden changes in flow velocities or depths, etc., may destabilise the animals during their progression over obstacles (Robert, personal observation). However, given the very limited knowledge available on the topic and the difficulties in quantifying such conditions, this type of disturbance is not taken into account in the ICE method.

B

General principles underlying the ICE method



Review of the ICE method

General principles and limits

The purpose of the ICE method adapted to the insular, overseas territories is to objectively diagnose the passability of obstacles by fish and macro-crustaceans during upstream migration, while avoiding as much as possible the need to bring in experts.

Similar to the method used in continental France, it should be possible for a **small team** (two or three people) to complete the assessment in a very **short time** (if possible fewer than three hours).

Caution. There is, however, a limitation concerning downstream migration. Given the complexity of the mechanisms involved and the in-depth knowledge required on the local hydrology, on any drawoff conditions and on the hydromechanical characteristics of each structure, it was decided not to establish criteria intended to assess the passability of structures in the downstream direction. **An assessment of the potential impact of a water intake on downstream migration will require a study of the specific structure by specialised technicians**. The field protocol for the ICE method is one means of collecting the indispensable data for such a study.

The diagnosis of discontinuities in upstream migration using the ICE method should make it fairly easy to determine the passability of a structure according to **passability classes** adapted to the species or **group of species**. The ICE method is essentially based on a comparison of, on the one hand, the type of obstacle, its geometric characteristics and hydraulic conditions, and on the other, the passage capabilities of the species analysed.

The general approach of the method is **to identify the potential passageway(s) for species at each obstacle**, to describe the geometric characteristics of the passageways and the hydraulic conditions in them, and to compare that information with the passage capabilities of the species in question. It should be noted that, for a given obstacle, the potential passageways may differ depending on the species and the biological stages of those species. In which case, analysis of all the potential passageways is required.

The potential passageways are those whose attractiveness for fauna (position and discharge) and continuity may enable passage. They do not include those said to be “parasite” passageways whose flow is not continuous to the river upstream of the structure (e.g. a pipe, under pressure, used to convey the minimum discharge). The description of the geometric characteristics of each passageway is prepared by plotting the longitudinal profile of the components making up the passageways.

The procedure is 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 from the bottom of the river immediately upstream of the structure through to the plunge pool downstream of the structure (starting from

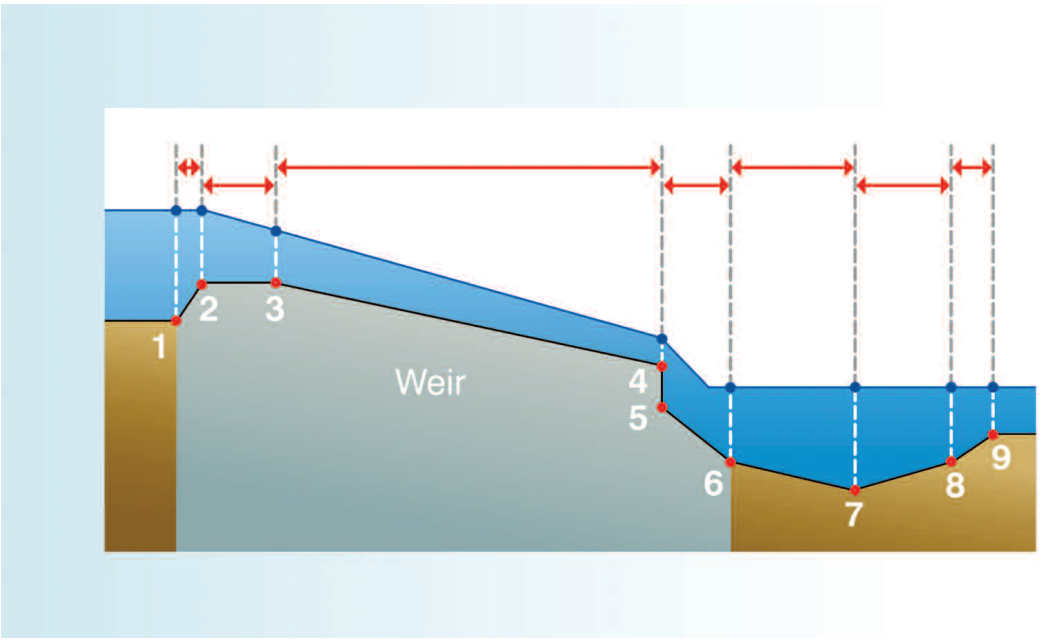
either upstream or downstream). The altimetric data of each point and the distance between points serve to plot one or more longitudinal profiles of the potential passageways for the species (or group of species) in question (Figures 22 and 23).

Figure 22

a, b © V. Burgun (OFB)

Examples of the longitudinal profiles that must be plotted in order to characterise a structure.
(a) On this type of structure with three identical gates, all closed, plotting of a single longitudinal profile is sufficient.
(b) For this weir, it is preferable to plot the longitudinal profile for the dewatered section as well because it may become a passageway under different hydrological conditions.

Figure 23



© Graphies for OFB

Example of a longitudinal profile for a simple structure. Modified after Baudoin et al.*, 2014.*

The passability of an obstacle depends above all on the hydraulic conditions pertaining at each point in the structure and that must be compared to the physical capabilities of the species in question. Mapping of the hydraulic gradient along the entire profile is therefore equally important and should 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, in short the hydrological conditions during migration periods, 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 (Figure 24). **Consequently, an ICE diagnosis should be carried out under the hydrological conditions most common during the migratory period of the targeted species.**

During periods of high discharge, measurements on certain structural features of the obstacle may be difficult, even dangerous for personnel and should not be undertaken. On the other hand, low-flow conditions make it easy to access structures and to measure the different structural features, but the measured hydraulic conditions can prove to be very detrimental to the diagnosis of passability (maximum head drop, reduced flow depths, reduced depth of the plunge pool, etc.) in that they are not representative of the conditions commonly encountered by fish and macro-crustaceans during their migration.

For these reasons, a number of visits under different hydrological conditions (low and medium flow conditions) may be necessary to determine or improve the ICE passability class. For example, the measurements on the structural features of the obstacle may be made during a low-flow period and the hydraulic gradients can be measured during a second visit when the discharge levels correspond to the migration periods of the species in question.

When a diagnosis is carried out under hydrological conditions differing significantly from those encountered by a species during its migratory period, it is still worthwhile, in addition to the standard assessment procedure, to determine the passability class, but without taking into account the disqualifying parameters resulting from the discharge (generally the water depth and flow velocity). 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.

Figure 24

a © P. Valade (Ocea Consult')
b © Deal de La Réunion
c, d © V. Burgun (OFB)

Examples of structures under different discharge conditions.
Glacis on the Sainte-Suzanne River on Réunion under low-flow (a) and high-flow (b) conditions. A weir in continental France under low-flow (c) and high-flow (d) conditions.

When a number of passageways have been diagnosed 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 method, whereas others may be easily passable. To be truly effective, the passageways diagnosed as 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 fraction of the total discharge flowing over or through the structure (lack of attractiveness).

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

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

If more precise assessment is required (complex structures or those of major importance for diadromous species), hydraulic modelling of the specific site is required. The model serves 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 and/or biological stages in question.

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.

There are a number of freeware programmes for this type of analysis, including the ones below.

- The FishXing programme was developed by the USDA-Forest Service Pacific Northwest Research Station. The programme, which may be downloaded from **https://www.fs.fed.us/biology/nsaec/fishxing/**, was initially designed to analyse the passage of fish through road structures, however it may be used on a more general basis, for example, 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/downloads.aspx**. 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. It was used in preparing this document to determine flow velocities on weir glacis (see the section on flow conditions over weirs with an inclined face).

N.B This document presents the ICE method. The field protocol, designed to ensure correct sizing and the safety of operations in the field, as well as a standardised procedure, is available in a separate document (Burgun *et al.*, 2015).

The different types of obstacles covered in upstream-migration diagnoses

The different types of obstacles covered in upstream-migration diagnoses by this method are the following:

- weirs, dams and fords comprising exclusively fixed components;
- structures having moving parts (gates) that may be partially or totally opened;
- road structures comprising hydraulic components (culverts, fords);
- mixed and more complex structures featuring different types of components.

In this document, different criteria have been established to diagnose the passability of each type of obstacle for the main species of fish and macro-crustaceans in the insular, overseas territories. Special sections are devoted to eels, *Sicydiinae* and macro-crustaceans in order to take into account their specific passage capabilities, respectively crawling, using a suction cup and walking.

The following sections are structured around these different factors and present the relevant criteria and assessment procedures.

N.B. **The ICE method for continental France proposes a pre-diagnosis of fish passes. On the islands, very few structures are equipped with a fish pass** (approximately twenty for all the islands combined). Given the lack of information on the passes and the fact that they were designed exclusively for specific species (e.g. *Gobiidae* on Réunion), it was **not deemed necessary to discuss here the criteria required to set up an equivalent pre-diagnosis for the French tropical islands.**

N.B. The main objective of the ICE method is to diagnose the passability of man-made obstacles and **it is important to take into account all types of obstacles** in adapting the method to the French overseas territories.

Consequently, in view of restoring continuity for entire rivers, the passage through fisheries must be taken into account in order to determine the overall situation and the limits to efforts to restore continuity on upstream structures.

But due to a lack of scientific data on the direct and indirect impacts of fisheries, it was decided not to include a diagnosis of fisheries in this document.

To determine the actual passage percentages through fisheries, it will be necessary to characterise, among other factors, the percentage of fish caught, the selectivity of the fishing procedures (size of migrators, their origin, etc.), the consequences for the adult populations upstream and for the ecological functioning of the river. **A specific study carried out by highly specialised technicians remains indispensable.**

Necessary expert intervention for diagnosis 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 egg, larval and free-embryo stages for amphidromous species (indigenous macro-crustaceans, *Gobiidae*, *Eleotridae*, etc.);
- the adults of certain macro-crustaceans (e.g. *Macrobrachium spp.*);
- the adults of catadromous species prior to reproduction (*Anguillidae*, *Kuhliidae*).

During their downstream migration, fauna 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 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 migrating downstream in different types of structures.

For the species in the insular, overseas environments, far less technical progress has been made and less practical feedback is available, however the initial studies and projects over the past decade have nonetheless produced technical results.

Among the main technical solutions developed to date are:
- the installation of fine screens diverting to one or more bypasses, a solution suited notably to the downstream migration of larger migrators (eels, *Kuhliidae*, adult *Macrobrachia*);
- reduced or halted water drawoffs during migratory periods, a solution suited notably to the downstream migration of early biological stages (eggs, free-embryos, larvae);
- the installation of "fish-friendly" turbines that do not injure fauna. This type of turbine is designed for low head drops, which means they are not well suited to the conditions in the overseas islands.

Generally speaking, behavioural barriers (lights, noises, electrical fields, bubbles, etc.) have turned out to be relatively ineffective for species in both temperate and tropical environments and do not currently provide sufficient results to merit their use. That being said, Fièvet *et al.* (2000) have apparently shown that light has a repulsive effect on adult and juvenile macro-crustaceans, but an attractive effect on larvae.

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 target species or group of species.

For more information on designing and sizing facilities intended to reduce injuries during downstream migration, a number of general technical guides may be consulted (Larinier *et al.*, 1994; Larinier and Travade, 1999, 2002, 2006; Courret and Larinier, 2008).

Taking into account current technical and biological knowledge, Antea - Ocea Consult' - Hydrétudes - Ecogea (2011) drafted for the Réunion Environmental Directorate a review of the different solutions potentially available to reduce the impact of water intakes on downstream migrators.

■ Special study required to diagnose a structure

Taking the example of a headrace for a hydroelectric plant (Figure 25), depending on the discharges flowing through the diversion system and in the headrace respectively, and on the configuration of the dam and intake at the plant, some of the downstream migrators transit via the diversion system (spillway, gates, flaps, etc.) and the rest are drawn into the headrace leading to the hydroelectric plant.

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 and the morphology of the migrators (primarily the size), 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 know-how, based not only on existing on-site studies, but also on in-depth knowledge of the functioning of installations, the hydrology of the river, the distribution of discharges at the site and the downstream-migration kinetics of the species in question.

Generally speaking, an assessment of the overall potential impact of a structure on downstream migration requires the site parameters presented below.

- **The percentage of migrators 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).

- **The potential injuries depending on:**
  - **the type and the characteristics of the hydromechanical devices equipping the installation** (turbines, pumps, etc.);
  - **the morphological characteristics (primarily the size) of the species.**
- **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).

For more information on assessing the potential effects of a structure or the cumulative effects of structures on migrators in rivers, see the methods guide drafted for continental France (Baudoin *et al.*, 2014).

Figure 25

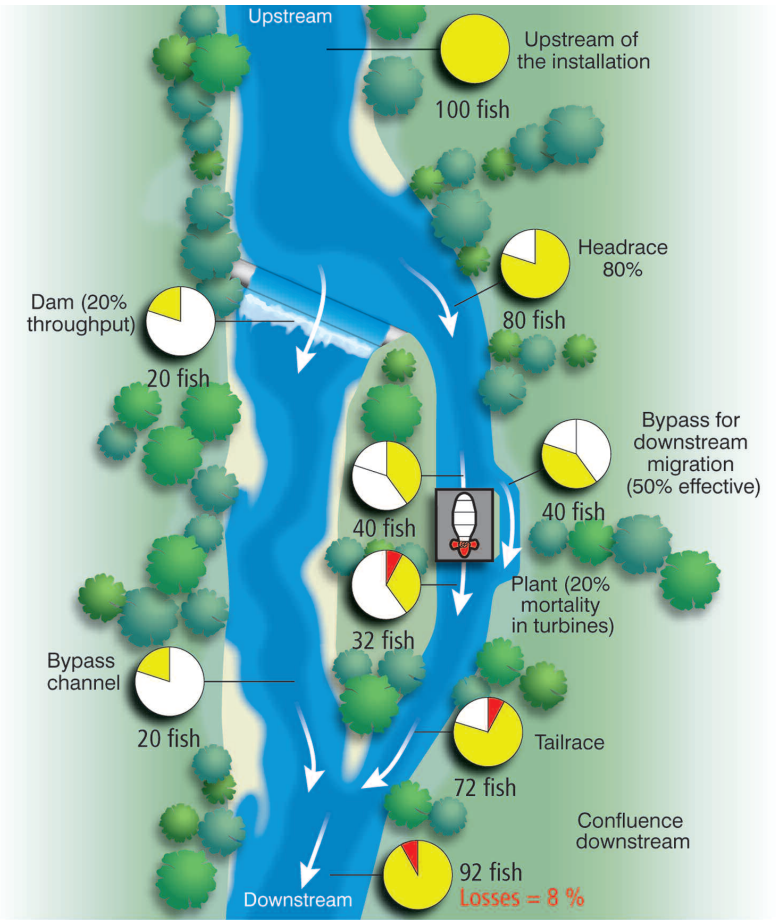


Diagram of a typical hydroelectric installation on a side channel and basic parameters for modelling its impacts on downstream migration. After Voegtlé and Larinier, 2004, modified by Baudoin et al., *2014.*

Caution. Given the complexity of the mechanisms involved in downstream migration and the in-depth knowledge required on the local hydrology, on drawoff conditions, on the characteristics of each structure and the downstream-migration kinetics of the species in question, it was decided not to establish criteria intended to assess the passability of structures in the downstream direction, similar to the identical decision taken for the ICE method developed for continental France. A specific study carried out by highly specialised technicians remains indispensable.

Further research is in all cases required to gain more knowledge on the migratory rhythms of species and the stimuli triggering migrations, as well as on the behaviour of species (during their different biological stages) on encountering an obstacle.

Definition of species groups

Presentation of the species groups

To meet the objectives of the ICE method, **the various species of fish and macro-crustaceans were grouped according to their passage capabilities** (see the section on the passage capabilities of fish and macro-crustaceans). Given the relative lack of knowledge and practical feedback on these species, the approach has been voluntarily simplified and groups may comprise species with fairly different characteristics (eco-ethological and morphological).

Caution. The groups and subgroups proposed here do not take into account the value of overcoming an obstacle for a species. For example, within a subgroup, some or all of the species may make (or not make) an attempt to overcome an obstacle depending on their ecological preferences, i.e. depending on the location of the obstacle within the patchwork of habitats required by the species.

A total of **five species groups were established,** where some are divided into subgroups. The distribution of species into different groups is discussed below and presented in table form at the end of this section (Tables 8 and 9).

For each group or subgroup of fish, 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 *in situ* visual observations of fish clearing obstacles.

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

N.B. For this method, an effort was made not to create an excessive number of groups. However, the violence of floods on the islands forces downstream migration of animals at all biological stages, thus creating a need to recolonise upstream sections for all the biological stages normally found in freshwaters.

For this reason, all the species are likely to move about and overcome obstacles during different biological stages (ranging from the juvenile to the adult stage).

■ Group 1. Fish with no particular morphological aptitude for passing obstacles

Group 1 comprises 21 small, generally benthic species that can swim very close to the bottom and take advantage of the low water velocities, from the *Eleotridae* and *Gobiidae* families (Figure 26).

Figure 26

a, b © P. Valade (Ocea Consult')
c, d © A. Collet (Ocea Consult')

Species in the first group.
*(a) Brown sleeper (*Eleotris klunzingerii*), (b) River goby (*Awaous commersonni*), (c) Chinestripe goby (*Stenogobius polyzona*), (d) Tropical carp-gudgeon (*Hypseleotris cyprinoides*).*

These species swim in successive "jumps" along the bottom, from one refuge to another. They live in the downstream sections of rivers. They do not have any special capabilities for overcoming obstacles (neither jumping, nor crawling, nor suction cups).

However, in the post-larval and juvenile stages, they can use the surface tension to climb vertical walls, an effective technique in overcoming obstacles.

Given the differences in passage capabilities (climbing or swimming) depending on the size of the fish, it was decided to split Group 1 into **two subgroups.**

Subgroup 1a comprises the older stages (subadult and adult) of the species, i.e. fish larger (measuring between 40 and 150 millimetres approximately) than those in Subgroup 1b.

To take into account the benthic behaviour of the species in Subgroup 1a, a **minimum water depth h_{min} of approximately 5 cm was selected** to ensure passage for the subgroup as a whole.

All of these species can take advantage of the lower water layers along river beds where the flow velocities are slower. To account for this particular feature and given the difficulty of measuring the flow velocities of the bottom layers, **a voluntarily over-estimated maximum speed of 1.5 to 3.0 m/s** (average maximum speed 2.25 m/s) was selected for Subgroup 1a.

Subgroup 1b comprises the post-larval and juvenile stages of the small, benthic species of Subgroup 1a. These stages are capable of using the superficial tension in wet areas near the flowing water to overcome subvertical obstacles.

Eleotris klunzingerii and *Awaous commersoni* have been observed climbing natural, subvertical obstacles several metres high and/or upstream of such obstacles, e.g. on the Langevin River on Réunion and the Bouyouni River on Mayotte. For *Awaous*, the pectoral fins form an "imperfect" suction cup that assists the fish in overcoming an obstacle (Blob *et al.*, 2006).

Given their size (15 to 50 mm) and their morphology, their swimming capabilities are necessarily limited, however no studies have been undertaken on the subject to date. Consequently, **maximum speeds U_{max} of 0.5 to 1.5 m/s (1.0 m/s average for the young stages) were selected**.

Following visual observations of fish under way (Valade and Voegtlé, personal observation), it would appear that they can make full use of their **climbing capabilities** (using the surface tension) **only when the maximum water depth does not exceed 1 cm. For greater depths, the water is considered deep enough for these young stages to swim.**

■ Group 2. Fish with jumping capabilities

This group comprises two genera with five species, namely the freshwater mullets *Agonostomus telfairii*, *Agonostomus monticola* and *Agonostomus catalai* and the rock flagtails *Kuhlia rupestris* and *Kuhlia sauvagii* (Figure 27).

Figure 27

a, d © P. Valade (Ocea Consult')
b © B. Voegtlé (Ecogea)
c © P. Hoarau (Ocea Consult')

Species in the second group.
*(a) Adult mullet (*Agonostomus spp.*) in rivers on Réunion, (b) Juvenile mountain mullet (*Agonostomus monticola*), (c) Rock flagtail/jungle perch (*Kuhlia rupestris*), (d) Rock flagtail (*Kuhlia sauvagii*).*

Adult rock flagtails migrate downstream to the sea to reproduce and then recolonise the river in order to pursue their development. Freshwater mullets are considered amphidromous species that reproduce in rivers (however, their migratory status is disputed in the scientific community, see the section on the different types of migrators). However, adult mullets can be transported downstream by floods during tropical storms and they then migrate back upstream to recolonise the vacated habitats (Smith and Kwak, 2014a).

In light of their respective morphologies, *Kuhlia* and *Agonostomus* would not, a priori, appear to have identical jumping capabilities. Jumping capabilities have been observed in juvenile *Agonostomus monticola* (Martinique / Guadeloupe, 2013, fish with a total length (Lp) of 40 to 100 mm, Voegtlé and Valade, personal observation) as well as in adults (Réunion, 2008, Lp of 150 to 200 mm, Voegtlé and Valade, personal observation). Additional

observations in 2014 and 2017 in Guadeloupe, at the Barthole (town of Vieux-Habitants) and Moreau (town of Goyave) water intakes, and at the Ravine Chaude ford, recorded jumps of 30 to 70 cm by fish estimated to be 10 to 30 cm in length (Robert, 2015).

For *Kuhlia*, no attempts to jump obstacles have been reported on the islands studied here, but the morphology of the species would indicate that they are capable of jumping. Restocking efforts in Australia have also produced evidence of *Kuhlia rupestris* moving upstream of small waterfalls, but no direct observations of how the fish overcame the obstacles have been made (Marsden, 2016). In captivity, *Kuhlia rupestris* has strong jumping capabilities, to the point that special conditions are required to confine it (Hutchison *et al.*, 2016).

Given the characteristics of the two genera in Group 2 and the variable sizes observed during migratory phases, four subgroups were created, two for each genus according to the biological stages.

Subgroup 2a comprises the subadults and adults of the freshwater mullets (*Agonostomus*) that were transported downstream by floods during tropical storms and then confronted with overcoming obstacles in order to recolonise upstream reaches of the river. These fish may vary significantly in size and a large range (100 to 250 mm) is proposed here to cover the various development stages.

They are excellent swimmers and jumpers, capable in certain configurations of overcoming head-drops exceeding one metre.

Maximum speeds U_{max} of 3.0 to 6.0 m/s (average 4.5 m/s) were selected for this group, which corresponds to the maximum speeds of the flathead mullet (*Mugil cephalus*), i.e. approximately 4 m/s for fish approximately 20 cm long, according to FishBase.

For this subgroup, the minimum water depth h_{min} selected to ensure passage is approximately 5 cm.

Subgroup 2b comprises the juveniles of the freshwater mullets (*Agonostomus*) that colonise river habitats following their larval phase in marine waters. The average size of the juveniles is 25 to 40 mm in the vicinity of the river mouth. However, the size class for this subgroup may be extended up to 100 mm to include all juveniles during their main colonisation phase in the river.

Maximum speeds U_{max} of 2.0 to 3.0 m/s (average 2.5 m/s) were selected.

For this subgroup as well, the minimum water depth h_{min} selected to ensure passage by swimming is approximately 5 cm.

Subgroup 2c comprises the subadults and adults of the rock flagtails (*Kuhlia*) that recolonise the river following reproducing in the ocean. The minimum adult size of these fish is greater than 170 mm for males and 250 mm for females (Hogan and Nicholson, 1987). The maximum size recorded for these species is 450 mm, for a weight of 2.7 to 3 kg, and the body depth is between 33 and 38% of its standard length (Merrick *et al.*, 1984; Randall *et al.*, 2001 in Pusey *et al.*, 2004).

Maximum speeds U_{max} of 2.5 to 6.0 m/s (average 4.25 m/s) were selected.

For this subgroup and a fish 25 cm long, the minimum water depth h_{min} selected to ensure passage by swimming is approximately 10 cm.

Subgroup 2d comprises the juveniles of the rock flagtails (*Kuhlia*) that colonise rivers following their larval phase in marine waters. The average size of the juveniles is 20 to 35 mm in the vicinity of the river mouth. However, the size class for this subgroup may be extended up to 100 mm to include all juveniles during their colonisation phase in the river.

Maximum speeds U_{max} of approximately 1.0 to 2.5 m/s (average speed 1.75 m/s) were selected.

For this subgroup, the minimum water depth h_{min} selected to ensure passage by swimming is approximately 5 cm.

■ Group 3. Fish with crawling capabilities

This group comprises the five eel species found in the studied French insular, overseas territories.

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

Their swimming capabilities are limited compared to other species of comparable size. For glass eels, the maximum swimming speeds are approximately 30 to 50 cm/s. For larger eels, the maximum swimming speeds are less than 2 m/s.

On the other hand, **they are very proficient at crawling** which, combined with their temporary capability to use oxygen from the air in very wet environments, enables them to overcome high physical barriers under limited flow (depth and velocity) conditions. In addition, the smallest eels can climb wet, vertical surfaces thanks to the surface tension between their bodies and the wet wall (the force is proportional to the surface area of the fish). As the fish grow, the surface-tension to weight ratio drops to the point that they can no longer climb vertical surfaces. The actual capacity to climb vertical or subvertical surfaces is therefore limited to eels measuring less than approximately 12 cm.

Certain tropical eel species can grow to sizes and weights significantly greater than those of European eels that served as the reference in developing the ICE method for continental France. In particular, the giant mottled eel *Anguilla marmorata* can grow up to 2 metres in length (Keith *et al.*, 2006). On Mayotte, eels over 700 mm long and weighing more than 1 kg are observed fairly regularly. They represent 8% of the eels caught in 2014 in the framework of the surveillance-monitoring network (Ocea Consult', 2014).

Finally, eels are not capable of jumping.

Given the differences in passage capabilities (climbing or swimming) depending on the size of the fish, it was decided to split Group 3 into three subgroups corresponding to the development stages (Figure 28).

Subgroup 3a corresponds to the "yellow" stage of giant mottled eels *Anguilla marmorata* and to the adults of other species (larger than 500 mm in length) that migrate upstream to recolonise habitats following flooding or intense dry periods. These large eels are heavy and muscular.

Subgroup 3b corresponds to "yellow" eels of all species between 100 and 500 mm in length.

Subgroup 3c comprises the younger eels less than 10 cm in length, corresponding essentially to the glass-eel stage. It should be noted that on entering river systems the glass eels of the tropical species are slightly smaller than European glass eels at the same stage, which means they have greater passage capabilities during the first few weeks of development in rivers due to the better surface-tension to weight ratio. **Given their swimming capabilities, any structure comprising a waterfall represents a major obstacle for this subgroup if they must overcome the obstacle by swimming.**

Because no data on the tropical taxa are available, the performance data of the European eels is used here. **Maximum speeds U_{max} of approximately 2.0 m/s were selected for Subgroup 3a, of 1.5 m/s for Subgroup 3b and of 0.5 m/s for the young eels in Subgroup 3c.**

Even though eels generally make use of their ability to breathe through their skin and to crawl over obstacles, it is likely that their **crawling technique is fully effective only when the water depth does not exceed 2 cm. For greater depths, the water is considered deep enough for elvers (Subgroup 3b) to swim. For the larger eels (Subgroup 3a), a water depth of approximately 5 cm is considered necessary for them to overcome an obstacle by swimming.**

Figure 28

a, b, c, d © P. Valade (Ocea Consult')

The three development stages of eels used to define the third group.
*(a) A mottled eel over 500 mm long (Subgroup 3a), (b) An African longfin eel (*Anguilla mossambica*, Subgroup 3b), (c) Translucid glass eels (*Anguilla spp.*, Subgroup 3c), (d) A pigmented elver (*Anguilla spp.*, Subgroup 3c).*

■ Group 4. Fish with a suction cup

Group 4 comprises the *Gobiidae Sicydiinae* species whose ventral fins are joined to form a suction cup (Figure 29). This particular feature enables the fish to overcome steep walls also using their mouth, e.g. *Sicyopterus lagocephalus*, or their pectoral fins, e.g. *Cotylopus acutipinnis* (Voegtlé *et al.*, 2002; Schoenfuss and Blob, 2003).

The juveniles of these species have impressive climbing capabilities in that they can overcome vertical and even overhanging surfaces. Given their greater weight, the climbing capabilities of adult fish are less impressive in terms of the steepness and/or the length of the climb (Voegtlé *et al.*, 2002).

Taking into account these differences, is was decided to divide Group 4 into two subgroups.

Subgroup 4a comprises the *Sicydiinae* subadults and adults. The fish in this subgroup are between 40 and 150 mm long.

All the fish in these species can take advantage of the lower water layers along river beds where the flow velocities are slower. In addition, the *Sicydiinae* have a special swimming technique to overcome obstacles where they "burst and attach", i.e. they first sprint and then attach to the substrate with their suction cup, before sprinting again.

Maximum speeds U_{max} of 2.0 to 4.5 m/s (average 3.25 m/s) were selected for Subgroup 4a.

For this entire subgroup, the minimum water depth h_{min} selected to ensure passage by swimming is approximately 5 cm.

Subgroup 4b comprises the *Sicydiinae* post-larvae and juveniles Depending on the species, the fish range in size between 15 and 40 mm. Passage possibilities must be analysed in terms of the availability and the layout of wet surfaces potentially providing passage.

Given their small size and their morphology, their swimming capabilities are *a priori* limited, however no studies have been undertaken on the subject to date. **Consequently, a maximum speed U_{max} of 0.5 to 1.5 m/s (average 1.0 m/s) was selected, similar to Subgroup 1b.**

For this entire subgroup, the minimum water depth h_{min} selected to ensure passage by swimming is approximately 1 cm.

Figure 29

a, c, d © P. Valade (Ocea Consult')
b © A. Collet (Ocea Consult')

Species in the fourth group.
(a) Subgroup 4a, bichique, Sicyopterus lagocephalus*, Indo-Pacific species, (b) Subgroup 4a,* Cotylopus rubripinnis*, a species endemic to the Comoros, (c) Subgroup 4a,* Cotylopus acutipinnis*, a species endemic to the Mascarenhas, (d) Subgroup 4b, juvenile bichiques* S. lagocephalus *(largest fish Lp ≈ 32 mm) and juvenile* C. acutipinnis *(smallest fish Lp ≈ 21 mm) one week after recruitment in freshwaters.*

N.B. Following *in situ* visual observations of fish making progress and the studies by Voegtlé *et al.* (2002) and Lagarde *et al.* (2016), **it was concluded that the fish in Group 4 (all stages) can make full use of their suction capabilities only when the maximum water depth does not exceed 1 cm.**

■ Group 5. Decapod crustaceans

Group 5 comprises exclusively the decapod macro-crustaceans (Figure 30). Decapod crustaceans have limited swimming and jumping capabilities, but they can overcome many obstacles by walking thanks to five pairs of legs (pereiopods), even though they use only three pairs (P3, P4 and P5) when walking.

Xiphocaris elongata has also been observed to jump (ricochet) off the water surface when attempting to cross a zone with a strong current (Fièvet *et al.*, 1998; Fièvet, 1999a; Monti, personal observation).

Passage capabilities may, however, diminish with the increase in size. Concerning the species in the *Atyidae* and *Xiphocarididae* families, the small size of adults does not significantly reduce their passage capabilities when compared with juveniles. Conversely, for species in the *Macrobrachium* genus, the relatively large size and weight of mature adults, e.g. over 30 grammes for some *Macrobrachium lar* (Sethi *et al.*, 2012; Ocea Consult', 2014a), can reduce their passage capabilities on vertical and subvertical walls, even though they can use their P1 pereiopods (strong pincers in some cases) to grasp asperities (Fièvet, 1999b).

These passage capabilities are virtually unlimited in natural environments (Ocea and Antea, 2013), except where rivers run dry or when a crustacean has become too large for climbing vertical walls in order to reach an upstream section. For these reasons, among macro-crustaceans, their natural, longitudinal distribution is determined essentially by a number of ecological constraints (habitat and thermal preferences, feeding, tolerance to hypoxia, etc.).

It was decided to create two subgroups.

Subgroup 5a comprises the adults in the *Macrobrachium* genus. Mature adults are larger than 40 to 60 mm (Sethi *et al.*, 2014; Ocea Consult', 2014b; Hoarau *et al.*, 2018). They have strong passage capabilities on wet surfaces. The amphidromous, freshwater crabs (*Grapsidae*) are also included in this subgroup.

Subgroup 5b comprises the species in the *Atyidae* and *Xiphocarididae* families, and the juveniles of the species in Subgroup 5a. This subgroup has even greater passage capabilities than Subgroup 5a for wet, vertical and even overhanging surfaces (Fièvet, 2000).

Figure 30

a, © P. Valade (Ocea Consult')
b © A. Collet (Ocea Consult')

Species in the fifth group.
(a) Subgroup 5a, monkey river prawn, Macrobrachium lar, *Réunion, (b) Subgroup 5b, long-nosed shrimp,* Caridina longirostris, *Mayotte.*

Species not mentioned in the groups

The atlases for freshwater fish and crustaceans on Martinique (Lim *et al.*, 2002), Guadeloupe (Monti *et al.*, 2010), Réunion (Keith *et al.*, 1999), the Comoros, Mascarenhas and Seychelles (Keith *et al.*, 2006) provide information on several dozen species of fish and crustaceans in the studied French insular, overseas territories.

In the interest of simplicity, it was decided to address here only the most frequently observed taxa having the greatest patrimonial and/or economic value.

The (supposedly) vicariant species are not common in the insular rivers and were not taken into account here given the major gaps in knowledge of their biological characteristics and passage capabilities.

For example, the small, pelagic species in the *Ambassidae* family (*Ambassis ambassis* and *A. natalensis*) or the *Syngnathidae* family (*Microphis lineatus*, *M. argulus* and *M. brachyurus*) are observed very rarely or essentially in the lowest sections of rivers and were therefore not included here.

Similarly, the two tarpon species (*Megalops atlanticus* and *M. cyprinoides*), that can migrate several hundred metres from the river mouth during their juvenile stage, were not taken into account.

The two euryhaline pike species (*Centropomus ensiferus* and *C. undecimalis*), observed very rarely in certain low sections of rivers on Martinique, were also excluded.

The cyrique crab (*Guinotia dentata*) lives in freshwater environments, but may be found on land several dozens of metres from rivers. Its ability to move over land led to its exclusion here.

In addition, only native species were taken into account. Generally speaking, the introduction of exogenous species to island environments can create serious ecological disturbances and potentially provoke a decline or even the disappearance of native species (trophic and spatial competition, predation, habitat degradation). It follows that a diagnosis of the passage capabilities of these species in view of proposing solutions to improve passage is not a good idea.

For this reason, a number of fish species, the *Mozambique tilapia* (*Oreochromis mossambicus*), the *Poeciliidae* family (guppy, molly, mosquitofish, swordtail), the giant gourami (*Osphronemus goramy*), the rainbow trout (*Oncorhynchus mykiss*) were not included. Concerning crustaceans, the giant river prawn (*Macrobrachium rosenbergii*) and the freshwater blueclaw crayfish (*Cherax quadricarinatus*) were introduced to the insular, overseas environments, but for the moment would not seem to have naturalised there (manager of the Saint-Paul Pond national nature reserve on Réunion, personal observation) and have to date had a very limited or no impact on the native crustacean populations.

Given the very limited available knowledge of the biology and migratory periods of gasteropod molluscs (in their various stages), they were not included here. It should be noted, however, that many gasteropod molluscs on tropical islands also have an amphidromous life cycle (McDowall, 2007). In some cases, molluscs and particularly the *Neritininae* species may migrate in massive numbers (Pyron and Covich, 2003; Blanco and Scatena, 2007).

The species taken into account here, their means of passage and the corresponding ICE groups are listed in Tables 7 and 8. Table 9 presents the theoretical swimming and jumping capabilities of the fish species.

Caution. These theoretical values are adjusted during the diagnosis of passability during upstream migration (see the next chapter) to take into account *in situ* visual observations of passages over obstacles.

Table 7 *Species included in the ICE method, their territories, passage techniques, sizes and ICE group.*

	Family	Species	Name in English (E) and in Creole (C)	FOT				Passage technique	Stage and/or length	ICE group
				Guadeloupe	Martinique	Mayotte	Réunion			
FISH	Anguillidae	*Anguilla bengalensis*	Indian mottled eel (E) / z'amab, z'anguille (C)			X	X	Swimming / Crawling	Lp > 500 mm	3a
		Anguilla bicolor bicolor	Indonesian shortfin eel (E) / z'amab, z'anguille (C)			X	X			
		Anguilla marmorata	Giant mottled eel, marbled eel (E) / z'amab, z'anguille (C)			X	X	Swimming / Crawling	100 mm < Lp < 500 mm	3b
		Anguilla mossambica	African longfin eel (E) / z'amab, z'anguille (C)			X	X			
		Anguilla rostrata	American eel (E) / z'anguille (C)	X	X			Swimming / Climbing	Lp < 100 mm	3c
	Eleotridae	*Butis butis*	Crazy fish, crimson-tipped flathead-sleeper, duckbill sleeper (E)			X	X	Swimming	Subadult / Adult (Lp > 40 mm)	1a
		Dormitator maculatus	Fat sleeper (E) / ti-nèg, dormeur (C)	X	X					
		Eleotris amblyopsis	Large-scaled spiny-cheek sleeper (E) / pitit dormè (C)	X						
		Eleotris klunzingerii	Brown sleeper, dusky sleeper (E) / cabot noir (C)			X	X			
		Eleotris mauritiana	Widehead sleeper (E) / cabot noir (C)			X	X			
		Eleotris perniger	Small-scaled spiny-cheek sleeper (E) / pitit dormè, flèche (C)	X	X					
		Gobiomorus dormitor	Bigmouth sleeper (E) / grand dormeur, dormeur (C)	X	X					
		Guavina guavina	Guavina (E) / dormeur (C)		X			Swimming / Climbing	Juvenile (Lp < 40 mm)	1b
		Hypseleotris cyprinoides	Tropical carp-gudgeon (E)			X	X			
		Ophieleotris cf *aporos*	Snakehead gudgeon (E)			X				
		Ophiocara porocephala	Northern mud gudgeon, spangled sleeper (E) / makanbale latet ron (C)			X				
	Gobiesocidae	*Gobiesox nudus*	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	X	X			Swimming / Suction cup	Subadult / Adult (Lp > 40 mm)	4a
									Juvenile (Lp < 40 mm)	4b
	Gobiidae	*Awaous banana*	River goby (E) / jolpot, loche (C)	X	X			Swimming	Subadult / Adult (Lp > 40 mm)	1a
		Awaous commersoni	Commerson's freshwater goby, river goby (E) / loche, cabot (C)			X	X			
		Ctenogobius pseudofasciatus	Slashcheek goby (E)		X					
		Glossogobius callidus	Tank goby (E)			X				
		Glossogobius giurus	Tank goby (E) / loche (C)			X	X			
		Glossogobius kokius	- (E) / loche, cabot (C)				X			
		Mugilogobius mertoni	Chequered mangrove goby, Merton's mangrove goby, meander goby (E) / gobi milet (C)			X		Swimming / Climbing	Juvenile (Lp < 40 mm)	1b
		Redigobius balteatus	Rhinohorn goby (E)			X				
		Redigobius bikolanus	Bigmouth goby, speckled goby (E) / gobi tase (C)			X				
		Stenogobius polyzona	Chinestripe goby (E) / cabot rayé (C)			X	X			
		Cotylopus acutipinnis	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)				X	Swimming / Suction cup	Subadult / Adult (Lp > 40 mm)	4a
		Cotylopus rubripinnis	Goby (E)			X				
		Sicydium plumieri	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)			X	X			
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)	X	X				Juvenile (Lp < 40 mm)	4b
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)	X	X					
	Kuhliidae	*Kuhlia rupestris*	Jungle perch, rock flagtail (E) / doule de roche, carpe (C)			X	X	Swimming / Jumping	Subadult / Adult (Lp > 100 mm)	2c
		Kuhlia sauvagii	Rock flagtail (E) / doule de roche, carpe (C)			X	X		Juvenile (Lp < 100 mm)	2d
	Mugilidae	*Agonostomus catalai*	Comoro mullet (E)			X		Swimming / Jumping	Subadult / Adult (Lp > 100 mm)	2a
		Agonostomus monticola	Mountain mullet (E) / milet (C)	X	X					
		Agonostomus telfairii	Fairy mullet (E) / chitte (C)			X	X		Juvenile (Lp < 100 mm)	2b

Table 7 (cont.) *Species included in the ICE method, their territories, passage techniques, sizes and ICE group.*

	Family	Species	Name in English (E) and in Creole (C)	FOT				Passage technique	Stage and/or length	ICE group
				Guadeloupe	Martinique	Mayotte	Réunion			
CRUSTACEANS	Atyidae	*Atya innocous*	Basket shrimp (E) / cacador, bouc, grand bouc (C)	X	X			Negligible swimming / Walking	All stages	5b
		Atya scabra	Camacuto shrimp (E) / cacador, bouc, grand bouc (C)	X	X					
		Atyoida serrata	- (E) / crevette bouledogue (C)			X	X			
		Caridina longirostris	Long-nosed shrimp (E) / chevaquine (C)			X				
		Caridina serratirostris	Ninja shrimp (E) / chevaquine, sevret tas blan (C)			X	X			
		Caridina typus	Typical caridina shrimp (E) / chevaquine (C)			X	X			
		Jonga serrei	Jonga (E) / petit bouc (C)	X						
		Micratya poeyi	Tiny basket shrimp (E) / petit bouc (C)	X	X					
		Potimirim glabra	Smooth potimirim (E) / petit bouc (C)	X						
		Potimirim potimirim	Potimirim (E) / petit bouc (C)	X	X					
	Grapsidae	*Sesarmops impressum*	- (E) / crabe de rivière (C)			X		Negligible swimming / Walking	Subadult / Adult	5a
		Varuna litterata	Peregrine crab, river swimming crab (E) / crabe de rivière (C)			X	X		Juvenile	5b
	Palaemonidae	*Macrobrachium acanthurus*	Cinnamon river shrimp (E) / chevrette, bouquet cannelle (C)	X	X			Negligible swimming / Walking	Subadult / Adult	5a
		Macrobrachium australe	Koua river prawn (E) / chevrette grand bras (C)			X	X			
		Macrobrachium carcinus	Bigclaw river shrimp (E) / ouassou, z'habitant, écrevisse, bouquet pintade (C)	X	X					
		Macrobrachium crenulatum	Striped river shrimp (E) / queue rouge, queue de madras (C)	X	X					
		Macrobrachium equidens	Rough river prawn (E) / camaron tacheté, kanmaron (C)			X				
		Macrobrachium faustinum	Bigarm river shrimp, Caribbean longarm shrimp (E) / alexis, gros mordant, écrevisse (C)	X	X					
		Macrobrachium heterochirus	Cascade river prawn (E) / grand bras, écrevisse (C)	X	X					
		Macrobrachium hirtimanus	- (E) / écrevisse, chevrette lecroc (C) (no longer present?)				?			
		Macrobrachium lar	Monkey river prawn (E) / chevrette, camaron, kanmaron gran lebra (C)			X	X		Juvenile	5b
		Macrobrachium lepidactylus	Madagascar scale prawn (E) / écrevisse, bétangue (C)			X	X			
		Palaemon pandaliformis	American grass shrimp (E) / bouquet potitinga (C)	X	X					
	Xiphocarididae	*Xiphocaris elongata*	Cricket shrimp, yellow-nosed shrimp (E) / pissette (C)	X	X			Negligible swimming / Walking	All stages	5b

Table 8 *ICE species groups and the corresponding passage capabilities.*

ICE species group	Family	Species	Main names in English (E) and in Creole (C)	Passage technique	Stage and/or length
1a	Eleotridae	All species	Sleepers (E) / cabot noir, dormeur, ti-nèg, flèche (C)	Swimming	Subadult / Adult (Lp > 40 mm)
	Gobiidae hors Sicydiinae	All species **except** ***Sicydiinae***	All species **except** ***Sicydiinae***		
1b	Eleotridae	All species	Sleepers (E) / cabot noir, dormeur, ti-nèg, flèche (C)	Swimming / Climbing	Juvenile (Lp < 40 mm)
	Gobiidae hors Sicydiinae	All species **except** ***Sicydiinae***	All species **except** ***Sicydiinae***		
2a	Mugilidae	All species	Mullets (E) / mulet, chitte (C)	Swimming / Jumping	Subadult / Adult (Lp > 100 mm)
2b					Juvenile (Lp < 100 mm)
2c	Kuhliidae	All species	Rock flagtails (E) / doule de roche, carpe (C)	Swimming / Jumping	Subadult / Adult (Lp > 100 mm)
2d					Juvenile (Lp < 100 mm)
3a	Anguillidae	All species	Eels (E) / z'amab, z'anguille (C)	Swimming / Crawling	Lp > 500 mm
3b					100 mm < Lp < 500 mm
3c				Swimming / Crawling / Climbing	Lp < 100 mm
4a	Gobiesocidae	*Gobiesox nudus*	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	Swimming / Suction cup	Subadult / Adult (Lp > 40 mm)
	Gobiidae Sicydiinae	*Cotylopus acutipinnis* *Cotylopus rubripinnis* *Sicydium plumieri*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C) Goby (E) Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)		
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)		
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)		
4b	Gobiesocidae	*Gobiesox nudus*	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	Swimming / Suction cup	Juvenile (Lp < 40 mm)
	Gobiidae Sicydiinae	*Cotylopus acutipinnis* *Cotylopus rubripinnis* *Sicydium plumieri*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C) Goby (E) Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)		
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)		
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)		
5a	Grapsidae	All species	River crabs (E) / crabe de rivière (C)	Negligible swimming / Walking	Subadult / Adult
	Palaemonidae	All species	Prawns (E) / bouquet, chevrette, crevette, écrevisse (C)		
5b	Atyidae	All species	Shrimp (E) / bouc, caradine, chevaquine, crevette (C)	Negligible swimming / Walking	All stages
	Grapsidae	All species	River crabs (E) / crabe de rivière (C)		Juvenile
	Palaemonidae	All species	Prawns (E) / bouquet, chevrette, crevette, écrevisse (C)		Juvenile
	Xiphocarididae	*Xiphocaris elongata*	Cricket shrimp (E) / pissette (C)		All stages

Table 9 *ICE species groups of fish and their theoretical swimming and jumping capabilities.*

ICE species group	Family	Species	Main names in English (E) and in Creole (C)	Stage and/or length	Jumping species and/or stage	Minimum water depth h_{min} required for swimming	Max. swimming speed U_{max} (m/s)			Height of jump (m)		
							Min	*Avg*	Max	Min	*Avg*	Max
1a	**Eleotridae**	All species	Sleepers (E) / cabot noir, dormeur, ti-nèg, flèche (C)	**Subadult / Adult (Lp > 40 mm)**	**No**	**0.05 m**	**1.50**	*2.25*	**3.00**	**-**	-	**-**
	Gobiidae hors *Sicydiinae*	All species **except *Sicydiinae***	All species **except *Sicydiinae***									
1b	**Eleotridae**	All species	Sleepers (E) / cabot noir, dormeur, ti-nèg, flèche (C)	**Juvenile (Lp < 40 mm)**	**No**	**0.01 m**	**0.50**	*1.00*	**1.50**	**-**	-	**-**
	Gobiidae hors *Sicydiinae*	All species **except *Sicydiinae***	All species **except *Sicydiinae***									
2a	**Mugilidae**	All species	Mullets (E) / mulet, chitte (C)	**Subadult / Adult (Lp > 100 mm)**	**Yes**	**0.05 m**	**3.00**	*4.50*	**6.00**	**0.40**	*0.90*	**1.60**
2b				**Juvenile (Lp < 100 mm)**	**Yes**	**0.05 m**	**2.00**	*2.50*	**3.00**	**0.20**	*0.30*	**0.40**
2c	**Kuhliidae**	All species	Rock flagtails (E) / doule de roche, carpe (C)	**Subadult / Adult (Lp > 100 mm)**	**Yes**	**0.10 m**	**2.50**	*4.25*	**6.00**	**0.30**	*0.90*	**1.60**
2d				**Juvenile (Lp < 100 mm)**	**Yes**	**0.05 m**	**1.00**	*1.75*	**2.50**	**0.10**	*0.20*	**0.30**
3a	**Anguillidae**	All species	Eels (E) / z'amab, z'anguille (C)	**Lp > 500 mm**	**No**	**0.05 m**	**< 2.00**			**-**	-	**-**
3b				**100 mm < Lp < 500 mm**	**No**	**0.02 m**	**< 1.50**			**-**	-	**-**
3c				**Lp < 100 mm**	**No**	**-**	**< 0.50**			**-**	-	**-**
4a	**Gobiesocidae**	*Gobiesox nudus*	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	**Subadult / Adult (Lp > 40 mm)**	**No**	**0.05 m**	**2.00**	*3.25*	**4.50**	**-**	-	**-**
	Gobiidae Sicydiinae	*Cotylopus acutipinnis*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)									
		Cotylopus rubripinnis	Goby (E)									
		Sicydium plumieri	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)									
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)									
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)									
4b	**Gobiesocidae**	*Gobiesox nudus*	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	**Juvenile (Lp < 40 mm)**	**No**	**0.01 m**	**0.50**	*1.00*	**1.50**	**-**	-	**-**
	Gobiidae Sicydiinae	*Cotylopus acutipinnis*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)									
		Cotylopus rubripinnis	Goby (E)									
		Sicydium plumieri	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)									
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)									
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)									

Review of passability classes

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

The method is essentially based on a comparison of the geometric characteristics of obstacles and the corresponding hydraulic conditions with the passage capabilities of the fish and macro-crustacean species analysed.

The procedure proposed here makes every attempt to be as logical and rigorous as possible, however a number of simplifications had to be made given the following:

- insufficient knowledge of the passage capabilities of certain species;
- variability in swimming capabilities within a species or group of species;
- the geometric complexity of some obstacles creating highly diverse hydraulic conditions for a given discharge;
- variability of hydrological and thermal conditions during the migratory periods.

With the above in mind and **following the lead of the method proposed for continental France**, it was deemed preferable to create only **five passability classes**.

Four classes, each with an index (0; 0.33; 0.66 and 1), were created and linked with a colour code to facilitate implementation and enhance understanding.

An **indeterminate class (NC)**, without an index, was created for cases 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.

Caution. The four passability classes (0; 0.33; 0.66 and 1) must not be interpreted as numerical values and/or as passage percentages. They are rather indicators of the need to undertake restoration work on the structure.

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 for a given group of species will be presented in detail 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(s).

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 or by a high percentage of the population(s). Upstream migration is possible only during a limited part of the migratory period or for a limited part of the population(s) in the given group. The obstacle may incur 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(s). But the obstacle can nonetheless cause non-negligible delays in migration.

The obstacle cannot be overcome during part of the migratory period by a significant part of the population(s) 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(s) 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 members in the given group can overcome it without injury.

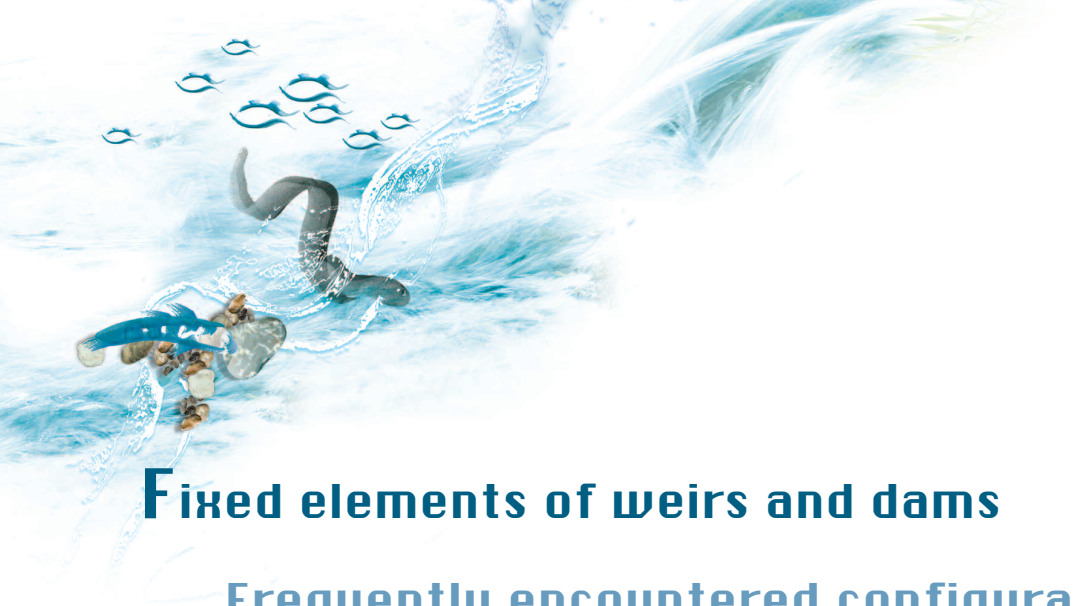
Barrier having indeterminate impact (ICE class = NC)

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

N.B. This classification system may also be applied to diagnoses of downstream migration. However, as noted in the chapter on the general principles of the ICE method, 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

Diagnosis of passability during upstream migration



Fixed elements of weirs and dams

Frequently encountered configurations

The hydraulic conditions at 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 (Figure 31), a number of different situations may exist and are described below.

1. Vertical or subvertical waterfalls that a fish can overcome only using special passage capabilities (jumping, crawling, climbing or suction cups) or, concerning macro-crustaceans, by walking.

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).

N.B. Consequently, similar to the ICE method developed for continental France, **a weir is considered vertical or subvertical when the slope of the downstream face is greater than 150% (56°).**

2. Inclined faces that fish can overcome by swimming. The passability of an inclined weir depends on the flow characteristics on the glacis (water depths, flow velocities) 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 or biological stage.

3. 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 longitudinal 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.

The fixed elements (spillway, glacis) of weirs and dams are generally made of riprap set in concrete or reinforced concrete, and may be protected by steel plates in rivers transporting large quantities of sediment (e.g. on Réunion). However, differences in construction materials do not significantly influence the flow conditions (water depths, flow velocities).

Caution. Hydraulic analysis of rock weirs with little or no concrete setting is more difficult than for "standard" weirs due to the variability in the organisation of the weir and in the shapes and sizes of the rocks, particularly given that their technical specifications are never very precise. **That is why special criteria were developed for this type of obstacle in the ICE method.**

Figure 31

a, b, c, d, e © B. Voegtlé (Ecogea)
f © P. Valade (Ocea Consult')

Different configurations of weirs and dams constituting obstacles.
(a) Vertical weir with a plunging jet, (b) Complex weir with a downstream waterfall and a glacis comprising an upstream step, (c) Inclined weir with a slight slope, (d) Inclined weir with a downstream, vertical waterfall, (e) Inclined weir with a small, downstream waterfall, (f) Vertical weir with a glacis made of riprap set in concrete.

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

- **vertical or subvertical waterfall**: the difference between the elevations of 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), 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 of 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 flow velocity on the glacis;
■ **stepped weirs**, i.e. weirs made up of several vertical steps separated by horizontal or inclined sections, the flow configuration and its description are more complex and passage of fish is generally more difficult.

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 the result of the cumulative effects of these parameters and often of the limiting impact of a single parameter.

In this section, the method used to determine the ICE passability class is presented for:
■ weirs with vertical or subvertical waterfalls (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 flap gates) is comparable to weirs with vertical or subvertical waterfalls.

Finally, where applicable given the specific passage capabilities, readers should refer to the sections on the species capable of walking (macro-crustaceans), crawling (eels), climbing using the surface tension (*Gobiidae* juveniles) and using a suction cup (notably the *Sicydiinae*).

For weirs and dams equipped with passage systems for diadromous fauna, an analysis of their effectiveness should be carried out by experts specialised in the hydraulic sizing of passage systems and in species ethology.

Vertical or subvertical obstacles (slope > 150%)

Passability criteria for jumping fish species

As noted in the section on the passage capabilities of fish, when the depth of the plunge pool is sufficient, jumping fish are capable of clearing maximum heights approximately equal to $Lp/2 + (U_{max} \sin\beta)^2 / 2g$ (Table 6). If the height and length of the jump are sufficient, the fish can resume their upstream migration if the hydraulic head and velocity of the water where they fall (crest of the weir or just upstream) permit it.

Definition of passability classes

Using Table 9 (previous chapter), which indicates the maximum theoretical jumping heights determined for the size class selected for a stage/species (i.e. for the given subgroup), the classification below is proposed, on the condition of sufficient hydraulic head and plunge-pool depth:

■ If the head-drop DH is less than the theoretical jumping height of the minimum length of fish Lp_{min} in the given subgroup, i.e. < 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 length of fish Lp_{min} (DH_{min}) and the average length of fish Lp_{avg} (DH_{avg}) in the given subgroup, 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 length of fish Lp_{avg} (DH_{avg}) and the maximum length of fish Lp_{max} (DH_{max}) in the given subgroup, 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 length of fish Lp_{max} in the given species (> DH_{max}), the obstacle is considered a t**otal barrier (ICE class = 0).**

Passability criteria for swimming (non-jumping) fish species

In general, vertical and subvertical obstacles create waterfalls that fish species cannot overcome except by jumping (with the exception of certain capabilities such as suction/climbing and crawling, by the *Sicydiinae* and eels respectively, that are discussed in separate sections).

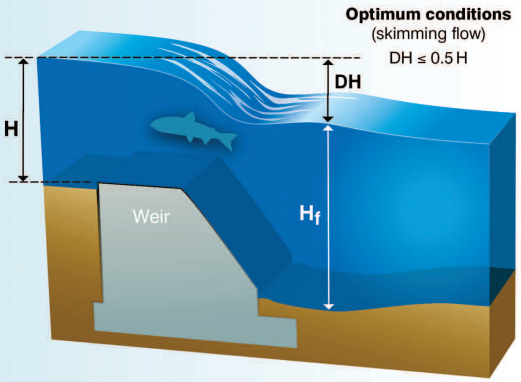
However, fish can nonetheless overcome vertical waterfalls by swimming when flow conditions meet several criteria (Figure 32), namely:

- **the water level is sufficient to create a "skimming flow.** This type of flow occurs when the head-drop DH is less than or equal to half the hydraulic head H at the weir. A virtual skimming flow (0.5 H < DH < H) may enable passage by swimming, 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 hydraulic head 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 condition that the other criteria (skimming flow, depth of plunge pool and sufficient hydraulic head) are met:

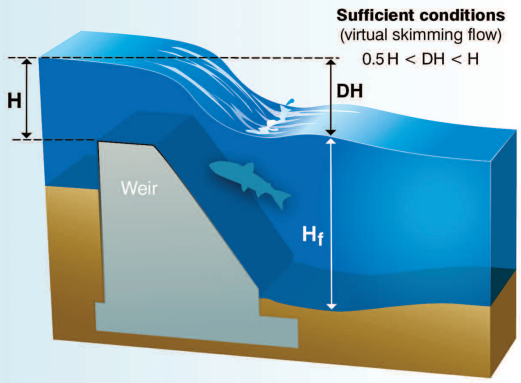
- when the flow velocity in the jet created by the head-drop DH is less than the maximum speed U_{max} assigned to the minimum fish length (Lp_{min}) for the given subgroup, the obstacle may be considered a **low-impact passable barrier (ICE class = 1);**
- when the flow velocity in the jet created by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

Figure 32



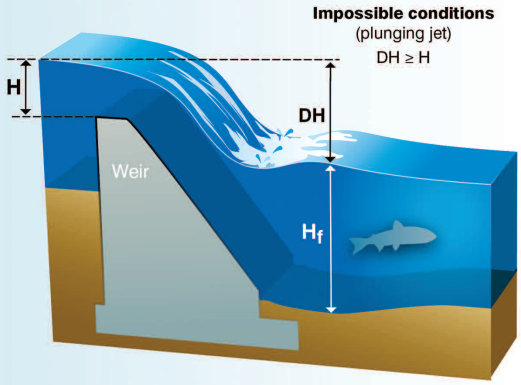
© B. Voegtlé (Ecogea)

Skimming flow



© B. Voegtlé (Ecogea)

Virtual skimming flow



© B. Voegtlé (Ecogea)

Plunging jet

Types of jets and passage conditions for swimming (non-jumping) species confronting a vertical or subvertical obstacle (slope > 150 % (56°)). After Baudoin et al.*, 2014.*

Determining passability classes

■ Threshold values used in the decision tree

Table 10 below shows approximate values for the minimum depths of plunge pools Hf_{min} required for passage as a function of the head-drop and the angle of incidence of the jet (or the slope of the weir).

Table 11 on the next page lists, for the various species, the threshold values used to determine the passability of a vertical or subvertical weir (slope > 150% (56°)).

These tables are accompanied by a decision tree (Figure 33) showing how the ICE passability classes are determined.

Table 10 *Approximate minimum depth Hf_{min} of a plunge pool required for fish to overcome a vertical or subvertical obstacle (slope > 150 %), as a function of the head drop (DH). After Baudoin* et al.*, 2014.*

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

Table 11 *Threshold values used to determine ICE passability classes, by swimming or jumping, for vertical and subvertical obstacles (slope > 150% (56°)).*

ICE group	Family	Species	Name in English (E) and in Creole (C)	FOT			
				Guadeloupe	Martinique	Mayotte	Réunion
1a	Eleotridae + Gobiidae except Sicydiinae	*Awaous banana*	River goby (E) / jolpot, loche (C)	X	X		
		Awaous commersoni	Commerson's freshwater goby, river goby (E) / loche, cabot (C)			X	X
		Butis butis	Crazy fish, crimson-tipped flathead-sleeper, duckbill sleeper (E)			X	X
		Ctenogobius pseudofasciatus	Slashcheek goby (E)		X		
		Dormitator maculatus	Fat sleeper (E) / ti-nèg, dormeur (C)	X	X		
		Eleotris amblyopsis	Large-scaled spiny-cheek sleeper (E) / pitit dormè (C)	X			
		Eleotris klunzingerii	Brown sleeper, dusky sleeper (E) / cabot noir (C)			X	X
		Eleotris mauritiana	Widehead sleeper (E) / cabot noir (C)			X	X
		Eleotris perniger	Small-scaled spiny-cheek sleeper (E) / pitit dormè, flèche (C)	X	X		
		Glossogobius callidus	Tank goby (E)			X	
		Glossogobius giurus	Tank goby (E) / loche (C)			X	X
		Glossogobius kokius	- (E) / loche, cabot (C)				X
1b		*Gobiomorus dormitor*	Bigmouth sleeper (E) / grand dormeur, dormeur (C)	X	X		
		Guavina guavina	Guavina (E) / dormeur (C)		X		
		Hypseleotris cyprinoides	Tropical carp-gudgeon (E)			X	X
		Mugilogobius mertoni	Chequered mangrove goby, Merton's mangrove goby, meander goby (E) / gobi milet (C)			X	
		Ophieleotris cf *aporos*	Snakehead gudgeon (E)			X	
		Ophiocara porocephala	Northern mud gudgeon, spangled sleeper (E) / makanbale latet ron (C)			X	
		Redigobius balteatus	Rhinohorn goby (E)			X	
		Redigobius bikolanus	Bigmouth goby, speckled goby (E) / gobi tase (C)			X	
		Stenogobius polyzona	Chinestripe goby (E) / cabot rayé (C)			X	X
2a	Mugilidae	*Agonostomus catalai*	Comoro mullet (E)			X	
		Agonostomus monticola	Mountain mullet (E) / milet (C)	X	X		
2b		*Agonostomus telfairii*	Fairy mullet (E) / chitte (C)			X	X
2c	Kuhliidae	*Kuhlia rupestris*	Jungle perch, rock flagtail (E) / doule de roche, carpe (C)			X	X
2d		*Kuhlia sauvagii*	Rock flagtails (E) / doule de roche, carpe (C)			X	X
3a	Anguillidae	*Anguilla bengalensis*	Indian mottled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla bicolor bicolor	Indonesian shortfin eel (E) / z'amab, z'anguille (C)			X	X
3b		*Anguilla marmorata*	Giant mottled eel, marbled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla mossambica	African longfin eel (E) / z'amab, z'anguille (C)			X	X
3c		*Anguilla rostrata*	American eel (E) / z'anguille (C)	X	X		
4a	Gobiesocidae + Gobiidae Sicydiinae	*Cotylopus acutipinnis*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)				X
		Cotylopus rubripinnis	Goby (E)			X	
		Gobiesox nudus	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	X	X		
4b		*Sicydium plumieri*	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)			X	X

The values indicated for (sub)groups 1b, 3 and 4 correspond to the passability classes set when the analysis takes into account only the swimming capabilities of species. In cases where the obstacle includes a crawling, suction or climbing zone, the assessment must ***also*** *use the special tables for these passage techniques (see the relevant sections).*

ICE group	Family	Stage and/or length	Jumping species and/or stage	Minimum hydraulic head (H_{min})	Threshold values for head-drops (DH) in diagnosing weirs with vertical or subvertical downstream faces > 150% (m)			
					ICE passability class			
					1	0.66	0.33	0
1a	Eleotridae + Gobiidae except Sicydiinae	Subadult / Adult (Lp > 40 mm)	No	0.05 m	≤ 0.15	]0.15 - 0.35]	]0.35 - 0.50]	> 0.50
1b		Juvenile (Lp < 40 mm)	No	0.01 m	-	≤ 0.10	]0.10 - 0.20]	> 0.20
2a	Mugilidae	Subadult / Adult (Lp > 100 mm)	Yes	0.05 m	≤ 0.40	]0.40 - 1.00]	]1.00 - 1.80]	> 1.80
2b		Juvenile (Lp < 100 mm)	Yes	0.05 m	≤ 0.20	]0.20 - 0.50]	]0.50 - 0.70]	> 0.70
2c	Kuhliidae	Subadult / Adult (Lp > 100 mm)	Yes	0.10 m	≤ 0.30	]0.30 - 0.90]	]0.90 - 1.60]	> 1.60
2d		Juvenile (Lp < 100 mm)	Yes	0.05 m	≤ 0.10	]0.10 - 0.35]	]0.35 - 0.50]	> 0.50
3a	Anguillidae	Lp > 500 mm	No	0.05 m	≤ 0.50	]0.50 - 0.70]	]0.70 - 0.90]	> 0.90
3b		100 mm < Lp < 500 mm	No	0.02 m	≤ 0.20	]0.20 - 0.35]	]0.35 - 0.50]	> 0.50
3c		Lp < 100 mm	No	-	-	-	-	-
4a	Gobiesocidae + Gobiidae Sicydiinae	Subadult / Adult (Lp > 40 mm)	No	0.05 m	≤ 0.20	]0.20 - 0.60]	]0.60 - 1.40]	> 1.40
4b		Juvenile (Lp < 40 mm)	No	0.01 m	-	≤ 0.10	]0.10 - 0.20]	> 0.20

■ Decision tree

The steps in determining the ICE passability class, by swimming or jumping, of a vertical or subvertical obstacle (Figure 33) are presented below.

1. Analysis of the hydraulic head at the obstacle

If the hydraulic head H ≥ H_{min} (Table 11), go to Step 2 because the hydraulic head 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 method (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 hydraulic head. Depending on the score of the subsequent analysis, it will be possible to decide whether or not to return to the site for measurements under other hydrological conditions.*

Caution. For fish jumping over small waterfalls, 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 and make forward progress. The narrower the crest of the weir, the easier it is for the fish to attain the upstream reach. In cases where the head-drop DH is close to DH_{min} and the thickness of the weir crest is not greater than the average length Lp_{avg} of the fish, the minimum hydraulic head H_{min} criterion may be neglected and the user may proceed directly to Step 2.

2. 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} (Table 10), then conditions are sufficient. Go to Step 3.

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

3. Jumping species

If the species in question are jumpers (Table 11), go to Step 5.

Otherwise, go to Step 4.

4. Type of flow

If DH ≤ 0.5 H, the flow may be considered a skimming flow. Go to Step 5.

If 0.5 H < DH ≤ H, the flow may be considered a virtual skimming flow. The structure will impact the species in question. The ICE passability class may not exceed 0.66. Go to Step 5 and select the ICE class indicated in Table 11 if it is less than or equal to 0.66, otherwise the ICE class is 0.66.

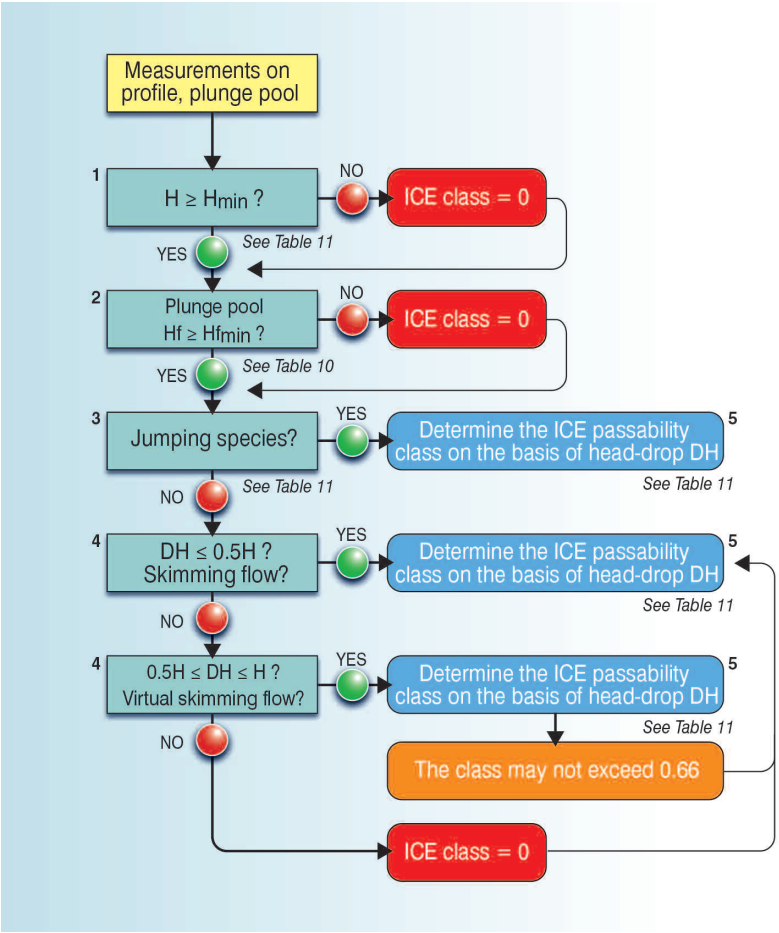
If DH > H, the flow is a plunging jet and the obstacle may be considered a total barrier in the sense of the ICE method (ICE class = 0).

N.B. *If the flow is near the transition points between plunging, virtual-skimming and skimming flows, it may be worthwhile to continue the assessment and, in Step 5, 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 score of the subsequent analysis, it will be possible to decide whether or not to return to the site for measurements under other hydrological conditions.*

5. Analysis of the head-drop

On the basis of the head-drop DH, use Table 11 to determine the ICE passability class of the structure.

Figure 33



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

Weirs with inclined downstream faces
(slope ≤ 150%)

Weirs with an inclined glacis may enable fish to overcome the obstacle by swimming.

Passability depends on the flow characteristics on the glacis (water depths, flow 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, the roughness of the glacis surface and the unit discharge q, i.e. the discharge per meter width.

The flow velocity on a glacis increases during the descent until the flow becomes uniform, at which point the water depth remains more or less constant over the entire glacis (Figure 34). The distance required for the flow to become uniform increases with the unit discharge (discharge per meter width, q) and decreases with the roughness of the underlying surface.

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) during the development of the ICE method for continental France (Baudoin *et al.*, 2014).

The modelling was carried out for a weir with a total head-drop of five metres (Figure 35), 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 (a 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);
- **the unit discharge (the discharge per meter width).** Seven unit discharges were tested, 0.125, 0.25, 0.5, 0.75, 1.0, 1.5 and 2.0 m³/s/m.

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, with respect to the distance from the crest (or the fall).

At the end of the hydraulic modelling, approximately 50 graphs had been produced (see the three examples in Figure 36).

The graphs reveal:

- an acceleration in the velocity starting at the crest until a certain distance at which the flow becomes uniform (constant flow velocities and water depths);
- that the maximum velocity increases with the unit discharge;
- that 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 36, 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.

■ 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:

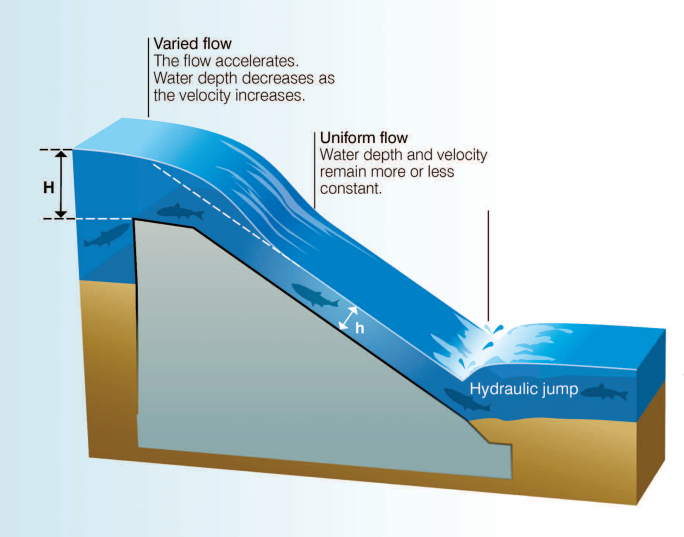
$$dt = \frac{dx}{(U\,\max - V(x))}$$

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

$$t(D) = \int_0^D \frac{dx}{(U\max - V(x))}$$

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.

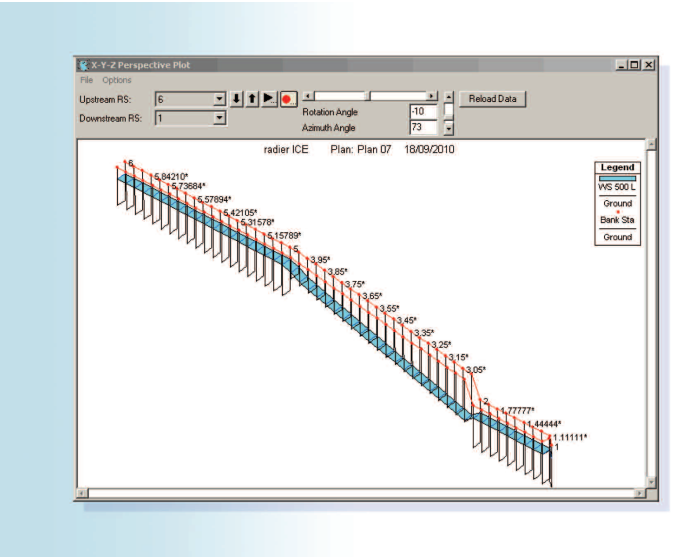
Figure 34



© Graphies for OFB

Changes in flow conditions along an inclined glacis. After Baudoin et al.*, 2014.*

Figure 35



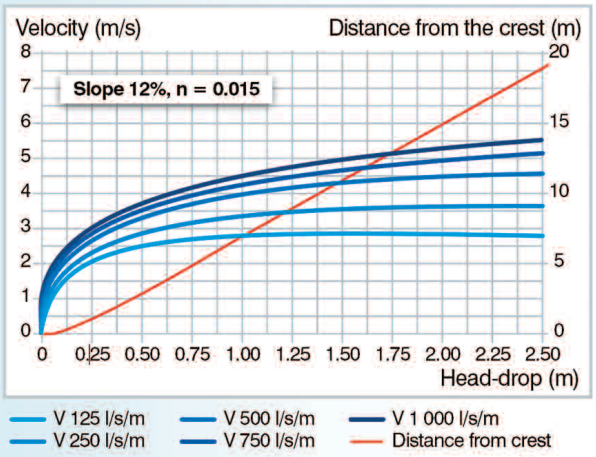
Graphic presentation of hydraulic modelling using the HEC RAS software. After Baudoin et al.*, 2014.*

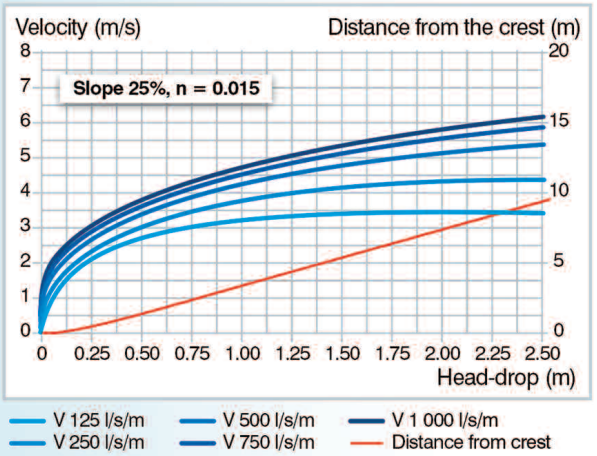
In this manner, on the basis of the hydraulic conditions obtained by modelling a given weir at a given unit discharge, it is possible to calculate the distance that can be overcome by a fish endowed with a maximum swimming speed U_{max} and an endurance t.

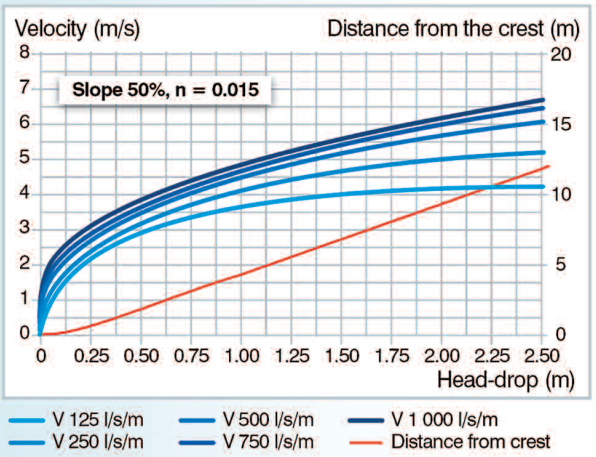
The results are presented as graphs indicating the head-drops and the distances that can be overcome by fish having maximum swimming speeds between 2 m/s and 7 m/s, as a function of their endurance at U_{max}.

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 coefficients n 0.01 to n 0.06), representing a total of approximately 300 graphs similar to that in Figure 37 and 3 000 endurance/head-drop combinations that fish can overcome.

Figure 36







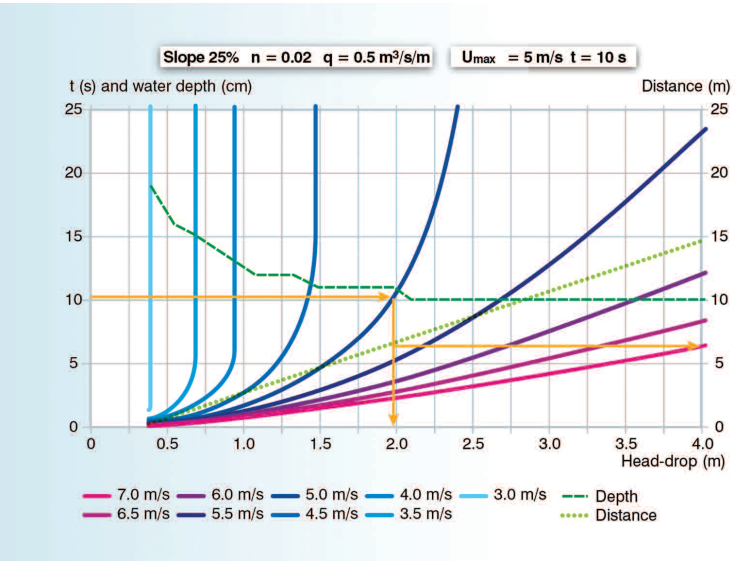
Graphs showing the relation between flow velocity, head-drop and distance from the weir crest as a function of the unit discharge (125 l/s/m to 1 000 l/s/m), the slope (12%, 25% and 50%) and the roughness of the glacis surface (Manning coefficient n = 0.015). After Baudoin et al., *2014.*

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 to swim.

The graph shown in Figure 37 presents the results for a 25% slope, a roughness coefficient n = 0.02 and a unit discharge q = 0.5 m³/s/m.

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 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.

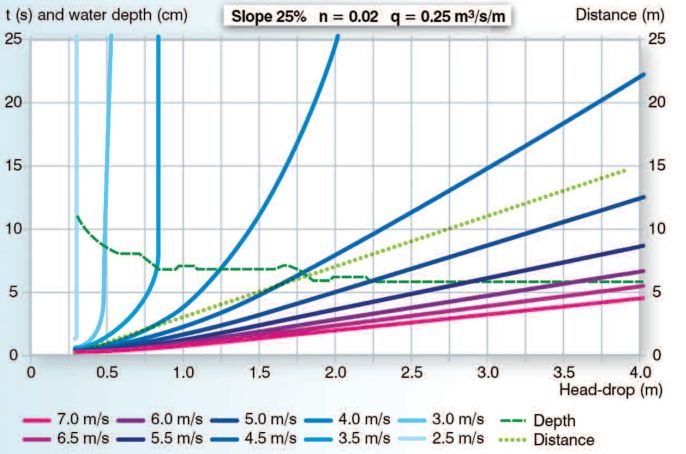
Figure 37

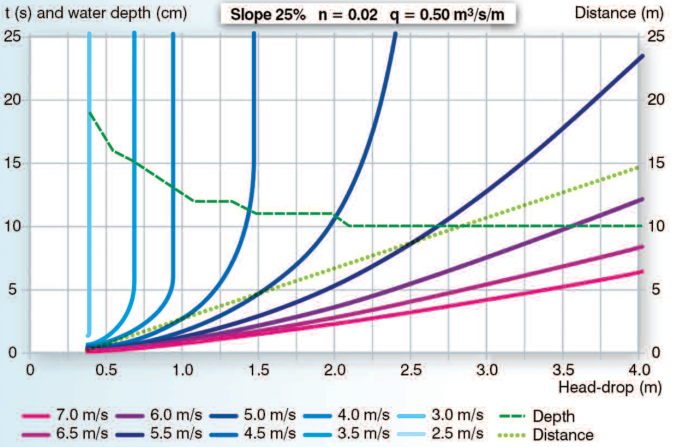


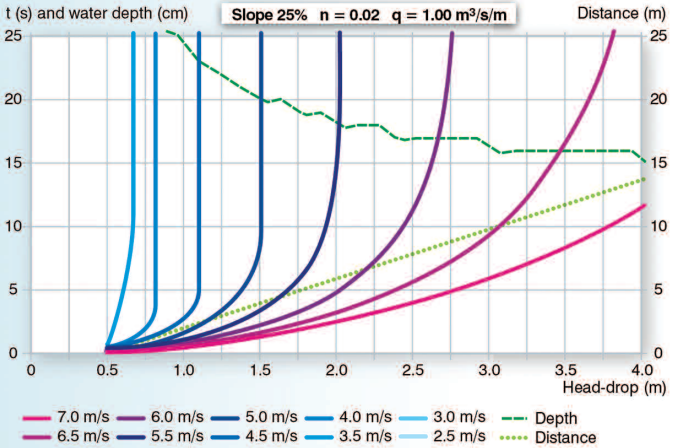
Relation between the passable head-drop (for a swimming fish), maximum swimming speed and endurance, given a slope of 25%, roughness n = 0.02 and unit discharge q = 0.5 m³/s/m. After Baudoin et al.*, 2014.*

The graphs shown in Figures 38, 39 and 40 show the influence of the unit discharge, the slope and the roughness of the glacis on the head-drops and distances that can be overcome by fish when swimming.

Figure 38

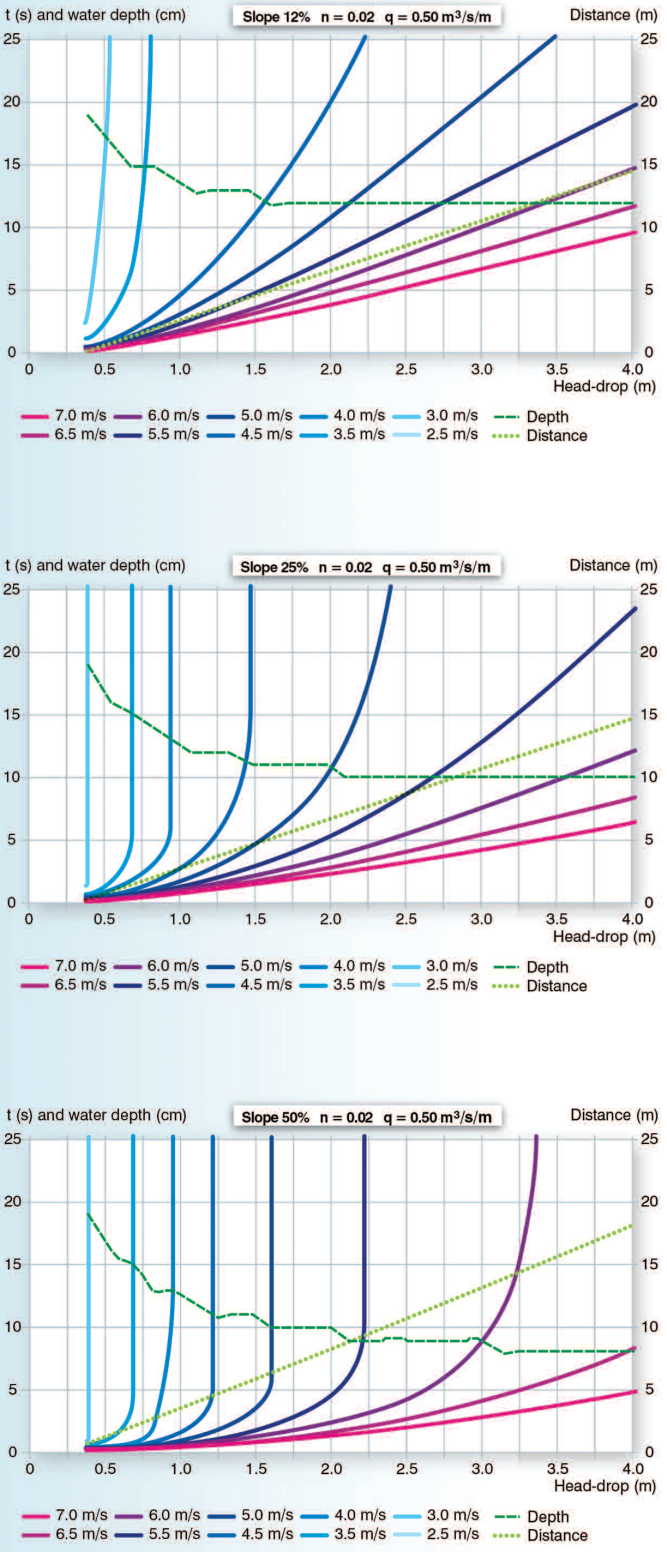






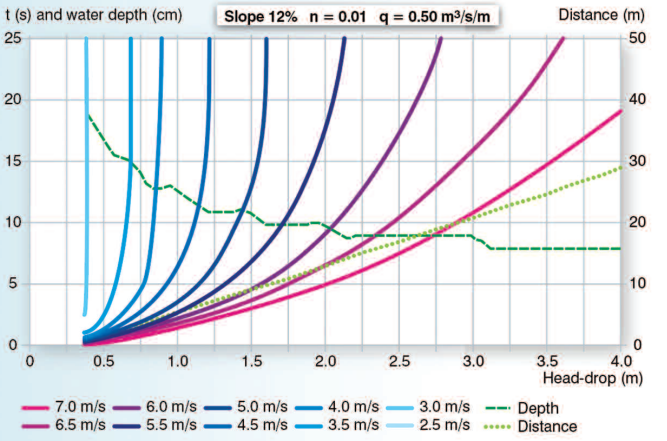
Passable head-drop (swimming) as a function of the maximum swimming speed U_{max} and the endurance t, on a glacis having a slope of 25% and roughness n = 0.02. The three graphs correspond to three different unit discharges (q = 0.25 m³/s/m, q = 0.5 m³/s/m and q = 1.0 m³/s/m). After Baudoin et al.*, 2014.*

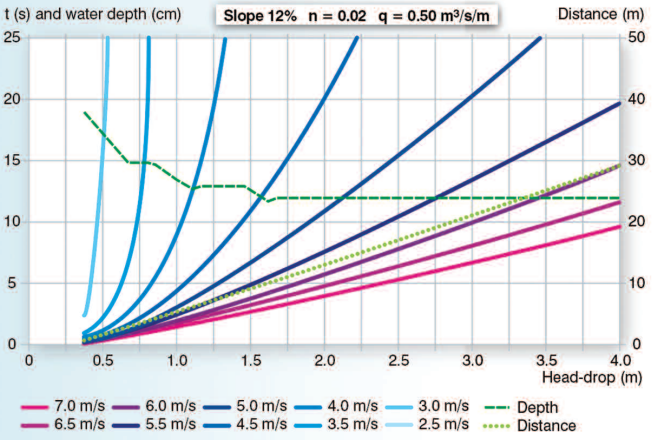
Figure 39

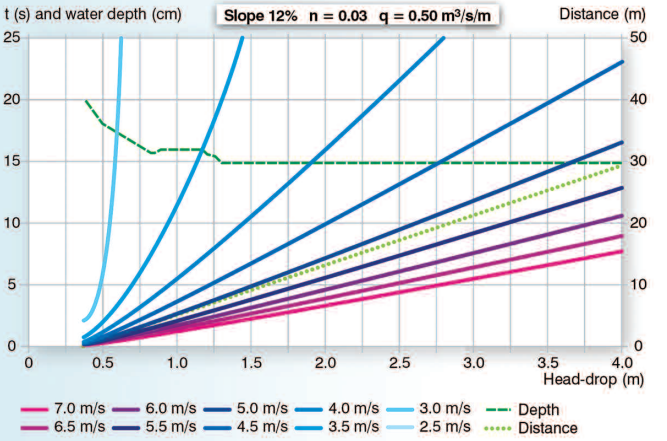


Passable head-drop (swimming) as a function of the maximum swimming speed U_{max} and the endurance t, for a unit discharge q = 0.5 m³/s/m. The three graphs correspond to three different slopes (12%, 25% and 50%) with a constant roughness n = 0.02. After Baudoin et al., *2014.*

Figure 40







Passable head-drop (swimming) as a function of the maximum swimming speed U_{max} and the endurance t, for a discharge q = 0.5 m³/s/m and a constant slope of 12%. The three graphs correspond to three different roughness values (n = 0.01, n = 0.02 and n = 0.03). After Baudoin et al., *2014.*

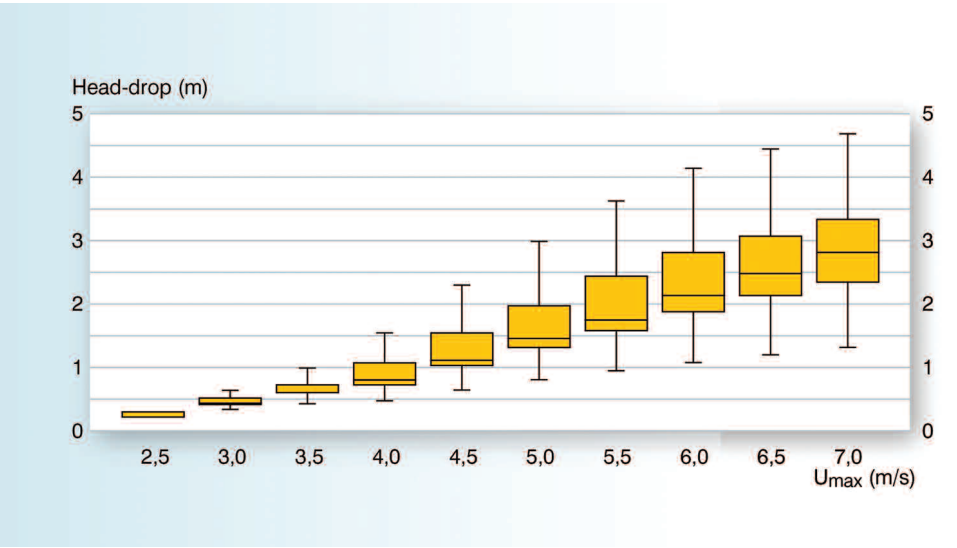
■ Statistical analysis of results

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, fish endurance values between 10 and 20 seconds were used (values that are generally linked to the U_{max} values of fish of all species, see the previous sections).

Figures 38 to 40 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 41 uses boxplots to show the passable head-drops as a function of the maximum swimming speed U_{max} of the fish (where the endurance is between 10 and 20 seconds), taking into account all the other tested parameters (slope, unit discharge, roughness).

Figure 41



Passable head-drops as a function of the maximum swimming speed U_{max} of the fish (where the endurance is between 10 and 20 seconds), whatever the values of the other tested parameters (slope, unit discharge, roughness). After Baudoin et al.*, 2014.*

■ 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 species or groups of species (swimming speeds for the selected length 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 body lengths 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 length Lp_{min} in the given subgroup, 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} lengths in the given subgroup, 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} lengths in the given subgroup, 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 length Lp_{max} in the given subgroup, the obstacle is considered a **total barrier (ICE class = 0)**.

Steps in the weir profile

A step is a break in the downstream face constituting a rupture in the longitudinal profile of the weir (Figures 42 and 43).

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 42

a © B. Voegtlé (Ecogea)
b © P. Valade (Ocea Consult')

Examples of steps in inclined downstream faces.
(a) Example of a weir with a step (Boungoumouhé River, Mayotte), (b) Example of a weir with a step (Blanche River, Martinique).

A step can cause two types of flow (Figure 43):

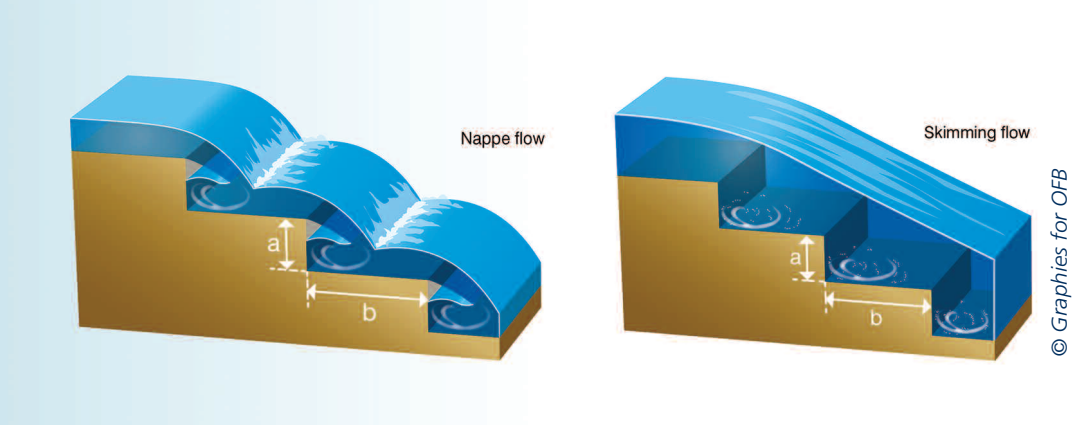
- **a nappe flow,** where the sheet of water falls over the crest of the step, resulting in a hydraulic jump;
- **a skimming flow,** where the discharge is sufficient to "erase" the step.

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 44 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.

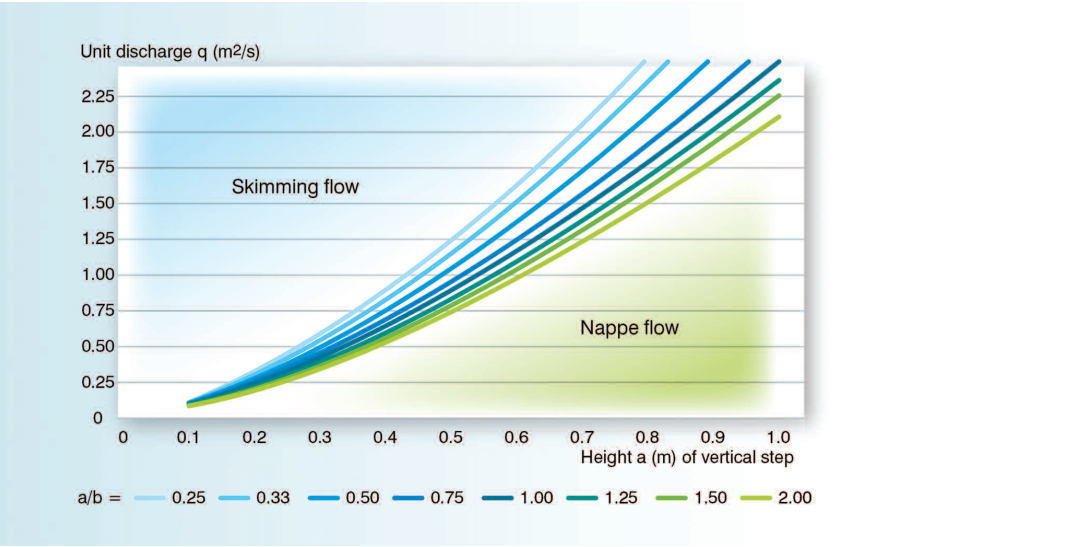
Figure 43



© Graphies for OFB

Nappe flow (with hydraulic jump) and skimming flow over weirs with steps. After Baudoin et al.*, 2014.*

Figure 44



Transition from a nappe flow (with hydraulic jump) to a skimming flow as a function of the unit discharge and step characteristics. After Yasuda and Ohtsu, 1999, modified by Baudoin et al.*, 2014.*

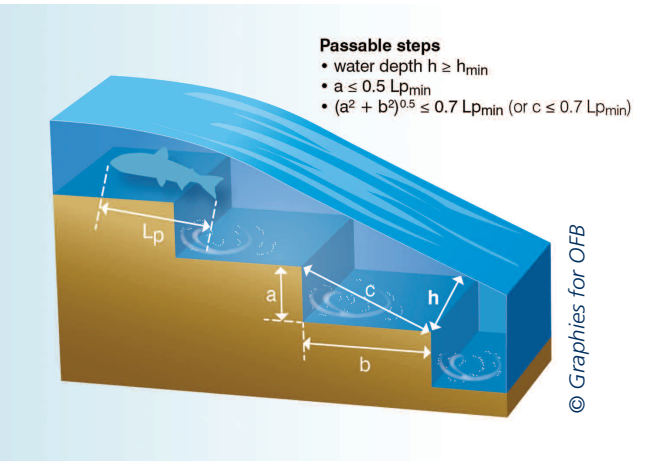
It is thought that fish can clear a step only by swimming and only if the following conditions are met (Figure 45):

- **a skimming flow exists** (the step is "erased");
- **the fish is long enough** (Lp of the species or subgroup) **compared to the size of the step.** It is necessary to check that the following conditions prevail:

$$a \leq 0.5\ Lp \text{ and } (a^2 + b^2)^{0.5} \leq 0.7\ Lp \text{ (or } c \leq 0.7\ Lp)$$

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 45



Necessary conditions for fish to overcome a step. After Baudoin et al.*, 2014.*

N.B. The position of the step on the glacis can influence passage in different manners, depending on the discharge flowing over the obstacle. For example, 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 method, 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 150%.

In cases where the water depth over the step is greater than twice the height of the step (h ≥ 2a), the step may be considered negligible and need not be taken into account in the passability analysis.

Downstream waterfall

Weirs with inclined downstream faces often have a waterfall at the downstream end that can reduce the passability of the structure (Figures 46 and 47).

The downstream waterfall must be analysed in the same manner as a vertical or subvertical 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 waterfall as shown in Table 12, using the same method as that developed for complex or mixed structures (see the section on complex structures).

Figure 46

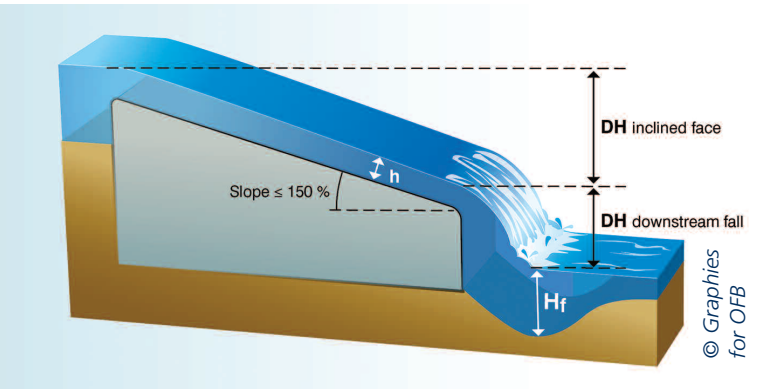


Diagram showing an inclined weir with a downstream waterfall. After Baudoin et al.*, 2014.*

Figure 47

a © B. Voegtlé (Ecogea)
b © P. Valade (Ocea Consult')

Flow over an inclined downstream face with a downstream waterfall.
(a) Goyaves Grande River (Guadeloupe), (b) Moala ford on the Ourovéni River (Mayotte).

Table 12

Table showing the overall ICE passability class for inclined weirs with a downstream waterfall. After Baudoin et al.*, 2014.*

		ICE class of the downstream waterfall			
		0	0.33	0.66	1
ICE class of the inclined section	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 in the decision tree

Table 13 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).

Table 14 lists, for the various species and subgroups, the threshold values used to determine the passability of an inclined weir (slope ≤ 150%) and notably the step sizes, water depths and head-drops corresponding to the various passability classes.

These tables are accompanied by a decision tree (Figure 48) showing how the ICE passability classes are determined.

Table 13

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

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

Table 14 *Threshold values used to determine ICE passability classes for inclined weirs (slope ≤ 150% (56°)).*

ICE group	Family	Species	Name in English (E) and in Creole (C)	FOT			
				Guadeloupe	Martinique	Mayotte	Réunion
1a	Eleotridae + Gobiidae except Sicydiinae	*Awaous banana*	River goby (E) / jolpot, loche (C)	X	X		
		Awaous commersoni	Commerson's freshwater goby, river goby (E) / loche, cabot (C)			X	X
		Butis butis	Crazy fish, crimson-tipped flathead-sleeper, duckbill sleeper (E)			X	X
		Ctenogobius pseudofasciatus	Slashcheek goby (E)		X		
		Dormitator maculatus	Fat sleeper (E) / ti-nèg, dormeur (C)	X	X		
		Eleotris amblyopsis	Large-scaled spiny-cheek sleeper (E) / pitit dormè (C)	X			
		Eleotris klunzingerii	Brown sleeper, dusky sleeper (E) / cabot noir (C)			X	X
		Eleotris mauritiana	Widehead sleeper (E) / cabot noir (C)			X	X
		Eleotris perniger	Small-scaled spiny-cheek sleeper (E) / pitit dormè, flèche (C)	X	X		
		Glossogobius callidus	Tank goby (E)			X	
		Glossogobius giurus	Tank goby (E) / loche (C)			X	X
		Glossogobius kokius	- (E) / loche, cabot (C)				X
1b		*Gobiomorus dormitor*	Bigmouth sleeper (E) / grand dormeur, dormeur (C)	X	X		
		Guavina guavina	Guavina (E) / dormeur (C)		X		
		Hypseleotris cyprinoides	Tropical carp-gudgeon (E)			X	X
		Mugilogobius mertoni	Chequered mangrove goby, Merton's mangrove goby, meander goby (E) / gobi milet (C)			X	
		Ophieleotris cf *aporos*	Snakehead gudgeon (E)			X	
		Ophiocara porocephala	Northern mud gudgeon, spangled sleeper (E) / makanbale latet ron (C)			X	
		Redigobius balteatus	Rhinohorn goby (E)			X	
		Redigobius bikolanus	Bigmouth goby, speckled goby (E) / gobi tase (C)			X	
		Stenogobius polyzona	Chinestripe goby (E) / cabot rayé (C)			X	X
2a	Mugilidae	*Agonostomus catalai*	Comoro mullet (E)			X	
		Agonostomus monticola	Mountain mullet (E) / milet (C)	X	X		
2b		*Agonostomus telfairii*	Fairy mullet (E) / chitte (C)			X	X
2c	Kuhliidae	*Kuhlia rupestris*	Jungle perch, rock flagtail (E) / doule de roche, carpe (C)			X	X
2d		*Kuhlia sauvagii*	Rock flagtails (E) / doule de roche, carpe (C)			X	X
3a	Anguillidae	*Anguilla bengalensis*	Indian mottled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla bicolor bicolor	Indonesian shortfin eel (E) / z'amab, z'anguille (C)			X	X
3b		*Anguilla marmorata*	Giant mottled eel, marbled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla mossambica	African longfin eel (E) / z'amab, z'anguille (C)			X	X
3c		*Anguilla rostrata*	American eel (E) / z'anguille (C)	X	X		
4a	Gobiesocidae + Gobiidae Sicydiinae	*Cotylopus acutipinnis*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)				X
		Cotylopus rubripinnis	Goby (E)			X	
		Gobiesox nudus	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	X	X		
4b		*Sicydium plumieri*	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)			X	X

The values indicated for (sub)groups 1b, 3 and 4 correspond to the passability classes set when the analysis takes into account only the swimming capabilities of species. In cases where the obstacle includes a crawling, suction or climbing zone, the assessment must ***also*** *use the special tables for these passage techniques (see the relevant sections).*

ICE species group	Family	Stage and/or length	Jumping species and/or stage	Minimum water depth h_{min} required for swimming	Maximum step dimensions (m)		Threshold values for head-drops (DH) in diagnosing inclined weirs ≤ 150% (m)			
							ICE passability class			
					a_{max}	c_{max}	1	0.66	0.33	0
1a	Eleotridae + Gobiidae except Sicydiinae	Subadult / Adult (Lp > 40 mm)	No	0.05 m	0.10	0.10	≤ 0.15	]0.15 - 0.35]	]0.35 - 0.50]	> 0.50
1b		Juvenile (Lp < 40 mm)	No	0.01 m	0.02	0.02	-	≤ 0.10	]0.10 - 0.20]	> 0.20
2a	Mugilidae	Subadult / Adult (Lp > 100 mm)	Yes	0.05 m	0.10	0.15	≤ 0.40	]0.40 - 1.00]	]1.00 - 1.80]	> 1.80
2b		Juvenile (Lp < 100 mm)	Yes	0.05 m	0.02	0.05	≤ 0.20	]0.20 - 0.50]	]0.50 - 0.70]	> 0.70
2c	Kuhliidae	Subadult / Adult (Lp > 100 mm)	Yes	0.10 m	0.10	0.20	≤ 0.30	]0.30 - 0.90]	]0.90 - 1.60]	> 1.60
2d		Juvenile (Lp < 100 mm)	Yes	0.05 m	0.02	0.05	≤ 0.10	]0.10 - 0.35]	]0.35 - 0.50]	> 0.50
3a	Anguillidae	Lp > 500 mm	No	0.05 m	0.40	0.70	≤ 0.50	]0.50 - 0.70]	]0.70 - 0.90]	> 0.90
3b		100 mm < Lp < 500 mm	No	0.02 m	0.10	0.20	≤ 0.20	]0.20 - 0.35]	]0.35 - 0.50]	> 0.50
3c		Lp < 100 mm	No	-	-	-	-	-	-	-
4a	Gobiesocidae + Gobiidae Sicydiinae	Subadult / Adult (Lp > 40 mm)	No	0.05 m	0.05	0.10	≤ 0.20	]0.20 - 0.60]	]0.60 - 1.40]	> 1.40
4b		Juvenile (Lp < 40 mm)	No	0.01 m	0.02	0.02	-	≤ 0.10	]0.10 - 0.20]	> 0.20

■ Decision tree

The steps in determining the ICE passability class, by swimming, of an inclined weir are presented below.

1. Analysis of the downstream waterfall, if it exists

If a waterfall does not exist, go to Step 2.

If a waterfall exists (slope > 150%) at the downstream end of the glacis, it is necessary to determine the passability of the waterfall using the assessment presented in the section on vertical and subvertical obstacles (start at Step 3 "*Jumping species*" in the decision tree).

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

If the obstacle is not a total barrier, then go on to Step 2.

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

If there is a downstream waterfall 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.

The depth must be sufficient, i.e. comply with the criteria for vertical waterfalls (see Step 2 in the decision tree for vertical and subvertical obstacles (slope > 150%)), taking into account the height of the downstream waterfall ($DH_{downstream\ fall}$). If $Hf \geq Hf_{min}$ (Table 10), the depth is sufficient. Go to Step 3. If $Hf < Hf_{min}$, the obstacle may be considered a total barrier (ICE class = 0).

If there is not a downstream waterfall 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 13 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 $Hf \geq Hf_{min}$ (Table 13), the depth is sufficient. Go to Step 3. If $Hf < Hf_{min}$, the obstacle may be considered a total barrier (ICE class = 0).

3. Analysis of the water depth on the glacis

If $h \geq h_{min}$ (Table 14), the water depth is sufficient. Go to Step 4.

If $h < h_{min}$, under the given hydrological conditions, the obstacle may be considered a total barrier in the sense of the ICE method (ICE class = 0). *However, the analysis should be pursued (go to Step 4) 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 site for measurements under other hydrological conditions.*

4. Analysis of steps on the inclined downstream face

If there are no steps or if the steps are negligible ($h \geq 2a$), go directly to Step 5.

If either dimension (a or c) of a single step exceeds the maximum values a_{max} and c_{max} listed in Table 14, 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 (a_{max} and c_{max}, Table 14), go to Step 5.

5. Analysis of the head-drop 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 waterfall), use Table 14 to determine the ICE passability class of the downstream face.

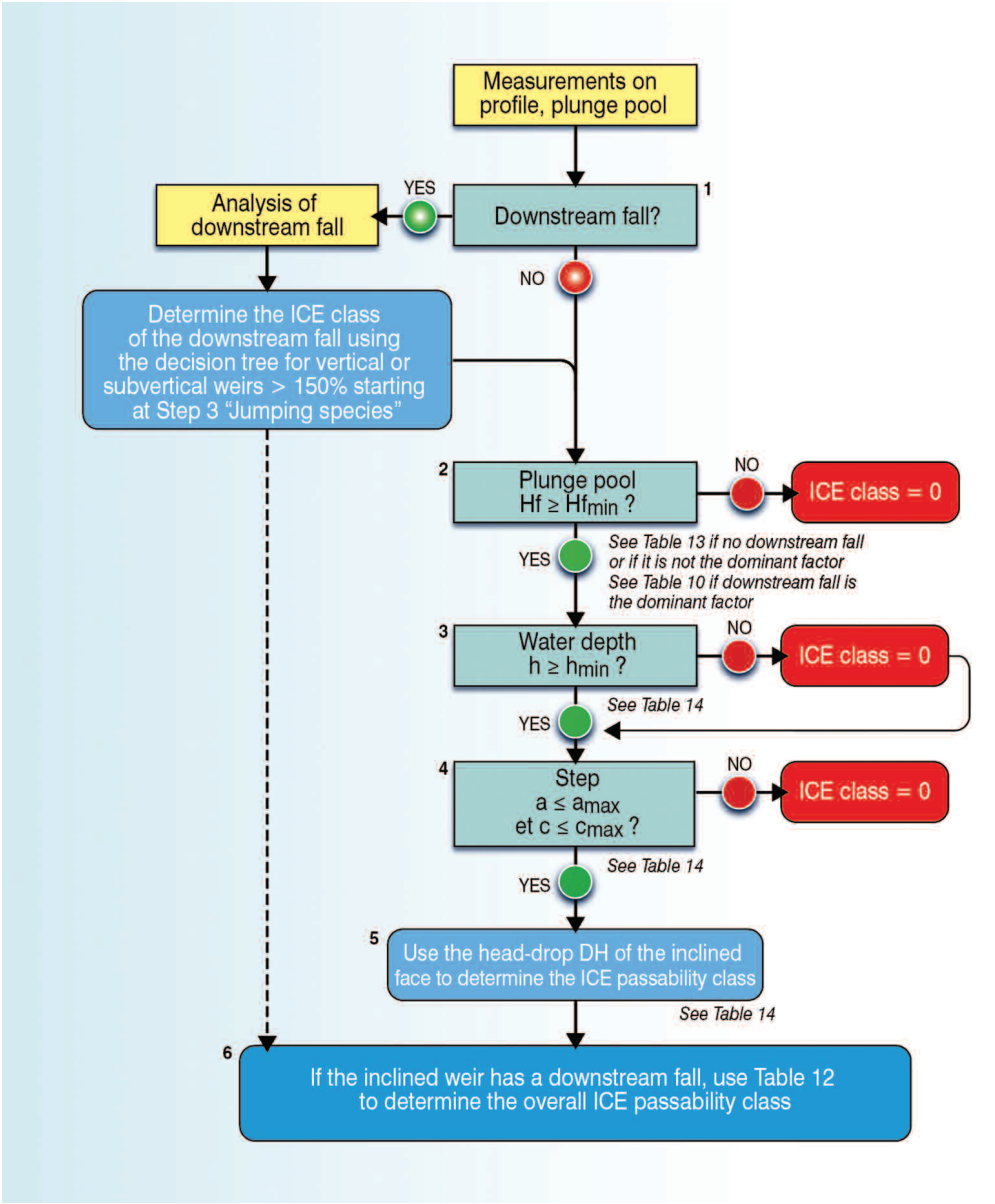
Go to Step 6.

6. Analysis of the overall passability of the structure

If the inclined weir has a downstream waterfall, use Table 12 to determine the overall ICE passability class.

If the inclined weir does not have a downstream waterfall, the overall ICE passability class is that resulting from Step 5.

Figure 48



Decision tree to determine ICE passability classes for swimming and jumping fish confronted with an inclined weir (slope ≤ 150% (56°)).

Rock weirs, a special case

General

In the French overseas territories, numerous configurations of rock weirs may be observed with head-drops ranging from less than 1 metre to several metres (Figure 49).

Depending on the physical and hydraulic configuration of each site, the rocks may be positioned according to different types of layout. A 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.

Depending on the situation, the rocks may be free standing or joined using concrete or tar.

Figure 49

a © P. Valade (Ocea Consult'), b, c, d © B. Voegtlé (Ecogea)

Examples of rock weirs in the French insular, overseas territories.
(a) Rock weir downstream of an abstraction weir (Bras des Lianes River, Réunion), (b) Stabilisation weir with joined rocks (Galets River, Réunion), (c) Rock weir designed to be passable for certain species with a pool-type fish pass (town of Grand'Rivière, Martinique), (d) Flow over natural rocks that is comparable to a rock weir (Mayotte).

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 entire glacis. The rougher the surface and the lower the unit discharge (q), the shorter the distance to create uniform conditions. The distance is approximately 3 to 4 metres for unit discharges of 1 to 2 $m^3/s/m$.

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.

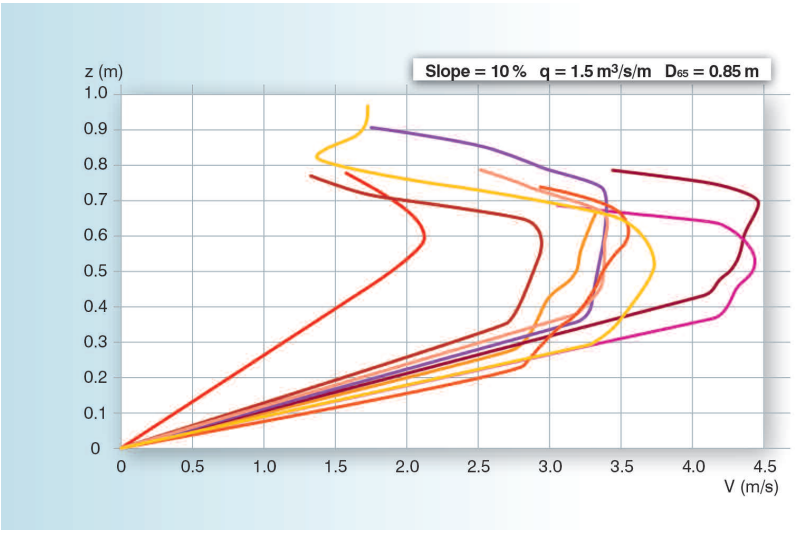
The flow conditions (water depths, flow velocities, types of flow) are determined by the slope of the glacis, the length of the glacis (or the head-drop), the unit discharge and the surface roughness, which itself depends on the size and shape of the rocks, their layout and whether or not they are joined.

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

In addition, contrary to standard weirs (see the section on weirs with inclined downstream faces (slope ≤ 150%)), the size of the rocks makes it impossible to model the flow conditions. The rocks are impediments to flow with dimensions similar to (or even greater than) the depth of the water, particularly under the hydrological conditions that generally prevail during the migratory periods of fish.

Figure 50 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 D_{65} = 0.85 m (Larinier *et al.*, 2006). The measurements at several points in the water column in a uniform section 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 water column.

Figure 50



Example of velocity profiles on a rock chute made up of joined rocks (D_{65} = 0.85 m) with a slope of 10%. After Larinier et al.*, 2006.*

For a given size of fish within a species or group of species, the passability of a rock weir depends on the flow velocities, water depths (between and/or above the rocks), the "hydraulic quality" of the sheet of water (no hydraulic jumps, no air gaps, etc.) and the distance to be covered (Figure 51).

Two factors limit passability:

- under low unit-discharge (q) conditions, 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 51).

Figure 51

a, b © M. Larinier (Pôle Ecohydraulique)

Flows over rock weirs vary in quality.
(a) Flow over a weir with the rocks joined by concrete, on a 12% slope. Fish can pass fairly easily along the edges where the flow is slower and via the spaces between rocks forming small basin, (b) Flow over a rock weir with a slope greater than 20%. The presence of multiple hydraulic jumps and waterfalls, without plunge pool between the rocks, may constitute obstacles blocking the passage of fish.

A difficult diagnosis

Assessing the passability of rock weirs is much more difficult than "standard" weirs due to the complexity and variability of the 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 (average values that, in most cases, would not apply to local hydraulic conditions and would not be of use in precisely assessing the passability of a structure).

Physical modelling in a laboratory may be possible, but is generally very complex given the difficulty of creating an accurate scale model capable of reproducing the actual hydraulic conditions 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 method.

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.

Passability criteria and classes

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

For the ICE method, 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 continental 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 fin.

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 obstacle zones (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, similar to that employed for the ICE method for continental France, 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 minimum values for water depth over rock weirs $h_{min\ rock}$ are indicated in Table 15.

Table 15 *Minimum water depth ($h_{min\ rock}$) enabling passage of rock weirs by swimming, as a function of the average slope of the weir. Modified after Baudoin* et al., *2014.*

Average slope	≤ 5%	]5% - 7%]	]7% - 9%]	]9% - 11%]	]11% - 13%]	]13% - 15%]
$h_{min\ rock}$ (cm)	10	15	20	25	30	40

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

■ 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), on the maximum swimming speeds of the species and on its endurance at those speeds.

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:

$$\frac{V_m}{\sqrt{g.h_m.l}} = 2.21.ln\left(\frac{h_m}{d_{84}}\right) + 6.00$$

where:

V_m: average flow velocity (m/s)

h_m: water depth (m)

d_{84}: diameter not exceeded by 84% of rocks in the weir (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.

However, similar to the values selected for minimum water depths required for passage, the hydraulic conditions determining 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 maximise the passage of 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 (Figure 52).

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

Figure 52

© B. Voegtlé (Ecogea)

A rock weir with a step.
The flow over the natural rocks is comparable to that for a rock weir and the vertical drop at the crest is comparable to a step (Mayotte).

N.B. Some obstacles may be seen either as rock weirs with a large step at the crest (e.g. Figure 52) 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, the presence of **a deep plunge pool is not indispensable.**

Determining passability classes

■ Threshold values used in the decision tree

Tables 16 and 17 indicate the head-drop threshold values determining 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 16 and those for average slopes > 9% are shown in Table 17.

The tables also indicate the maximum height and length (a_{max} et c_{max}) of steps if they exist.

Table 15 (above) provides the necessary minimum water depth ($h_{min\ rock}$) that must be checked.

These tables are accompanied by a decision tree (Figure 53) showing how the ICE passability classes are determined.

Table 16 *Threshold values used to determine ICE passability classes for rock weirs (average slope ≤ 9%).*

ICE group	Family	Species	Name in English (E) and in Creole (C)	FOT			
				Guadeloupe	Martinique	Mayotte	Réunion
1a	Eleotridae + Gobiidae except Sicydiinae	*Awaous banana*	River goby (E) / jolpot, loche (C)	X	X		
		Awaous commersoni	Commerson's freshwater goby, river goby (E) / loche, cabot (C)			X	X
		Butis butis	Crazy fish, crimson-tipped flathead-sleeper, duckbill sleeper (E)			X	X
		Ctenogobius pseudofasciatus	Slashcheek goby (E)		X		
		Dormitator maculatus	Fat sleeper (E) / ti-nèg, dormeur (C)	X	X		
		Eleotris amblyopsis	Large-scaled spiny-cheek sleeper (E) / pitit dormè (C)	X			
		Eleotris klunzingerii	Brown sleeper, dusky sleeper (E) / cabot noir (C)			X	X
		Eleotris mauritiana	Widehead sleeper (E) / cabot noir (C)			X	X
		Eleotris perniger	Small-scaled spiny-cheek sleeper (E) / pitit dormè, flèche (C)	X	X		
		Glossogobius callidus	Tank goby (E)			X	
		Glossogobius giurus	Tank goby (E) / loche (C)			X	X
		Glossogobius kokius	- (E) / loche, cabot (C)				X
1b		*Gobiomorus dormitor*	Bigmouth sleeper (E) / grand dormeur, dormeur (C)	X	X		
		Guavina guavina	Guavina (E) / dormeur (C)		X		
		Hypseleotris cyprinoides	Tropical carp-gudgeon (E)			X	X
		Mugilogobius mertoni	Chequered mangrove goby, Merton's mangrove goby, meander goby (E) / gobi milet (C)			X	
		Ophieleotris cf *aporos*	Snakehead gudgeon (E)			X	
		Ophiocara porocephala	Northern mud gudgeon, spangled sleeper (E) / makanbale latet ron (C)			X	
		Redigobius balteatus	Rhinohorn goby (E)			X	
		Redigobius bikolanus	Bigmouth goby, speckled goby (E) / gobi tase (C)			X	
		Stenogobius polyzona	Chinestripe goby (E) / cabot rayé (C)			X	X
2a	Mugilidae	*Agonostomus catalai*	Comoro mullet (E)			X	
		Agonostomus monticola	Mountain mullet (E) / milet (C)	X	X		
2b		*Agonostomus telfairii*	Fairy mullet (E) / chitte (C)			X	X
2c	Kuhliidae	*Kuhlia rupestris*	Jungle perch, rock flagtail (E) / doule de roche, carpe (C)			X	X
2d		*Kuhlia sauvagii*	Rock flagtails (E) / doule de roche, carpe (C)			X	X
3a	Anguillidae	*Anguilla bengalensis*	Indian mottled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla bicolor bicolor	Indonesian shortfin eel (E) / z'amab, z'anguille (C)			X	X
3b		*Anguilla marmorata*	Giant mottled eel, marbled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla mossambica	African longfin eel (E) / z'amab, z'anguille (C)			X	X
3c		*Anguilla rostrata*	American eel (E) / z'anguille (C)	X	X		
4a	Gobiesocidae + Gobiidae Sicydiinae	*Cotylopus acutipinnis*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)				X
		Cotylopus rubripinnis	Goby (E)			X	
		Gobiesox nudus	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	X	X		
		Sicydium plumieri	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
4b		*Sicydium punctatum*	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)			X	X

The values indicated for (sub)groups 1b, 3 and 4 correspond to the passability classes set when the analysis takes into account only the swimming capabilities of species. In cases where the obstacle includes a crawling, suction or climbing zone, the assessment must ***also*** *use the special tables for these passage techniques (see the relevant sections).*

ICE species group	Stage and/or length	Maximum step dimensions (m)		Head-drop (DH) threshold values (m) for diagnosing rock weirs											
				Slope ≤ 5%				5% < Slope ≤ 7%				7% < Slope ≤ 9%			
				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
1a	Subadult / Adult (Lp > 40 mm)	0.10	0.10	∞	-	-	-	≤ 0.4	]0.4 - 1.5]	> 1.5	-	-	≤ 0.7	]0.7 - 1.8]	> 1.8
1b	Juvenile (Lp < 40 mm)	0.02	0.02	-	≤ 0.4	> 0.4	-	-	-	≤ 0.4	> 0.4	-	-	-	> 0.0
2a	Subadult / Adult (Lp > 100 mm)	0.10	0.15	∞	-	-	-	∞	-	-	-	≤ 1.8	> 1.8	-	-
2b	Juvenile (Lp < 100 mm)	0.02	0.05	∞	-	-	-	≤ 1.0	]1.0 - 3.0]	> 3.0	-	≤ 0.5	]0.5 - 1.1]	]1.1 - 1.8]	> 1.8
2c	Subadult / Adult (Lp > 100 mm)	0.10	0.20	∞	-	-	-	∞	-	-	-	≤ 1.1	> 1.1	-	-
2d	Juvenile (Lp < 100 mm)	0.02	0.05	≤ 0.4	> 0.4	-	-	-	≤ 0.7	]0.7 - 3.0]	> 3.0	-	≤ 0.3	> 0.3	-
3a	Lp > 500 mm	0.40	0.70	∞	-	-	-	≤ 1.0	]1.0 - 3.0]	> 3.0	-	≤ 0.5	]0.5 - 1.1]	]1.1 - 1.8]	> 1.8
3b	100 mm < Lp < 500 mm	0.10	0.20	∞	-	-	-	≤ 0.4	]0.4 - 1.5]	> 1.5	-	-	≤ 0.7	]0.7 - 1.8]	> 1.8
3c	Lp < 100 mm	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4a	Subadult / Adult (Lp > 40 mm)	0.05	0.10	∞	-	-	-	≤ 1.0	> 1.0	-	-	≤ 0.5	]0.5 - 1.9]	> 1.9	-
4b	Juvenile (Lp < 40 mm)	0.02	0.02	-	≤ 0.4	> 0.4	-	-	-	≤ 0.4	> 0.4	-	-	-	> 0.0

Table 17 *Threshold values used to determine ICE passability classes for rock weirs (average slope > 9%).*

ICE group	Family	Species	Name in English (E) and in Creole (C)	FOT			
				Guadeloupe	Martinique	Mayotte	Réunion
1a	Eleotridae + Gobiidae except Sicydiinae	*Awaous banana*	River goby (E) / jolpot, loche (C)	X	X		
		Awaous commersoni	Commerson's freshwater goby, river goby (E) / loche, cabot (C)			X	X
		Butis butis	Crazy fish, crimson-tipped flathead-sleeper, duckbill sleeper (E)			X	X
		Ctenogobius pseudofasciatus	Slashcheek goby (E)		X		
		Dormitator maculatus	Fat sleeper (E) / ti-nèg, dormeur (C)	X	X		
		Eleotris amblyopsis	Large-scaled spiny-cheek sleeper (E) / pitit dormè (C)	X			
		Eleotris klunzingerii	Brown sleeper, dusky sleeper (E) / cabot noir (C)			X	X
		Eleotris mauritiana	Widehead sleeper (E) / cabot noir (C)			X	X
		Eleotris perniger	Small-scaled spiny-cheek sleeper (E) / pitit dormè, flèche (C)	X	X		
		Glossogobius callidus	Tank goby (E)			X	
		Glossogobius giurus	Tank goby (E) / loche (C)			X	X
		Glossogobius kokius	- (E) / loche, cabot (C)				X
1b		*Gobiomorus dormitor*	Bigmouth sleeper (E) / grand dormeur, dormeur (C)	X	X		
		Guavina guavina	Guavina (E) / dormeur (C)		X		
		Hypseleotris cyprinoides	Tropical carp-gudgeon (E)			X	X
		Mugilogobius mertoni	Chequered mangrove goby, Merton's mangrove goby, meander goby (E) / gobi milet (C)			X	
		Ophieleotris cf *aporos*	Snakehead gudgeon (E)			X	
		Ophiocara porocephala	Northern mud gudgeon, spangled sleeper (E) / makanbale latet ron (C)			X	
		Redigobius balteatus	Rhinohorn goby (E)			X	
		Redigobius bikolanus	Bigmouth goby, speckled goby (E) / gobi tase (C)			X	
		Stenogobius polyzona	Chinestripe goby (E) / cabot rayé (C)			X	X
2a	Mugilidae	*Agonostomus catalai*	Comoro mullet (E)			X	
		Agonostomus monticola	Mountain mullet (E) / milet (C)	X	X		
2b		*Agonostomus telfairii*	Fairy mullet (E) / chitte (C)			X	X
2c	Kuhliidae	*Kuhlia rupestris*	Jungle perch, rock flagtail (E) / doule de roche, carpe (C)			X	X
2d		*Kuhlia sauvagii*	Rock flagtails (E) / doule de roche, carpe (C)			X	X
3a	Anguillidae	*Anguilla bengalensis*	Indian mottled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla bicolor bicolor	Indonesian shortfin eel (E) / z'amab, z'anguille (C)			X	X
3b		*Anguilla marmorata*	Giant mottled eel, marbled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla mossambica	African longfin eel (E) / z'amab, z'anguille (C)			X	X
3c		*Anguilla rostrata*	American eel (E) / z'anguille (C)	X	X		
4a	Gobiesocidae + Gobiidae Sicydiinae	*Cotylopus acutipinnis*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)				X
		Cotylopus rubripinnis	Goby (E)			X	
		Gobiesox nudus	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	X	X		
4b		*Sicydium plumieri*	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)			X	X

The values indicated for (sub)groups 1b, 3 and 4 correspond to the passability classes set when the analysis takes into account only the swimming capabilities of species. In cases where the obstacle includes a crawling, suction or climbing zone, the assessment must ***also*** *use the special tables for these passage techniques (see the relevant sections).*

ICE species group	Stage and/or length	Maximum step dimensions (m)		Head-drop (DH) threshold values (m) for diagnosing 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
		a_{max}	c_{max}	1	0.66	0.33	0	1	0.66	0.33	0	1	0.66	0.33	0	0
1a	Subadult / Adult (Lp > 40 mm)	0.10	0.10	-	≤ 0.3	]0.3 - 1.0]	> 1.0	-	-	≤ 0.4	> 0.4	-	-	-	> 0.0	> 0.0
1b	Juvenile (Lp < 40 mm)	0.02	0.02	-	-	-	> 0.0	-	-	-	> 0.0	-	-	-	> 0.0	> 0.0
2a	Subadult / Adult (Lp > 100 mm)	0.10	0.15	≤ 1.0	]1.0 - 4.0]	> 4.0	-	≤ 0.5	]0.5 - 2.4]	> 2.4	-	-	≤ 0.9	]0.9 - 3.4]	> 3.4	> 0.0
2b	Juvenile (Lp < 100 mm)	0.02	0.05	-	≤ 0.5	]0.5 - 1.0]	> 1.0	-	-	≤ 0.4	> 0.4	-	-	-	> 0.0	> 0.0
2c	Subadult / Adult (Lp > 100 mm)	0.10	0.20	≤ 0.5	]0.5 - 3.2]	> 3.2	-	-	≤ 2.2	> 2.2	-	-	≤ 0.6	]0.6 - 3.3]	> 3.3	> 0.0
2d	Juvenile (Lp < 100 mm)	0.02	0.05	-	-	≤ 0.5	> 0.5	-	-	-	> 0.0	-	-	-	> 0.0	> 0.0
3a	Lp > 500 mm	0.40	0.70	-	≤ 0.5	]0.5 - 1.0]	> 1.0	-	-	≤ 0.4	> 0.4	-	-	-	> 0.0	> 0.0
3b	100 mm < Lp < 500 mm	0.10	0.20	-	≤ 0.3	]0.3 - 1.0]	> 1.0	-	-	≤ 0.4	> 0.4	-	-	-	> 0.0	> 0.0
3c	Lp < 100 mm	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
4a	Subadult / Adult (Lp > 40 mm)	0.05	0.10	-	≤ 1.4	]1.4 - 4.0]	> 4.0	-	≤ 0.6	]0.6 - 2.4]	> 2.4	-	-	≤ 0.9	> 0.9	> 0.0
4b	Juvenile (Lp < 40 mm)	0.02	0.02	-	-	-	> 0.0	-	-	-	> 0.0	-	-	-	> 0.0	> 0.0

■ Decision tree

The steps in determining the ICE passability class of a rock weir are presented below.

1. Analysis of the minimum water depth in the passageway

If a continuous passageway exists with a minimum water depth $h \geq h_{min\ rock}$ (Table 15), the depth is sufficient. Go to Step 2.

If a continuous passageway does not exist (the fish encounter sections where $h < h_{min\ rock}$), under the given hydrological conditions the obstacle may be considered a total barrier in the sense of the ICE method (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 site 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.

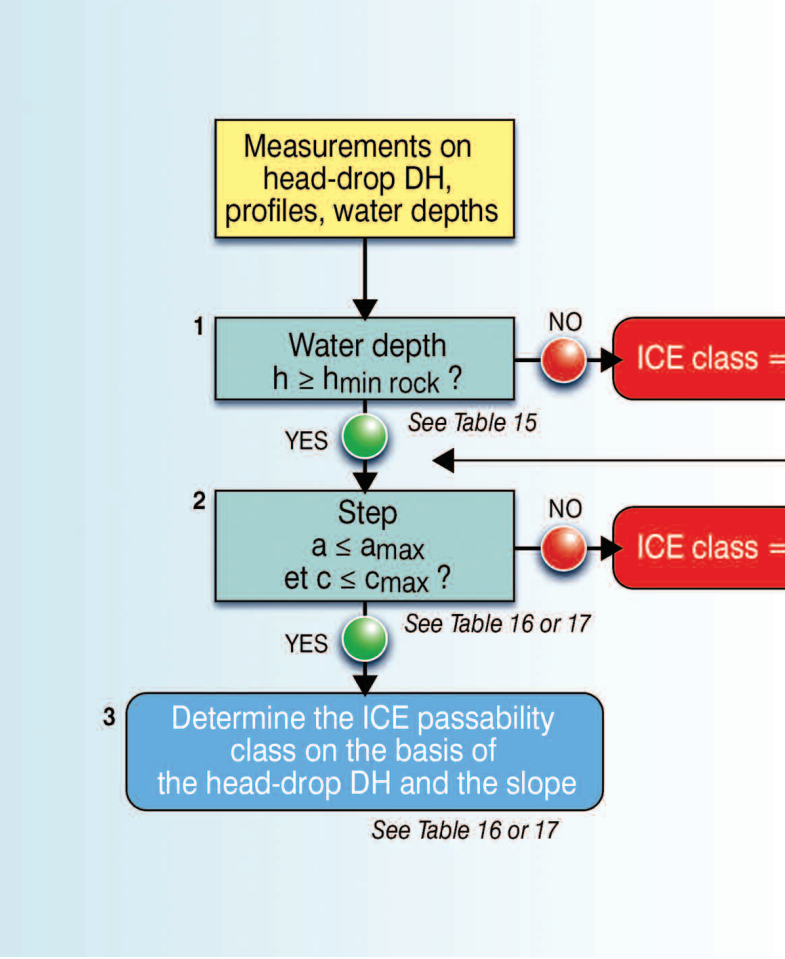
If either dimension (a or c) of a single step exceeds the maximum values a_{max} and c_{max} listed in Tables 16 and 17, the obstacle may be considered a total barrier (ICE class = 0).

If the dimensions (a and c) of all steps are lower than the threshold values (a_{max} and c_{max}, Tables 16 and 17), go to Step 3.

3. Analysis of the head-drop and of the slope

On the basis of the head-drop DH and the slope of the weir, use Table 16 and 17 to determine the ICE passability class of the structure.

Figure 53



Decision tree to determine ICE passability classes for fish swimming over rock weirs.

Moving parts of a structure

Overflows

The difficulty of passing gates or flap gates (Figure 54) is not significantly different than that of passing vertical or subvertical obstacles. **Consequently, the passability of flows over structures with moving parts should be assessed in the same manner** (see the section on vertical and subvertical obstacles with a slope > 150%).

In order to accurately determine the passability of the structure, knowledge on gate management is required (opening frequency, periods, etc.).

Figure 54

a, b © B. Voegtlé (Ecogea)

Flows over the moving parts (gates) of weirs.
(a) Flap gate on the Kwalé River (Mayotte), (b) Flap gate for water abstraction (Mayotte).

Underflows

Passability criteria

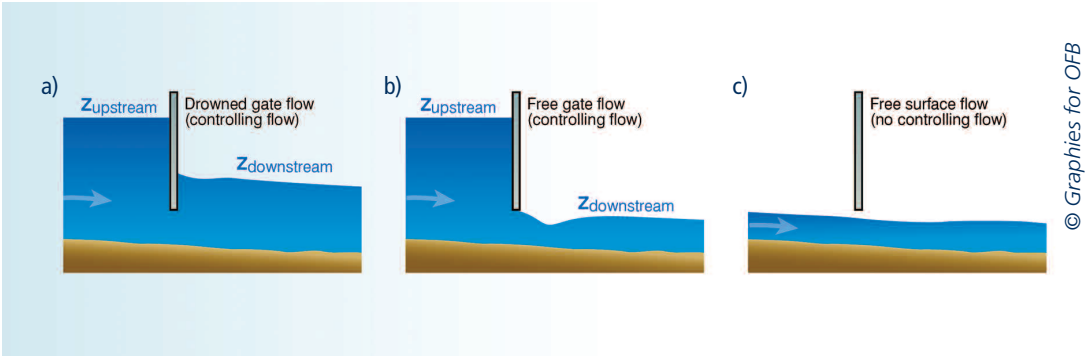
Even though this type of flow (i.e. under a lifted gate) is not frequent in the studied French insular, overseas territories, it is nonetheless worthwhile to acquire the data required to determine the passability of these gates by the various groups of species.

■ The different types of flows under gates

When there is a controlling flow behind the gate, the opening is completely submerged (filled) and the flow is comparable to that through an orifice (Figure 55a, b). The flow contracts and may be very fast.

When there is not a controlling flow behind the gate (Figure 55c) i.e. the water level upstream of the gate ($Z_{upstream}$) is lower than the underside of the gate, the flow is not accelerated as is the case for a gate with a controlling flow. **The result is a free-surface flow and the passability assessment is identical to that for an inclined weir.**

Figure 55



© Graphies for OFB

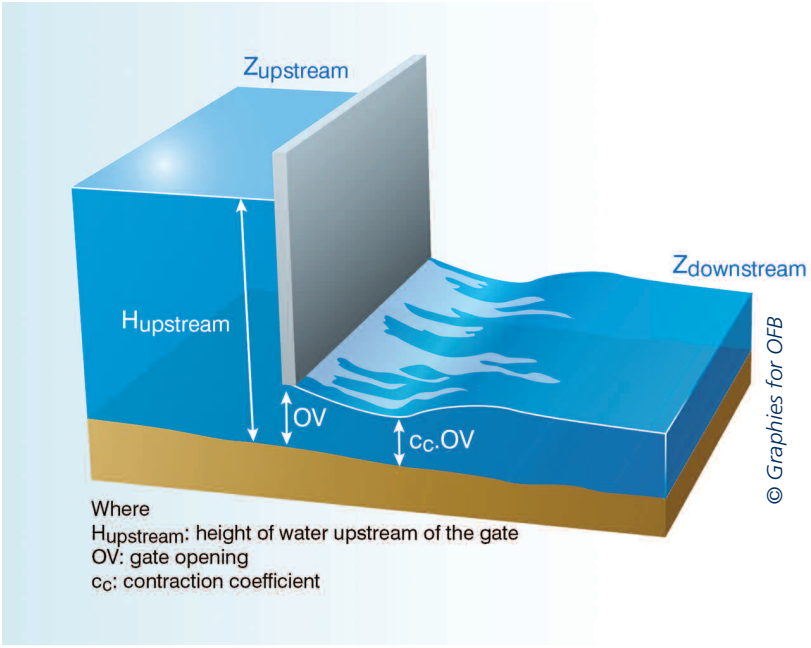
Diagrams of gates with and without controlling flows. After Baudoin et al.*, 2014.*

■ Drowned and free gate flows

Free gate flow

For a free gate flow (Figure 56), 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 (V_{max}) and may be roughly calculated as: $V_{upstream} = \sqrt{(2.g.H_{upstream})}$

Figure 56



© Graphies for OFB

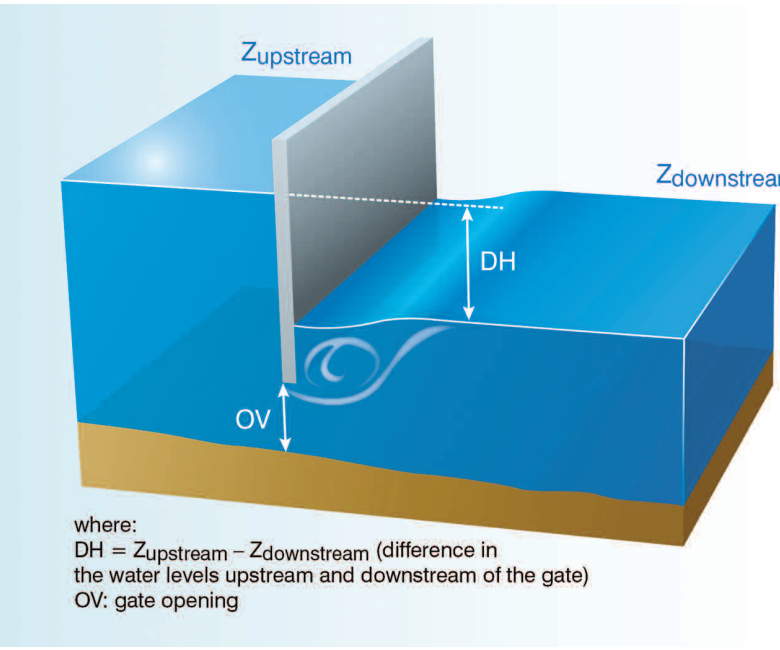
Parameters used to qualify a free gate flow. After Baudoin et al.*, 2014.*

For the ICE method, the maximum velocity V_{max} must be compared to the swimming capabilities of the given species or group of species.

Drowned gate flow

Conversely, **for a drowned gate flow** (Figure 57), 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 difference in the water levels upstream and downstream of the gate must be taken into account when assessing the flow conditions at the gate.

Figure 57



Parameters used to qualify a drowned gate flow. After Baudoin et al.*, 2014.*

The average velocity of the flow at the opening may be roughly calculated as $\sqrt{(2.g.DH)}$

■ 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 length class Lp_{min}, Lp_{avg} and Lp_{max}), it is possible to determine the ICE 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 flow velocities under a gate, other factors such as the thickness of the gate, its shape and the roughness of the glacis can also influence the hydraulic conditions.

As long as the depth of water in the contracted section and the gate opening are sufficient for the fish to pass, 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 length Lp_{min} for the given subgroup, 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 lengths for the given subgroup, 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 lengths for the given subgroup, 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 length Lp_{max} for the given subgroup, the obstacle may be considered a **total barrier (ICE class = 0)**.

Size of opening

The flow depth (notably in the contracted section) 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.

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 height of the gate opening (OV_{min}) corresponding to approximately two times the water depths (h_{min}) selected for the various species.** The water depth in the contracted section, though less great, will nonetheless remain within the h_{min} values set previously.

For Kuhliidae, *for example, the minimum gate opening OV_{min} is approximately 20 cm for the adults/subadults and approximately 10 cm for juveniles (Subgroup 2d).*

Determining passability classes

■ Threshold values used in the decision tree

Table 18 lists, for the various species, the threshold values used to determine the passability classes for passage under a gate or through an orifice.

The table is accompanied by a decision tree (Figure 58) showing how the ICE passability classes are determined.

Table 18 *Threshold values used to determine ICE passability classes for passage under gates or through bottom orifices.*

ICE group	Family	Species	Name in English (E) and in Creole (C)	FOT			
				Guadeloupe	Martinique	Mayotte	Réunion
1a	Eleotridae + Gobiidae except Sicydiinae	*Awaous banana*	River goby (E) / jolpot, loche (C)	X	X		
		Awaous commersoni	Commerson's freshwater goby, river goby (E) / loche, cabot (C)			X	X
		Butis butis	Crazy fish, crimson-tipped flathead-sleeper, duckbill sleeper (E)			X	X
		Ctenogobius pseudofasciatus	Slashcheek goby (E)		X		
		Dormitator maculatus	Fat sleeper (E) / ti-nèg, dormeur (C)	X	X		
		Eleotris amblyopsis	Large-scaled spiny-cheek sleeper (E) / pitit dormè (C)	X			
		Eleotris klunzingerii	Brown sleeper, dusky sleeper (E) / cabot noir (C)			X	X
		Eleotris mauritiana	Widehead sleeper (E) / cabot noir (C)			X	X
		Eleotris perniger	Small-scaled spiny-cheek sleeper (E) / pitit dormè, flèche (C)	X	X		
		Glossogobius callidus	Tank goby (E)			X	
		Glossogobius giurus	Tank goby (E) / loche (C)			X	X
		Glossogobius kokius	- (E) / loche, cabot (C)				X
1b		*Gobiomorus dormitor*	Bigmouth sleeper (E) / grand dormeur, dormeur (C)	X	X		
		Guavina guavina	Guavina (E) / dormeur (C)		X		
		Hypseleotris cyprinoides	Tropical carp-gudgeon (E)			X	X
		Mugilogobius mertoni	Chequered mangrove goby, Merton's mangrove goby, meander goby (E) / gobi milet (C)			X	
		Ophieleotris cf *aporos*	Snakehead gudgeon (E)			X	
		Ophiocara porocephala	Northern mud gudgeon, spangled sleeper (E) / makanbale latet ron (C)			X	
		Redigobius balteatus	Rhinohorn goby (E)			X	
		Redigobius bikolanus	Bigmouth goby, speckled goby (E) / gobi tase (C)			X	
		Stenogobius polyzona	Chinestripe goby (E) / cabot rayé (C)			X	X
2a	Mugilidae	*Agonostomus catalai*	Comoro mullet (E)			X	
		Agonostomus monticola	Mountain mullet (E) / milet (C)	X	X		
2b		*Agonostomus telfairii*	Fairy mullet (E) / chitte (C)			X	X
2c	Kuhliidae	*Kuhlia rupestris*	Jungle perch, rock flagtail (E) / doule de roche, carpe (C)			X	X
2d		*Kuhlia sauvagii*	Rock flagtails (E) / doule de roche, carpe (C)			X	X
3a	Anguillidae	*Anguilla bengalensis*	Indian mottled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla bicolor bicolor	Indonesian shortfin eel (E) / z'amab, z'anguille (C)			X	X
3b		*Anguilla marmorata*	Giant mottled eel, marbled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla mossambica	African longfin eel (E) / z'amab, z'anguille (C)			X	X
3c		*Anguilla rostrata*	American eel (E) / z'anguille (C)	X	X		
4a	Gobiesocidae + Gobiidae Sicydiinae	*Cotylopus acutipinnis*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)				X
		Cotylopus rubripinnis	Goby (E)			X	
		Gobiesox nudus	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	X	X		
4b		*Sicydium plumieri*	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)			X	X

The values indicated for (sub)groups 1b, 3 and 4 correspond to the passability classes set when the analysis takes into account only the swimming capabilities of species. In cases where the obstacle includes a crawling, suction or climbing zone, the assessment must ***also*** *use the special tables for these passage techniques (see the relevant sections).*

ICE species group	Stage and/or length	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)			
				ICE passability class			
				1	0.66	0.33	0
1a	Subadult / Adult (Lp > 40 mm)	0.05 m	0.10 m	≤ 0.10	]0.10 - 0.25]	]0.25 - 0.45]	> 0.45
1b	Juvenile (Lp < 40 mm)	0.01 m	0.02 m	-	≤ 0.05	]0.05 - 0.10]	> 0.10
2a	Subadult / Adult (Lp > 100 mm)	0.05 m	0.10 m	≤ 0.45	]0.45 - 1.00]	]1.00 - 1.80]	> 1.80
2b	Juvenile (Lp < 100 mm)	0.05 m	0.10 m	≤ 0.20	]0.20 - 0.40]	]0.40 - 0.60]	> 0.60
2c	Subadult / Adult (Lp > 100 mm)	0.10 m	0.20 m	≤ 0.30	]0.30 - 0.80]	]0.80 - 1.60]	> 1.60
2d	Juvenile (Lp < 100 mm)	0.05 m	0.10 m	≤ 0.05	]0.05 - 0.25]	]0.25 - 0.45]	> 0.45
3a	Lp > 500 mm	0.05 m	0.10 m	≤ 0.40	]0.40 - 0.60]	]0.60 - 0.80]	> 0.80
3b	100 mm < Lp < 500 mm	0.02 m	0.04 m	≤ 0.10	]0.10 - 0.25]	]0.25 - 0.45]	> 0.45
3c	Lp < 100 mm	-	-	-	-	-	-
4a	Subadult / Adult (Lp > 40 mm)	0.05 m	0.10 m	≤ 0.20	]0.20 - 0.50]	]0.50 - 1.40]	> 1.40
4b	Juvenile (Lp < 40 mm)	0.01 m	0.02 m	-	≤ 0.05	]0.05 - 0.10]	> 0.10

■ Decision tree

The steps in determining the ICE passability class of passage under a gate or through an orifice are presented below.

1. Analysis of the gate opening

If the gate opening or the height of the orifice OV ≥ OV_{min} (Table 18), the height of the passage under the gate and the depth at the point of contraction are sufficient. Go to Step 2.

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

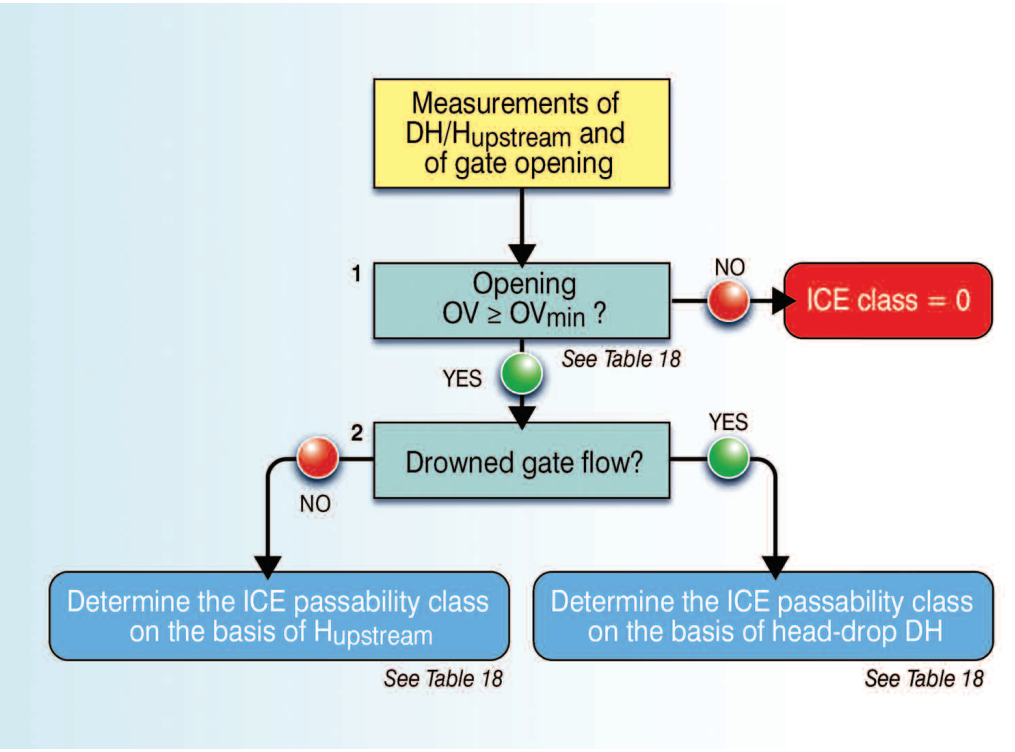
2. Analysis of the head-drop DH (drowned gate) or of the height of the water behind the gate $H_{upstream}$ (free gate flow)

For a drowned gate, determine the ICE passability class as a function of the head-drop DH (Table 18).

For a free gate flow, determine the ICE passability class as a function of the water behind the gate $H_{upstream}$ (see Table 18).

N.B. For a free-surface flow (gate without a controlling flow), the structure may be considered a weir with moving parts. For this operating mode, the assessment procedure is simply that intended for a weir (see the sections on weirs).

Figure 58



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

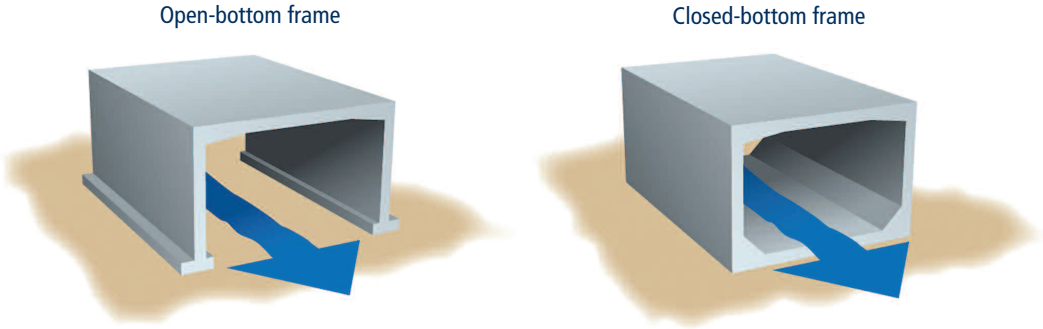
Road/rail structures

The different types of structures

This section deals with passability assessments on road, highway and rail structures (Figure 59), whose characteristics vary widely, including open-bottom frames, closed-bottom frames, culverts, arches and certain types of similar structures (fords, bridge aprons, etc.).

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

Figure 59



© Graphies for OFB

a © P. Valade (Ocea Consult')
b © B. Voegtlé (Ecogea)

Examples of different types of structures.

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 greater than that of the upstream section of the river, 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 torrential (Figure 60).

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 60

a © B. Voegtlé (Ecogea)
b © F. Mayeras (Ecogea)

Examples of high flow velocities in culverts.
(a) Culvert on the Saint-Étienne River (Réunion), (b) Ford over the Maronne River (continental France).

■ 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.

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 61).

Figure 61

© B. Voegtlé (Ecogea)

Example of very low water depths on the apron of a road bridge.
Passage of the Beja River (Mayotte).

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

Fish may also be blocked at the downstream end of structures by waterfalls (Figure 62). 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 water level if no preventive measures (bed-control devices) were taken to stabilise the bed following the installation of the structure.

For a culvert, given the increased flow velocity inside the structure, the angle of incidence of the jet at the outlet can increase the difficulty of overcoming the downstream waterfall.

More rarely, there may be a step inside the structure, often the result of poor adjustment of the various components making up the structure. The frequent low water depths make passage particularly difficult, even if the step is not particularly high.

Figure 62

a, b, c, d © B. Voegtlé (Ecogea)

Examples of waterfalls downstream of road structures.
(a) Ravine Chaude bridge over the Goyaves Grande River (Guadeloupe), (b) Blanche River (Martinique), (c) Beauvallon apron on the Roches River (Réunion), (d) Baimbridge bridge over the Goyaves Grande River (Guadeloupe).

■ Poor positioning of the head of the structure

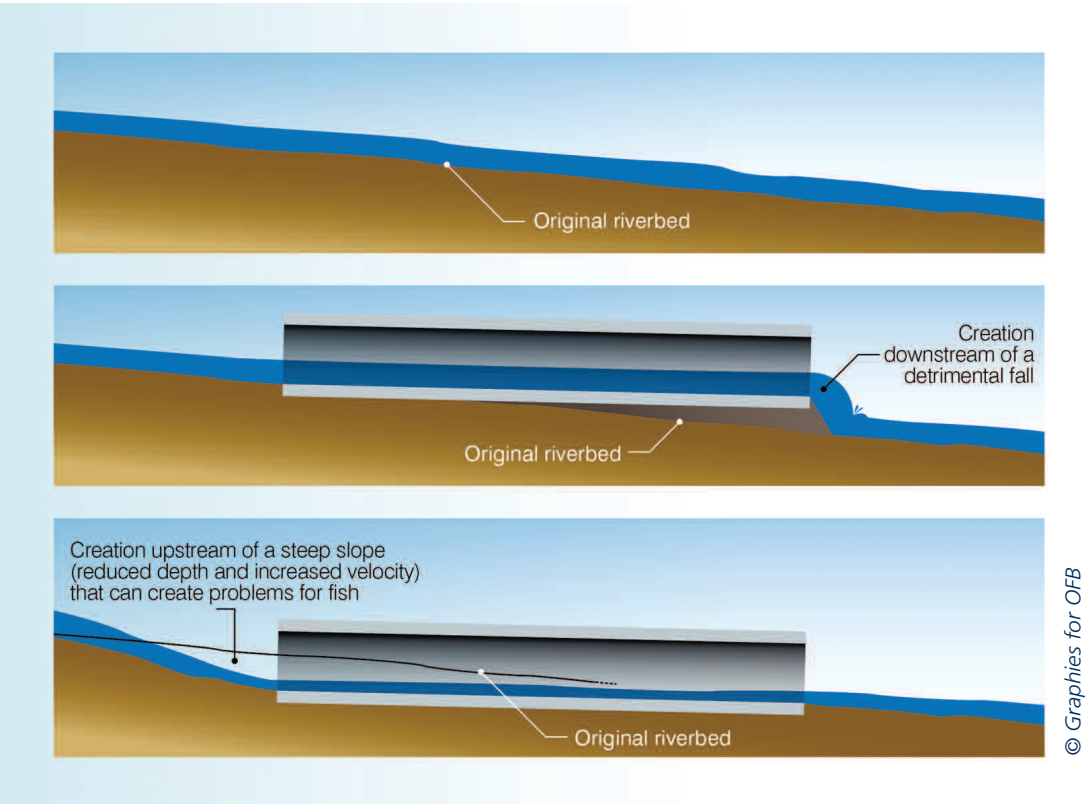
Poor positioning of the head of the structure may, in some cases, result in the creation, just upstream in the riverbed, of a zone characterised by high velocities and low water depths that fish have difficulty in overcoming (Figures 63 and 64).

Figure 63

© B. Voegtlé (Ecogea)

Example of high flow velocities induced upstream of culverts.
Culverts on the Saint-Étienne River (Réunion).

Figure 64



© Graphies for OFB

Examples of the problems created by poor longitudinal positioning of a road or rail structure. After Baudoin et al.*, 2014.*

■ An **accumulation of debris at the entry or inside the structure** is a frequent cause of obstacles for migrators (Figure 65). This often occurs when the structure is too small compared to the width of the river (resulting in a major reduction in the available width for flow) and when the air passage (between the water line and the top of the structure) is not sufficient.

Figure 65

a, b © *B. Voegtlé (Ecogea)*

Examples of structures significantly blocked by debris.
(a) and (b) Blocked structures on rivers on Martinique.

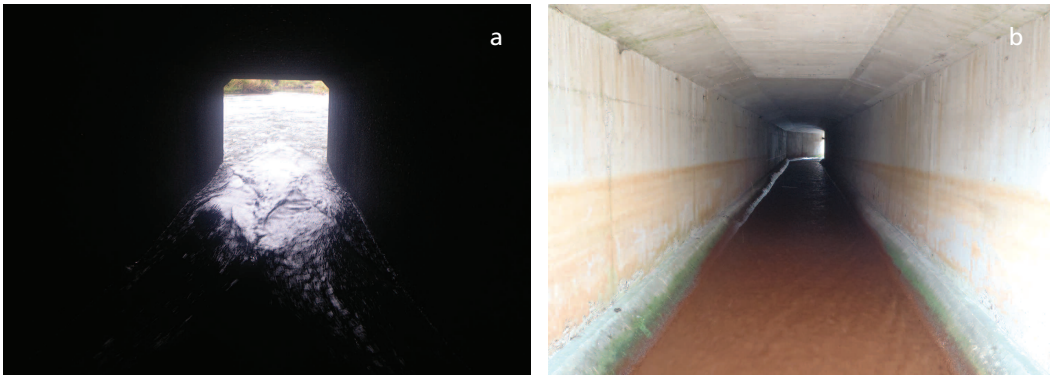
■ Abrupt changes in light

When there is an abrupt change in the intensity of light at the entry of a culvert (Figure 66), 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 method.

For more information, one notable source is the reports published by the Ecology ministry (Egis Environnement-Hydrosphère, 2007 and 2008).

Figure 66



a © B. Voegtlé (Ecogea)
b © M. Chanseau (OFB)

Examples of structures causing more or less progressive changes in light.
(a) A fairly sudden change in light that can limit day-time passage of the structure, (b) A larger structure producing a more progressive change in light.

Assessment procedure

Similar to other types of obstacles, the assessment of passability consists of identifying and qualifying the factors likely to limit the movement of the various species or groups of species. The most important factors are the velocity/distance parameters, followed by the water depth and the presence of waterfalls/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 significant.

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 (several percent), fish, particularly small species, are obliged to use their maximum speed U_{max} and the limiting factors are the flow velocities inside the structure and the length of the structure.

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 their maximum speed, fish can swim more or less at their sustained-swimming speed. In which case, the length of the structure becomes the limiting factor (but to a much lesser degree than in structures with a steep slope).

■ Swimming speed of 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 under conditions of aerobic glycolysis (P_{aer}) corresponds 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 (1986), the muscular energy (power x time) under anaerobic conditions (W_{ana}) provide 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 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 D 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 ($U_{max} \approx 3\, U_{cr}$). Therefore, 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 speed U_{cr} , as long as the flow velocity remains below the cruising speed.

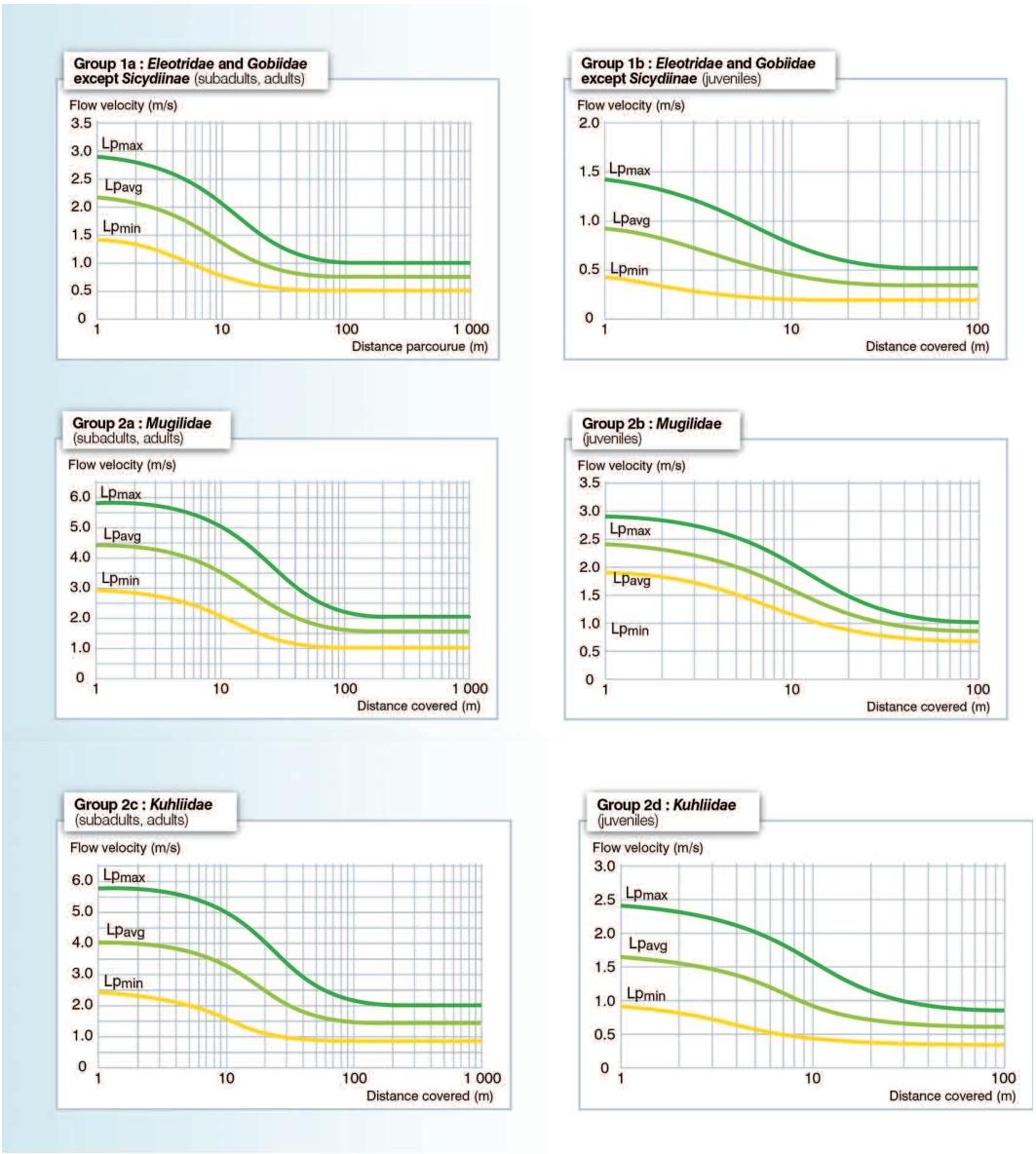
When the flow velocity exceeds two-thirds of the maximum swimming speed, the distance covered is maximum when the fish swims at its maximum speed.

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

For the various species groups, assuming that fish adjust their speed to the flow velocity in order to obtain optimum conditions (see above), the distances covered as a function of the flow velocity are shown on a semi-log plot (Figures 67 and 68).

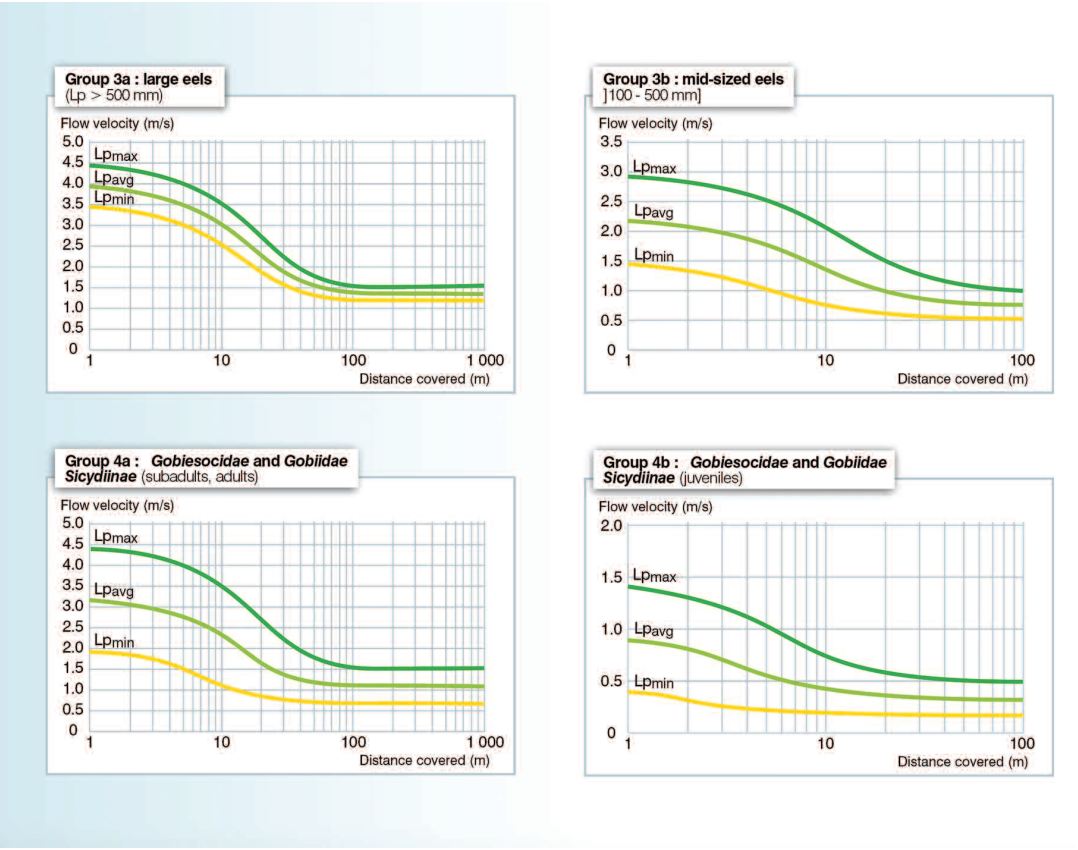
For each species group or subgroup, the dark green, light green and yellow lines correspond to the largest (Lp_{max}), average (Lp_{avg}) and smallest (Lp_{min}) fish, respectively.

Figure 67



Distance covered as a function of the flow velocity for species Groups 1 and 2.

Figure 68



Distance covered as a function of the flow velocity for species Groups 3 and 4.

Definition of passability classes

For weirs with inclined downstream faces (see the section on weirs with inclined downstream faces (slope ≤ 150%)), it is 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 at relevant discharges, either using hydraulic modelling software (*FishXing*, *Hec-Ras* or similar software) or simply by measuring the flow velocities in the structure. Measurements are not always easy to carry out, particularly if the structure is too small to enable entry.

The curves in Figures 67 and 68 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 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 coefficients n=0.01 to 0.03) and unit discharges between 0.05 and 2 m³/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 waterfall

A large number of culverts and road structures have a waterfall at their downstream end (Figure 69) that can limit or block the passage of fish.

The downstream waterfall should be analysed to determine its passability using the same method as that for weirs having a vertical or subvertical downstream face. To start the assessment, the passability class of the waterfall should be determined using the decision tree and the corresponding table presented in the section on vertical and subvertical obstacles (slope > 150%).

To incorporate the downstream waterfall in the passability diagnosis of the structure, it is proposed here to adopt the same method as that for complex or mixed structures (see the section on complex structures) or for inclined weirs with a downstream waterfall (see the section on weirs with inclined downstream faces (slope ≤ 150%)), that is to downgrade the overall ICE passability class of the structure or to select the class of the most difficult part (downstream waterfall or culvert).

Consequently, the overall ICE passability class of the structure should be determined on the basis of the classes of the two parts of the structure (upstream structure and downstream waterfall), using Table 19.

Step in the structure

Similar to weirs, a step in the structure can substantially degrade the passage conditions, 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.

Figure 69

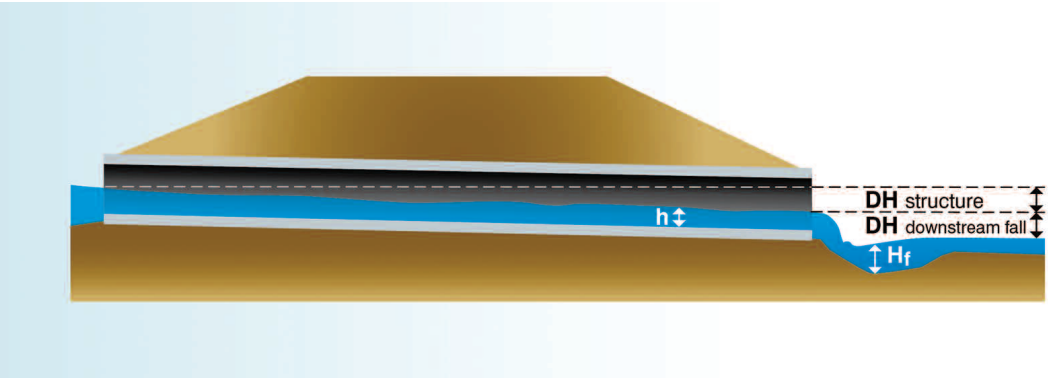


Diagram showing a road structure with a downstream waterfall. After Baudoin et al.*, 2014.*

Table 19 *Table to determine the overall ICE passability class for road structures with a downstream waterfall. After Baudoin* et al.*, 2014.*

		ICE class of the downstream waterfall			
		0	0.33	0.66	1
ICE class of the culvert	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

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

In this case, to determine the passability class, it is necessary to use the same criteria as those for standard weirs, i.e. the criteria concerning notably the relative dimensions of the step with respect to the average length Lp_{avg} of the given 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, and the flow 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 internal flow 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).

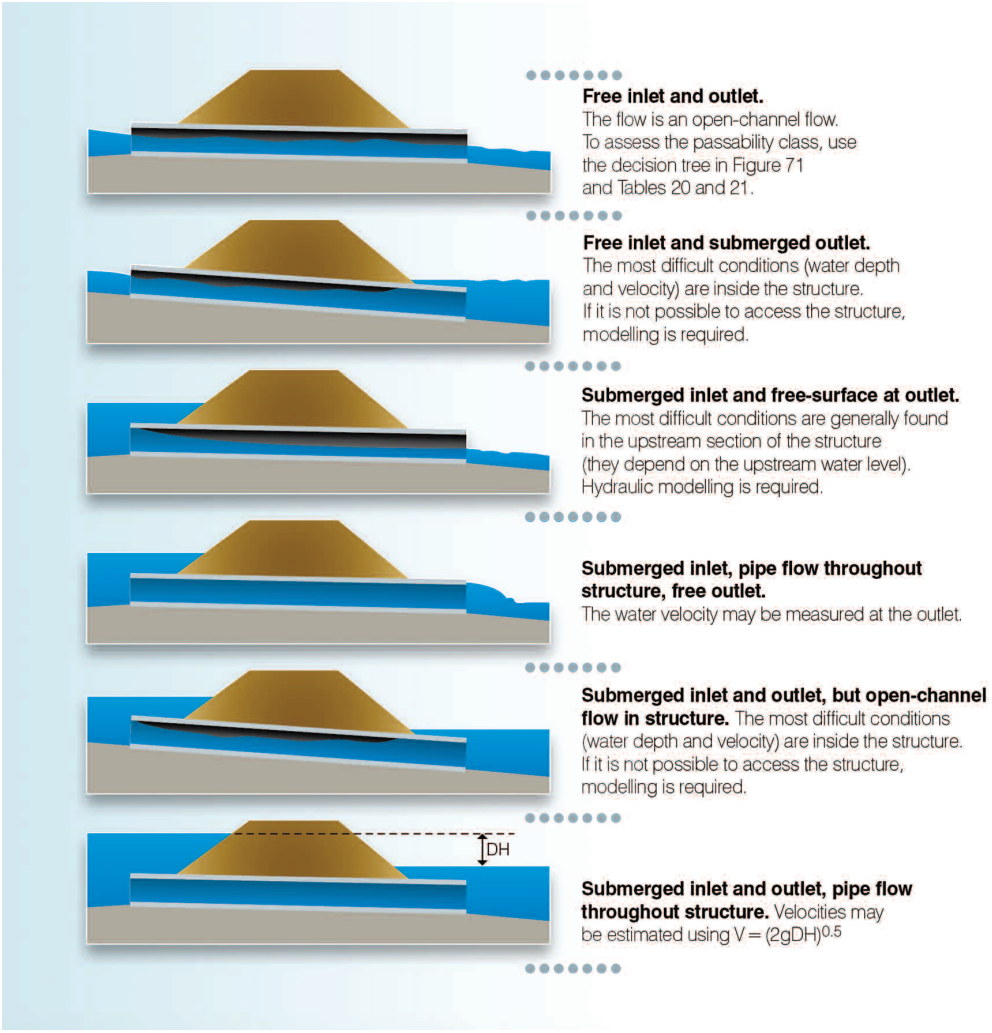
The downstream outlet of the structure may also be (partially) submerged. In which case, measurements of flow velocities and depths at the outlet are not representative of the flow conditions inside the structure.

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 (Tables 20 and 21)**. The resulting passability class should be considered the maximum class** (real ICE class ≤ the calculated class) **and serves essentially to determine whether hydraulic modelling is worthwhile.**

Figure 70 shows various flow configurations through culverts and discusses the methods used to determine passability.

Figure 70



Various flow configurations in culverts and the methods used to assess passability by swimming.

Determining passability classes

■ Threshold values used in the decision tree

Table 20 presents the passability classes of a structure as a function of its length and slope.

In certain cases, when the slope is very low, it is also necessary to integrate the flow velocities with respect to the length of the structure (Table 21) in order 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 are accompanied by a decision tree (Figure 71) showing how the ICE passability classes are determined.

Table 20 *Threshold values used to determine ICE passability classes for road structures and culverts, depending on their slope and length, for swimming fish.*

ICE group	Family	Species	Name in English (E) and in Creole (C)	FOT			
				Guadeloupe	Martinique	Mayotte	Réunion
1a	Eleotridae + Gobiidae except Sicydiinae	*Awaous banana*	River goby (E) / jolpot, loche (C)	X	X		
		Awaous commersoni	Commerson's freshwater goby, river goby (E) / loche, cabot (C)			X	X
		Butis butis	Crazy fish, crimson-tipped flathead-sleeper, duckbill sleeper (E)			X	X
		Ctenogobius pseudofasciatus	Slashcheek goby (E)		X		
		Dormitator maculatus	Fat sleeper (E) / ti-nèg, dormeur (C)	X	X		
		Eleotris amblyopsis	Large-scaled spiny-cheek sleeper (E) / pitit dormè (C)	X			
		Eleotris klunzingerii	Brown sleeper, dusky sleeper (E) / cabot noir (C)			X	X
		Eleotris mauritiana	Widehead sleeper (E) / cabot noir (C)			X	X
		Eleotris perniger	Small-scaled spiny-cheek sleeper (E) / pitit dormè, flèche (C)	X	X		
		Glossogobius callidus	Tank goby (E)			X	
		Glossogobius giurus	Tank goby (E) / loche (C)			X	X
		Glossogobius kokius	- (E) / loche, cabot (C)				X
1b		*Gobiomorus dormitor*	Bigmouth sleeper (E) / grand dormeur, dormeur (C)	X	X		
		Guavina guavina	Guavina (E) / dormeur (C)		X		
		Hypseleotris cyprinoides	Tropical carp-gudgeon (E)			X	X
		Mugilogobius mertoni	Chequered mangrove goby, Merton's mangrove goby, meander goby (E) / gobi milet (C)			X	
		Ophieleotris cf *aporos*	Snakehead gudgeon (E)			X	
		Ophiocara porocephala	Northern mud gudgeon, spangled sleeper (E) / makanbale latet ron (C)			X	
		Redigobius balteatus	Rhinohorn goby (E)			X	
		Redigobius bikolanus	Bigmouth goby, speckled goby (E) / gobi tase (C)			X	
		Stenogobius polyzona	Chinestripe goby (E) / cabot rayé (C)			X	X
2a	Mugilidae	*Agonostomus catalai*	Comoro mullet (E)			X	
		Agonostomus monticola	Mountain mullet (E) / milet (C)	X	X		
2b		*Agonostomus telfairii*	Fairy mullet (E) / chitte (C)			X	X
2c	Kuhliidae	*Kuhlia rupestris*	Jungle perch, rock flagtail (E) / doule de roche, carpe (C)			X	X
2d		*Kuhlia sauvagii*	Rock flagtails (E) / doule de roche, carpe (C)			X	X
3a	Anguillidae	*Anguilla bengalensis*	Indian mottled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla bicolor bicolor	Indonesian shortfin eel (E) / z'amab, z'anguille (C)			X	X
3b		*Anguilla marmorata*	Giant mottled eel, marbled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla mossambica	African longfin eel (E) / z'amab, z'anguille (C)			X	X
3c		*Anguilla rostrata*	American eel (E) / z'anguille (C)	X	X		
4a	Gobiesocidae + Gobiidae Sicydiinae	*Cotylopus acutipinnis*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)				X
		Cotylopus rubripinnis	Goby (E)			X	
		Gobiesox nudus	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	X	X		
4b		*Sicydium plumieri*	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)			X	X

The values indicated for (sub)groups 1b, 3 and 4 correspond to the passability classes set when the analysis takes into account only the swimming capabilities of species. In cases where the obstacle includes a crawling, suction or climbing zone, the assessment must ***also*** *use the special tables for these passage techniques (see the relevant sections).*

ICE species group	Stage and/or length	Minimum water depth h_{min} required for swimming	Maximum step dimensions (m)		Slope threshold values (%)						
					L structure ≤ 20 m				L structure > 20 m		
					ICE passability class				ICE passability class		
			a_{max}	c_{max}	NC	0.66	0.33	0	NC	0.33	0
1a	Subadult / Adult (Lp > 40 mm)	0.05 m	0.10	0.10	≤ 0.75	]0.75 - 1.25]	]1.25 - 2.00]	> 2.00	≤ 0.75	]0.75 - 1.50]	> 1.50
1b	Juvenile (Lp < 40 mm)	0.01 m	0.02	0.02	-	≤ 0.50	]0.50 - 1.00]	> 1.00	-	≤ 0.50	> 0.50
2a	Subadult / Adult (Lp > 100 mm)	0.05 m	0.10	0.15	≤ 2.00	]2.00 - 4.00]	]4.00 - 10.0]	> 10.0	≤ 2.00	]2.00 - 4.00]	> 4.00
2b	Juvenile (Lp < 100 mm)	0.05 m	0.02	0.05	≤ 0.75	]0.75 - 1.25]	]1.25 - 2.00]	> 2.00	≤ 0.75	]0.75 - 1.50]	> 1.50
2c	Subadult / Adult (Lp > 100 mm)	0.10 m	0.10	0.20	≤ 1.00	]1.00 - 4.00]	]4.00 - 10.0]	> 10.0	≤ 1.00	]1.00 - 4.00]	> 4.00
2d	Juvenile (Lp < 100 mm)	0.05 m	0.02	0.05	≤ 0.50	]0.50 - 1.25]	]1.25 - 2.00]	> 2.00	≤ 0.50	]0.50 - 1.25]	> 1.25
3a	Lp > 500 mm	0.05 m	0.40	0.70	≤ 1.00	]1.00 - 2.00]	]2.00 - 4.00]	> 4.00	≤ 1.00	]1.00 - 2.00]	> 2.00
3b	100 mm < Lp < 500 mm	0.02 m	0.10	0.20	≤ 0.75	]0.75 - 1.25]	]1.25 - 2.00]	> 2.00	≤ 0.75	]0.75 - 1.50]	> 1.50
3c	Lp < 100 mm	-	-	-	-	-	-	-	-	-	-
4a	Subadult / Adult (Lp > 40 mm)	0.05 m	0.05	0.10	≤ 0.75	]0.75 - 2.00]	]2.00 - 8.00]	> 8.00	≤ 0.75	]0.75 - 2.00]	> 2.00
4b	Juvenile (Lp < 40 mm)	0.01 m	0.02	0.02	-	≤ 0.50	]0.50 - 1.00]	> 1.00	-	≤ 0.50	> 0.50

Table 21 *Threshold values used to determine ICE passability classes for road structures and culverts, depending on their length and the flow velocities inside the structure, for swimming fish.*

ICE group	Family	Species	Name in English (E) and in Creole (C)	FOT			
				Guadeloupe	Martinique	Mayotte	Réunion
1a	Eleotridae + Gobiidae except Sicydiinae	*Awaous banana*	River goby (E) / jolpot, loche (C)	X	X		
		Awaous commersoni	Commerson's freshwater goby, river goby (E) / loche, cabot (C)			X	X
		Butis butis	Crazy fish, crimson-tipped flathead-sleeper, duckbill sleeper (E)			X	X
		Ctenogobius pseudofasciatus	Slashcheek goby (E)		X		
		Dormitator maculatus	Fat sleeper (E) / ti-nèg, dormeur (C)	X	X		
		Eleotris amblyopsis	Large-scaled spiny-cheek sleeper (E) / pitit dormè (C)	X			
		Eleotris klunzingerii	Brown sleeper, dusky sleeper (E) / cabot noir (C)			X	X
		Eleotris mauritiana	Widehead sleeper (E) / cabot noir (C)			X	X
		Eleotris perniger	Small-scaled spiny-cheek sleeper (E) / pitit dormè, flèche (C)	X	X		
		Glossogobius callidus	Tank goby (E)			X	
		Glossogobius giurus	Tank goby (E) / loche (C)			X	X
		Glossogobius kokius	- (E) / loche, cabot (C)				X
1b		*Gobiomorus dormitor*	Bigmouth sleeper (E) / grand dormeur, dormeur (C)	X	X		
		Guavina guavina	Guavina (E) / dormeur (C)		X		
		Hypseleotris cyprinoides	Tropical carp-gudgeon (E)			X	X
		Mugilogobius mertoni	Chequered mangrove goby, Merton's mangrove goby, meander goby (E) / gobi milet (C)			X	
		Ophieleotris cf aporos	Snakehead gudgeon (E)			X	
		Ophiocara porocephala	Northern mud gudgeon, spangled sleeper (E) / makanbale latet ron (C)			X	
		Redigobius balteatus	Rhinohorn goby (E)			X	
		Redigobius bikolanus	Bigmouth goby, speckled goby (E) / gobi tase (C)			X	
		Stenogobius polyzona	Chinestripe goby (E) / cabot rayé (C)			X	X
2a	Mugilidae	*Agonostomus catalai*	Comoro mullet (E)			X	
		Agonostomus monticola	Mountain mullet (E) / milet (C)	X	X		
2b		*Agonostomus telfairii*	Fairy mullet (E) / chitte (C)			X	X
2c	Kuhliidae	*Kuhlia rupestris*	Jungle perch, rock flagtail (E) / doule de roche, carpe (C)			X	X
2d		*Kuhlia sauvagii*	Rock flagtails (E) / doule de roche, carpe (C)			X	X
3a	Anguillidae	*Anguilla bengalensis*	Indian mottled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla bicolor bicolor	Indonesian shortfin eel (E) / z'amab, z'anguille (C)			X	X
3b		*Anguilla marmorata*	Giant mottled eel, marbled eel (E) / z'amab, z'anguille (C)			X	X
		Anguilla mossambica	African longfin eel (E) / z'amab, z'anguille (C)			X	X
3c		*Anguilla rostrata*	American eel (E) / z'anguille (C)	X	X		
4a	Gobiesocidae + Gobiidae Sicydiinae	*Cotylopus acutipinnis*	Bichique, goby (E) / cabot bouche ronde, bichique (juvenile) (C)				X
		Cotylopus rubripinnis	Goby (E)			X	
		Gobiesox nudus	Clingfish, padded clingfish (E) / tétard, macouba, colle-roche (C)	X	X		
4b		*Sicydium plumieri*	Plumier's stone-biting goby, sirajo (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicydium punctatum	Spotted algae-eating goby (E) / colle-roche, loche, titiri (juvenile) (C)	X	X		
		Sicyopterus lagocephalus	Bichique, red-tailed goby (E) / cabot à bec de lièvre, cabot bouche ronde, bichique (juvenile) (C)			X	X

*The values indicated for (sub)groups 1b, 3 and 4 correspond to the passability classes set when the analysis takes into account only the swimming capabilities of species. In cases where the obstacle includes a crawling, suction or climbing zone, the assessment must **also** use the special tables for these passage techniques (see the relevant sections).*

Stage and/or length	Minimum water depth h_{min} required for swimming	Maximum step dimensions (m)		Threshold values for flow velocities inside the structure (m/s)											
				L structure ≤ 20 m				20 m < L structure ≤ 50 m				L structure > 50 m			
				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
Subadult / Adult (Lp > 40 mm)	0.05 m	0.10	0.10	≤ 0.55	]0.55 - 1.00]	]1.00 - 1.50]	> 1.50	≤ 0.50	]0.50 - 0.80]	]0.80 - 1.10]	> 1.10	≤ 0.50	]0.50 - 0.75]	]0.75 - 1.00]	> 1.00
Juvenile (Lp < 40 mm)	0.01 m	0.02	0.02	≤ 0.20	]0.20 - 0.35]	]0.35 - 0.60]	> 0.60	≤ 0.20	]0.20 - 0.35]	]0.35 - 0.50]	> 0.50	≤ 0.15	]0.15 - 0.30]	]0.30 - 0.50]	> 0.50
Subadult / Adult (Lp > 100 mm)	0.05 m	0.10	0.15	≤ 1.50	]1.50 - 2.65]	]2.65 - 4.10]	> 4.10	≤ 1.10	]1.10 - 1.85]	]1.85 - 2.70]	> 2.70	≤ 1.00	]1.00 - 1.55]	]1.55 - 2.15]	> 2.15
Juvenile (Lp < 100 mm)	0.05 m	0.02	0.05	≤ 0.85	]0.85 - 1.15]	]1.15 - 1.50]	> 1.50	≤ 0.70	]0.70 - 0.85]	]0.85 - 1.10]	> 1.10	≤ 0.65	]0.65 - 0.85]	]0.85 - 1.00]	> 1.00
Subadult / Adult (Lp > 100 mm)	0.10 m	0.10	0.20	≤ 1.15	]1.15 - 2.45]	]2.45 - 4.10]	> 4.10	≤ 0.90	]0.90 - 1.70]	]1.70 - 2.70]	> 2.70	≤ 0.85	]0.85 - 1.45]	]1.45 - 2.15]	> 2.15
Juvenile (Lp < 100 mm)	0.05 m	0.02	0.05	≤ 0.35	]0.35 - 0.70]	]0.70 - 1.15]	> 1.15	≤ 0.35	]0.35 - 0.60]	]0.60 - 0.90]	> 0.90	≤ 0.35	]0.35 - 0.60]	]0.60 - 0.85]	> 0.85
Lp > 500 mm	0.05 m	0.40	0.70	≤ 1.70	]1.70 - 1.95]	]1.95 - 2.45]	> 2.45	≤ 1.35	]1.35 - 1.55]	]1.55 - 1.75]	> 1.75	≤ 1.15	]1.15 - 1.35]	]1.35 - 1.55]	> 1.55
100 mm < Lp < 500 mm	0.02 m	0.10	0.20	≤ 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
Lp < 100 mm	-	-	-	≤ 0.20				≤ 0.20				≤ 0.15			
Subadult / Adult (Lp > 40 mm)	0.05 m	0.05	0.10	≤ 0.85	]0.85 - 1.65]	]1.65 - 2.65]	> 2.65	≤ 0.70	]0.70 - 1.20]	]1.20 - 1.85]	> 1.85	≤ 0.65	]0.65 - 1.10]	]1.10 - 1.55]	> 1.55
Juvenile (Lp < 40 mm)	0.01 m	0.02	0.02	≤ 0.20	]0.20 - 0.35]	]0.35 - 0.60]	> 0.60	≤ 0.20	]0.20 - 0.35]	]0.35 - 0.50]	> 0.50	≤ 0.15	]0.15 - 0.35]	]0.35 - 0.50]	> 0.50

■ Decision tree

The steps in determining the ICE passability class of road structures and culverts (Figure 71) are presented below.

1. Analysis of the downstream waterfall, if it exists

If a waterfall does not exist, go to Step 6.

If a waterfall exists at the downstream end of the structure, passability should be determined using the method for vertical or subvertical weirs (start the assessment at Step 2 in the decision tree in the section on vertical and subvertical weirs (slope >150%)).

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

If the downstream waterfall is not a total barrier (ICE class > 0), go on to Step 2.

2. Analysis of the water depth in the structure

If the water depth is greater than the minimum, i.e. $h \geq h_{min}$ (Tables 20 and 21), 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 method (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 site 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 either dimension (a or c) of a single step exceeds the maximum values a_{max} and c_{max} listed in Tables 20 and 21, 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 (a_{max} and c_{max} in Tables 20 and 21), go to Step 4.

4. Analysis of the slope

On the basis of the length of the structure ($L \leq 20$ m or $L > 20$ m) and its slope, use Table 20 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 ($L \leq 20$ m, $20 \text{ m} < L \leq 50$ m or $L > 50$ m) and the measured or estimated flow velocities, use Table 21 to determine the ICE passability class of the structure. Then 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 whether the structure lies under the natural riverbed

Check whether the entire structure is positioned lower than the natural riverbed.

If the entire structure lies below the natural riverbed, go to Step 8.

Otherwise, 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.

Otherwise, 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 along a transect) and compare it to the **wetted riverbed**.

If the cumulative structure width is between 75% and 125% of the riverbed width, the structure is considered a low-impact passable barrier (ICE class = 1).

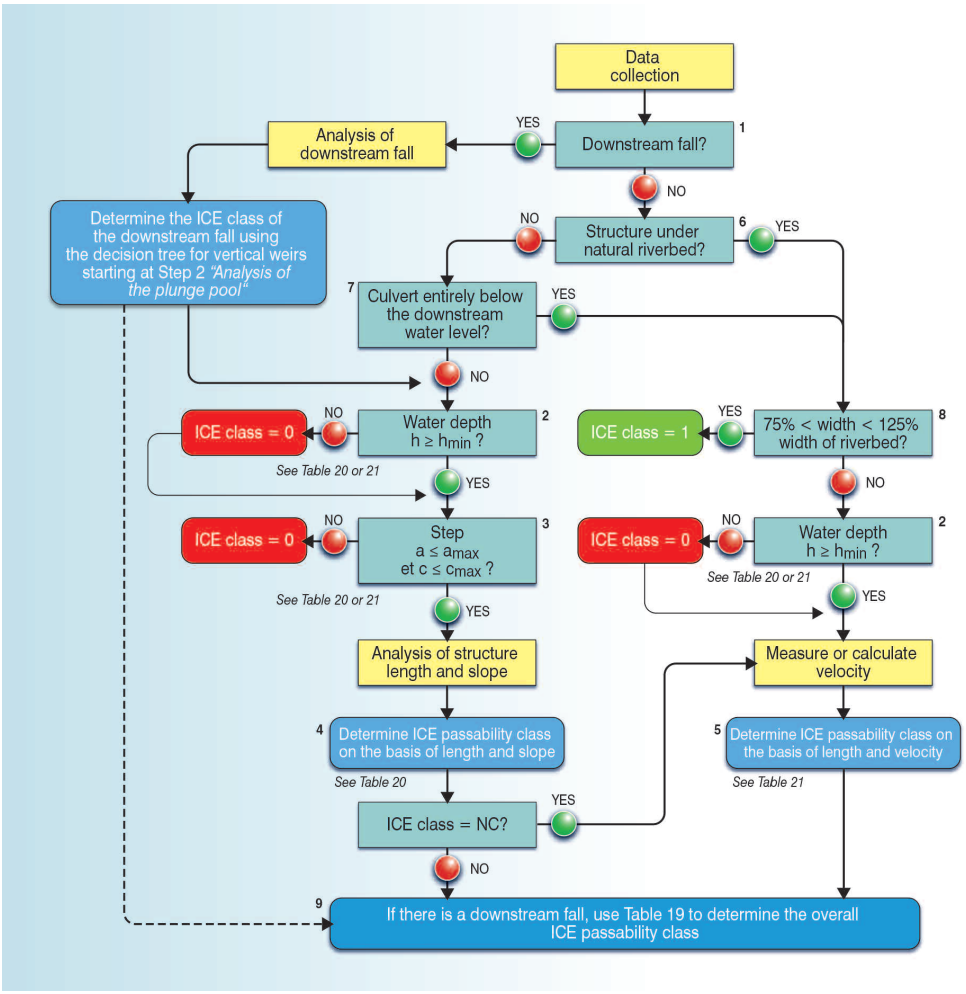
If not, check that $h \geq h_{min}$ (see Step 2), then go to Step 5. If the above condition ($h \geq h_{min}$) is not met, then the obstacle is considered a total barrier (ICE class = 0).

9. Analysis of the overall passability of the structure

If the road structure or culvert has a downstream waterfall, use Table 19 to determine the overall ICE passability class.

If the structure does not have a downstream waterfall, the overall ICE passability class is that resulting from Step 4 or Step 5.

Figure 71



Decision tree to determine ICE passability classes for fish swimming through road structures or culverts.

Complex and mixed structures

Complex or mixed obstacles are structures made up of different materials and/or configurations along the longitudinal axis (e.g. a concrete vertical or inclined weir followed downstream by a rock chute) 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.).

For the ICE method, it was decided to break these complex structures down into a series of "simple" structures (Figure 72), then to determine the passability of each part separately and finally to calculate a passability class for the structure as a whole. The assessment procedure is presented below.

The approach is comparable in terms of its rationale to that used for inclined weirs or road/rail structures having a downstream waterfall (see the sections on these types of structures).

Breaking a complex structure into a series of “simple” structures along the longitudinal axis

Each “simple” structure, as part of the overall complex structure, must be assigned to one of the five following 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.

N.B. The passability of obstacles comprising moving parts (gates) and were overflows exist should be assessed in the same manner as vertical and subvertical obstacles (slope > 150%).

However, this breakdown is valid only if the hydraulic conditions for each “simple” structure are not overly influenced by the presence of the other parts (Figure 73).

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, a diagnosis will realistically require more in-depth analysis calling on hydraulic modelling to describe the flow conditions throughout the structure 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 the maximum class (real ICE class ≤ the composite class) **and serves essentially to determine whether hydraulic modelling is worthwhile** (see the example in Figure 73).

Figure 72

a, b © P. Valade (Ocea Consult')

Examples of complex structures than can be broken down into a series of "simple" structures.
(a) A structure that can be broken down into an inclined weir and a downstream rock weir (Pérou River, Guadeloupe), (b) A structure that can be broken down into two successive inclined weirs (Saint-Louis River, Guadeloupe).

Figure 73

© B. Voegtlé (Ecogea)

Example of a structure than cannot be broken down into "simple" structures.
In this case (controlling flow under a gate, followed by an inclined weir), the structure cannot be broken down into 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. Note that 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).

Determining the passability class for each part of a structure

The passability class for each of the “simple” structures is determined using the methods for each type of obstacle presented in the previous sections.

Determining the passability class for the complex 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 22 presents the results for a structure made up of two “simple” structures.

Table 22 *Table to determine the overall ICE class for a complex structure comprising two “simple” structures.*

		ICE class of the downstream structure				
		0	0.33	0.66	1	NC
ICE class of the upstream structure	0	0	0	0	0	0
	0.33	0	0	0.33	0.33	NC (≤ 0.33)
	0.66	0	0.33	0.33	0.66	NC (≤ 0.66)
	1	0	0.33	0.66	1	NC
	NC	0	NC (≤ 0.33)	NC (≤ 0.66)	NC	NC

For a set of "x" simple structures, 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 22 should be used.

Below are a number of examples.

- *For a complex structure comprising 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 22 if x = 2 or one class lower than the worst simple structure if x ≥ 3).*
- *For a complex structure comprising 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 22 if x = 2 or one class lower than the worst simple structure if x ≥ 3).*
- *For a complex structure comprising 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 complex structure comprising 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 22).*

The crawling capabilities of eels

Specific approach

■ General

During their upstream migration, eels are capable of overcoming obstacles in **two potential ways:**

- **swimming,** when the water depth is sufficient and the flow velocity relatively limited;
- **crawling,** over wet surfaces with at most a thin sheet of water.

■ Size of eels and passage technique

The smallest eels (glass eels) can "climb" vertical walls offering no particular support, thanks to the surface tension between their bodies and the wet wall (the force is sufficient to counteract gravity). However, in growing, the weight to surface tension ratio increases, which explains why only the smallest eels can use this technique.

Older fish 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, **three subgroups were created.**

- **Subgroup 3a** corresponds to the "yellow" stage of giant mottled eels *Anguilla marmorata* and to the adults of other species (larger than 500 mm in length) that migrate up rivers to recolonise habitats following flooding or intense dry periods. These large eels are very strong.
- **Subgroup 3b** corresponds to "yellow" eels of all species between 100 and 500 mm in length.
- **Subgroup 3c** comprises the younger eels less than 100 mm in length, corresponding essentially to the glass-eel stage.

■ Passability criteria

Given their swimming capabilities, any structure comprising a waterfall represents a major obstacle for glass eels and young elvers (Subgroup 3c) if they must overcome the obstacle by swimming.

For elvers and yellow eels (Subgroup 3b), threshold values for the passability classes are presented in the tables used with the various decision trees, similar to the other species (see the previous sections addressing each type of obstacle).

However, **the diagnosis of structure passability for eels must take into account the special crawling capabilities of 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 for the overseas ICE method is similar to that for continental France. It consists first of checking that a potential crawl way exists for the fish and then assessing passability on the basis of two criteria that are simple to measure or estimate, i.e. the distance the fish must cover and the slope of the crawl way.

Check that a crawl way exists

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 existence of potential rest zones in the crawl way can also significantly increase the chances of passage.

One part of the population can overcome some relatively high, natural waterfalls (a few dozen metres), particularly when the waterfalls are located in the lower sections of rivers and the population consists of a majority of younger fish (better crawling capabilities and climbing up vertical walls by glass eels, see below). These waterfalls offer numerous irregularities (small basins, relatively flat areas wetted by the waterfall) where small eels can rest during their passage over the obstacle (Figure 74).

On man-made obstacles, flows are generally more uniform and rest areas along a potential crawl way are more limited in number, if not totally absent.

Figure 74

a, b © B. Voegtlé (Ecogea)

Example of natural waterfalls offering potential rest zones (cracks and crevices) and a degree of passability for glass eels.
(a) Boungoumouhé waterfall (Mayotte), (b) Niagara waterfall (Réunion).

The combination of these parameters that are difficult to assess (rough surfaces, rest areas) and their variability over an entire obstacle make their inclusion in the ICE method highly problematic.

Consequently, it was decided not to include the "roughness" parameter in the search for and the analysis of potential crawl ways for eels over obstacles.

A usable crawl way is characterised by a continuous section where the water depth is very low, less than 5, 2 and 1 cm for Subgroups 3a, 3b and 3c respectively (Figure 75).

N.B. **A crawl way for eels may also be considered a potential passageway for *Sicydiinae* or the post-larvae and juveniles of small, benthic species using suction techniques and as a walkway for macro-crustaceans.**

Figure 75

a, c, d, e, f © B. Voegtlé (Ecogea)
b © P. Valade (Ocea Consult')

Examples of potential crawl ways for eels that should be analysed (marked by the red arrows). The arrows also represent potential passageways for Sicydiinae *or the post-larvae and juveniles of small, benthic species using suction techniques and as walkways for macro-crustaceans (photos from Martinique, Mayotte and Réunion).*

Caution. In addition to the possibilities of passage by crawling in areas along the flow, eels can theoretically also overcome obstacles by swimming. For this reason, the analysis of passability by crawling should always be carried out in parallel with the use of the decision trees presented above (see the sections on each type of structure) for yellow eels and elvers (Subgroups 3a and 3b). For glass eels (Subgroup 3c), analysis of passability by swimming is not necessary given their significantly reduced swimming capabilities.

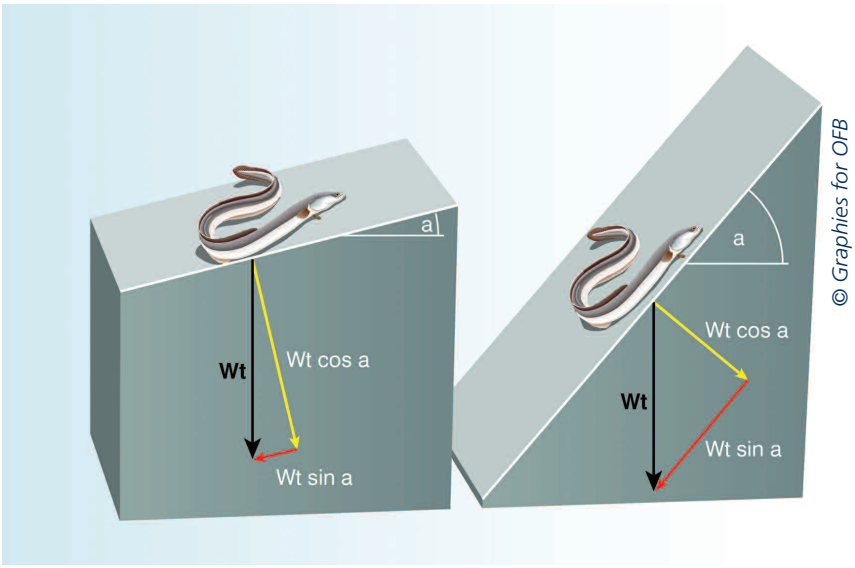
Slope

On the basis of experiments carried out on test installations (Legault, 1992; Voegtlé and Larinier, 2000; Lagarde *et al.*, 2016), the slope of a crawl way was deemed the main parameter in determining the passability of an obstacle.

Taking "a" as the slope of the surface expressed as an elevation angle (in degrees), the weight of a fish can be broken down into a normal component (Wt cos a) and a tangential component (Wt sin a) (Figure 76). 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 (Table 23).

For the slightest slopes, less than or equal to 20 to 30% (e.g. 15°, Voegtlé and Larinier, 2000), eels are less sensitive to breaks in roughness or to increases in the hydraulic conditions. 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 the surface tension is not an essential factor (Figure 76). Such slight slopes also correspond to nappe flows where eels may progress more rapidly by swimming, if the hydraulic conditions permit.

Figure 76



© Graphies for OFB

Breakdown of an eel's weight (Wt) into two components, one favourable to maintaining the eel in place in yellow and the other unfavourable in red. After Baudoin et al.*, 2014.*

The greater the angle of the slope, the greater the effort that eels must make to progress up the slope. Starting with slopes in the 100 to 175% (45 to 60°) range, eels 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, which must find support points in sufficient number, but not too closely positioned.

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 conditions, neither of which, in general, can be precisely measured.

However, any camber (lateral slope) in the crawl way can significantly limit the passage capabilities of eels.

Table 23 *Approximate values for the favourable (cos a) and unfavourable (sin a) parameters for passage of eels by crawling, as a function of the slope. After Baudoin* et al.*, 2014*

	Slope (% and equivalent in degrees)									
	14%	32%	48%	100%	130%	173%	230%	300%	500%	∞
	8°	18°	26°	45°	53°	60°	66°	72°	79°	90°
cos a	0.99	0.95	0.90	0.70	0.60	0.50	0.40	0.31	0.20	0.00
sin a	0.14	0.31	0.43	0.70	0.80	0.87	0.91	0.95	0.98	1.00

N.B. The assessment of passability by crawling must take into account the steepest of the longitudinal and latitudinal slopes (camber) in the crawl way (Figure 75e).

Distance to be overcome

In light of current knowledge and in a pragmatic approach, it was judged, similar to the case for eels in the ICE method for continental France, 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 for each biological stage is to determine the passability of structures by combining two factors, the length and the slope of the potential crawl way.

If the crawl way is made up of different sections (different slopes), each section should be assessed separately.

Similar to the European eel (*Anguilla anguilla*, Figure 77a), the crawling capabilities of *A. rostrata* (Martinique and Guadeloupe), *A. marmorata*, *A. mossambica* (Figure 77b), *A. bicolor bicolor* and *A. bengalis* (Réunion and Mayotte) depend on the size of each fish and on the configuration of the obstacle.

Figure 77

a © V. Marty, OFB
b © P. Valade, Ocea Consult'

(a) European eels, a glass eel and an elver (A. anguilla), (b) An African longfin eel (A. mossambica).

Determining passability classes

■ Threshold values used in the decision tree

Tables 24, 25 and 26 indicate the applicable passability class as a function of the slope and the distance to be covered for the three subgroups of eels.

These tables are accompanied by a decision tree (Figure 78) showing how to determine the ICE passability classes.

Table 24 *Passability classes for structures offering a crawl way for Subgroup 3a (eels > 500 mm in length) as a function of the slope and the length of the crawl way.*

Slope P (in %)	Distance 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	1	0.66	0.33	0.33	0	0
100 < P ≤ 150	1	0.66	0.33	0.33	0	0	0
150 < P ≤ 300	1	0.66	0.33	0	0	0	0
300 < P ≤ ∞	1	0.33	0	0	0	0	0

Table 25 *Passability classes for structures offering a crawl way for Subgroup 3b (eels between 100 and 500 mm in length) as a function of the slope and the length of the crawl way.*

Slope P (in %)	Distance 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
300 < P ≤ ∞	0.66	0.33	0	0	0	0	0

Table 26 *Passability classes for structures offering a crawl way for Subgroup 3c (glass eels < 100 mm in length) as a function of the slope and the length of the crawl way.*

Slope P (in %)	Distance 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
300 < P ≤ ∞	0.66	0.66	0.66	0.33	0	0	0

■ Decision tree

The steps in determining the ICE passability class of structures for crawling eels are presented below.

1. Check that a crawl way exists

If one or more continuous passageways exist with a very low flow depth (< 5 cm for Subgroup 3a, < 2 cm for Subgroup 3b, < 1 cm for Subgroup 3c), then plot the longitudinal profile of the potential passageways (or simply that of the most favourable of the passageways) and go to Step 2.

If no crawl ways exist, eels are required to swim. In this case, go directly to Step 3.

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 2), it will be possible to decide whether or not to return to the site for measurements under other discharge conditions.

2. Analysis of structure passability by crawling

First, determine the ICE passability class on the basis of the total, cumulative length and the average slope of each crawl way, using Tables 24 to 26.

If a given crawl way consists of different sections, determine the passability class of each section using the same tables. If one or more of the sections are assigned an ICE passability class lower than the class for the crawl way as a whole, the lowest class determines the result for the entire crawl way.

If a number of potential crawl ways exist, go through the same procedure for each crawl way and, among the results, select the highest ICE passability class for the structure as a whole.

Then go to Step 3.

3. Determine the passability of the structure by swimming (whether or not crawl ways exist)

For elvers and yellow eels, determine passability using the various decision trees for the different types of structures in the same manner as for the other fish species.

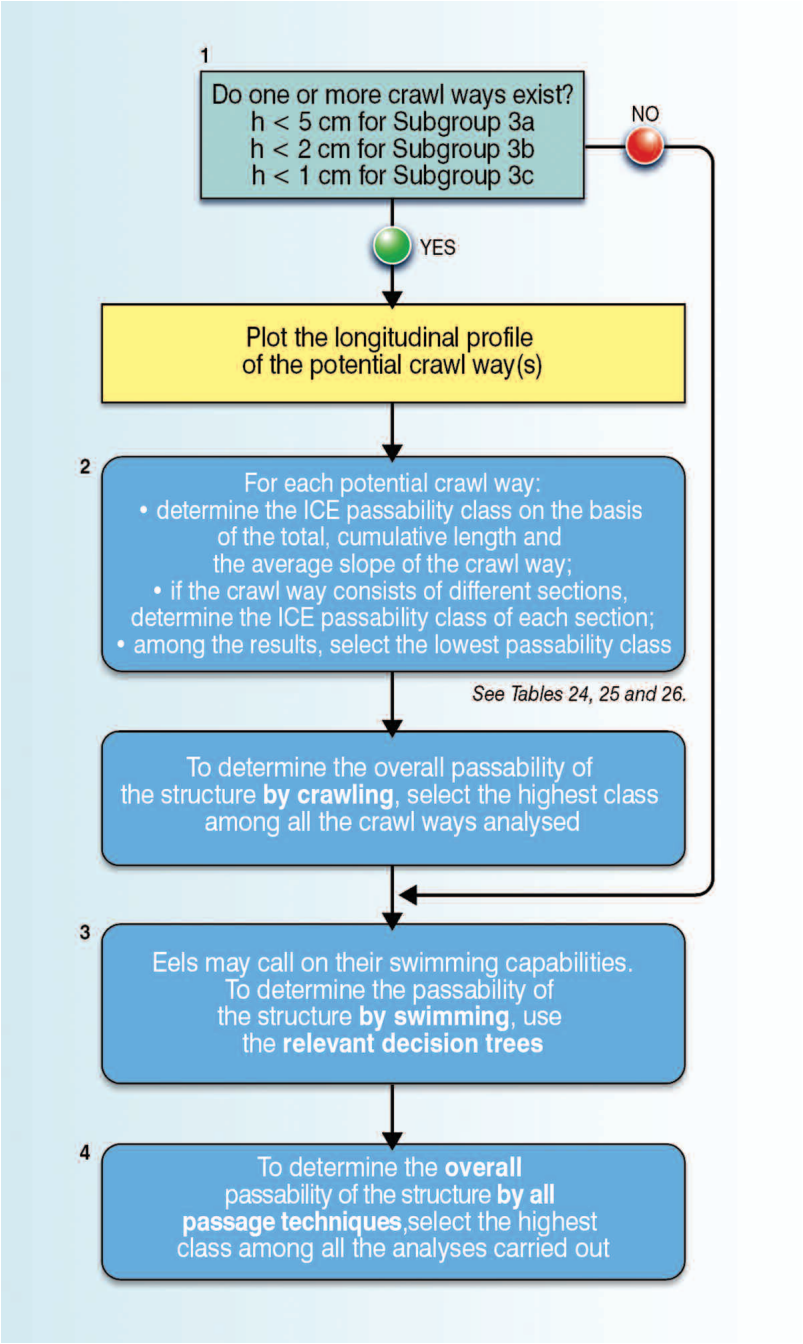
For glass eels, the obstacle may be considered a total barrier (ICE class = 0).

Go to Step 4.

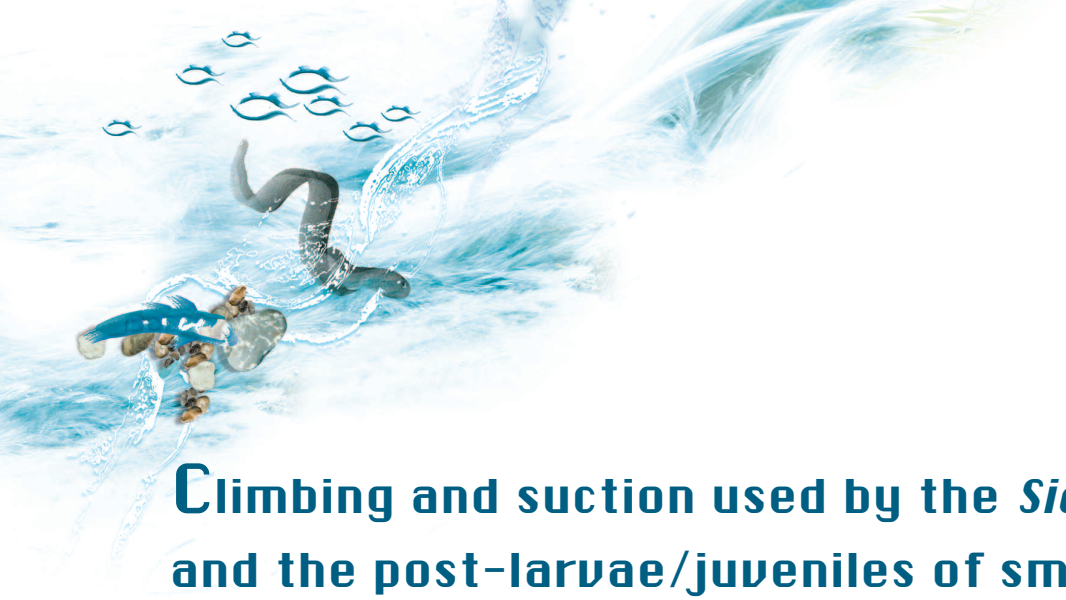
4. Determine overall passability of the structure taking into account all passage techniques

For the structure as a whole, select the highest ICE passability class among those calculated for passage by crawling (Step 2) and those calculated for passage by swimming (Step 3).

Figure 78



Decision tree to determine ICE passability classes for crawling eels.



Climbing and suction used by the *Sicydiinae* and the post-larvae/juveniles of small, benthic species

Specific approach

■ General

The ventral fins of the *Gobiidae Sicydiinae* species (Group 4) are joined to form a suction cup that the fish can use to climb steep walls. They can also use their mouths and/or pectoral fins.

This technique using the suction cup is employed by the fish primarily when the water depth or the flow velocities are not compatible with their swimming capabilities.

In addition, the post-larval stages and the juveniles of small, benthic species (Subgroup 1b) can use the surface tension of wet surfaces to overcome subvertical obstacles along the watered river bed.

During their growth, however, similar to eels, the weight to surface tension ratio increases, which explains why the smallest fish can make the most use of this technique to climb vertical walls and why this capability declines with their increase in size. Consequently only the post-larvae and juveniles of the benthic species in Group 1 are capable of climbing.

■ Size and specific aspects

To take into account the specific aspects of each stage and/or group of species, **three subgroups were created:**

- **Subgroup 1b**, comprising the post-larval and juvenile stages of the small, benthic species in Group 1, i.e. the *Eleotridae* and the *Gobiidae* (except *Sicydiinae*);
- **Subgroup 4a**, comprising the *Sicydiinae* subadults and adults. The fish vary in length between 40 and 150 mm;
- **Subgroup 4b**, comprising the *Sicydiinae* post-larvae and juveniles. Depending on the species, the fish vary in length between 15 and 40 mm.

■ Passability criteria

Similar to the other species, threshold values for the passability classes are presented in the tables used with the various decision trees (see the previous sections addressing each type of obstacle).

However, **diagnosis of structure passability by these three subgroups (1b, 4a, 4b) must take into account their specific climbing and suction techniques.** That is why it appeared necessary to formulate specific passability criteria for these techniques.

The proposed method is relatively similar to that presented above for the assessment of passability by crawling eels. The proposed solution is first to check that one or more potential passageways (climbing or suction) exist for the fish and then to assess their passability on the basis of two criteria that are simple to measure or estimate, i.e. the distance the fish must cover and the slope of the passageway. If the passageway is made up of different sections (different slopes), each section should be assessed separately.

Check that a passageway exists for the climbing and suction techniques

The existence of potential rest zones in the passageway can also significantly increase the chances of passage. Similar to young eels, one part of the population can overcome some relatively high, natural waterfalls (a few dozen metres), particularly when the waterfalls are located in the lower sections of rivers and the population consists of a majority of very young fish (better climbing and suction capabilities up vertical walls by the smallest fish, see below).

There are very few objective data available on *in situ* passage conditions for natural and man-made obstacles by *Sicydiinae* or the post-larvae and juveniles of small, benthic species, given that such information is very difficult to acquire without employing major human and material resources. This is due in large part to the great variability of factors likely to influence the passage of an obstacle in the natural environment, e.g. simultaneity of migratory flows and favourable hydrological conditions for passage of the obstacle, the physiological condition of the fish, the heterogeneity of obstacle configurations, major variation in hydraulic conditions, etc.

However, studies carried out on test installations, notably on Réunion (Voegtlé *et al.*, 2000; Lagarde *et al.*, 2016), show (*a minima* for *Sicydiinae*) that:

- whatever the slope and flow conditions, the type of surface would appear to have a relatively minor impact on passage capabilities, even if fish clearly prefer smoother surfaces (natural rocks, concrete, steel) to rougher surfaces that make use of the suction cup more difficult;
- upstream migration is easier if the fish can travel over a surface that is just barely humidified (very thin sheet of water);
- the greater the slope, the lower the percentage of successful passages. On average, 58% of fish can overcome a 50° slope, 45% a 70° slope and only 20% a 90° slope.

A passageway for the climbing and suction techniques is characterised by a continuous section where the water depth is very low, less than 1 cm, between the downstream and upstream parts of the structure. In general, this type of passageway for the *Sicydiinae* and the post-larvae and juveniles of small, benthic species may also be considered a potential crawl way for glass eels and a walkway for macro-crustaceans (Figure 75).

Caution. In addition to the climbing and suction techniques, the fish may simply swim over the obstacle. In this case, for each of the subgroups, the decision trees presented in the previous sections for each type of obstacle should be used.

Slope

On the basis of experiments, among other factors, carried out on test installations (Voegtlé *et al.*, 2002; Lagarde *et al.*, 2016), the slope of a potential passageway for the climbing and suction techniques was deemed the main parameter in determining the passability of an obstacle.

On the slightest slopes (≤ 20-30%), the fish, similar to eels, must overcome only a small fraction of their weight. Over 90% of their weight helps them maintain their position and they essentially do not need to call on the surface tension or the suction technique (Figure 76 and Table 23). The greater the angle of the slope, the greater the effort that fish must make to progress up the slope. Starting with slopes in the 100 to 175% (45 to 60°) range, fish 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 surface. The surface tension and the suction technique are then indispensable in helping them maintain their position on the surface.

These conditions favour the smallest fish.

N.B. The assessment of passability by the climbing and suction techniques must take into account the steepest of the longitudinal and latitudinal slopes (camber) in the passageway (Figure 75).

Distance to be overcome

In light of current knowledge and in a pragmatic approach, it was judged, similar to the case for eels, that the greater the distance to be overcome, the greater the probability that a fish will encounter excessive flow velocities, unsuitable water depths and/or breaks in the slope that are not compatible with its climbing or suction capabilities. In addition, the greater the slope, the faster the fish will tire. It should also be noted that Lagarde *et al.* (2000) revealed that, compared to *S. lagocephalus*, *Cotylopus* juveniles have lesser passability capabilities. However, these factors were not taken into account here in the interest of simplicity.

The proposed solution for each subgroup is to determine the passability of structures by combining two factors, the length and the slope of the potential passageway using the climbing and suction techniques.

If the passageway is made up of different sections (different slopes), each section should be assessed separately.

Determining passability classes

■ Threshold values used in the decision tree

Tables 27, 28 and 29 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 (Figure 79) showing how to determine the ICE passability classes.

Table 27 *Passability classes for structures offering a passageway by climbing for Subgroup 1b (post-larvae and juveniles of small, benthic species, i.e.* Eleotridae *and* Gobiidae *except* Sicydiinae*) as a function of the slope and the length of the passageway.*

Slope P (in %)	Distance 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 ≤ 75	1	1	1	1	1	0.66	0.66
75 < P ≤ 150	1	1	1	1	0.66	0.66	0.33
150 < P ≤ 300	1	1	1	0.66	0.66	0.33	0.33
300 < P ≤ 600	1	1	0.66	0.66	0.33	0.33	0
600 < P ≤ ∞	1	0.66	0.66	0.33	0.33	0	0

Table 28 *Passability classes for structures offering a passageway (suction technique) for Subgroup 4a (*Gobiidae Sicydiinae *sub-adults and adults) as a function of the slope and the length of the passageway.*

Slope P (in %)	Distance 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 ≤ 75	1	1	1	1	1	1	0.66
75 < P ≤ 150	1	1	1	1	1	0.66	0.66
150 < P ≤ 300	1	1	1	1	0.66	0.66	0.33
300 < P ≤ 600	1	1	1	0.66	0.66	0.33	0.33
600 < P ≤ ∞	1	1	1	0.66	0.33	0.33	0.33

Table 29 *Passability classes for structures offering a passageway (suction technique) for Subgroup 4b (*Gobiidae Sicydiinae *post-larvae and juveniles) as a function of the slope and the length of the passageway.*

Slope P (in %)	Distance 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 ≤ 150	1	1	1	1	1	1	1
150 < P ≤ 300	1	1	1	1	1	1	0.66
300 < P ≤ 600	1	1	1	1	1	0.66	0.66
600 < P ≤ ∞	1	1	1	1	0.66	0.66	0.66

N.B. **Some structures and natural waterfalls may have potential passageways with more or less camber or overhangs.** In certain cases, as long as the surfaces remain wet**, the passageway may provide some degree of passage (notably for *Sicydiinae*).** Given the extreme variability of the possible configurations (camber, overhangs, large cracks, etc.), it is currently difficult to devise simple criteria to determine the passability of the potential passageways. **In these cases, the person running the assessment must study the situation and use their judgement to assign a passability class.**

■ Decision tree

The steps in determining the passability of a structure using the climbing or suction techniques by *Sicydiinae* or the post-larvae and juveniles of small, benthic species (Subgroups 1b, 4a and 4b) are presented below.

1. Check that a passageway exists for the climbing and suction techniques

If one or more continuous passageways exist with a very low flow depth (< 1 cm approximately), then plot the longitudinal profile of the potential passageways (or simply that of the most favourable of the passageways) and go to Step 2.

If no passageways exist, fish are required to swim. In this case, go directly to Step 3.

However, if a passageway is not manifest, it may nonetheless be worthwhile to determine the passability class for more favourable hydrological conditions under which a passageway may appear. Depending on the score of the subsequent analysis (Step 2), it will be possible to decide whether or not to return to the site for measurements under other discharge conditions.

2. Analysis of structure passability using the climbing and suction techniques

First, determine the ICE passability class on the basis of the total, cumulative length and the average slope of each passageway, using Tables 27 to 29.

If a given passageway consists of different sections, determine the ICE 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 passageway as a whole, the lowest class determines the result for the entire passageway.

If a number of potential passageways exist, go through the same procedure for each one and, among the results, select the highest ICE passability class for the structure as a whole.

Then go to Step 3.

3. Determine the passability of the structure by swimming (whether or not passageways using the climbing and suction techniques exist)

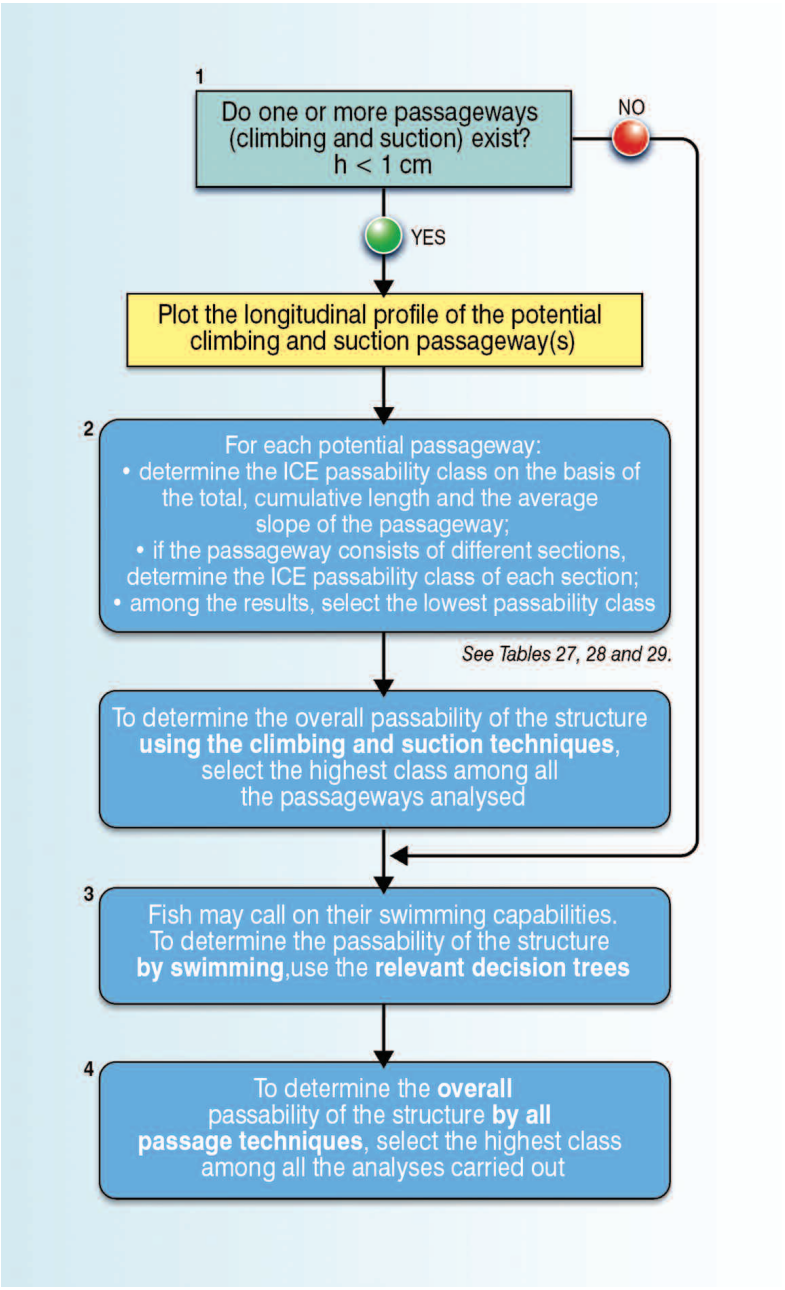
Determine passability by swimming using the various decision trees for the different types of structures in the same manner as for the other fish species.

Go to Step 4.

4. Determine overall passability of the structure taking into account all passage techniques

For the structure as a whole, select the highest ICE passability class among those calculated for passage using the climbing and suction techniques (Step 2) and those calculated for passage by swimming (Step 3).

Figure 79



Decision tree to determine ICE passability classes using the climbing and suction techniques by Sicydiinae *and the post-larvae and juveniles of small, benthic species.*

The walking capabilities of macro-crustaceans

Specific approach

■ General

Decapod macro-crustaceans (Group 5) have limited swimming and jumping capabilities, with the exception of a few special cases such as *Xiphocaris elongata*.

On the other hand, they have excellent walking capabilities given their five pairs of legs (pereiopods). This technique is employed by these species primarily when the water depth is very low or the flow velocities exceed their swimming capabilities.

These species may reasonably be expected to find more favourable passage conditions along the edges of flows (lower flow velocities and less turbulence) than in areas with stronger flows.

Crustaceans mainly use three pairs of legs, namely the pereiopods P3, P4 and P5, but they can also grasp objects with the pincers at the end of the pereiopods P1. This technique enables small crustaceans to climb wet, vertical walls and even to overcome overhangs.

For the species in the *Macrobrachium* genus, the relatively large size and weight of adults can reduce their passage capabilities on vertical and subvertical walls, when compared with juveniles. On the other hand, given their small size, the passage capabilities of adults in species in the *Atyidae* and *Xiphocarididae* families are not significantly reduced by their growth.

■ Subgroups

To take into account the specific aspects of each stage and/or species, **two subgroups were created:**

■ **Subgroup 5a** comprises the adults and subadults of species in the *Macrobrachium* genus and amphidromous, freshwater crabs (*Grapsidae*). These crustaceans have strong passage capabilities on wet surfaces, but have difficulties in overcoming vertical walls, particularly over long distances;

■ **Subgroup 5b** comprises the species in the *Atyidae* and *Xiphocarididae* families (all stages), and the juveniles of the species in Subgroup 5a. This subgroup has even greater passage capabilities than Subgroup 5a for wet, vertical and even overhanging surfaces.

■ Passability criteria

The proposed method is relatively similar to those presented above for the assessment of passability using the crawling or the climbing/suction techniques.

The first step is to check that one or more potential walkways exist for the macro-crustaceans and then to assess their passability on the basis of two criteria that are simple to measure or estimate, i.e. the distance the crustaceans must cover and the slope of the walkway(s). If the walkway is made up of different sections (different slopes), each section should be assessed separately.

Check that a favourable walkway exists

Objective data on *in situ* passage conditions over natural or man-made obstacles by macro-crustaceans are in short supply, given that such information is very difficult to acquire without employing major human and material resources due to the extreme variability of the factors likely to influence passage in the natural environment, e.g. simultaneity of migratory flows and favourable hydrological conditions for passage of the obstacle, the physiological condition of the crustaceans, the heterogeneity of obstacle configurations, major variation in hydraulic conditions, etc.

That notwithstanding, visual observations of crustaceans making progress (Voegtlé and Valade, personal observation) **would indicate that a favourable walkway is an area with a very low water depth (< 1 cm) from the downstream to the upstream part of the structure.** It is therefore reasonable to assume that a favourable walkway for macro-crustaceans is similar to passageways using the climbing and suction techniques or crawl ways for glass eels (Figure 75).

N.B. In general, a man-made obstacle creates flows that are not conducive to direct passage by walking in the main flows (plunging jet, high flow velocities), which leads, by simplification, to assuming that the more favourable passageway for decapod crustaceans is a walkway (if it exists) along the flow. **However**, in **certain cases** (rock weirs between two side walls, concentrated flows between wing walls, etc.), **passageways in deeper areas may exist, on the condition that flow velocities along the bottom not exceed certain limits. Given currently available knowledge, the existence, description and degree of passability requires study by a competent technician.**

Slope

On the basis of experiments, among other factors, carried out on test installations (Voegtlé *et al.*, 2002; Lagarde *et al.*, 2016), the slope of a potential walkway was deemed the main parameter in determining the passability of an obstacle.

On the slightest slopes (≤ 20-30%), the crustaceans, similar to eels, must overcome only a small fraction of their weight (Figure 76 and Table 23).

The greater the angle of the slope, the greater the effort that crustaceans must make to progress up the slope (Hamano *et al.*, 1995; Fièvet, 1999b). Starting with slopes in the 100 to 175% (45 to 60°) range, crustaceans 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 surface.

These conditions favour the smallest crustaceans.

N.B. **The assessment of passability by walking must take into account the steepest of the longitudinal and latitudinal slopes (camber) in the walkway (Figure 75).**

Distance to be overcome

In light of current knowledge and in a pragmatic approach, it was judged, similar to the case for eels and *Gobiidae*, that the greater the distance to be overcome, the greater the probability that a macro-crustacean will encounter excessive flow velocities, unsuitable water depths and/or breaks in the slope that are not compatible with its walking capabilities. In addition, the greater the slope, the faster the crustacean will tire.

The proposed solution for each subgroup is to determine the passability of structures by combining two factors, the length and the slope of the potential walkway.

If the walkway is made up of different sections (different slopes), each section should be assessed separately.

Determining passability classes

■ Threshold values used in the decision tree

Tables 30 and 31 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 (Figure 80) showing how to determine the ICE passability classes.

Table 30 *Passability classes for structures offering a walkway for Subgroup 5a (*Grapsidae *and* Palaemonidae *sub-adults and adults) as a function of the slope and the length of the walkway.*

Slope P (in %)	Distance 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 ≤ 75	1	1	1	1	1	0.66	0.66
75 < P ≤ 150	1	1	1	1	0.66	0.66	0.33
150 < P ≤ 300	1	1	1	0.66	0.66	0.33	0.33
300 < P ≤ 600	1	1	0.66	0.66	0.33	0.33	0.33
600 < P ≤ ∞	1	0.66	0.66	0.33	0.33	0.33	0

Table 31 *Passability classes for structures offering a walkway for Subgroup 5b (*Atyidae, Xiphocarididae *and juveniles in the* Grapsidae *and* Palaemonidae *families) as a function of the slope and the length of the walkway.*

Slope P (in %)	Distance 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 ≤ 75	1	1	1	1	1	1	1
75 < P ≤ 150	1	1	1	1	1	1	1
150 < P ≤ 300	1	1	1	1	1	1	1
300 < P ≤ 600	1	1	1	1	1	1	1
600 < P ≤ ∞	1	1	1	1	1	0.66	0.66

■ Decision tree

The steps in determining the ICE passability class of structures for walking crustaceans are presented below.

1. Check that a walkway exists

If one or more continuous walkways exist with a very low flow depth (< 1 cm approximately), then plot the longitudinal profile of the potential walkways (or simply that of the most favourable of the walkways) and go to Step 2.

Otherwise, go to Step 3.

However, if a walkway is not manifest, it may nonetheless be worthwhile to determine the passability class for more favourable hydrological conditions under which a walkway may appear. Depending on the score of the subsequent analysis (Step 2), it will be possible to decide whether or not to return to the site for measurements under other discharge conditions.

2. Analysis of structure passability by walking

First, determine the ICE passability class on the basis of the total, cumulative length and the average slope of each walkway, using Tables 30 and 31.

If a given walkway 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 walkway as a whole, the lowest class determines the result for the entire walkway.

If a number of potential walkways exist, go through the same procedure for each walkway and, among the results, select the highest ICE passability class for the structure as a whole.

Then go to Step 3.

3. Analyse the passability of the structure by other potential passageways (whether or not walkways with low water depths exist)

On studying the situation, do any other potential passageways exist in areas with deeper water?

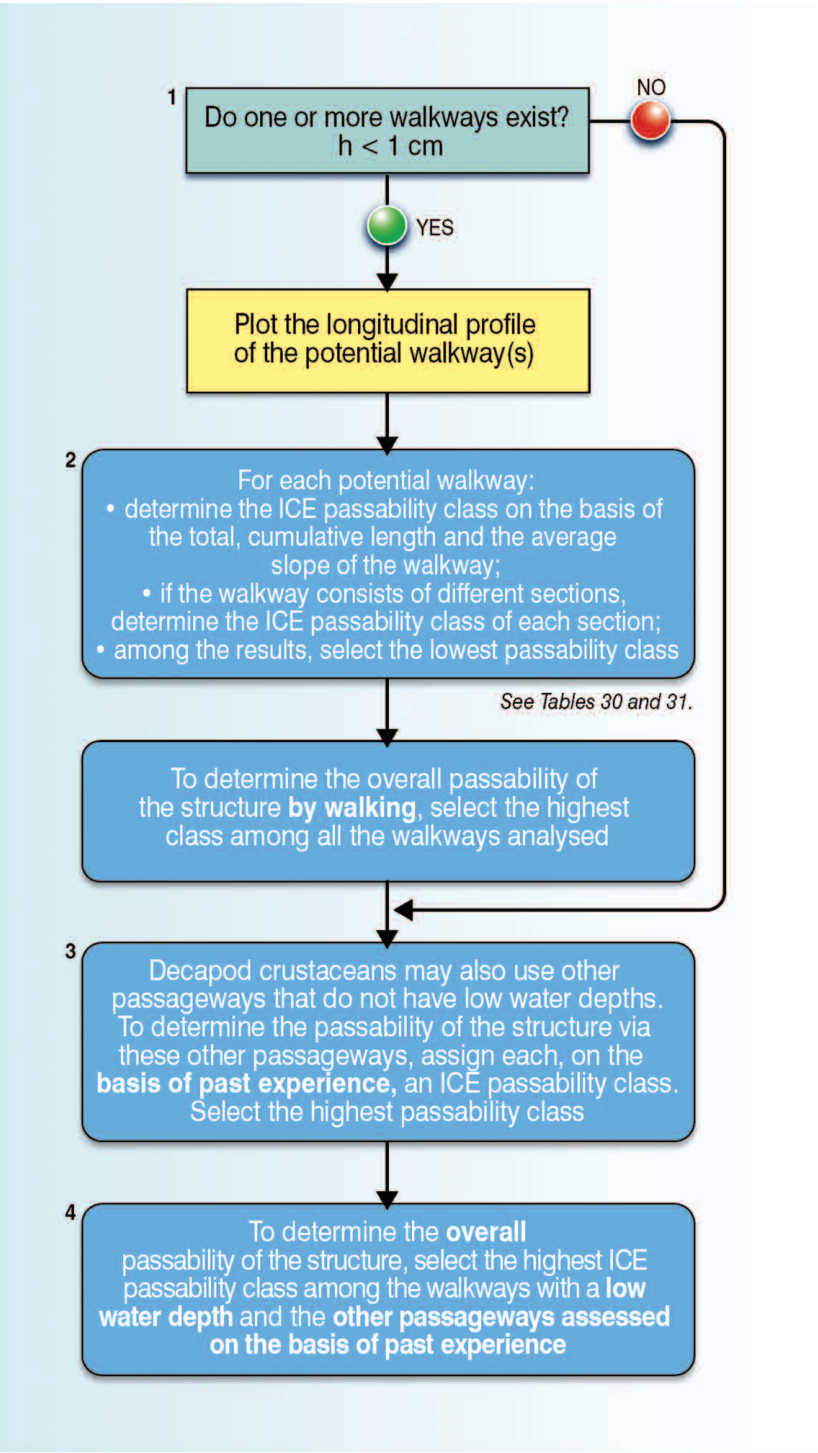
If so, assess the passageways and, on the basis of past experience, assign a passability class to each, then select the highest ICE passability class among the results.

Go to Step 4.

4. Determine the overall passability of the structure

For the structure as a whole, select the highest ICE passability class among those calculated for passage using a walkway with a low water depth (Step 2) and those calculated on the basis of past experience for other passageways (Step 3).

Figure 80



Decision tree to determine ICE passability classes for walking macro-crustaceans.

References

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 a_{max} and c_{max} 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 a_{max} and c_{max} 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 (expressed in metres), i.e. the difference between the water levels upstream ($Z_{upstream}$) and downstream ($Z_{downstream}$).
  - DH_{max}: Maximum theoretical head-drop that can be overcome by a fish of length Lp_{max}.
  - DH_{min}: Maximum theoretical head-drop that can be overcome by a fish of length Lp_{min}.
  - DH_{avg}: Maximum theoretical head-drop that can be overcome by a fish of length Lp_{avg}.
  - $DH_{extreme}$: The head-drop (for vertical weirs, inclined faces and flows under gates) 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 DH_{max} 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 $DH_{extreme}$, the structure necessarily constitutes a total barrier.
- **g:** The acceleration of gravity (9.81 m/s²).
- **h:** The depth of a flow of water (expressed in metres).
  - h_{min}: Absolute minimum depth (or minimum thickness of a sheet of water) required for a fish to swim. The value is a function of the size and morphology of the fish. In the ICE method, the value of h_{min} is indicated for each species or group of species. It corresponds roughly to 1.5 times the average body depth (hp_{avg}) of the species or group of species under consideration. This parameter is used in diagnosing the passability of inclined weirs.
  - $h_{min\ rock}$: Absolute minimum depth (or minimum thickness of a sheet of water) required for a fish to swim and to provide smooth flow over a rock weir. The value is a function of the morphology of the fish and of the slope of the glacis. In the ICE method, the value of $h_{min\ rock}$ is indicated for each species or group of species. This parameter is used in diagnosing the passability of rock weirs.

- **hp:** Body depth of fish (expressed in metres). The value is a function of the morphology of the fish and corresponds to a form factor (**k**) multiplied by the length of the fish.

  hp_{min}: Minimum body depth of a species or of a given biological stage. This body depth corresponds to a fish of length **Lp_{min}**.

  hp_{max}: Maximum body depth of a species or of a given biological stage. This body depth corresponds to a fish of length **Lp_{max}**.

  hp_{avg}: Body depth corresponding to the average between **hp_{min}** and **hp_{max}**. This body depth corresponds to a fish of length **Lp_{avg}**.

- **H:** Hydraulic head of water over a spillway, notch or gate (expressed in metres).

  $H_{upstream}$: The depth of water behind a gate. This parameter is used for ICE diagnoses of flows under gates or through orifices under pressure, but where the downstream outflow is free.

  H_{min}: Absolute minimum hydraulic head enabling the passage of a species. 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 diagnosing the passability of vertical waterfalls.

- **Hf:** Depth of the water in the plunge pool at the foot of an obstacle (expressed in metres).

  Hf_{min}: 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 diagnosing the passability of vertical and subvertical waterfalls and for inclined weirs.

- **k:** Form factor of a fish (dimensionless). The value is a function of the morphology of the fish. It corresponds to the body depth of the fish (**hp**) divided by the length of the fish (**Lp**).

- **L:** Length of a structure that must be overcome (expressed in metres). This parameter is used when diagnosing the passability of road and rail structures and in special cases for eels when a crawl way exists.

  Lp: Total length of a fish (expressed in metres).

  Lp_{min}: Minimum length of a given species or biological stage taken into account in the ICE method.

  Lp_{max}: Maximum length of a given species or biological stage taken into account in the ICE method.

  Lp_{avg}: Length corresponding to the average between **Lp_{min}** and **Lp_{max}** of a given species or biological stage taken into account in the ICE method.

- **n:** Manning coefficient (dimensionless). This coefficient represents the roughness of the river bed and banks.

- **OV:** Opening of a gate (expressed in metres).

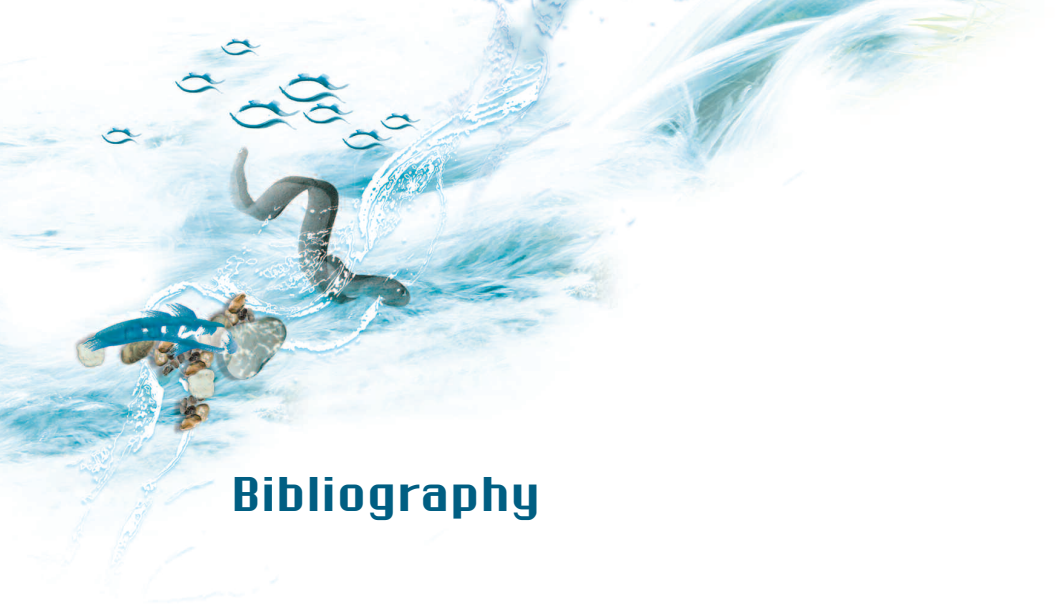
  OV_{min}: Absolute minimum opening (expressed in metres) of a gate required for the passage of the given fish species. In the ICE method, the value of **OV_{min}** is indicated for each species or group of species. This value is used in diagnosing the passability of gates (via flows under the gate).

- **P_{aer}:** Maximum muscular power (expressed in watts) developed during aerobic glycolysis. It is proportional to the maximum cruising speed **U_{cr}** prior to the shift to anaerobic conditions.

- **P_{ana}:** Maximum muscular power (expressed in watts) developed during anaerobic glycolysis. It is proportional to the maximum speed **U_{max}**.

- **q:** Unit discharge, i.e. the discharge per meter width (expressed in $m^3/s/m$ or m^2/s).

- **t or t_U:** Time (or endurance, expressed in seconds) during which a fish can swim at speed **U**. The endurance of a fish t_{Umax} at its top speed U_{max} is generally between 10 and 20 seconds.
- **U:** Swimming speed of a fish (expressed in metres per second).
  - U_{max}: Maximum (also top or sprint) swimming speed of a fish.
  - 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).
- 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.
- 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, for the ICE diagnosis, part of the length of the fish is added to the calculated value.
- $Z_{upstream}$: Elevation of the water line upstream of an obstacle (expressed in metres or metres asl).
- $Z_{downstream}$: Elevation of the water line downstream of an obstacle (expressed in metres or metres asl).
- Z_{weir}: Elevation of a weir (expressed in metres or metres asl).



Bibliography

- Aboussouan A. (1969). Note sur les « bichiques » de l'île de La Réunion. Revue des Travaux de la Station Marine d'Endoume 9 : 25-31.
- Antea, Ocea Consult', Hydrétudes, Ecogea (2011). Évaluation de la continuité écologique des 13 rivières pérennes de la Réunion. Rapports pour la DEAL, Service Eau et Biodiversité.
- Arda (2012). Observation des Flux Migratoires de poissons et de macro-crustacés diadromes de la Réunion. Rapport final. Soutien FEDER, Région Réunion et DEAL Réunion.
- Balon E.K., Bruton M.N. (1994). Fishes of the Tatinga River, Comoros, with comments on freshwater amphidromy in the goby *Sicyopterus lagocephalus*. Ichthyological Exploration of Freshwaters 5: 25-40.
- Baudoin J.M., Burgun V., Chanseau M., Larinier M., Ovidio M., Sremski W., Steinbach P., Voegtlé B. (2014). Évaluer le franchissement des obstacles par les poissons. Principes et méthodes. Onema. 200 pages.
- Bauer R.T. (2011). Amphidromy and migrations of freshwater shrimps. II. Delivery of hatching larvae to the sea, return juvenile upstream migration, and human impacts. New Frontiers in Crustacean Biology: 157-168.
- Bauer R.T. (2013). Amphidromy in shrimps: a life cycle between rivers and the sea. Latin American Journal of Aquatic Research 41: 633-650.
- Bauer R.T., Delahoussaye J. (2008). Life History Migrations of the Amphidromous River Shrimp Macrobrachium Ohione from a Continental Large River System. Journal of Crustacean Biology 28: 622-632.
- Beach M.H. (1984). Fish pass design. Criteria for the design and approval of fish passes and other structures to facilitate the passage of migratory fishes in rivers. Ministry of Agriculture, Fisheries and Food, Lowestoft, Fisheries Research Technical Report 78, 45p.
- Bell K. (1997). Complex recruitment dynamics with Doppler-like effects caused by shifts and cycles in age-at-recruitment. Canadian Journal of Fisheries and Aquatic Sciences 54: 1668-1681.
- Bell K. (1999). An overview of goby-fry fisheries. Naga, the ICLARM quarterly 22: 30-36.
- Bell K. (2009). What Comes Down Must Go Up: The Migration Cycle of Juvenile-Return Anadromous Taxa. American Fisheries Society Symposium 69: 321-341.
- Bell K., Brown J.A. (1995). Active salinity choice and enhanced swimming endurance in 0 to 8-d-old larvae of diadromous gobies, including *Sicydium punctatum* (Pisces), in Dominica, West Indies. Marine Biology 121: 409-417.
- Bell M.C., (1986). Fisheries handbook of engineering requirements and biological criteria. Fish. Eng. Res. Prog., U.S. Army Corps of Eng., North Pacific Div., Portland, Oregon, 290 p.
- Bell M.C., Delacy A.C. (1972). A compendium on the survival of fish passing through spillways and conduits. Fish. Eng. Prog., U.S.Army Corps of Eng., North Pacific Div., Portland, Oregon, 121p.
- Blanco J.F., Scatena F.N. (2007). The spatial arrangement of neritina virginea (*gastropoda*: *neritidae*) during upstream migration in a split-channel reach. River Research and Applications 23: 235-245.
- Blaxter J.H.S., Dixon W. (1959). Observations on the swimming speeds of fish. Journal du Conseil Permanent International pour l'Exploration de la Mer 24(3) : 472-479.
- Blob R.W., Rai R., Julius M.L., Schoenfuss H.L. (2006). Functional diversity in extreme environments: effects of locomotor style and substrate texture on the waterfall-climbing performance of Hawaiian gobiid fishes. Journal of Zoology 268: 315-324.
- Burgun V., Chanseau M., Kreutzenberger K., Marty V., Pénil C., Tual M., Voegtlé B. (2015). ICE. Informations sur la continuité écologique. Protocole de terrain pour l'acquisition des données. Onema. Collection Guides et Protocoles, 84p.

■ Castro-Santos T. (2006). Modeling the effect of varying swim speeds on fish passage through velocity barriers. Transactions of the American Fisheries Society 135: 1230-1237.
■ Chanseau M., Croze O., Larinier M. (1999). Impact des aménagements sur la migration anadrome du saumon atlantique (Salmo salar L.) sur le gave de Pau (France). Bulletin Français de la Pêche et de la Pisciculture : 211-237.
■ Clough S.C., Lee-Elliott I.H., Turnpenny A.W.H., Holden S.D.J., Hinks C. (2002). Swimming speeds in fish: Phase 2. R & D Technical Report W2-026/TR3, Environment Agency.
■ Clough S.C., Turnpenny A.W.H. (2001). Swimming speeds in fish: Phase 1. R & D Technical Report W2-026/TR1, Environment Agency, Bristol, 94 pp.
■ Courret D., Larinier M. (2008). Guide pour la conception de prises d'eau « ichyocompatibles » pour les petites centrales hydroélectriques. Rapport ADEME - GHAAPPE. 60p +annexes.
■ Covich A.P., Crowl T.A, Hein C.L., Townsend M.J., McDowell W.H. (2009). Predator-prey interactions in river networks: Comparing shrimp spatial refugia in two drainage basins. Freshwater Biology 54: 450-465.
■ Cruz (1987). Reproductive biology and feeding habits of Cuyamel, Joturus pichardi, and Tepemechín, *Agonostomus monticola* (Pisces; *Mugilidae*) from Río Plátano, Mosquitia, Honduras. Bulletin of Marine Science 40: 63-72.
■ Delacroix P., Champeau A. (1992). Ponte en eau douce de *Sicyopterus lagocephalus* (Pallas) poisson *Gobiidae* amphibionte des rivières de la Réunion. Hydroécologie Appliquée 1: 49-63.
■ DWA, (2006). Funktionskontrolle von Fischaufstiegsanlagen [Monitoring of effectiveness of fish upstream migration facilities], DWA-Themen, p. 35, 41, 42, 45, 112-118.
■ Egis Environnement - Hydrosphère (2007-2008). Étude de l'impact des modifications des conditions d'éclairement des cours d'eau franchis par des infrastructures de transport sur la circulation piscicole. Rapport pour le ministère de l'Écologie, du Développement et de l'Aménagement durables. Rapports phase 1 et 2.
■ Ellien C., Werner U., Keith P. (2014). Morphological changes during the transition from freshwater to sea water in an amphidromous goby, *Sicyopterus lagocephalus* (Pallas 1770) (*Teleostei*). Ecology of Freshwater Fish 25: 48-59.
■ European Environment Agency (2011). Landscape fragmentation in Europe; Joint EEA-FOEN report, 87 p., ISBN: 978-92-9213-215-6.
■ FAO and DVWK (2002). Fish Passes - Design, Dimensions and Monitoring (English version of DVWK, 1996).
■ Fahlbusch F.E. (1994). Scour in Rock Riverbeds Downstream of Large Dams. Hydropower & Dams 1(4): 30-32.
■ Feutry P., Castelin M., Grondin H., Cruaud C., Couloux A., Keith P. (2012a). First record of *Kuhlia sauvagii* Regan, 1913 (Perciformes) in Mayotte and Réunion islands, Western Indian Ocean. Cybium 1913: 493-494.
■ Feutry P., Castelin M., Ovenden J.R., Dettaï A., Robinet T., Cruaud C., Keith P. (2013). Evolution of diadromy in fish: insights from a tropical genus (*Kuhlia* species). The American naturalist 181: 52-63.
■ Feutry P., Tabouret H., Maeda K., Pécheyran C., Keith P. (2012b). Diadromous life cycle and behavioural plasticity in freshwater and estuarine *Kuhliidae* species (*Teleostei*) revealed by otolith microchemistry. Aquatic Biology 15: 195-204.
■ Feutry P., Valade P., Ovenden J.R., Lopez P.J., Keith P. (2012c). Pelagic larval duration of two diadromous species of *Kuhliidae* (*Teleostei*: *Percoidei*) from Indo-Pacific insular systems. Marine and Freshwater Research 63: 397-402.
■ Fièvet E. (1998). Distribution et capacités d'expansion des crevettes d'eau douce de la région Caraïbe : exemple des genres *Macrobrachium* et *Atya* (*Crustacea*: *Caridea*). Biogeographica 74: 1-22.
■ Fièvet E., Bonnet-Arnaud P., Menard C., Tachet H. (1998). Étude de la migration amont des crevettes d'eau douce au niveau des obstacles artificiels, implications pour les dispositifs de franchissement. Rapport DIREN Guadeloupe, Parc National de la Guadeloupe et ESA CNRS 5023 Université Lyon 1. Convention d'étude.
■ Fièvet E., Le Guennec B. (1998). Migration de masse de *Sicydium spp.* (*Gobiidae*) dans les rivières de Guadeloupe : implications pour le schéma hydraulique des mini centrales hydroélectriques "au fil de l'eau." Cybium 22: 293-296.
■ Fièvet E. (1999a). Daylight Migration of Freshwater Shrimp (*Decapoda*: *Caridea*) over a Weir during Water Release from the Impoundment. Crustaceana 72: 351-356.

■ Fièvet E. (1999b). An experimental survey of freshwater shrimp upstream migration in an impounded stream of Guadeloupe Island, Lesser Antilles. Archiv für Hydrobiologie 144: 339-355.
■ Fièvet E. (2000). Passage facilities for diadromous freshwater shrimps (*Decapoda*: *Caridea*) in the Bananier River, Guadeloupe, West Indies. Regulated Rivers: Research and Management 16: 101-112.
■ Fièvet E., Doledec S., Lim P. (2001). Distribution of migratory fishes and shrimps along multivariate gradients in tropical island streams. Journal of Fish Biology 59: 390-402.
■ Fièvet E., Roux A., Redaud L., Sérandour J.M. (2000). Conception des dispositifs de franchissements pour la faune amphidrome (crevettes et poissons) des cours d'eau antillais : une revue. Bulletin Français de la Pêche et de la Pisciculture 357/358 : 241-256.
■ Fritz Ö., Larsson K. (1996). Betydelsen av skoglig kontinuitet för rödlistade lavar. En studie av halländsk bokskog. [The significance of long forest continuity to red-listed lichens. A study of beech forest in the province of Halland, SW Sweden.] Svensk Botanisk Tidskrift 90: 241-262.
■ Gomes P., Larinier M. (2008). Etude sur la mortalité des anguilles suite à leur passage au travers des turbines Kaplan. Etablissement de formules prédictives. Rapport GHAAPPE RA 08.01, 43 p. + annexes.
■ Hamano T., Yoshimi K., Hayashi K.-I., Kakimoto H., Shokita S. (1995). Experiments on fishways for freshwater amphidromous shrimps. Nippon Suisan Gakkaishi 61: 171-178.
■ Hoarau P. (2005). Dynamique structurale des populations de « bichiques » (*Sicyopterus lagocephalus*), Gobidés amphidromes des rivières de La Réunion. Thèse de doctorat, Université de La Réunion, 264 p.
■ Hoarau P., Treilhes C., Valade P. (2018). Reproductive biology and recruitment in an amphidromous prawn *Macrobrachium australe* in Reunion Island. Invertebrate Biology 137(3): 231-239.
■ Hogan A., Nicholson J. (1987). Sperm motility of sooty grunter, *Hephaestus fuliginosus* (Macleay), and jungle perch, *Kuhlia rupestris* (Lacépède), in different salinities. Marine and Freshwater Research 38 (4): 523-528.
■ Hutchison M., Lee P., Norris A., Nixon D., Shorten D., Borchert T., Wang S., Chilcott K., Palmer P., Marsden T., Carton G., Kowitz L. (2016). Developing jungle perch fingerling production to improve fishing opportunities. Fisheries Research and Development Corporation, project n° 2012/2013.
■ Keith P. (2003). Biology and ecology of amphidromous *Gobiidae* of the Indo-Pacific and the Caribbean regions. Journal of Fish Biology 63: 831-847.
■ Keith P., Marquet G., Valade P., Bosc P., Vigneux E. (2006). Atlas des poissons et des crustacés d'eau douce des Comores, Mascareignes et Seychelles, Muséum National d'Histoire Naturelle, Paris, collection Patrimoines Naturels : 65, 250 p.
■ Keith P., Vigneux E., Bosc P. (1999). Atlas des poissons et des crustacés d'eau douce de la Réunion. Muséum National d'Histoire Naturelle, Paris, collection Patrimoines Naturels : 39, 136 p.
■ Lagarde R. (2016). Dynamiques de dévalaison des larves de *Sicydiinae* de la rivière Langevin - impact de l'aménagement hydroélectrique. Rapport Hydrô-Réunion, 36 p.
■ Lagarde R. (2018). Phénologies, mécanismes et perturbations anthropiques des dynamiques de migration dulçaquicoles des espèces amphidromes : cas des *Sicydiinae* de La Réunion. Thèse de doctorat, Université de La Réunion, 300p.
■ Lagarde R., Borie G. & Ponton D. (2020). Dams select individual morphology but do not modify upstream migration speed of tropical amphidromous gobies. River Research and Applications 36, 57 67.
■ Lagarde R., Faivre L., Grondin H., Courret D. (2016). Etude des capacités de franchissement des poissons et macro-crustacés amphihalins de La Réunion. Rapport d'activité HydroRéunion 2015.
■ Lagarde R., Teichert N., Boussarie G., Grondin H., Valade P. (2015). Upstream migration of amphidromous gobies of La Réunion Island: implication for management. Fisheries Management and Ecology 22: 437-449.
■ Larinier M. (2002). Biological factors to be taken into account in the design of fishways, the concept of obstructions to upstream migration. Bulletin Français de la Pêche et de la Pisciculture Suppl. 364 : 28-38.
■ Larinier M. (2008). Fish passage experience at small-scale hydro-electric power plants in France. Hydrobiologia 609: 97-108.
■ Larinier M., Dartiguelongue J. (1989). La circulation des poissons migrateurs : le transit à travers les turbines des installations hydroélectriques. Bulletin Français de la Pêche et de la Pisciculture : 1-87.
■ Larinier M., Porcher J.P., Travade F., Gosset C. (1994). Passe à poissons. Expertise. Conception des ouvrages de franchissement. Conseil Supérier de la Pêche, Paris, collection Mise au point. 285 p. + annexes.
■ Larinier M., Chorda J., Ferlin O. (1995). Le franchissement des seuils en enrochements par les poissons migrateurs. Etude expérimentale. Rapport Ghaappe 95/05 - Hydre 161, 25p.

■ Larinier M., Courret D., Gomes P. (2006). Guide technique pour la conception des passes naturelles. GHAAPPE-CNR-AEAG. Rapport GHAAPPE RA.06.05-V1. 48 p. + annexes.
■ 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). The design of fishways for shad. Bulletin Français de la Pêche et de la Pisciculture Suppl. 364 : 135-146.
■ Larinier M., Travade F. (2002). Downstream migration: problems and facilities. Bulletin Français de la Pêche et de la Pisciculture Suppl. 364 : 181-207.
■ Larinier M., Travade F. (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: 91-99. ISBN 978-3-939057-19-2.
■ Lauritzen D.V., Hertel F., Gordon M.S. (2005). A kinematic examination of wild sockeye salmon jumping up natural waterfalls. Journal of Fish Biology 67: 1010-1020.
■ Lauritzen D.V., Hertel F.S., Jordan L.K., Gordon M.S. (2010). Salmon jumping: behaviour, kinematics and optimal conditions, with possible implications for fish passageway design. Bioinspiration and Biomimetics 5, doi: 10.1088/1748-3182/5/3/035006.
■ Legault A. (1986). Comportement d'escalade de l'anguille et colonisation du bassin versant de la Sèvre Niortaise. Les publications de l'ENSA de Rennes n°3, 41p.
■ Legault A. (1987). L'anguille dans le bassin de la Sèvre Niortaise. Biologie, écologie, exploitation. Les publications de l'ENSA de Rennes n°6, 305p.
■ Legault A. (1992). Etude de quelques facteurs de sélectivité de passes à anguilles. Bulletin Français de la Pêche et de la Pisciculture 325 : 83-91.
■ LEMA (2006). LOI n°2006-1772 du 30 décembre 2006 sur l'eau et les milieux aquatiques. Page 53. Journal Officiel de la République Française.
■ Lewis A.D., Hogan A.E. (1987). The enigmatic jungle perch - recent research provides some answers. SPC Fisheries Newsletter 40: 22-31.
■ Lim P., Meunier J.-F., Keith P., Noël P.-Y. (2002). Atlas des poissons et des crustacés d'eau douce de la Martinique. Muséum National d'Histoire Naturelle, Paris, collection Patrimoines Naturels : 51.
■ Lucas M.C., Baras E. (2001). Migration of Freshwater Fishes. Oxford: Blackwell Science, 420 p.
■ Maeda K., Yamasaki N., Kondo M., Tachihara K. (2008). Reproductive biology and early development of two species of sleeper, *Eleotris acanthopoma* and *Eleotris fusca* (*Teleostei*: *Eleotridae*). Pacific Science 62 (3): 327-340.
■ Maeda K., Yamasaki N., Tachihara K. (2007). Size and age at recruitment and spawning season of sleeper, genus *Eleotris* (*Teleostei*: *Eleotridae*) on Okinawa Island, southern Japan. Raffles Bulletin of Zoology Suppl. 14: 199-207.
■ March J.G., Benstead J.P., Pringle C.M., Scatena F.N. (2003). Damming tropical island streams: problems, solutions and alternatives. BioScience 53: 1069.
■ Marcy B.C., Fletcher D.E., Martin F.D., Paller M.H., Reichert M.J.M. (2005). Fishes of the Middle Savannah River basin: with emphasis on the Savannah River site. The University of Georgia Press, Athens, GA., 462 p.
■ Marsden T. (2016). Developing jungle perch fingerling production to improve fishing opportunities. St Helens Creek Restocking Sampling. Australian Fish Passage Services for Department of Agriculture Fisheries and Forestry, Queensland, Australia, Rapport préparé par les Services des passes à poissons Australien (AFPS) pour le Département de l'Agriculture, des Pêches et de la Forêt (DAFF), 15 p.
■ Mc Dowall R.M. (1988). Diadromy in Fishes : Migrations between Freshwater and Marine Environments. Croom Helm, London.
■ Mc Dowall R.M. (2007). On amphidromy, a distinct form of diadromy in aquatic organisms. Fish and Fisheries 8: 1-13.
■ Mc Dowall R.M. (2010). Why be amphidromous: Expatrial dispersal and the place of source and sink population dynamics? Reviews in Fish Biology and Fisheries 20: 87-100.
■ Mc Leave (1980). Swimming performance of European eel elvers. Journal of Fish Biology 16: 445-452.
■ Meixler M.S., Bain M.B., Walter M.T. (2009). Predicting barrier passage and habitat suitability for migratory fish species. Ecological Modelling 220: 2782-2791.

■ Mennesson M., Keith P. (2017). Evidence of two species currently under the name of *Eleotris fusca* (*Gobioidei*: *Eleotridae*) in the Indian Ocean. Cybium 41:213-220.
■ Merrick J. R., Schmida G. E. (1984). Australian Freshwater Fishes: Biology and Management. Griffith Press Limited, South Australia.
■ Monti D., Keith P., Vigneux E. (2010). Atlas des poissons et des crustacés d'eau douce de la Guadeloupe. Muséum National d'Histoire Naturelle, Paris, collection Patrimoines Naturels : 69.
■ Morandi B., Rivière-Honegger A., Cottet M. (2015). Étude en sciences humaines et sociales sur l'eau et les milieux aquatiques en Martinique. Les représentations et les pratiques associées aux cours d'eau. Étude n°043-12-2014. Rapport CNRS, CIRAD, ODE Martinique, ONEMA, 218 p. + annexes.
■ Myers G.S. (1949). Usage of anadromous, catadromous and allied terms for migratory fishes. Copeia 1949: 89.
■ Nordén B., Appelqvist T. (2001). Conceptual problems of ecological continuity and its bioindicator. Biodiversity and Conservation 10: 779-791.
■ Ocea Consult' (2014a). Suivi des réseaux de contrôle de surveillance de la qualité des masses d'eau de surface de l'île de Mayotte - Volet Poissons et macro-crustacés. Programme de l'année 2014. Rapport de synthèse pour le compte du BRGM-Mayotte.
■ Ocea Consult' (2014b). Accompagnement pour l'élaboration d'un projet d'arrêté de pêche en eau douce sur les cours d'eau de Mayotte. Rapport pour le compte de la DEAL 976. 60 p.
■ Ocea Consult' (2014c). Suivi 2013 des éléments biologiques " poissons et macro-crustacés " des rivières du bassin Réunion. Rapport final pour le compte de l'Office de l'Eau de La Réunion, 232 p.
■ Ocea et Antea (2013). Expertise écologique et hydrologique de l'impact de la prise EDF du Bras Patience - Réunion. Rapport pour le Groupement Hydraulique EDF, La Réunion. 12 pages.
■ Ohlson M., Tryterud E. (1999). Long-term spruce forest continuity - A challenge for a sustainable Scandinavian forestry. Forest Ecology and Management 124: 27-34.
■ Økland B., Bakke A., Hågvar S., Kvamme T. (1996). What factors influence the diversity of saproxylic beetles? A multi-scaled study from a spruce forest in southern Norway. Biodiversity and Conservation 5: 75-100.
■ Olivier J.-M., Mérigoux S., Forcellini M., Grondin H., Mathieu C., Péru N., Richarson M., Sagnes P., Usseglio-Polatera P., Valade P. (2012). Conception d'indices de bio-évaluation de la qualité écologique des rivières de l'île de La Réunion à partir des poissons et macro-crustacés et des invertébrés benthiques. Rapport final Univ Lyon I CNRS ENTPE - LEHNA, ARDA, Europe FEDER, Office de l'eau Réunion, 506 p.
■ Olivier T.J. (2013). Amphidromous life History of the Caridean shrimp *Macrobrachium ohione* (*Decapoda*: *Palaemonidae*) from the Mississippi River system. Ph.D. dissertation, University of Louisiana, 169 p.
■ Olivier T.J., Handy K.Q., Bauer R.T. (2013). Effects of river control structures on the juvenile migration of *Macrobrachium ohione*. Freshwater Biology 58: 1603-1613.
■ Ovidio M., Philippart J.-C. (2002). The impact of small physical obstacles on upstream movements of six species of fish. Hydrobiologia 483: 55-69.
■ Phillip D.A.T. (1993). Reproduction and feeding of the mountain mullet, *Agonostomus monticola*, in Trinidad, West Indies. Environmental Biology of Fishes 37(1): 47-55.
■ Powers P., Osborn J. (1985). Analysis of barriers to upstream fish migration. U.S. Dept. of Energy, Bonneville Power Adm., Div. of Fish and Wildlife, Final Project Report, 120 p.
■ Préfet de la Martinique (2014). Arrêté préfectoral n°2014307-0011 reconduisant l'arrêté N° 09-03540 du 25 septembre 2009 et l'arrêté N° 2013301-0020 du 28 octobre 2013 portant interdiction de la pêche et de la commercialisation des poissons et crustacés pêchés dans les rivières situées sur le territoire de la Martinique. Page 2.
■ Préfet de La Réunion (2008a). Arreté n°1742 du 15 juillet 2008 réglementant la pêche maritime professionnelle dans les eaux du département de La Réunion. Page 22.
■ Préfet de La Réunion (2008b). Arrêté n°1743 du 15 juillet 2008 réglementant l'exercice de la pêche maritime de loisir dans les eaux du département de la Réunion. Page 12.
■ Pusey B.J., Kennard M., Arthington A. (2004). Freshwater Fishes of North-Eastern Australia. CSIRO Publishing, 700 p.
■ Pyron M., Covich A.P. (2003). Migration patterns, densities, and growth of *Neritina punctulata* snails in Rio Espiritu an Rio Mameyes, Northeastern Puerto Rico. Caribbean Journal of Science 39: 338-347.

■ Réveillac E. (2008). Histoires de vie larvaire et dispersion des *Anguillidae* : vers une approche bio-évolutive. Thèse de doctorat, Université de La Rochelle, 232 p.
■ Rice E., Kadavy K.C., Robinson K.M. (1998). Roughness of loose rock riprap on steep slopes. Journal of Hydraulic Engineering 124: 179-185.
■ Robert M. (2015). Analyse des capacités de franchissement des espèces de poissons et de macro-crustacés des cours d'eau des DOM insulaires pour le diagnostic de l'impact des ouvrages transversaux sur la continuité écologique et le dimensionnement des ouvrages de franchissement. Rapport du Parc National de Guadeloupe pour l'Onema et l'Université des Antilles, 33p.
■ Robinet T., Feunteun E. (2002). First observation of shortfinned *Anguilla bicolor bicolor* and longfinned *Anguilla marmorata* silver eels in Reunion island. Bulletin Français de la Pêche et de la Pisciculture 364 : 87-95.
■ Robinet T., Lecomte-Finiger R., Escoubeyrou K., Feunteun E. (2003). Tropical eels *Anguilla spp.* recruiting to Réunion Island in the Indian Ocean: taxonomy, patterns of recruitment and early life histories. Marine Ecology Progress Series 259: 263-272.
■ Rose F. (1974). The epiphytes of oak. In: Morris MG and Perring FH (eds) The British Oak. Its History and Natural History. EW Classey, Faringdon, pp 250-273.
■ Ruggles C.P. (1980). A review of the downstream migration of atlantic salmon. Freshwater and Anadromous Div. Ressource Branch Dept. of Fisheries and Oceans, Halifax, Nova Scotia, Can. Tech. Rep. of Fisheries and Aquatic Sci. 953, 39p.
■ Ruggles C.P., Murray D.G. (1983). A review of fish response to spillways . Freshwater and Anadromous Div. Ressource Branch Dept. of Fisheries and Oceans, Halifax, Nova Scotia, Can. Tech. Rep. of Fisheries and Aquatic Sci. 1172, 30p.
■ Schoenfuss H.L., Blob R.W. (2003). Kinematics of waterfall climbing in Hawaiian freshwater fishes (*Gobiidae*): vertical propulsion at the aquatic-terrestrial interface. Journal of Zoology 261: 191-205.
■ Schübel A. (1998). Pêcheurs de bichiques de La Réunion. Rapport final d'études en Sciences Sociales à l'Université de La Réunion, réalisé à IDEA Consultants, en partenariat avec l'ARDA, le CSP et la DIREN 974, 314p.
■ Sethi S.N., Ram N., Venkatesan V. (2012). Length-weight relationship of *Macrobrachium lar* (Fabricius, 1798), an endemic freshwater prawn in streams and ponds of Andaman and Nicobar Islands. Indian Journal of Fisheries 59: 157-161.
■ Sethi S.N., Ram N., Venkatesan V. (2014). Reproductive biology of *Macrobrachium lar* (fabricius, 1798) in Andaman Islands. Indian Journal of Marine Sciences 43: 1-8.
■ Smith W.E., Kwak T.J. (2014a). A capture-recapture model of amphidromous fish dispersal. Journal of Fish Biology 84: 897-912.
■ Smith W.E., Kwak T.J. (2014b). Otolith microchemistry of tropical diadromous fishes: spatial and migratory dynamics. Journal of Fish Biology 84: 913-28.
■ Sörenson I. (1951). An investigation of some factors affecting the upstream migration of the eel. Institute of Freshwater Research, Drottningholm, Report 32: 126-132.
■ Stuart T.A. (1962). The leaping behaviour of salmon and trout at falls and obstructions. Freshwater and Salmon Fisheries Research 28: 1-46.
■ Sugeha H.Y., Aoyama J., Tsukamoto K. (2006). Downstream migration of tropical anguilid silver eels from lake Poso, Central Sulawesi, Indonesia. Limnotek 13(1): 18-25.
■ Tabouret H. (2012). Les poissons migrateurs amphihalins des départements d'outre-mer : état des lieux. Partie 1 : synthèse générale sur les DOM insulaires. Rapport final ONEMA-MNHN, 276 p.
■ Tabouret H. (2013). Les poissons migrateurs amphihalins des départements d'outre-mer : état des lieux. Partie 2 : Quels outils de gestion ? Expérience internationale et propositions. Rapport final ONEMA-MNHN, 82p.
■ Teichert N. (2012). Variabilité des traits d'histoire de vie chez les *Gobiidae* (*Sicydiinae*) amphidromes de l'île de la Réunion : *Sicyopterus lagocephalus* (Pallas, 1770) et *Cotylopus acutipinnis* (Guichenot, 1863). Thèse de doctorat, Université de Pau et des Pays de l'Adour, 342 p.
■ Teichert N., Keith P., Valade P., Richarson M., Metzger M., Gaudin P. (2013). Breeding pattern and nest guarding in *Sicyopterus lagocephalus*, a widespread amphidromous *Gobiidae*. Journal of Ethology 31: 239-247.

■ Teichert N., Valade P., Grondin H., Trichet E., Sardenne F., Gaudin P. (2016). Pelagic larval traits of the amphidromous goby *Sicyopterus lagocephalus* display seasonal variations related to temperature in La Réunion Island. Ecology of Freshwater Fish 25: 234-247.
■ Thinus Z., Guillot F. (2016). Impact à la dévalaison de l'anguille des centrales hydroélectrique de grande capacité de l'aval de La Seine. Rapport de synthèse CEREMA Normandie Centre, 63 p.
■ Thorstad E.B., Fiske P., Aarestrup K., Hvidsten N.A., Harsaker K., Heggberget T.G., Okland F. (2005). Upstream migration of Atlantic salmon in three regulated rivers. In Spedicato M.T., Lembo G., Marmulla G. (eds) Aquatic telemetry: advances and applications. Proceedings of the Fifth Conference on Fish Telemetry held in Europe, Ustica, Italy, 9-13 June 2003, pp 111-121.
■ Valade P., Lord C., Grondin H., Bosc P., Taillebois L., Lida M., Tsukamoto K., Keith P. (2009). Early life history and description of larval stages of an amphidromous goby, *Sicyopterus lagocephalus* (*Gobioidei*: *Sicydiinae*). Cybium 33: 309-319.
■ Valade P., Roger E., Grondin H., Bosc P., Larinier M., et Voegtlé B. (2004). Etude du franchissement des ouvrages de captage d'eau (Transfert Est-Ouest) par les larves de bouche-rondes (bichiques) lors de la dévalaison. Rapport ARDA-ONEMA-SIEE pour le compte du Département de La Réunion, 63p.
■ Veronese A. (1937). Erosion of a bed downstream from an outlet, Colorado A & M College, Fort Collins, United States.
■ Videler J.J. (1993). Fish Swimming. Chapman & Hall, 206p.
■ Voegtlé B. (2014). Simulation des mortalités induites par les aménagements hydroélectrique lors de la migration de dévalaison des smolts de saumon atlantique. Bassin du Gave d'Oloron. Rapport de synthèse pour la DDTM 64.
■ Voegtlé B. (2010a). Simulation des mortalités induites par les aménagements hydroélectriques lors de la migration de dévalaison des smolts de saumon atlantique. Bassin de la Nive. Rapport DDTM 64 - Ecogea, 52 p. + annexes.
■ Voegtlé B. (2010b). Simulation des mortalités induites par les aménagements hydroélectriques lors de la migration de dévalaison des anguilles argentées. Bassin de la Nive. Rapport DDTM 64 - Ecogea, 46 p. + annexes.
■ Voegtlé B., Larinier M. (2000). Etude sur les capacités de franchissement des civelles et anguillettes. Site hydroélectrique de Tuilières sur la Dordogne (24) et Barrage estuarien d'Arzal sur la Vilaine (56). Rapport Ghaappe RA00.05/ Migado G15-00-RT, 69p. + annexes.
■ Voegtlé B., Larinier M. (2008). Définition d'une stratégie de restauration de l'axe migration pour l'anguille. Cours d'eau du Gave de Pau. Rapport Midival-Ecogea-Ghaappe RA08.02, 42 p. + annexes.
■ Voegtlé B., Larinier M., Bosc P. (2002). Étude sur les capacités de franchissement des cabots bouche-rondes (*Sicyopterus lagocephalus*, Pallas, 1770) en vue de la conception de dispositifs adaptés aux prises d'eau du transfert Salazie (Ile de La Réunion). Bulletin Français de la Pêche et de la Pisciculture 364 : 109-120.
■ Wardle C.S. (1980). Effects of temperature on the maximum swimming speed of fishes. In Environmental Physiology of Fishes, Plenum Press, 723 p.: 519-531.
■ WFD (2000). Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water.
■ Wouthuyzen S., Aoyama J., Sugeha H.Y., Miller M.J., Kuroki M., Minegishi Y., Suharti S.R., Tsukamoto K. (2009). Seasonality of spawning by tropical anguillid eels around Sulawesi Island, Indonesia. Naturwissenschaften 96: 153-158.
■ Yamasaki N., Kondo M., Maeda K., Tachihara K. (2011). Reproductive biology of three amphidromous gobies, *Sicyopterus japonicus*, *Awaous melanocephalus*, and *Stenogobius sp.*, on Okinawa Island. Cybium 35: 345-359.
■ Yasuda Y., Ohtsu I. (1999). Flow resistance of skimming flow in stepped channels. Proceedings of the 28th IAHR Congress, Graz, Austria, Session B14, 6 p.
■ Zhou Y. (1982). The swimming speed of fish in towed gears, a reexamination of the principles. Department of Agriculture and Fisheries for Scotland, Working Paper No. 4, 55p.
■ Zydlewski J., Wilkie M.P. (2012). Freshwater to Seawater Transitions in Migratory Fishes. Fish Physiology 32: 253-326.

List of illustrations

List of tables

Acknowledgements

The authors wish to heartily thank all the contributors and the members of the work groups, as well as their organisations, who made it possible to expand, improve and illustrate this publication by rereading it and making available their knowledge and observations in the field, notably:

- Anil Akbaraly (Mayotte Departmental Council)
- François Ghione (Mayotte Environmental Directorate)
- Jean-Pierre Gout (Martinique Environmental Directorate)
- Julie Gresser (Martinique Water Office)
- Raphaël Lagarde (Hydrô Réunion)
- Joël Li-Tsoe (Guadeloupe Environmental Directorate)
- Pierre Minou (ARDA)
- Dominique Monti (University of the Caribbean)
- Alexandre Moullama (Reunion Water Office)
- Isabelle Nasso (Guadeloupe Water Office)
- Fabian Rateau (Martinique Water Office)
- Alain Reuge (Guadeloupe Environmental Directorate)
- Marie Robert (Guadeloupe National Park)
- Sabine Staal (Réunion Water Office)
- Loïc Thouvignon (French Biodiversity Agency, Mayotte local office)

The concepts brought into play in this publication are based on profound and complex knowledge that could not have been so instructively illustrated without the graphic design work provided by Béatrice Saurel and Christian Couvert (Graphies), on the one hand, and the translation by Cary Bartsch, on the other, whom we wish to thank.

Finally, we wish to pay particular tribute to Julie Gresser and Fabian Rateau (Martinique Water Office), on the one hand, and Hélène Udo and Stéphanie Couprie (French Biodiversity Agency), on the other, for their management of the partnerships and agreements that made it possible to bring together all the participants in this project spanning multiple territories, and of course Véronique Barre and Béatrice Gentil-Salasc for their remarkably attentive work in finalising and publishing this work.

Coordination

Julie Gresser (Martinique Water Office)
Karl Kreutzenberger (French Biodiversity Agency)
Bruno Voegtlé (Ecogea consulting firm)

Authors

Karl Kreutzenberger (French Biodiversity Agency)
Pierre Sagnes (French Biodiversity Agency)
Pierre Valade (Ocea Consult' consulting firm)
Bruno Voegtlé (Ecogea consulting firm)

Publication

Véronique Barre (French Biodiversity Agency)
Béatrice Gentil-Salasc (French Biodiversity Agency)

Translation

Bartsch & Cie (info@bartsch.fr)

Graphic design and layout

Christian Couvert (Graphies) - Diagrams
Béatrice Saurel - Artistic illustrations and graphic layout

Citation

Kreutzenberger K., Sagnes P., Valade P. and Voegtlé B., 2020. Assessing the passage of obstacles by fish and macro-crustaceans in the French tropical islands of the Atlantic and Indian Oceans. Concepts and design. French Biodiversity Agency. *Knowledge for action* series. 176 pages.

List of publications in the *Knowledge for action* series

■ 1. River hydromorphology. A primer
(2010, English translation in 2013)

■ 2. Managing sediment transport in rivers. A primer
(2011, in French)
■ 3. Evaluating the ecosystem services of aquatic environments. Scientific, political and operational issues
(2011, English translation in 2012)
■ 4. Observed trends in river flow rates in France
(2012, English translation in 2013)
■ 5. Improving control over nutrients by restoring river hydromorphology
(2012, English translation in 2013)
■ 6. Mapping techniques and hydrogeological models to characterise seawater intrusion in French coastal aquifers and assess the potential impact of sea-level rise
(2013, English translation in 2013)
■ 7. Structural characteristics of priority abstractions of use in designing protection systems
(2013, English translation in 2013)
■ 8. Economic analysis for management of water and aquatic environments
(2013, English translation in 2014)
■ 9. Perspectives of the social sciences on the implementation of water policies
(2013, English translation in 2015)
■ 10. Designing ambitious projects for river restoration. Feedback from projects in Europe integrating the human and social sciences
(2014, English translation in 2014)
■ 11. Assessing the passage of obstacles by fish. Concepts, design and application
(2014, English translation in 2015)
■ 12. Management of aquatic environments and flood prevention
(2014, English translation in 2015)
■ 13. Freshwater fish and climate change. Current situation and adaptation strategies
(2014, English translation in 2015)
■ 14. Contribution of stakeholder perceptions to managing aquatic environments
(2014, English translation in 2015)
■ 15. Effectiveness of micropollutant elimination in WWTPs for household wastewater. Report on the ARMISTIQ research project
(2014, in French)
■ 16. Contribution of hydro-economic models to water management in France
(2015, English translation in 2015)
■ 17. Invasive alien species in aquatic environments, Practical knowledge and management insights. Vol. 1, Practical knowledge
(2015, English translation in 2016)
■ 18. Invasive alien species in aquatic environments, Practical knowledge and management insights. Vol. 2, Management insights
(2015, English translation in 2016)
■ 19. Protecting priority abstractions from nonpoint-source pollution, current situation and outlook for the future
(2015, in French)
■ 20. On the usefulness of hydrological models in predicting low-flow levels
(2015, in French)
■ 21. Extrapolation methods for river discharges when permanent gauging stations do not exist
(2015, in French)
■ 22. Diffuse pollution and protection of water resources. Territorial practices in the European Union
(2016, English translation in 2016)
■ 23. Promoting cooperation between producers of drinking water and farmers in protecting abstraction supply zones
(2016, in French)
■ 24. The cost of degradation in aquatic environments for water users. An assessment of compensatory expenses
(2017, in French)
■ 25. Scientific data and recommendations on creating planted discharge zones
(2017, in French)
■ 26. Ecological damage and ecological torts. How does society deal with and remediate damage to water and aquatic environments?
(2017, English translation in 2018)
■ 27. River restoration in France. Changes in definitions and methods over time and space. Outlook for the future
(2017, English translation in 2017)
■ 28. Cumulative impact of water reservoirs on aquatic environments. A collective science-advice report
(2017, in French)
■ 29. Invasive alien species in aquatic environments, Practical knowledge and management insights. Vol. 3, Management insights (cont.)
(2018, English translation in 2018)
■ 30. Mid and long-term projections of demand for drinking water. An assessment of current methods and practices
(2019, in French)
■ 31. The benefits of preserving groundwater. Why assign a monetary value and how?
(2018, in French)
■ 32. Lessons from the human and social sciences on eliminating micropollutants in aquatic environments
(2018, in French)
■ 33. Synergies between agro-ecology and ecological networks
(2019, in French)
■ 34. Assessing the passage of obstacles by fish and macro-crustaceans in the French tropical islands of the Atlantic and Indian Oceans. Concepts and design
(2019, English translation in 2020)

https://professionnels.ofb.fr/en/knowledge-for-action

ISBN Web : 978-2-38170-104-2
ISBN Print : 978-2-38170-105-9
Printed in France by Cloître in May 2021.
This document was produced using plant-based inks and printed on 100% PEFC paper from sustainably managed forests and verified sources, by a printer compliant with all environmental standards.

.

AFAQ ISO 14001 Version 2004

Over 100 000 structures (dams, weirs, bridges, box culverts and culverts, etc.) have been inventoried in French rivers. Fragmentation of natural habitats has been acknowledged as one of the main causes of biodiversity loss. At different points in their life cycle, many species need to move freely, occasionally over large distances, in order to access specific habitats conducive to their growth, reproduction, feeding, rest and/or protection. The EU Water framework directive (WFD, 2000), thanks to efforts by the international community, highlighted the value of gaining knowledge of, preserving and restoring ecological continuity in hydrosystems and riparian corridors.

In the French tropical islands of the Atlantic and Indian Oceans, a survey still under way has revealed the existence of over one thousand obstacles in rivers. But virtually all indigenous fish and macro-crustacean species in these territories move between the marine, estuarine and river environments in fulfilling their life cycle. Consequently, they are highly sensitive to physical barriers in rivers.

How can the passability of these obstacles be assessed? For which species and types of structure? Is the scientific knowledge currently available concerning the French overseas territories sufficient to develop a standardised assessment and diagnostic procedure? It was with these questions in mind that the French Biodiversity Agency, in conjunction with the respective Environmental Directorates and Water Offices in the overseas territories, and in a partnership with the Ocea Consult' and Écogea consulting firms, decided to adapt the ICE (Information on the Continuity of Ecosystems) method, originally designed for continental France, to the conditions prevalent in the French tropical islands.

This book in the *Knowledge for action* series pulls together and clearly presents the main scientific and technical knowledge available on ecological continuity for fish and macro-crustaceans in the overseas territories, the physical capabilities of the species in question, the various types of obstacles encountered and their potential impacts. Providing in-depth information and richly illustrated, it offers readers a precise description of the ICE method, its basic principles and applications, and instructs on how to implement the method in one's own local environment.

Karl Kreutzenberger is a Government Public Works Engineer (ITPE) and an expert for the French Ecology ministry. Since 2013, as a member of the general management of the French Biodiversity Agency, he has been the scientific and technical coordinator for national research programmes on ecological continuity and river hydromorphology.

Pierre Sagnes has a Ph.D in aquatic ecology and taught for 15 years at the University of Lyon 1. Since 2014, he has been in charge of the OFB-IMFT ecohydraulics R&D centre within the French Biodiversity Agency, where his duties include technical support, research and training in the field of ecohydraulics.

Pierre Valade is an engineer in the water sciences and techniques (ISIM). He graduated with a diploma in technological research in the environmental sciences (UMII), and worked for ten years as a project manager at CRITT ARDA. Since 2010, he has managed the Ocea Consult' consulting firm on Réunion, carrying out studies and applied-research programmes on the ecological functioning of freshwater environments on tropical islands.

Bruno Voegtlé is a civil engineer (ENSIP), hydraulics engineer (ENSEEIHT) and co-director of Écogea, a consulting firm for the management of the aquatic environment, headquartered in Muret (Haute-Garonne department). He is specialised in ecohydraulics and particularly in the initial studies and management of projects to restore ecological continuity for fish.

With support from:

ODE Office de l'eau Martinique
Office de l'eau Réunion
Office de l'Eau Guadeloupe
Parc national de la Guadeloupe
Liberté • Égalité • Fraternité République Française – Direction de l'environnement, de l'aménagement et du logement – Martinique
Liberté • Égalité • Fraternité République Française – Direction de l'environnement, de l'aménagement et du logement – Réunion
Liberté • Égalité • Fraternité République Française – DEAL Guadeloupe
Liberté • Égalité • Fraternité République Française – Direction de l'Environnement, de l'Aménagement et du Logement – Mayotte

OFB Office français de la biodiversité
Écogea
Ocea Consult'