TG 2 "Estimation of barrier-related mortality"

Deliverables 2.1.1 & 2.2.3

Which data to collect and how to estimate mortality of downstream-migrating eels at hydropower facilities

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Glossary

This glossary contains, in alphabetic order, a brief definition of the words in green in the document (where they first appear).

Amphihaline: describes a species whose life cycle alternates between the sea and fresh water.

Bar rack: rack placed upstream of the turbines, first to stop large debris passing through the turbines, and second, if the separation between the bars is sufficiently small, to stop the fish and guide them to a possible outfall.

Biomass: weight of living matter

Blade: spoon-shaped part of a Francis turbine, which is rotated by the flow of water against the blade.

Chute (downstream): channel collecting water and fish immediately downstream from the downstream migration outfalls of a bar rack.

Classified flow (Qx): for a given watercourse at a given plant, the average daily flow is under x days out of 100 at the classified flow Qx. For example, Q75, Q90, Q95, Q97.5 and Q99 classified flows are traditionally used to characterise the strong values of a watercourse.

Dam: fixed or mobile structure that blocks more than the flood stage of a watercourse.

Downstream migration: migration of the fish (here, the silver or even yellow eel) to the downstream area of the watershed.

Escapement: number (or proportion) of individuals that manage to avoid the turbines, either by passing through the spillways or the outfall.

Equipment flow: flow through the turbines in nominal operation (full power).

Fish friendly: used to describe equipment or a facility designed to greatly limit the impact on the fish.

Gill arches: bony parts that support the gills of the fish.

Glass eel: the juvenile stage of the European eel, which arrives in the estuaries and starts the upstream migration in the downstream part of the watershed area.

Head loss: in hydraulics, energy dissipated by the friction of the liquid (for example, here, when the flow passes through a water intake rack).

Hydrometric station: device installed on a watercourse which allows the flow to be continuously assessed and to record the values obtained.

Hub: central part of the turbine, which the rotation axle goes through.

Intake channel: channel that takes the water from a watercourse to a hydropower generating station.

Kelts: used to describe the salmon that migrate downstream following breeding.

Mantle: fixed part of a turbine, inside which the moving parts operate.

Net head: the net head is the difference in height between the water levels upstream and downstream of the turbines when operating. It is different from the gross head which, conversely, is measured when the turbines are stopped.

Normal speed: component of the speed of the perpendicular run-off to the bar rack.

Operculum: bony flap that covers the gills of certain fish.

Outfall (downstream migration): opening made in a structure or a bar rack, allowing the fish to move downstream.

Percentile: each of the 99 values that divide the elements of a statistical distribution into 100 equal parts (or, by extension, each of these 100 parts).

Quartile: each of the three values that divide the elements of a statistical distribution into four equal parts (or, by extension, each of those four parts).

Recruitment: number of individuals reaching an age class, a stage of development or a given size.

Regime (of a watercourse): set of hydrological characteristics of a watercourse and the way they change over time.

Reserved flow: it is the regulatory minimum flow of water (sometimes expressed as a percentage of the average total flow) that the owners or managers of a hydraulic structure (dam, weir, hydropower facility...) must reserve in the watercourse for a minimum functioning of the related ecosystems. It must particularly ensure that the fish and invertebrates can live there and that the spawning grounds are preserved in the breeding season.

Silver eel: the last stage of the life cycle of the European eel, when it migrates downstream and returns to the Sargasso Sea.

Smolt: juvenile stage of fish from the Salmonidae family, which is the stage when it migrates from freshwater to the sea.

Spillways: structure or parts of the facility that allows floodwater to pass through the facility, while controlling the maximum levels reached to maintain them below the levels required to ensure the stability of the facility.

Tangential speed: component of the outflow speed towards the top of the bar rack by the inclining racks and towards the direction by the angled bar racks. This current allows fish to be guided to the possible outfalls.

Turbine: rotating device, designed to use the force of a fluid to produce mechanical energy. This energy is fed to an alternator that produces electricity.

Turbine flow: flow of water passing through one or more turbines.

Upstream migration: migration of the fish (here the young stages of the eels, glass eels and elvers) upstream of the watershed areas.

Vane: part of a Kaplan turbine activated by the flow of the water.

Watershed: geographical area that is drained by a watercourse and its tributaries.

Weir: fixed or mobile structure, often overflow spillway, that blocks more than the flood stage of a watercourse.

Yellow eel: stage of the life cycle when the European eel undergoes its greatest growth in the continental habitat, before returning to the sea as silver eels.

Introduction

Given the general loss of biodiversity in the aquatic environment from an ecological perspective, amphihaline[1] migratory fish have suffered a significant drop in numbers, particularly in the North Atlantic (Limburg and Waldman, 2009). The situation is particularly concerning in the case of the European eel *(Anguilla anguilla)*, which has seen a greater decline since the 1980s (ICES, 2007). This species is also listed as critically endangered by the IUCN[2] (Pike *et al.,* 2020).

Despite the restocking measures initiated by a European Regulation in 2007 (No. 1100/2007), the European eel population has not been restored; the annual recruitment of yellow eels in European waters in 2018 was 29% of the estimated average between 1960 and 1979 (ICES, 2019). Thus, as part of a precautionary principle applied to the European eel, the International Council for the Exploration of the Sea (ICES) recommended in 2019 that all the anthropogenic impacts (recreational and commercial fishing of all stages of development, hydroelectricity, pumping stations and pollution) reducing recruitment and escapement of silver eels should not exist or as close as possible to zero by 2020 (ICES, 2019).

Due to their specific biological cycle, European eels belong to a single population, that needs to be managed in a uniform and coordinated way in the different countries involved. Cooperation must therefore be optimised between the relevant stakeholders (fishermen, hydropower plants, managers, scientists, communities, services and national operators...) at different levels (local, regional, national) and in the different countries of its distribution area. Therefore, the main goals of the Interreg Sudoe SUDOANG programme, which includes Spain, Portugal and south-west France, are to share expertise, the best assessment tools and to facilitate, among these three countries, the cooperation actions aimed at restoring the European eel population.

The decline of this species may be attributed to numerous factors linked to human activities: fishing, alteration of habitats and ecological continuity, water quality... Habit fragmentation plays an essential role among them (Feunteun, 2002). In fact, an individual, to complete its life cycle, must first cross the Atlantic Ocean in its larval form, approach then make its way into (more or less upstream) the continental hydrographic network to spend several years growing there, before setting off to the ocean to cross it a second time before breeding. During this cycle, the successful outcome of the migration phases in the watercourses (upstream migration, then downstream migration) is therefore essential. During these journeys, the eels can come across a large number of hydraulic structures (weirs, dams, water intakes…), which hinder their progress to a greater or lesser extent, potentially causing delays or bottlenecks (in both migration directions), or even the death of individuals (Trancart *et al.*, 2020). Those deaths can mainly be seen i) during the upstream migration, when the juveniles (glass eels, elvers) gather downstream of the barriers and become easier prey for other species (or for poachers) and ii) during the downstream migration, when the older individuals are lured into the water intakes of the hydropower plants and they pass through the operating turbines. However, that also happens when they are trapped in cooling water intakes of nuclear and thermal power plants, or the water for irrigation or drinking water supplies.

[1] The words in green are defined in the Glossary at the start of the document.
[2] International Union for Conservation of Nature.

Over the last two decades, France has developed a methodology to estimate the mortality rate of the eels migrating downstream past a hydropower plant. This method has particularly enabled the impact on the eels to be calculated on a scale of certain facilities and certain migration routes, prior to the implementation to measures to offset the impacts of the hydropower facilities. This document describes that method, which is based on knowledge of i) of the migratory activity, ii) of the distribution of the fish over the different passage routes past the structures, iii) of the effectiveness of any possible downstream systems and iv) injury to the fish when passing through the spillways and turbines. Along with estimating the number of eels migrating downstream and the size structure (produced by the EDA model, see the deliverables of SUDOANG TG4), this allows the number of eels impacted by the structures to be estimated *in fine*.

The formalisation of this method, set out here, will allow all the stakeholders involved in safeguarding the eel to produce a mortality diagnosis on the scale of a hydropower facility, or even of a migration route if they have all the data needed for the different calculations.

*N.B.: this method can be applied to any other species provided that the data needed are available. In France, for example, a similar approach is applied to estimate the mortality of Atlantic salmon smolts (*Salmo salar*).*

This document is divided into 4 parts:

- The first part sets out the different types of turbines that a fish can come up against, as those turbines may result in deaths and the possible solutions to limit them

- The second part describes the methodological approach developed throughout the rest of the document

- The third part considers the data needed for the different calculations

- The fourth part develops the method as such and sets out the way to combine the different data to lead to the required diagnosis. A specific example is considered.

1. Mortalities caused by the turbines and solutions to reduce them

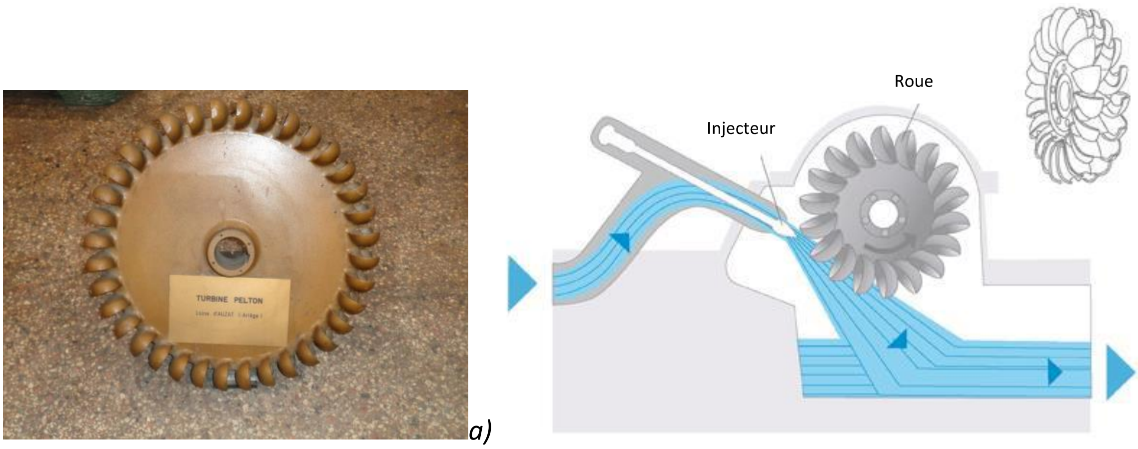
The mortality of fish during their passage through the turbines can be caused by different phenomena:

- **Blows and abrasions**: direct contacts with the fixed or mobile parts of the turbine causing external (bruising, lacerations, fractures of the spine, gashes that can even sever the body) and/or internal (bleeding, lesions to different organs) injuries (Larinier & Dartiguelongue, 1989; Larinier & Travade, 2002).
- **Entrapment in the gaps between the fixed and moving parts of the wheel**: if the space between the moving parts and the mantle or the hub is large enough for fish to get caught there, but smaller than their body width, meaning they are likely to be entrapped and crushed or severed (Odeh, 1999).
- **Changes in pressure:** the pressure when entering the turbine is much higher than the exit pressure. That sharp drop in pressure may cause external and internal injuries (blown eyes, swim bladder bursting, different bleeding …) (Larinier & Dartiguelongue, 1989; Odeh, 1999; Cada, 2001).
- **Shearing forces:** the shearing phenomenon is caused following the displacement of two contiguous masses of water at very different speeds. This phenomenon is important in the wake of the wheel and it causes injuries to large fish (particularly eels migrating downstream), as different parts of the body can be exposed to a very wide range of outflow speeds. This results in inverted or ripped-off operculum, broken gill arches, or even decapitation (Larinier & Dartiguelongue, 1989; Cada, 2001).

Depending on their configuration, their size and their rotation speed, different turbines have different impacts on the passage of the fish and therefore different mortality probabilities.

1.1. The different types of turbines

The Kaplan, Francis and Pelton are the three most common types of turbines used in France.

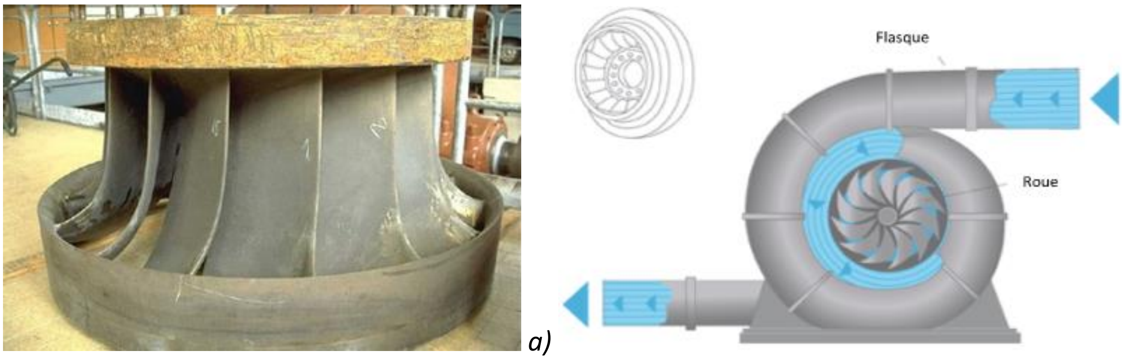


a) b)

***Figure 1**. a) Pelton-type turbine (photo P. Sagnes – OFB) ; b) operating principle (www.landeskraftwerke.bayern).*

The **Pelton turbine** wheel (Figure 1) is set in motion by high-speed jets of water. The water is brought to the turbines by penstocks, which results in great pressure being obtained in the injector. The jet from the injector results in a mortality rate of 100% for all fish species, because the speed and water pressure are too strong and the opening of the injector too narrow to allow them to survive. However, the mortality rate of eel due to this type of turbine is rather low, as these turbines usually harness the high mountain heads (>50 m) in areas where there are usually no eels.

Francis turbines (Figure 2) consist of 7 to 19 spoon-shaped blades attached to a central shaft and to two revolving surfaces, the roof and the belt. The intake of the water is peripheral and its exit is axial. These turbines are usually installed on high to medium heads (> 20 m) and can be powered flows ranging from several hundred L/s to over 200 m^3/s. However, traditionally, Francis turbines were installed on low heads in France (in the early 20th century) and can therefore affect the eel. The turbine flow can be controlled by adjusting the opening of the guides.
The Francis turbines result in generally large mortalities in high to medium head conditions, due to the associated great rotation speeds. However, eel mortality in this type of turbines is inversely proportional to the size of the wheel, because the larger the wheel, the greater the gap between the blades and the fish are more likely to pass through without suffering great impacts.

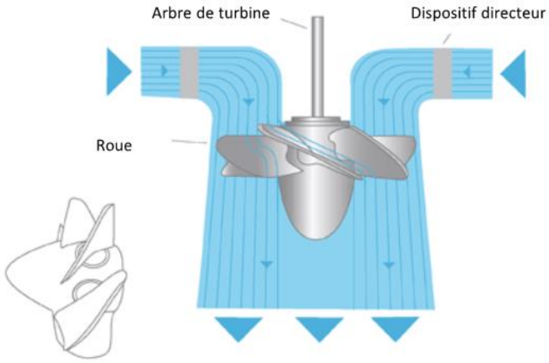


a) *b)*

***Figure 2**. a) Francis-type turbine (photo P. Sagnes – OFB); b) operating principle (www.landeskraftwerke.bayern).*

In the case of the **Kaplan turbines** (Cada, 2001) (Figure 3), the wheel consists of 3 to 8 vanes, attached to a central hub, without an external belt.


a)



b)

***Figure 3**. a) Kaplan-type turbine (photo D.Courret – OFB); b) operating principle (www.landeskraftwerke.bayern).*

The use of the Kaplan turbines is reserved for low head generating stations, under 30 m. These turbines can be used for wide ranges of equipment flows (which can exceed 600 m^3/s in the case of the the largest turbines). The turbine flow may be controlled by adjusted the orientation of the vanes ("simple adjustment" for the Kaplan turbine) and also by adjusting the opening of the guides ("double adjustment" for the Kaplan turbine). When the vanes are fixed (non-adjustable turbine flow), it is known as a "*propeller*" turbine.

In the case of a given Kaplan turbine, whose rotation speed is constant, the mortalities vary depending on the vane orientation and the turbine flow. In fact, the weaker the turbine flows, the more the vanes close, significantly increasing the mortalities from impacts. As the eels migrate downstream during strong flow periods, the inter-vane space of the Kaplan turbines is generally considered to be maximum at that time; therefore, the lowest estimated mortality values are considered.

1.2. Different solutions allow eel mortality to be limited during downstream migration

There are different solutions to reduce fish mortality in hydropower turbines.

1.2.1. Turbining operations

1.2.1.1. Turbining targeted shutdowns

Turbining targeted shutdowns consists of stopping the turbines of a hydropower generating station for a limited (to minimise economic losses) and well-defined time (during the fish passage period) in order to limit mortalities as far as possible (see, for example, the approach proposed by Teichert *et al.*, 2020a). Any difficulty when implementing this solution lies in the fact of correctly identifying the global downstream migrating period of the species in question, then effectively targeting the downstream migration episodes during that period. As regards a facility, this solution can only therefore be used for one, or even two target species. If the stream of fish consists of several species to be protected, this solution is not feasible as it involves too frequent stops, which are generally not cost-effective.

In France, this solution is mainly used to protect silver eels, when any other more efficient solution is not feasible (such as fitting fine racks, which will be discussed later). In order to target eel turbining stoppages, predicting the downstream migration episodes accurately and sufficiently in advance is essential, in order to be able to stop the turbines at the right time. Therefore, as part of the French national "eel" R&D programme (Baran & Basilico, 2012), two type of experiments were conducted:

- Using "bio-monitors" such as MIGROMAT©[3] (Adam*,* 2000), whose efficiency is somewhat limited (15-20% efficiency: MacNamara & McCarthy, 2011), rather better (66-73% efficiency: Bruijs. *et al.,* 2003; also see non-published results in Schwevers & Adam, 2019). It should be noted that using bio-monitors can cause (1) eel supply problems each year before the downstream migration period, with the risk of missing the first episodes and (2) problems of individuals' health suffering during extended holding.

- With the help of models taking into account the environmental parameters likely to drive the downstream migration phenomenon (flow, temperature, turbidity, weather…). This second method can result in greater efficiencies than the first (e.g.: around 77% on average over 6 seasons of monitoring the level of the Tuilières power plant on the River Dordogne, but with a significant energy loss, see De Oliveira *et al.,* 2015). It needs local data, burdensome to acquire, which allow the number of eels migrating downstream to be contextualised in selected environmental parameters. It should however be noted that a recent study (Teichert *et al.*, 2020b) credits criteria based solely on the flow evolutions and shows that a certain transferability of predictive models between sites, when showing hydrology close to natural hydrology; on the other hand, this transferability is better when performed between watersheds of similar sizes.

1.2.1.2. Avoid low flow turbining for the Kaplan turbines

In the case of the Kaplan turbines, as has been previously described, fish mortality increases when the turbine flow reduces, particularly due to the smaller gap between the vanes when they close (Berg, 1986; Bruijs et *al.,* 2003).

In the case of power plants fitted with multiple turbines and highly equipped compared to the flows of the watercourse, one solution to reduce mortality could therefore be not to run each turbine at full power. However, the efficiency of the solution is rather limited (Kroll, 2015) as fish mortality often remains significant, even when the vanes are fully open (i.e., when the turbine flow is maximum).

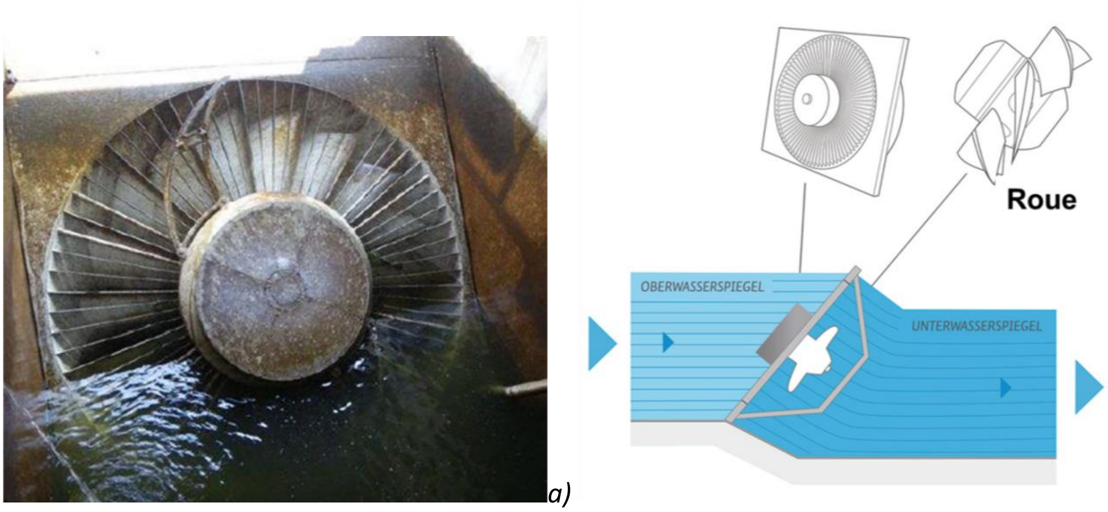
In the case of poorly equipped power plants compared to the flows of the watercourse, this is not an appropriate solution as the turbining is already at full power during the eel downstream migration episodes.

[3] This biomonitor consists of measuring the locomotion activity of eels held in capativity in basins and of envisaging, by analysing the recorded signal, the imminent natural downstream migration periods.

1.2.2. Fish-friendly turbines

The development of "fish-friendly" turbines, i.e., turbines that do not or cause very little damage to the fish, is relatively recent and is still a work in progress in some cases. In France, a turbine is recognised as fish-friendly only following positive biological tests: the injuries and mortality must be zero or near zero for fish introduced into the turbine and kept for up to 48 or even 96 hours post-experiment (Baran & Courret, 2013). In no case is fish-friendliness recognised solely based on the technical characteristics or operating characteristics of the turbine. In fact, even the machines developed specifically for this purpose are not necessarily considered to be satisfactory in their first version. As regards the eels, the biological tests must be conducted using individuals which are larger than 60 cm, in order to be representative of the size of females migrating downstream (the mortality rate of smaller individuals migrating downstream, often males, can only be lower).

Two types of fish-friendly turbines are today recognised in France[4]. They are the ichtyophile© VLH ("very low head") (Figure 4) and the hydrodynamic screw turbines, provided that they comply with certain precautions (Figure 5). More extensive testing is expected in particular with two other types of turbines, the "Alden" turbine and the "FishFlow Innovations" turbines, whose early results are encouraging. Other types of fish-friendly turbines are currently being developed.



a) b)

Figure 4. *a) Ichtyophile© VLH turbine (photo ECOGEA); b) operating principle (www.landeskraftwerke.bayern).*

The VLH turbines were tested *in situ* and the mortality rate for the eels (of sizes between 60 cm and 1m) has been seen to be under 1% (ECOGEA, 2011).

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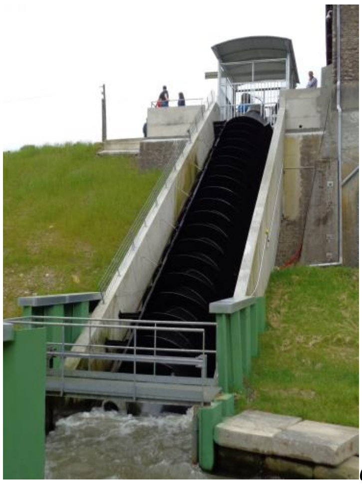
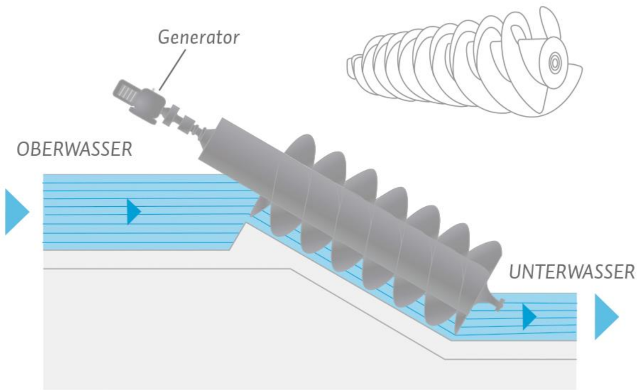
[4] https://patbiodiv.ofb.fr/fiche-methodologique/continuite-ecologique/turbines-ichtyocompatibles-140



a)



b)

***Figure 5**. a) "Hydrodynamic screw-type turbine (photo P. Sagnes – OFB); b) operating principle (www.landeskraftwerke.bayern).*

The hydrodynamic screw turbines were tested in Germany (Späh, 2001), in The Netherlands (Merkx et Vriese, 2007) and in England (Fishtek, 2007, 2008, 2009). The survival rates are very high or even total for several species, particularly for the eel, if certain precautions are taken: smaller gap between the screw and its mantle (ideally < 5 mm and in all cases < 10 mm), smooth mantle surface, upstream shut-off valve covered with rubber and not protruding upstream compared to the mantle.

These two types of fish-friendly turbines are however limited to low to medium head structures (between 1.4 and 2.8 m for the VLH and between 1 and 10 m for the hydrodynamic screws). The deployment of these turbines is generally easier in the case of new facilities, as changing the turbine of existing power plants may require significant civil engineering work.

1.2.3. Catching-transporting fish

The solution of catching the downstream-migrating fish upstream of a facility and then transporting them downstream is only feasible when it is technically and financially possible to install a device capable of catching a substantial part of the downstream population (fishery, entrapment device). This is very difficult in the case of the silver eel due to the fact that they generally migrate downstream in periods of strong flows.

This solution may be of interest when it means that the passage can be avoided through a chain of several facilities on a watercourse. Several operations of this type are in progress for the eel. One such case has been on the River Shannon in Ireland since the start of the 2000s (McCarthy *et al.,* 2008; MacNamara & McCarthy, 2013) and there have been conducted on several watercourses in Sweden since 2010. Thus, between 2015 and 2017, 47,000 silver eels were caught and then transported downstream from several hydropower plants on four Swedish watercourses (Sandberg, 2018). In a study conducted on the River Stour in the United Kingdom, 86% of the fish caught in the water-retention pond of a hydropower plant and released downstream successfully reached the sea (Piper *et al.,* 2020). This study concluded that catching and transporting of silver eels is a method that seems efficient, but the catching is very burdensome. This type of device is very rare as it is very difficult (often impossible) to deploy efficiently.

1.2.4. Physical barriers: "fish-friendly" fine racks

Behavioural barriers sound, light, bubble screens, electricity…) have not so far shown satisfactory results regarding their ability to stop downstream migrating eels before they enter the turbines. "Fine rack" type physical barriers are the only devices which efficiently stop the eels.

"Fish-friendly" water intakes (Figure 6) consist of a bar rack with small gaps between the bars, which not only stops the fish, but also guides them to one or more outfalls flowing into a chute which takes them undamaged downstream of the power plant (Courret et Larinier, 2008). The surface of bar rack is inclined or angled, and the gap between the bars must be precisely sized, in order to not only allow the passage of individual fish through the turbines to be limited, but also reduce the time taken to cross the barrier.

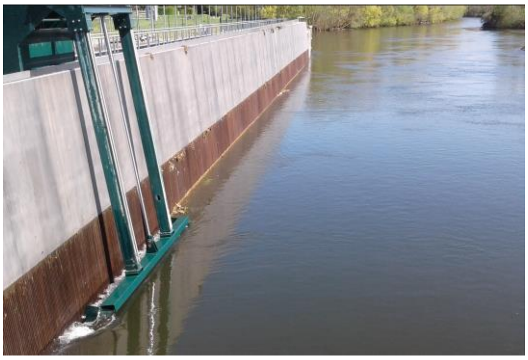

a)

b)

Figure 6. *Fish-friendly water intakes. a) inclined bar rack; b) Angled bar rack (photos P. Sagnes - OFB).*

However, their installation can involve certain constraints (Courret & Larinier, 2008) on the dimensions of the water intakes to respect the biological efficiency criteria (approach speed and speed at the bar rack level, the increase in the number of drifting objects stopped by the rack compared to a conventional rack).

Two fish-friendly water intake configurations are feasible (Courret & Larinier, 2008):
- Either a nearly vertical bar rack and angled at α to the outflow direction (Figure 7); the outfall is then positioned at the downstream end of the bar rack. When the bar rack is long, outfalls may be installed along the middle.

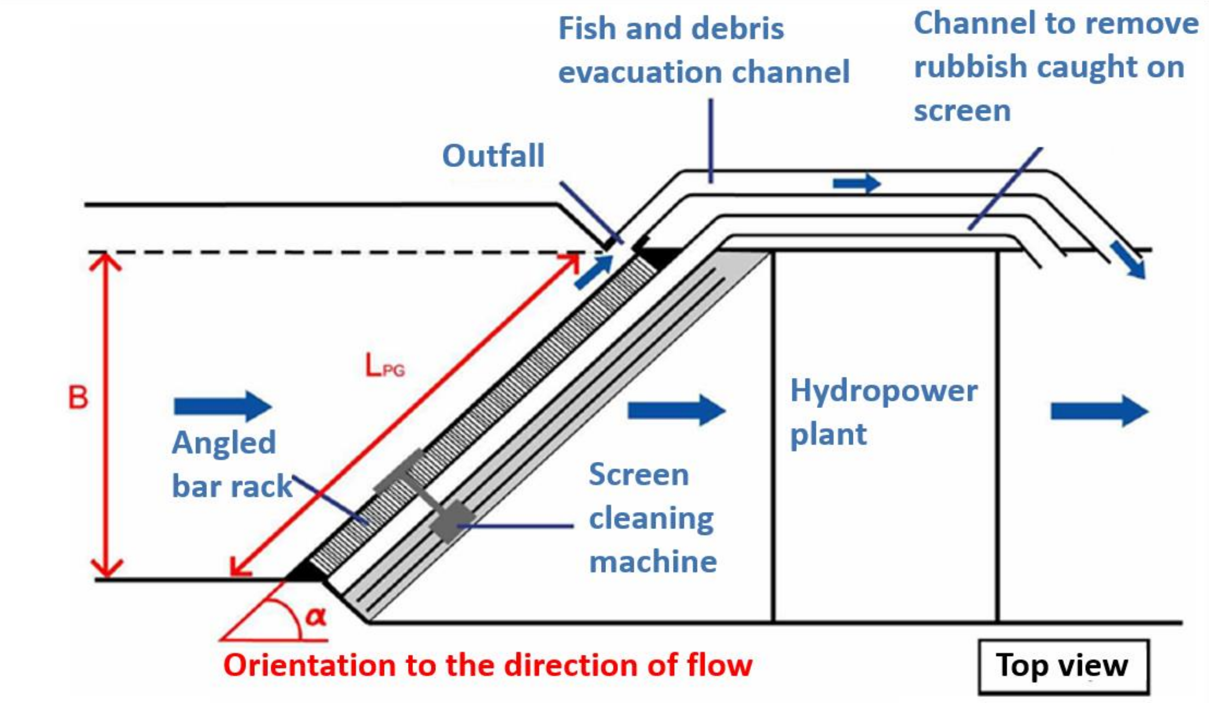


Figure 7. *Angled bar rack, top view. According to Courret & Larinier (2008).*

- Or a bar rack (Figure 8) inclined at an angle β to the horizontal and perpendicular the outflow; the outfall(s) (depending on the width of the water intake) are generally placed at the top of the bar rack.

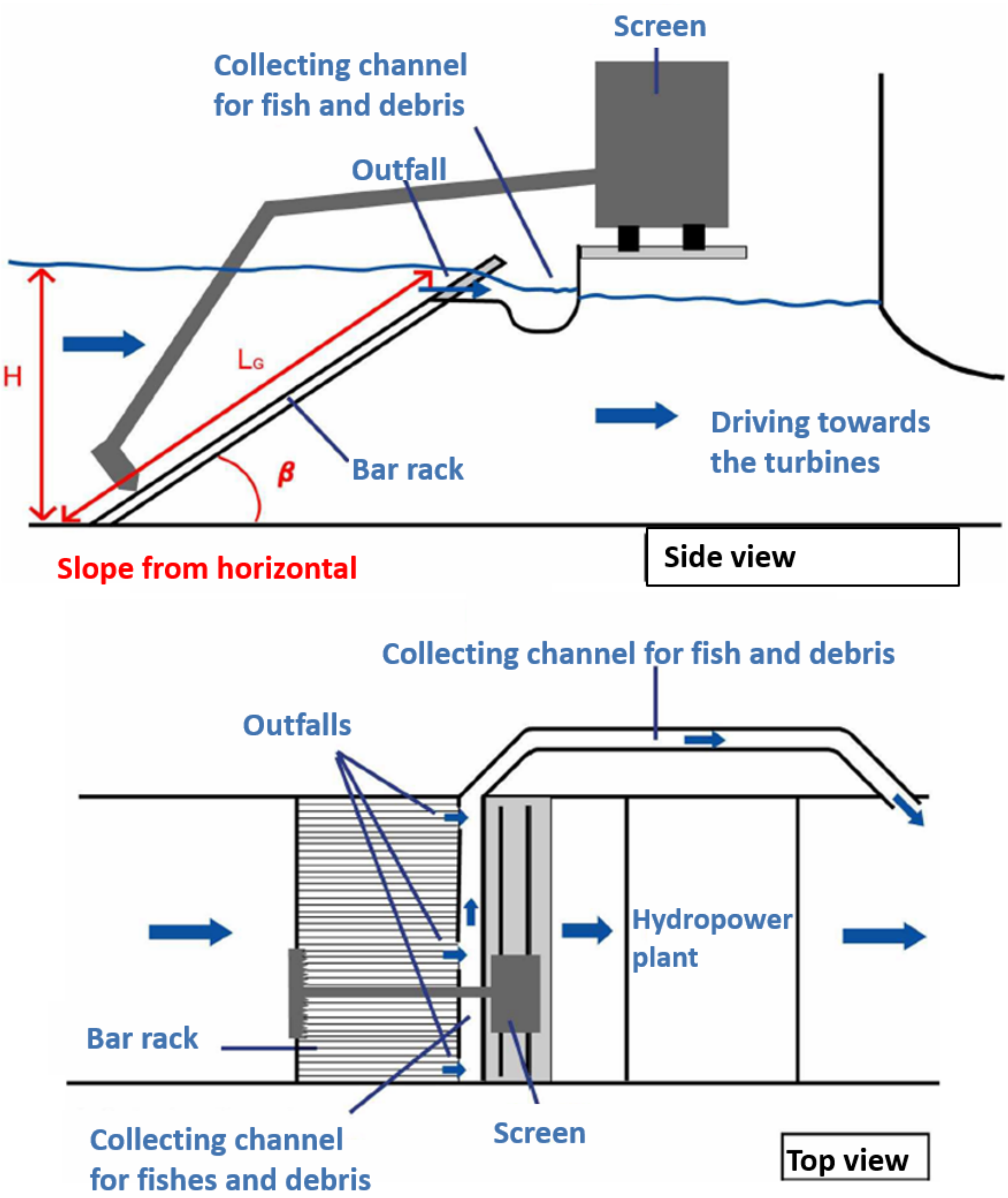


Figure 8. *Inclined bar rack. Top: side view; bottom: top view. According to Courret & Larinier (2008).*

The bars are most often vertical and perpendicular to the rack, but they can also be horizontal in the case of angled bar racks. That is the case for certain water intakes in Germany, Sweden, Austria, France and Switzerland (Ebel, 2013; Calles, 2016).

Some angled bar racks are placed on the continuation of the bank. This type of installation allows the fish to be guided to the downstream end of the bar rack, but the currentology on each site needs to be studied in order to efficiently guide the fish and to the limit the risk of impingements on the rack.

2. Proposed methodological approach in this guide

Estimating a global mortality rate of downstream migrating silver eels at a hydropower facility requires their structure in size classes to be known and is the result of the sum of different mortality estimates, to be carried out according to the passage routes of the fish. The proposed approach is divided into **5 stages** (Figure 9):

Stage 1: Establishing the overall downstream migration period and, within that period, the flow conditions of the watercourse immediately upstream of the facility will allow the proportion of fish crossing the facility through the spillway structures (weirs, gates, flaps, etc.) and the proportion of fish that will be lured to the water intake of the hydropower facility to be estimated. It should be noted that determining the flows may also be useful to define the generation station's turbining conditions

Stage 2: Whether mortality is possible at the spillway structures (weirs, gates, flaps, etc.) should then be estimate.

Stage 3: For the fish going towards the generating station, the proportion that is going to pass through the turbines and those that will use a secure passage route (for example, a downstream migration outfall associated to a bar rack) should be estimated.

N.B.: During Stage 3, only the efficiency of the fine bar racks will be described in this guide. In fact, there is too much feedback regarding other solutions to be able to provide rules allowing their efficiency to be estimated. If need be, an expert may be called on to estimate this efficiency.

Stage 4: The morality rate should be estimated for the fish that have gone through a turbine.

Stage 5: The mortalities caused by all the passage routes must be added up to estimate the total mortality.

The different stages, shown in Figure 9 by a number, are discussed in detail in the following chapters, which set out in turn:

- The data needed to be acquired or pooled (terms **in bold**, Chapter 3)

- The different calculation methods in order to estimate mortality (Chapter 4)

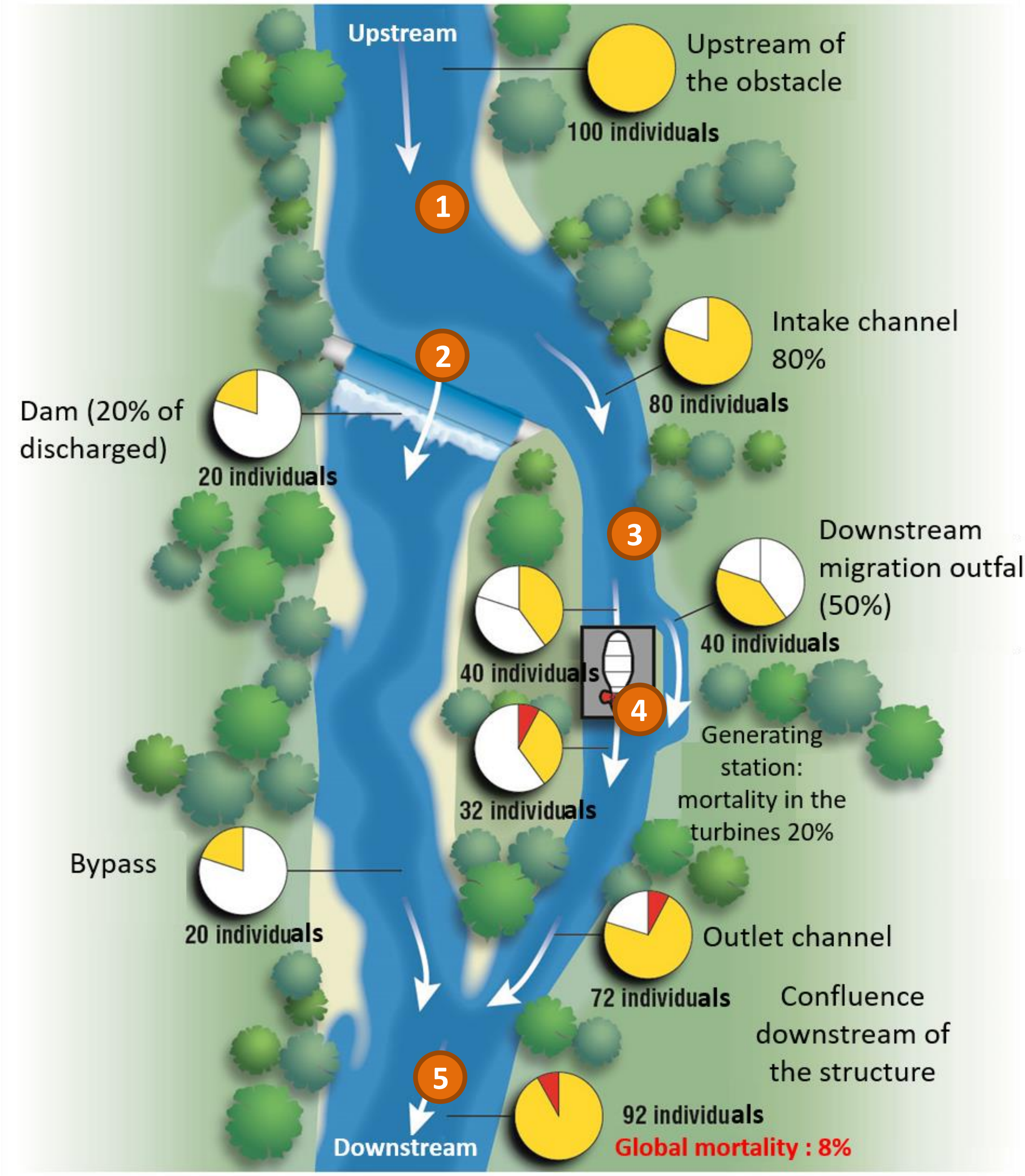


Figure 9. *Five stages in order to estimate a mortality rate for downstream migrating eels at the level of a hydropower facility. In yellow: proportion of live individuals; in red: proportion of dead individuals According to Baudoin* et al. *(2014).*

3. Data needed to determine a mortality diagnosis for downstream migrating eels at the level of a hydropower facility.

The parameters **in bold** in this chapter indicate the type of data to be acquired or pooled to perform the diagnosis. They are summarised in Table 1 at the end of Chapter 3.

3.1. Assessment of the number of individuals at the facility and their size

The method set out in this guide allows a relative mortality rate (in percentage) of eels migrating downstream past hydropower structures to be assessed. If the **number of eels migrating downstream** at the level of the facility is known, the number of impacted eels can be estimated. A model to predict the number of silver eels produced at a given level of a watershed area and their structure in sizes (Eel Density Analysis, EDA, version 2.3) has been developed for France, Spain and Portugal within SUDOANG (GT4 – Escapement, example in Figure 10), mainly based on sampling data obtained by electric fishing. This model allows, for example, past and current escapement of silver eels (Briand *et al.,* 2018) to be estimated.

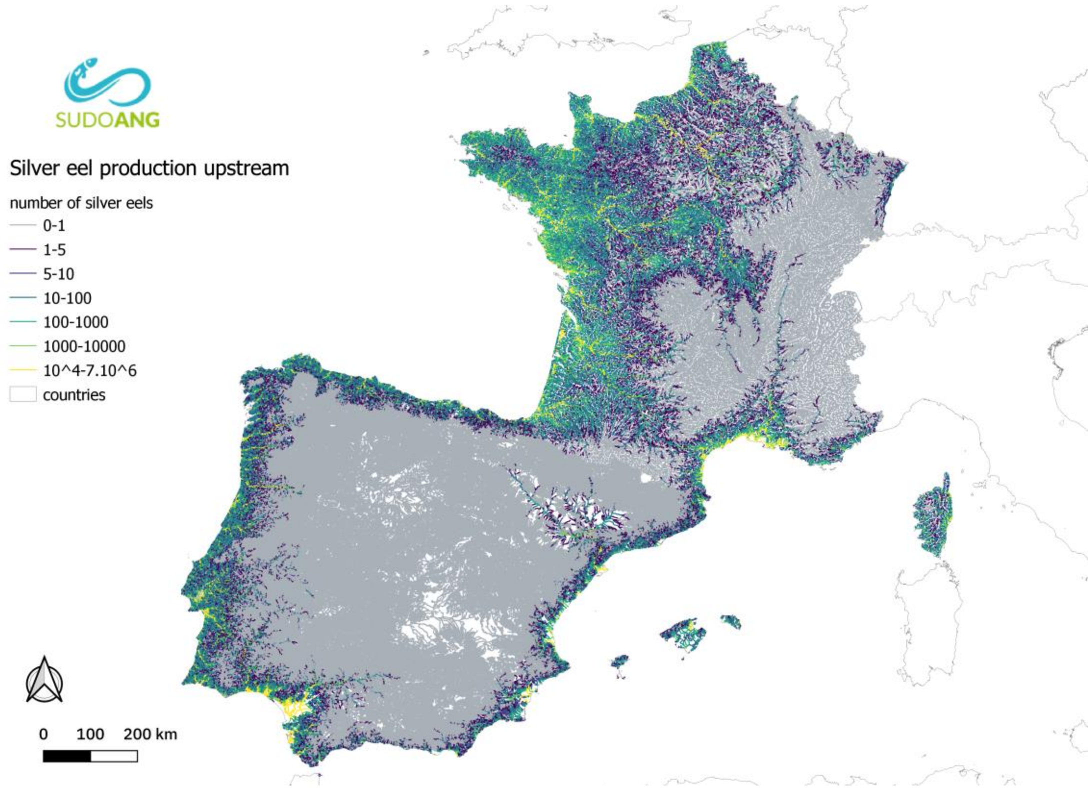


Figure 10. *Example of estimating the number of silver eels produced in French, Spanish and Portuguese watercourses. According to Model EDA 2.3, developed as part of SUDOANG GT4 (provisional results, model being developed).*

The size of the individuals migrating downstream can vary from around 25 cm to over 1 m. It is important to establish the size classes found upstream of the hydropower plant studied, along with their proportions. The size of the eels upstream of a facility may be linked to its location in the watershed area. Females are larger than males (from 40 to over 90 cm compared to 25 to 50 cm, respectively) (Holzner, 1999; Acou, 1999; Gosset *et al.,* 2002; DWA, 2005; data collected as part of SUDOANG GT 1) and generally colonise zones further upstream of the watershed areas (Lasne *et al.,* 2008). A hydropower plant located upstream of a watershed area is therefore likely to particularly impact large eels (mainly females), while a plant downstream will potentially impact fish of different sizes (including females from the upstream).

It is therefore not always easy to obtain information on the precise size of the individuals without potentially burdensome sampling campaigns. To this end, we draw on the available knowledge:

- Local fishery data, which provide information of the potential presence of eel and on the size of the individuals caught
- Studies conducted on the nearby watershed areas, with facilities at a comparable distance from the sea
- Certain SUDOANG GT4 results, which allow the size structure of the downstream migrating eels to be modelled using the predicted size structure for yellow eels and the sex ratio.

3.2. Proportion of individuals migrating downstream through spillway structures *vs* proportion of individuals lured into the water intake

This paragraph sets out the data needed to carry out Stage 1 of Figure 9.

3.2.1. Migration period and respective flows

The **eel downstream migration period**, which can differ from one site to another, is important to know as it allows the **flows that the fish will find at the level of the facility to be defined**. These flows allow the proportions of fish taking the different routes downstream to be calculated.

If the flow data at the level of the power plant or in its immediate proximity are not directly available, it is important to use other existing data to calculate an at-best estimate. Different methods can therefore be used, consisting of either linearly combining observations from a set of stations, or surface reports from watershed areas, or resorting to modelling tools (see Lebecherel *et al.,* 2015). We here propose a conventional method (see Chapter 4), using the data from the closest hydrometric station possible (upstream or downstream) of the facility in question. In France, the data are available in the Banque Hydro database (http://www.hydro.eaufrance.fr/indexd.php).

One the data have been retrieved or estimated, the daily flows during the migration period will allow the classified flow curve to be plotted and enabling the characteristics of the watercourse's hydrology to be determined (Figure 11). They correspond to a non-exceedance frequency (i.e., different Q_X for non-exceeded flows X % of the time).

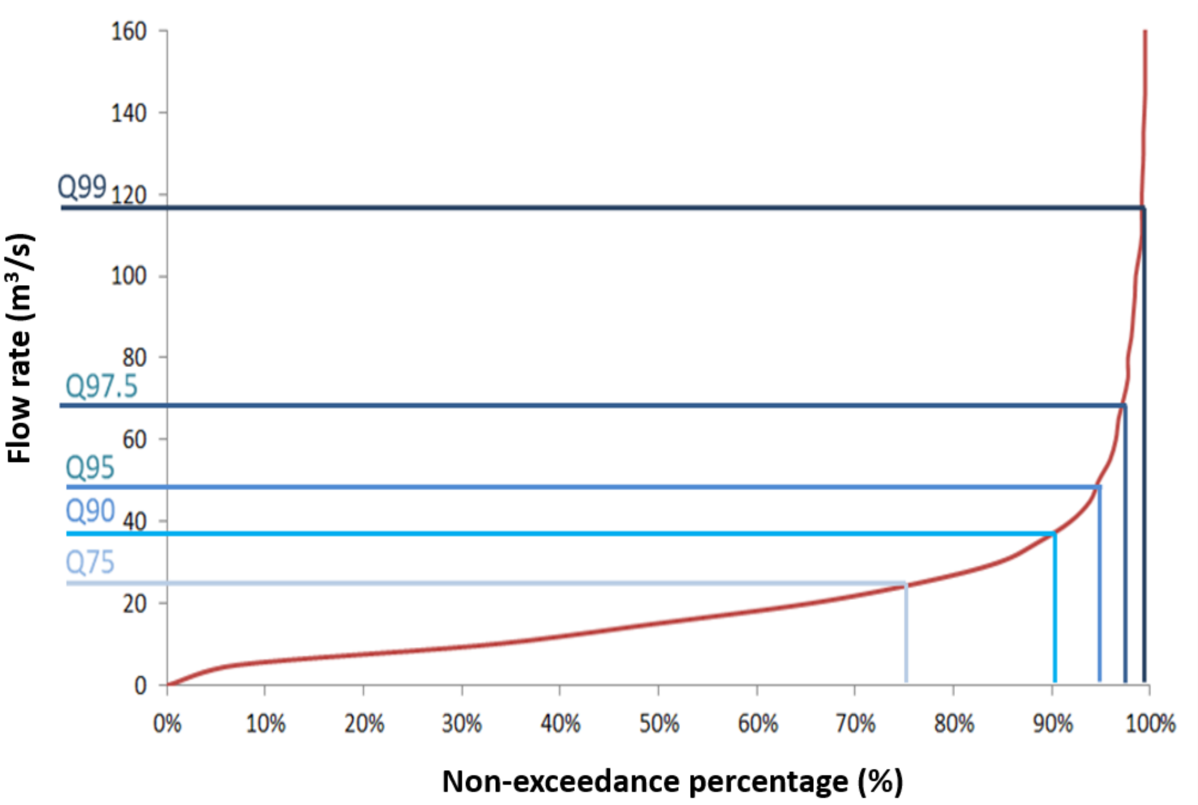


Figure 11. *Example of a classified flow curve (Gave d'Aspe, France, between 2000 and 2011) during the eel downstream migration period (from October to January here), which allows the characteristics flows of a watercourse for a given period to be defined (Qx = non-exceeded flow x % to the time). Curve established during the data analysis of SUDOANG deliverable 2.2.2.*

The importance and interest of these characteristic flows, in the diagnostic approach recommended by this guide, are set out in Chapter 4.

3.2.2. Reserved flow and equipment flow

The **reserved flow** (m^3/s) is the base level that a manager must leave in a watercourse immediately downstream of an uptake structure or headwork (Figure 12). It is therefore the minimum flow that must cross at the level of a weir to allow water to be supplied to a headrace. In certain cases, if they are released at the bottom of the weir, the flows through the downstream migration outfalls and the fish crossing devices can participate in the reserved flow.

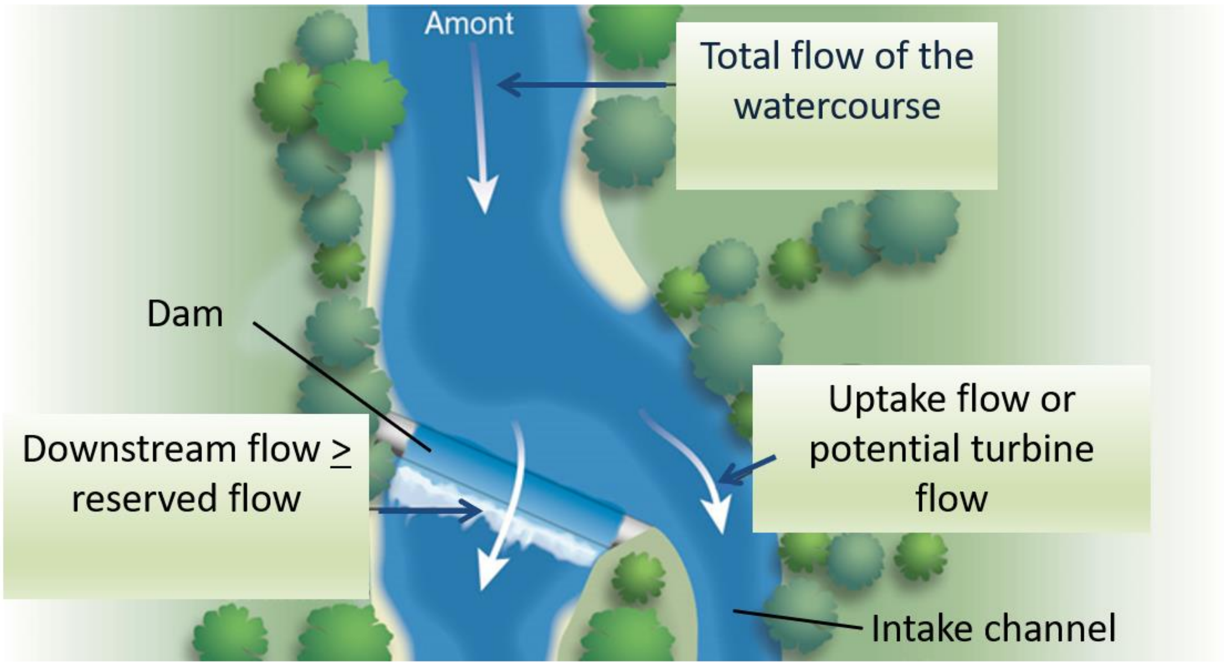


Figure 12. *Diagram of the distribution of the flows at the level of a weir. According to Baudoin* et al. *(2014).*

The **equipment flow** (m^3/s) is the flow through all the turbines when the hydropower plant is operating at full power.

In terms of the flow of the watercourse during the downstream migration period, these two flows are included in the calculation of the proportions of downstream migrating individuals at the level of the spillway structures (weir, gates, flaps, etc.) and those lured into the water intake.

3.3.Mortality rate at the level of spillway structures

This paragraph sets out the data needed to carry out Stage 2 of Figure 9.

If the passage of the downstream migrating fish at the level of the spillway structures is generally considered to be non-traumatising, it can lead to injuries, or even mortalities, in certain cases. This damage is difficult to quantify, but certain criteria allow, *a minima*, to define whether or not that passage route is safe:
- **The head** at the weir, represented by the difference between the upstream side and the downstream side in the flow conditions of the downstream migrating episodes; the fish can be injured if this height is too large due to too high a speed on impact
- **The height of water in the reception area**: the fish may be injured when they arrive downstream if the stilling pool is not sufficiently deep in the reception area, due to blows or abrasion against the bed
- **Whether or not there are "hazards" at the level of the catchwater drain** (such as dissipation blocks): the fish can be injured if those elements are located in the reception area

-Tthe draught and the roughness over the crest of the weir and the inclined facing: if the draught is not sufficient and roughness is present, there is a risk of injuries from blows or abrasion when passing the barrier.

3.4. Efficiency of the bar rack

This paragraph sets out the data needed to carry out Stage 3 of Figure 9.

N.B.: We only discuss here the parameters that allow the efficiency of a bar rack proposed in the framework of a setting up of a fish-friendly intake to be assessed. The efficiency of other types of devices possibly in place upstream of the turbines, where there is not sufficient feedback available at the time of writing, will require an expert opinion case by case.

The role of the bar rack is to stop the fish and then to guide them towards one (or more) outfall(s) leading to a chute, which takes them unharmed downstream of the power plant. The parameters allowing the efficiency of a bar rack to be assessed are set out below (according to Courret & Larinier, 2008).

3.4.1. Size of the individuals upstream of the hydropower plant

This parameter (described above, see Paragraph 3.1) is important as, to reiterate, the smaller the fish, the more likely they are to pass through a given bar rack. Moreover, the larger the fish, the higher their mortality rate is at a given turbine.

3.4.2. Outflow speeds upstream of the bar rack

The normal speed (V_N, Figure 13) at the level of the bar rack is the component of the outflow speed that reaches the bar rack perpendicularly. If this speed is too high, it may cause the fish to be impinged on the rack, followed by death.

The tangential speed (V_T, Figure 13) is the component of the outflow speed towards the outfalls, either towards the top of the bar rack in the case of inclined bar racks or towards the downstream end for angled bar racks. The higher this speed, the greater the number of fish efficiently guided towards the outfall(s).

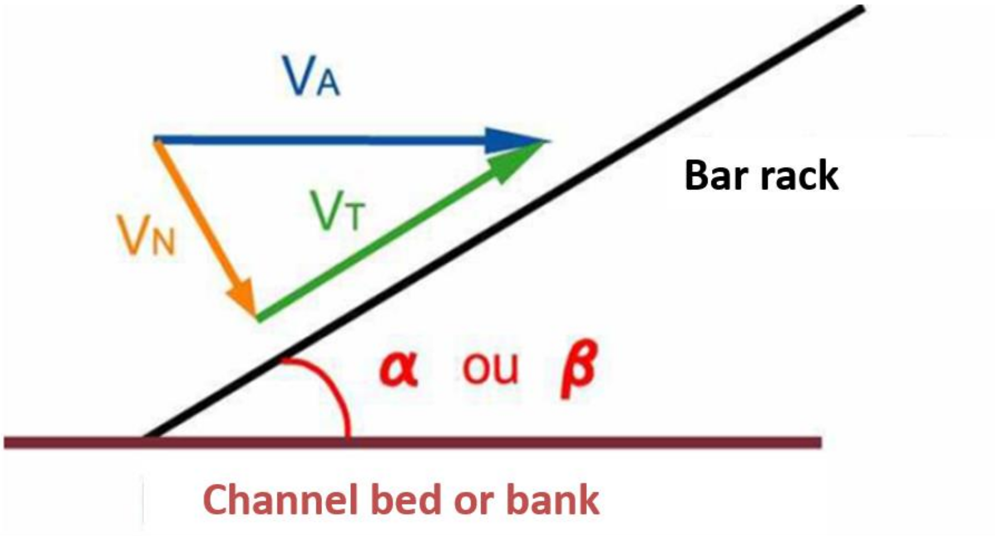


***Figure 13**. The different components of the outflow speed upstream of an inclined bar rack. V_A: approach speed; V_N: normal speed; V_T: tangential speed. According to Courret & Larinier (2008).*

3.4.3. Bar rack characteristics

The smaller the **gap between the bars**, the more efficient the bar rack is at stopping the smaller fish. Only a strict physical barrier, mechanically preventing the individuals from passing through, seems to be able to efficiently stop the eel[5]. The eel's body is very supple, but it can be physically blocked by its head, that is rigid and larger than the rest of the body, becoming stuck in a rack. The size of the eel's heads is therefore the benchmark to establish the efficient size of the inter-bar gap to stop them.

The incline or angle of the bar rack also have an impact on its efficiency. The smaller angle β (for an inclined bar rack) or α (for an angled bar rack), the more fish are efficiently guided towards the outfalls, as the tangential speed is then maximised.

The submerged zone of the bar rack allows the average normal speed to be calculated based on the turbine flow. That speed is positively correlated with the risk of fish becoming impinged on the bar rack.

3.4.4. Characteristics of the outfalls

The presence of outfall(s) is essential to guarantee the escapement of the individuals stopped by a bar rack. In fact, if that element is not present, the fish can either:

- Turn around and cross the facility at the level of the spillway structures (they will then a *minima* be delayed during their migration)
- Or be impinged against the rack due to exhaustion, which is synonymous with death
- Or pass through the bar rack and risk being injured or killed by the turbines.

[5] There are also racks that cause a behavioural barrier, used, for example, to protect salmon smolts, but this example is not developed here.

It is also important to know **the number of outfalls and their location**. In fact, a badly placed or badly sized outfall can compromise the efficiency of a bar rack.

The flow on entry to the outfalls must be sufficient compared to the turbine flow in order to attract the fish and make sure they are efficiently lured into the downstream chute. To ensure that flow is sufficient, **the size of the entrance to the outfall** must not be too small. Moreover, the acceleration or deceleration of the outflow must be limited on entry to the outfall to prevent the fish being unwilling to enter.

3.5. Elements to calculate the mortality rate at the turbines

This paragraph sets out the data needed to carry out Stage 4 of Figure 9.

3.5.1. Size of the individuals upstream of the hydropower plant

The size of the individuals also intervenes in this stage of the assessment, considering that the larger individuals have a higher mortality rate than the smaller ones during their passage through a given turbine. In fact, the probabilities of collisions with the mobile components, along with the shearing phenomena, are higher for the larger individuals.

3.5.2. Turbine characteristics

The type of turbine partly determines the mortality rate. The formula allowing the mortality to be estimated are not the same depending on the type of turbine. As regards the fish-friendly turbines, the parameters considered below are not helpful, as the mortality rates are then considered to be zero (or nearly zero) for the eel.

In the case of turbines of the same type and comparable sizes, the greater the **number of blades or vanes**, the higher the estimated mortalities given the increased probability of the fish colliding with the moving parts.

Furthermore, the faster **the rotation speed of the wheel**, the greater the risk of the fish colliding with the moving parts.

However, the larger the **diameter of the turbine**, the lower the estimated mortality, as the greater space between the blades (or vanes) around the wheel results in fewer deaths. Furthermore, for the same turbine flow, a wheel with a large diameter will have a lower rotation speed than a wheel with a smaller diameter, which will result in fewer mortalities.

3.5.3. Equipment flow and turbine flow per turbine

The **equipment flow** is used in the calculation of the proportions of individuals migrating downstream through the spillway structures (weir, gates, flaps, etc.) and of those lured into the outfall. The **flow turbined by each turbine** value is used in the assessment formula of the mortality rates in the turbines.

In the case of the power plants fitted with several turbines with different mortality rates, the **distribution of the total flow between the different turbines over the set of the turbining range** needs to be known in order to work out the average mortality rate caused by the turbines.

3.5.4. Head

The head **value is used in the assessment formula of the mortality rates in the turbines. In the case of turbines of the same type, globally, the higher the head, the faster the rotation speeds and the greater the mortality rates observed.**

3.6.Summary table of the different information to be known

The different parameters to be banked (Table) will be in a second step (see Chapter 4) used in the calculation formula allowing the mortality rate of silver eels migrating downstream at a hydropower facility to be determined.

Table 1. *Types of data to be collected to estimate the morality of eels migrating downstream at a hydropower plant. The power plant data and the way of banking them are set out in SUDOANG Deliverable 1.1.1.*

Biological data
- **Downstream migration period** (in order to determine the flows to be considered) - **Size of the individuals** upstream of the structure (cm), if possible, establish the distribution in **size classes** ***- Potentially, number/density of eels migrating downstream in order to estimate the absolute mortalities*** *(in terms of individuals, biomass, number of lost eggs…)*
Hydrological data
- **Watercourse flows** during the downstream migration period (m^3/s), if possible, over at least a decade - As applicable, **reserved flow** (m^3/s) ***- Potentially, any useful data*** ***to estimate the flows*** *of interest* ***at the facility*** [6]
Hydropower facility data
Spillway structures (weir, gate, flap, etc.)
Head (m) **Water height at bottom of weir** at downstream migrating flows (m) **Type of facing** (vertical or sloping [°]) **Presence or absence of hazards** under the head or on the facing
Bar rack and outfall(s)
Submerged zone of the bar rack (m^2) **Incline or angle** of the bar rack (°)

[6] For example: surface area of the watershed at the level of the structure compared to the surface area at the level flow measurement station used, which allows a flow to be estimated at the structure (see the calculation method in Paragraph 4.1.2).

Free gap between the bars of the bar rack (mm) **Normal speed** at the bar rack (m/s) **Tangential speed** at the bar rack (m/s) **Presence of outfall(s)** **Number and locations** of the outfalls **Size of the entrance** of the outfall(s) (m) **Flow on entry to the outfall** (m^3/s) (to be compared to the turbine flow)
Turbines
Turbine and equipment flow per turbine (m^3/s)
Distribution of the total flow between the different turbines over the whole turbining range **Types and number of turbines** used **Diameter** of the wheel(s) (m) **Rotation speed** of each turbine (turns/min) **Net head** (m) **Number of blades or vanes**

4. Establishing the diagnosis, calculation methods

4.1. Escapement rates at the spillway structures

This paragraph sets out the way to use the data to carry out Stage 1 of Figure 9.

4.1.1. Phase 1: Global downstream migration period and flows triggering downstream migration episodes

Monitoring of the watercourses with different hydrological regimes have shown that the triggering of the downstream migration of the silver eels is strongly linked to the increases in flow and turbidity of the water. This has particularly been observed during the trapping campaigns in France, on the River Nive at Halsou (Gosset *et al.,* 2000, 2001, 2002) and also during the radio-tracking campaigns on the Gave de Pau downstream (Subra *et al.,* 2005, 2006; Bau *et al.,* 2010, 2011, 2013; Travade *et al.,* 2009). In France, current knowledge shows that the eel downstream migration periods are variable depending on the years and the watercourses and they can sometimes be very long. A summary report by Acou *et al.* (2009) concluded that it can be observed across Europe throughout the year, even though the silver eel migratory intensity is at its maximum during the second half of the year between August and December. When studying mortality rates in the rivers of south-west France, a downstream migration period from October to the end of January was selected (ECOGEA, 2014). However, there is growing evidence that the downstream migration period may start between August and October and continue until April, or even June, particularly following dry autumns, as indicated by the monitoring in France:

- On the River Dronne with downstream migration observed overall from the end of October to the end of June from 2011-2012 to 2014-2015 (Verdeyroux & Guerri, 2015)
- On the Dordogne with downstream migration observed from October to March (Tuilières Scientifique Committee, 2016)
- On the Bresle with, in 2009, downstream migrations observed essentially from early August to end of December, but also to some extent throughout the year (Euzenat *et al.,* 2011)
- Or even on the Orne (FCPPMA14, 2014a) and the Touques (FCPPMA14, 2014b).

As the downstream migration period may be different from one watercourse to another, it seems to be **essential to know as much as possible on the context of the route studied**, or even to carry out monitoring if necessary, in order to be able to put forward a relevant mortality estimate.

As regards the **flows triggering downstream migration episodes** during that period, the mortality assessments conducted in France so far are based on the results obtained by Bau *et al*. (2013) (Figure 14). In this study, the processing of 562 structure crossings on the Gave de Pau has allowed the proportion of eels migrating downstream for different characteristic values of flows calculated during **the migration period**.

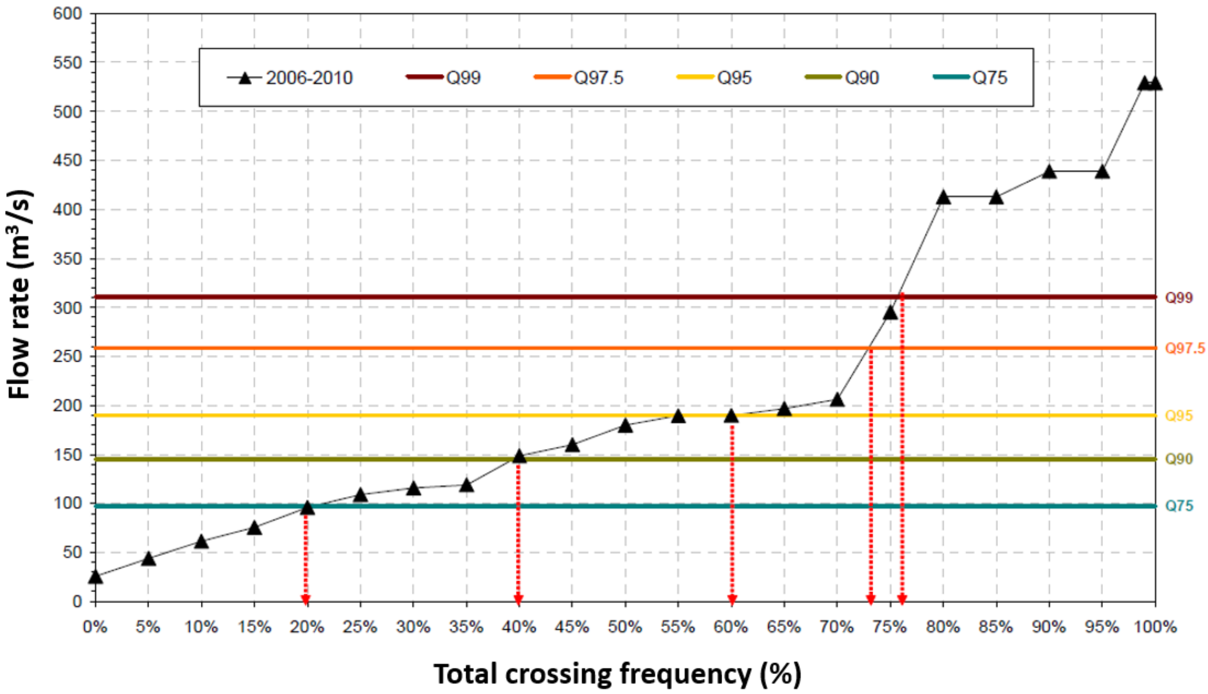


Figure 14. *Characteristic flows of the eel downstream migration periods on the Gave de Pau (between 2006 and 2010) and combined passages of the individuals. Qx = flow not exceeded during x% of time. According to Bau* et al. *(2013).*

These results, validated on another watercourse (the Dronne, cf. Drouineau *et al.*, 2017), point to a near equal distribution of the fish passages between five **characteristic flow values**:

- 20% of the fish migrate downstream at a discharge of the 3rd quartile of the daily flows of the migration period considered (Q75)
- 20% of the fish migrate downstream at a discharge of the 90th percentile of the daily flows of the migration period considered (Q90)
- 20% of the fish migrate downstream at a discharge of the 95th percentile of the daily flows of the migration period considered (Q95)
- 20% of the fish migrate downstream at a discharge of the 97.5th percentile of the daily flows of the migration period considered (Q97.5)
- 20% of the fish migrate downstream at a discharge of the 99th percentile of the daily flows of the migration period considered (Q99)

However, data collected very recently as part of the SUDOANG programme have shown that the proportions of downstream migrating eels according to the flows may differ between sites (Figure 15). Even though the direct comparison of the downstream migration kinetics between these different sites may particularly be distorted by different catch or observation probabilities of the individuals migrating downstream at strong flows, it can be considered that variability exists between sites. In certain watercourses, the majority of eels seem to thus migrate downstream in a flow lower than Q70 (e.g.: the Aulne) while, in others, the majority of the eels seem to migrate downstream in flows over Q80, or even Q90 (e.g.: the Sèvre Niortaise).

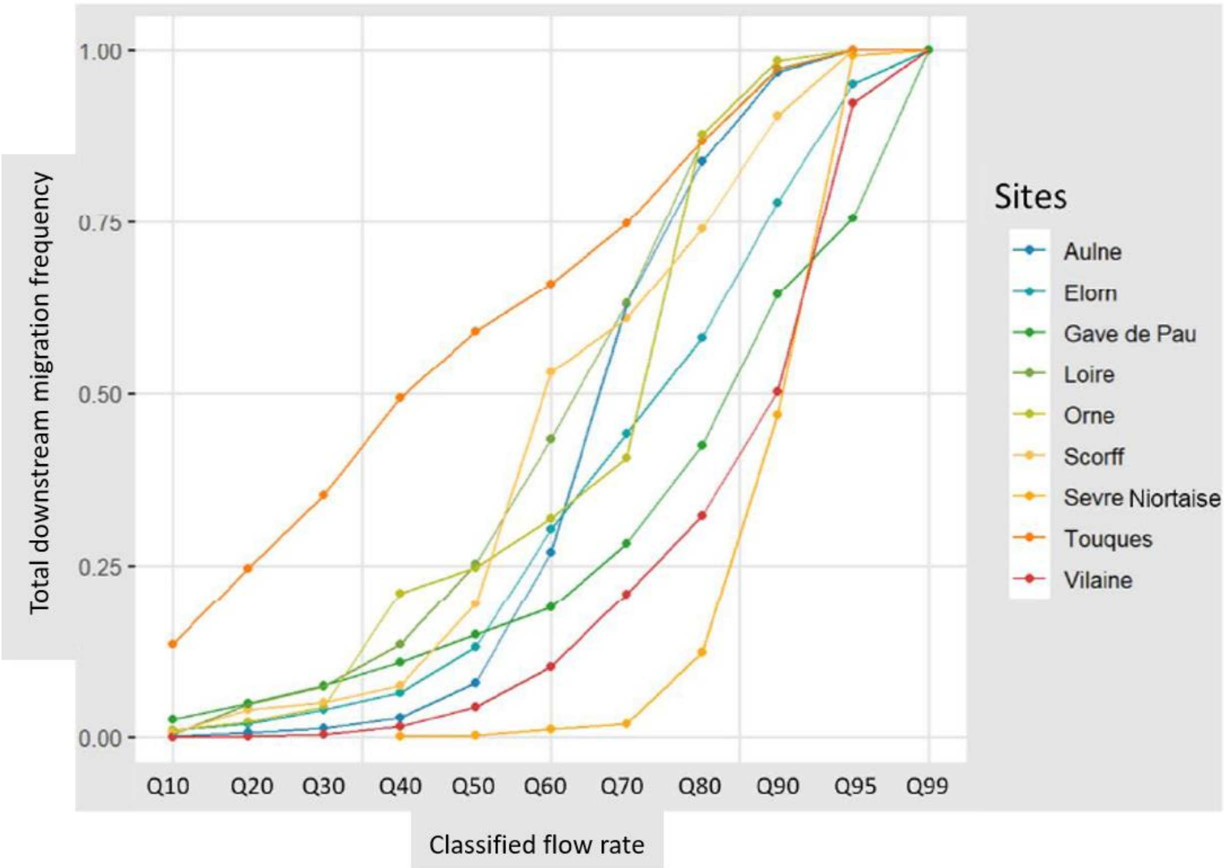


Figure 15. *Combined proportion of individuals migrating downstream at different classified flows (eel downstream migration flows), in different watercourses, with Qx = flow not exceeded during x% of time (according to data gathered as part of SUDOANG deliverable 2.2.2). N.B.: The Gave de Pau curve, the French benchmark as of the time of writing, is not the same to the one in Figure 14 because the flow records used here are different: they are the set of records available for the estimated eel downstream migration periods, i.e., hydrological data recorded between 1923 and 2017 for this watercourse.*

By default, in the absence of local knowledge on the downstream migration kinetics and in order to put forward a confidence interval for the proposed mortality estimates, it would be interesting to **test two**

contrasting scenarios on the studied site. Two mortality assessments could thus be proposed, based respectively on a) downstream migration kinetics comparable to that of the Aulne (majority of individuals migrating downstream in the range of weakest flows) and b) downstream migration kinetics comparable to that of the Sèvre Niortaise (majority of individuals migrating downstream in the range of strongest flows) (see the proportions of downstream migrating individuals to be considered at different flows in Table 2).

Table 2. *Proportions of downstream migrating individuals for different characteristic flow values in different watercourses (Qx = flow not exceeded during x% of time). These values have been obtained by applying a logistic model to the data in Figure 15 (this modelling is presented in SUDOANG Deliverable 2.2.2).*

Sites	Q10	Q20	Q30	Q40	Q50	Q60	Q70	Q80	Q90	Q95	Q99
Aulne	0,00672	0,00939	0,02202	0,04948	0,10135	0,17315	0,22079	0,19642	0,12612	0,06492	0,02964
Elorn	0,00430	0,00605	0,01434	0,03308	0,07173	0,13654	0,20551	0,22122	0,16667	0,09491	0,04565
Gave de Pau	0,00252	0,00355	0,00849	0,01999	0,04533	0,09470	0,16782	0,22577	0,21290	0,14316	0,07577
Loire	0,01108	0,01531	0,03517	0,07554	0,14113	0,20609	0,21376	0,15578	0,08677	0,04125	0,01813
Orne	0,00866	0,01204	0,02797	0,06159	0,12090	0,19166	0,22047	0,17676	0,10508	0,05175	0,02312
Scorff	0,00887	0,01233	0,02860	0,06284	0,12282	0,19323	0,22009	0,17478	0,10321	0,05063	0,02258
Sèvre Niortaise	0,00101	0,00143	0,00344	0,00823	0,01944	0,04443	0,09434	0,17241	0,24316	0,24198	0,17015
Touques	0,04728	0,05992	0,11797	0,18793	0,21759	0,17555	0,10483	0,05175	0,02315	0,00990	0,00415
Vilaine	0,00153	0,00217	0,00521	0,01241	0,02889	0,06390	0,12664	0,20409	0,23998	0,19655	0,11864

If possible, it is of course more appropriate to check the downstream migration rate on the watercourse considered in the assessment in order to fine-tune it, but acquiring that information generally involves more complex field operations and repeated over several years.

4.1.2. Phase 2: Calculating the daily flows at the facility

The preceding phase requires the **daily flows** immediately upstream of the facility in question to be known, *a minima* during the eel migration period considered.

If these values are not directly known, the **existing data** should be recovered for the closest hydrometric station possible (upstream or downstream) of the facility in question (see Paragraph 3.2.1), for the previously defined downstream migration period. A least a decade should be studied in order to include both years with strong hydrology and ones with weak hydrology in the analysis. The average daily flows at the structure may then be recalculated by applying a correction, for example **pro rata of the surface area of the watershed** considered (see Lebecherel *et al.*, 2015). Therefore, the Myer formula is often used:

$$Q_{TOT} = Qs \times (Sa / Ss)^{0.8}$$

where:
- Q_{TOT}: Flow immediately upstream from the facility (m^3/s)
- Qs: Flow at the level of the hydrometric station used (m^3/s)
- Sa: Surface area of the watershed at the level of facility (km^2)
- Ss: Surface area of the watershed at the level of the hydrometric station used (km^2)

If there is no significant contribution or uptake between the facility and the hydrometric station studied, these "flow-flow" models may provide very satisfactory results (Andréassian *et al.*, 2012).

Once these values are obtained, the different characteristic flow values defined in 4.1.1 may be calculated.

4.1.3. Phase 3: Estimating the proportion of individuals migrating downstream at the level of the spillway structures

The **simplest model** consists of considering that the distribution of the fish between the different passage routes (weir *vs* generating station) is performed **pro rata of the flows** along those same routes. In this case:

$$P = Q_{DEV} / Q_{TOT}$$

where:
- P: Passage probability of the fish at the level of the spillway structures
- Q_{DEV}: Overflow discharged by the spillway structures (m^3/s)
- Q_{TOT} : Flow of the watercourse immediately upstream of the facility (m^3/s)

This simple approach however does not take into account the configuration of the spillway and intake structures, which may significantly influence the distribution of the fish.

In greater detail, the formulas from a synthesis of studies that have monitored eels tracked by telemetrics at 6 hydropower facilities over 4 downstream migrating seasons can be used (Bau *et al.,* 2013). The results show that the rate of silver eels passing in the overflow at the weirs is very low, while the watercourse **flow** does not become very significantly higher to the **turbine flow** at the power plant. In fact, the currentology does not attract the fish towards the weir below a certain overflow discharge and, furthermore, low water above the weir makes them more reluctant to use that passage route.

Hence, **the proportion of fish passing in the weir overflow discharge is not fully in line depending on the ratio between the overflow discharged at the weir and the total flow of the watercourse**.

Bau *et al.* (2013) propose a general formula (the most widely used) which allows the proportion of individuals migrating downstream passing through a spillway structure such as a weir to be estimated (Figure 16):

$$P = \exp(\eta)/(1+\exp(\eta))$$

with: $\eta = -3{,}94 + 7{,}29 * (Q_{DEV}/Q_{TOT})$

where:
- P: Passage probability of the fish at the level of the spillway structures
- Q_{DEV}: Overflow discharged by the spillway structures (m^3/s)
- Q_{TOT} : Flow of the watercourse immediately upstream of the facility (m^3/s)

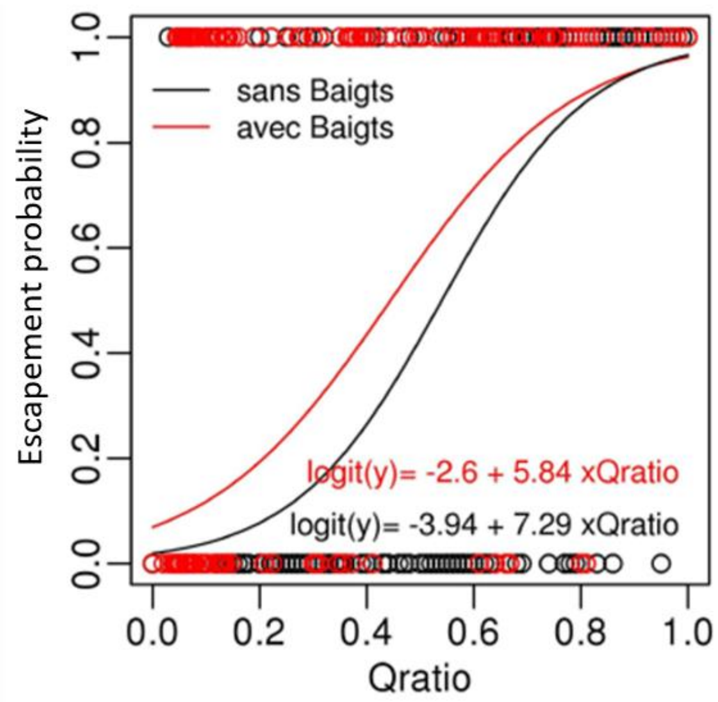


Figure 16. *Predicting the escapement probability of eels migrating downstream through the spillway of a dam according to the distribution of the flow between the dam and the hydropower generating station (Qratio = overflow discharge at the dam divided by the total flow of the watercourse). The black curve is the general formula (see text). According to Bau* et al*. (2013).*

Bau *et al.* (2013) showed that P likewise depended on the **physical layout of the facility**, as it particularly determines the angle of the outflows respectively towards the spillway structures and towards the generating station. A formula has therefore been proposed for each of the five facilities studied and it may be deemed wise to use one of these five specific formulas if the physical layout of the power plant in question strongly resembles one of the following facilities.

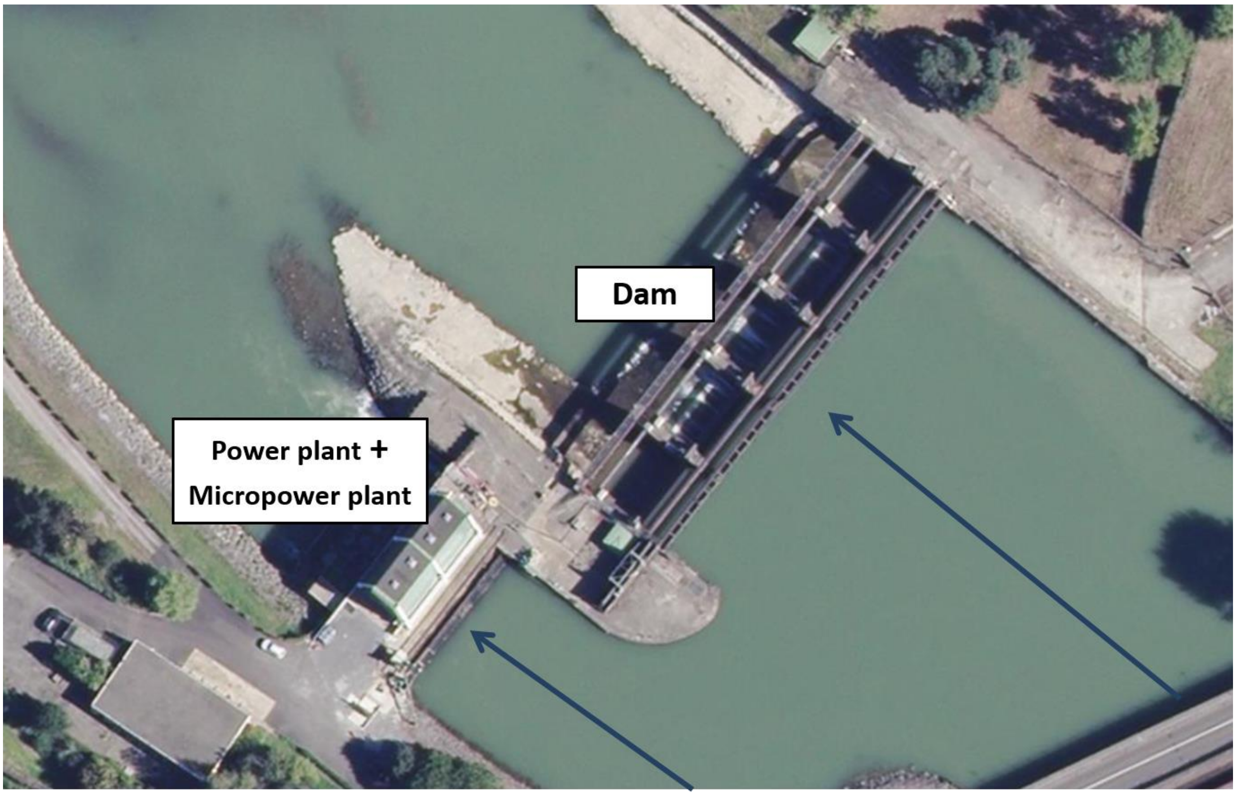


Figure 17. *Aerial view of the Artix hydropower facility (Gave de Pau, France). From Google Maps.*

In the case of the Artix power plant, the dam and the plants are aligned (Figure 17). The formula for this layout is as follows:

$$\mathbf{P = exp(\eta)/(1+exp(\eta))}$$

with: $\boldsymbol{\eta = -4.99 + 7.91 * (Q_{DEV}/Q_{TOT})}$

where:

- P: Passage probability of the fish at the level of the spillway structures
- Q_{DEV}: Overflow discharged by the spillway structures (m^3/s)
- Q_{TOT} : River flow (m^3/s)

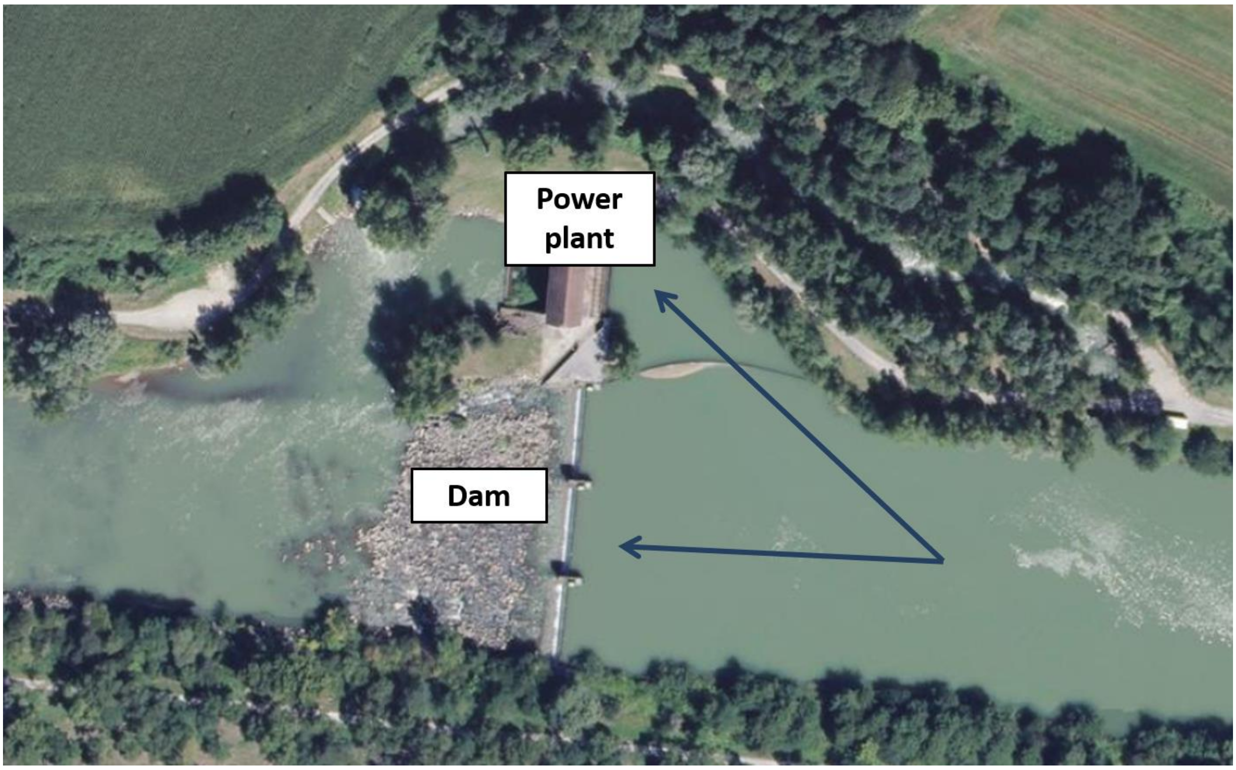


Figure 18. *Aerial view of the Biron hydropower facility (Gave de Pau, France). From Google Maps.*

The layout of the Biron facility (Figure 18) is relatively comparable to the Artix one, but the watercourse is significantly broadened by the power plant. The formula for this layout is as follows:

$$P = \exp(\eta)/(1+\exp(\eta))$$

with: $\eta = -1.69 + 4.53 * (Q_{DEV}/Q_{TOT})$

where:
- P: Passage probability of the fish at the level of the spillway structures
- Q_{DEV}: Overflow discharged by the spillway structures (m^3/s)
- Q_{TOT} : River flow (m^3/s)

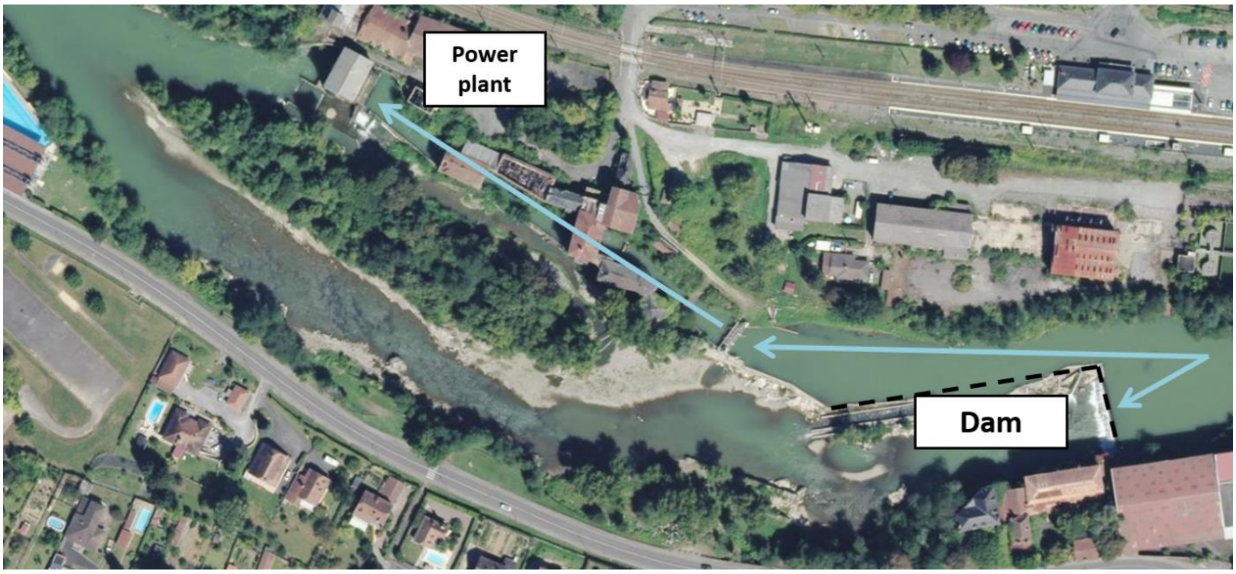


Figure 19. *Aerial view of the Sapso hydropower facility (Gave de Pau, France). From Google Maps.*

As regards the Sapso facility (Figure 19), the dam is longer than in the previous cases and has a pronounced angle to the route of the watercourse; the power plant is at the end of an intake channel. This layout makes it easier to lure the fish into the intake. The formula for this layout is as follows:

$$P = \exp(\eta)/(1+\exp(\eta))$$

with: $\eta = -5.83 + 9.36*(Q_{DEV}/Q_{TOT})$

where:
- P: Passage probability of the fish at the level of the spillway structures
- Q_{DEV}: Overflow discharged by the spillway structures (m^3/s)
- Q_{TOT} : River flow (m^3/s)

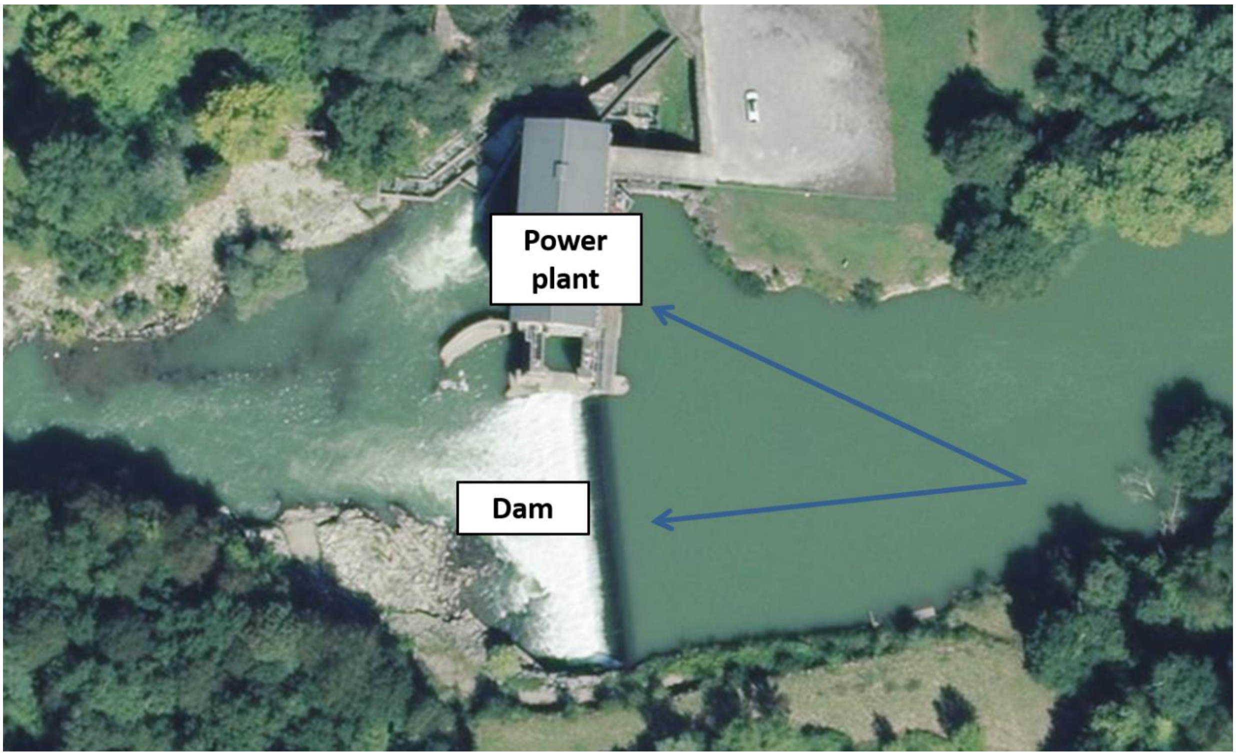


Figure 20. *Aerial view of the Castetarbe hydropower facility (Gave de Pau, France). From Google Maps.*

The Castetarbe power plant (Figure 20) is aligned with the weir. It is fitted with a bar rack with 25 mm gaps between the bars, which stops the fattest eels making their way towards the adjacent weir. Hence, the larger the eel, the more likely they are to pass through the weir. The formula for this layout therefore includes a parameter relating to the size of the fish. The formula is as follows:

$$P = \exp(\eta)/(1+\exp(\eta))$$

with: $\eta = -11.7 + 5.61*(Q_{DEV}/Q_{TOT}) + 0.0129*LT$

where:
- P: Passage probability of the fish at the level of the spillway structures
- Q_{DEV}: Overflow discharged by the spillway structures (m^3/s)
- Q_{TOT} : River flow (m^3/s)
- LT: Fish length (mm)

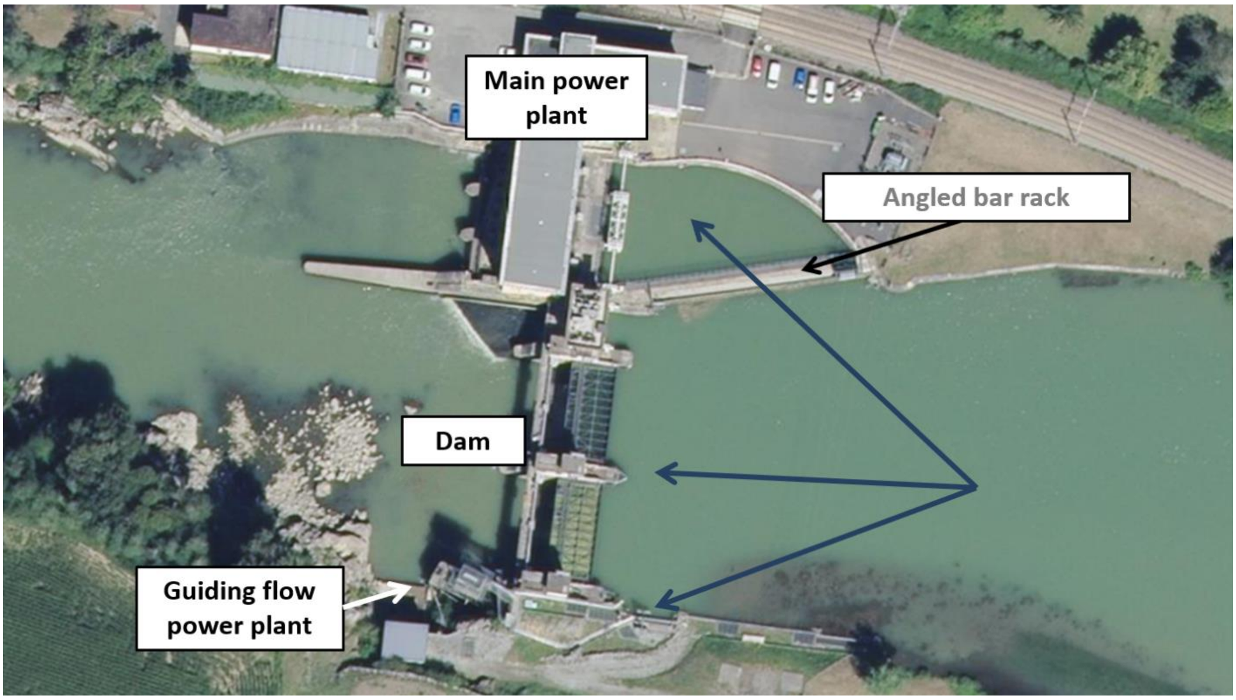


Figure 21. *Aerial view of the Baigts hydropower facility (Gave de Pau, France). From Google Maps.*

The Baigts facility (Figure 21) has an angled bar rack on the continuation of the bank and which guies the fish to the dam with a space of 30 mm between the bars at the time of the study (reduced to 20 mm today). The distribution of fish between the different passage routes depends, as in the previous case, on their size, which is again a parameter included in the equation[7]. The formula for this layout is as follows:

$$P = \exp(\eta)/(1+\exp(\eta))$$

with: $$\eta = - 6.,2 + 3.64*(Q_{DEV}/Q_{TOT}) + 0.00817 \times LT$$

where:
- P: Passage probability of the fish at the level of the spillway structures
- Q_{DEV}: Overflow discharged by the spillway structures (m^3/s)
- Q_{TOT} : River flow (m^3/s)
- LT: Fish length (mm)

[7] It should be noted that the power plant that turbines the attraction flow of a fishway, on the left bank, has a bar rack with a gap of 20 mm between the bars.

4.1.4. Phase 4: Estimating the overflow discharged at the weir

Once the correct formula has been chosen (see preceding phase), the Q_{DEV}/Q_{TOT} ratio used in each of the formula, has to be determined as accurately as possible. Therefore, **the overflow discharge (Q_{DEV})**, which corresponds to **the part of the total flow (Q_{TOT}) which is not turbined**[8] needs to be calculated. In general:

$$Q_{DEV} = Q_{TOT} - Q_{TUR}$$

where:
- Q_{DEV}: Overflow discharged by the spillway structures (m^3/s)
- Q_{TOT}: Flow of the watercourse immediately upstream of the facility (m^3/s)
- Q_{TUR}: Turbine flow (m^3/s)

If the water diverted by the facility is not directly returned to the bottom of the weir, a reserved flow (Q_{RES}) must be discharged at the weir to supply the bypassed section. In this case, the value of Q_{DEV} may not be lower than that of Q_{RES}.

→ The **escapement probability of the eels at the weir** is therefore calculated using the correct formula (Phase 3) for each classified flow of interest (Qx_1, Qx_2, Qx_3… Qx_n), an average (weighed by the proportion of fish migrating downstream at each Qx_i, see Paragraph 4.1.1) is then calculated in order to estimate an average escapement rate.

4.2. Estimating the mortality at the passage of the spillway structures

This paragraph sets out the way to use the data to carry out Stage 2 of Figure 9.

There is no **accurate formula** to calculate this mortality, which is very often considered to be zero during the assessment. According to the currently known criteria[9], fish migrating downstream are considered not to be injured when:

- The **head is under a dozen metres**
- The **reception pool at the bottom of the head** is **deep enough**, i.e., the stilling pool is at least a quarter of the head or has a depth of at least 1 m for heads under 4 m
- There is a **lack of hazards** at the bottom of the head.

Beyond a case-by-case appraisal taking these factors into account, the mortality of eels during their passage through the weirs and spillway structures has barely been studied. However, fish may face a risk of abrasion on certain types of weirs and/or of collisions on the masonry parts or on the substrate

[8] This is a misnomer, as in fact the flow does not pass through the turbines or in the downstream migration outfalls as applicable.

[9] See "Mortality Risk" tab on: https://patbiodiv.ofb.fr/fiche-methodologique/continuite-ecologique/demarche-diagnostic-devalaison-franchissabilite-ouvrage-120

at the bottom of the head. Therefore, the use of a 0% mortality rate at certain weirs may be an under-estimation.

4.3. Efficiency of the bar rack and of the associated outfalls (if they exist)

This paragraph sets out the way to use the data to carry out Stage 3 of Figure 9.

There is currently **no accurate formula** taking into account the characteristics of a bar rack to calculate the efficiency. However, in order to provide aspects to help with the assessment, this paragraph includes:

- The criteria currently recommended in France (Courret & Larinier, 2008), which allows around 100% efficiency to be obtained when stopping downstream migrating eels over 55 cm in length (Tomanova *et al.*, 2019)[10]; when necessary, certain criteria applied in other countries will also be raised.

- Expert opinions on the efficiency, in terms of stopping and guiding the eels towards a safe route, of different bar racks with different layouts.

4.3.1. Maximum free space between the bars

Unlike salmon smolts, which may hesitate before crossing a sufficiently constricted bar rack, some eels tend to go up to the bar racks and force their way through. They must therefore be stopped by a physical barrier, through which they are unable to pass. A bar rack is that physical barrier for an eel if the maximum free space between the bars is smaller than the width of its head. In France, the recommended space between the bars (angled and inclined bar racks) is **20 mm** to stop and guide **females** measuring over 50 to 60 cm. It may be reduced to **15 mm** (Courret et Larinier, 2008)[11] for power plants located upstream of the watershed areas, where there is a significant presence of smaller **males**.

4.3.2. Maximum permissible normal speed at the bar rack

Too faster a normal speed (V_N) at the bar rack (Figure 22) may **exhaust the fish** and, *in fine*, cause their **impingement against the rack**. In F, the recommended maximum value for this speed is around 0.5 m/s (Courret et Larinier, 2008)[12].

[10] Monitoring 194 tagged individuals, at 5 hydropower plants on the River Ariège (France)

[11] 20 mm recommended in the USA (U.S. Fish and Wildlife Service, 2017), 9 to 18 mm in Germany and 12.5 mm in the United Kingdom (Ebel, 2013 ; DWA, 2005; Environment Agency, 2012).

[12] 0.5 m/s also recommended in the United Kingdom (Environment Agency, 2012), around 0.6 m/s in the USA (U.S. Fish and Wildlife Service, 2017) and around 0.4 m/s in Germany (Ebel, 2013).

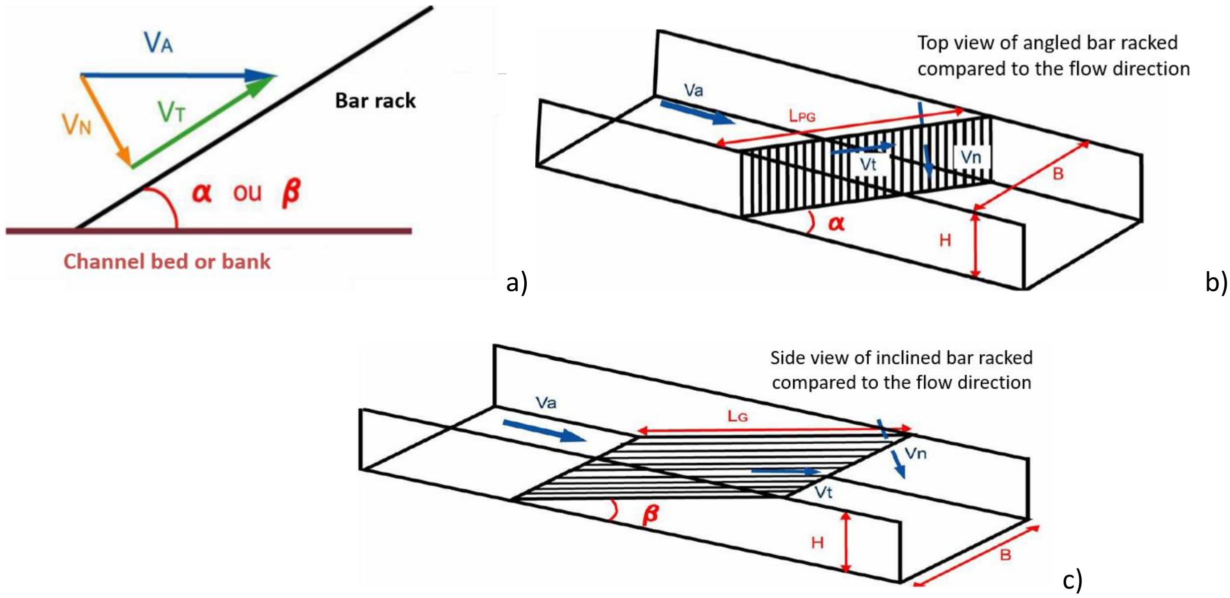


Figure 22. *a) Components of the outflow speed approaching a bar rack (cf. Figure 13) and angle to the bank [α, angled bar rack, b)] incline to the bottom of the channel [β, inclined bar rack, c)]. According to Courret & Larinier (2008).*

In order to obtain the normal speed (V_N) at the bar rack, the outflow approach speed (V_A, Figure 22) must first be known:

$$V_A = Q_{TUR}/S$$

where:
- V_A: Approach speed (m/s)
- Q_{TUR}: Turbine flow (m^3/s)
- S: Outflow section of the intake (m^2)

The normal speed (V_N) can then be calculated thanks to the approach speed (V_A) and Angle α (Angled bar racks) or β (inclined bar racks) (see Figure 22):

$$V_N = V_A \times \sin\alpha$$ (for the angled bar racks)

$$V_N = V_A \times \sin\beta$$ (for the inclined bar racks)

The normal speed may likewise be obtained by dividing the maximum turbine flow by the submerged zone of the bar rack:

$$V_N = Q_{TUR}/A$$

where:
- V_N: Normal speed (m/s)
- Q_{TUR}: Turbine flow (m^3/s)
- A: Submerged zone of the bar rack (m^2)

It should be noted that **guiding the fish** to the outfalls will be much better the higher the tangential speed (V_T, Figure 22) is compared to the normal speed (V_N). This tangential speed VT (m/s) can be calculated thanks to the normal speed V_N and to angle α (angled bar racks) or β (inclined bar racks).

$$V_T = V_A \times \cos\alpha$$ (for the angled bar racks)

$$V_T = V_A \times \cos\beta$$ (for the inclined bar racks)

4.3.3. Incline of the inclined bar racks

The incline of the inclined bar racks is an important parameter as it directly influences the rack surface (see above) and allows the fish to be guided more or less quickly to the outfalls. The greater the bar rack incline (i.e., the small the angle between the rack and the ground), the quicker the tangential speed and the greater the number of fish will be efficiently guided to the top of the bar rack, where the outfall(s) must be located. Thus, it is recommended that **angle β** (Figure 22) is **smaller or equal to 26°**, in order for the tangential speed (V_T) to be at least twice as high to the normal speed (V_N) (Courret et Larinier, 2008)[13]. However, when the average approach speed is over 0.80-0.85 m/s, the bar rack must be at a greater incline (less than 26°) to respect the maximum normal speed criteria.

4.3.4. Angle of the angled bar racks

The angle of the bar rack creates a tangential outflow to the bar rack, which allows the fish to be guided to an outfall positioned at the upstream end. The more the bar rack is angled (the smaller the angle between the bar rack and the edge of the bank), the greater number of fish will be efficiently guided to the outfall. It is recommended that **angle α** (Figure 22) is **smaller or equal to 45°**, in order for the tangential speed (V_T) to be greater or equal to the normal speed (V_N) (Courret et Larinier, 2008)[14].

In the case of a "conventional" bar rack (bars perpendicular to the axis of the rack), due to an acceleration of the outflow speed along the bar rack, and to keep a normal speed (V_N) under 0.55 m/s (see Paragraph 4.3.2), the recommended maximum **approach speed (V_A) is 0.5 m/s**. It can be slightly higher if angle α is reduced and the surface area of the bar rack increased (Raynal *et al.,* 2014).

Some angled bar racks have horizontal bars or bars placed in the direction of the current (Figure 23). In these cases, the normal speed does not change along the bar rack (Raynal *et al.,* 2014 ; Szabo-Meszaros *et al.,* 2018) and the recommended maximum approach speed is 0.6 m/s for an angle of 45°. If the approach speed is higher, angle α will need to be reduced to 40°, 35° r 30° for approach speeds of 0.65, 0.75 and 0.85 m/s, respectively.

[13] The recommendation is the same in Switzerland (Hefti, 2012).
[14] The recommendation is the same in the USA (U.S. Fish and Wildlife Service, 2017).

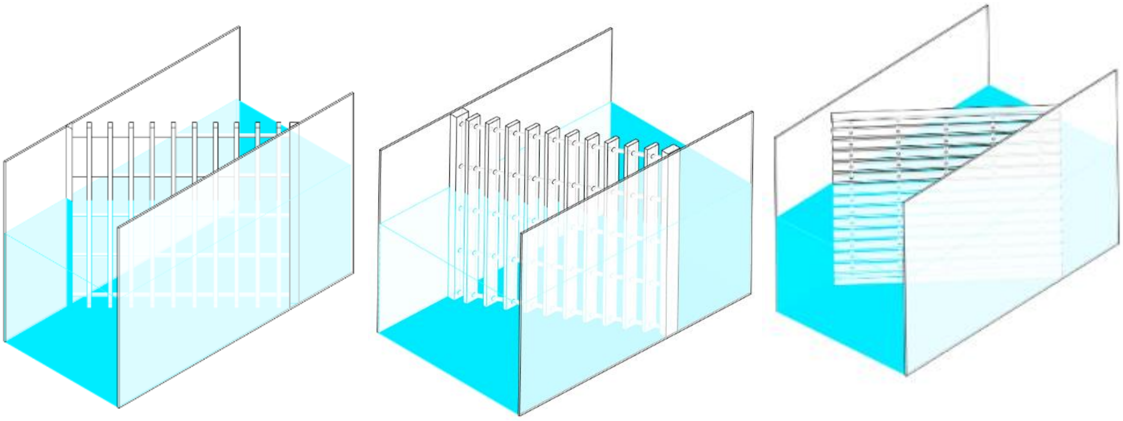


Figure 23. *Schematic diagram of the 3 bar assembly methods in the case of angled racks: "conventional" rack on the left, bars aligned in the direction of the outflow in the centre, and horizontal bars on the right (according to Lemkecher* et al.*, accepted).*

4.3.5. Recommendations for outfalls and downstream chutes

4.3.5.1. Existence of one or more well-placed outfalls

Once the fish are stopped by the bar rack, the outflows must quickly guide them to a downstream migration outfall.

In the case of inclined bar racks (Figure 24), the outfall(s) are generally placed on the surface, at the top of the bar rack. Several need to be installed if the bar rack is very wide.

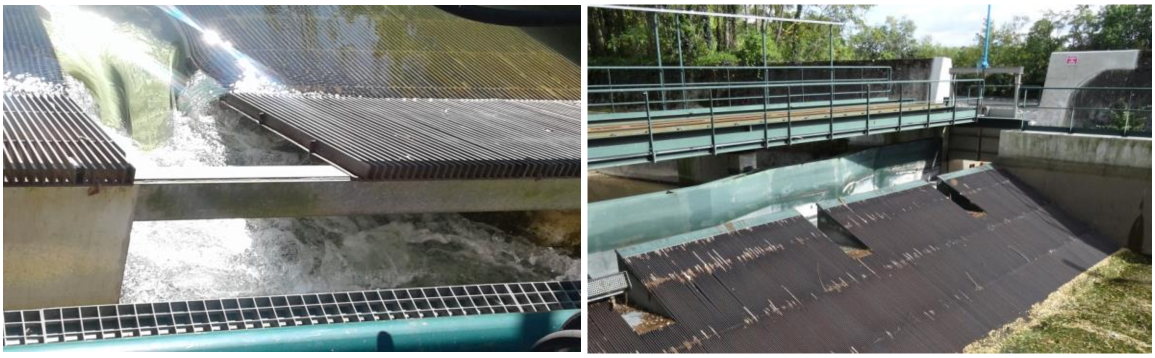


Figure 24. *Outfalls at the top of the inclined bar racks (photos P. Sagnes – OFB).*

The **recommended space between the outfalls** depends on their number and their position: it is recommended to leave:

- Around 6 m between two outfalls on bank
- Around 5 m between an outfall on the bank and one outfall not located on the bank
- Around 4 m between two outfalls not located on the bank
- Around 2 m between an outfall not located on the bank and a bank

In France, it is also recommended to plug the top of the rack between the outfalls (at their height) in order to generate cross currents to guide the fish.

<u>In the case of the angled bar racks</u> (Figure 25), the outfall must be located at and as close as possible of the **upstream end** of the rack. The ideal is that the outfall height matches the entire depth. In the case of very long bar racks, using intermediate outfalls can be considered (Courret & Larinier, 2008).

Figure 25. *Outfall upstream of an angled bar rack (photo M. Larinier – Onema).*

Bed outfalls are viable for the eel, which tends to keep to the bottom of the intake channel when it is efficiently stopped by a bar rack. However, these outfalls easily silt up and are difficult to maintain.

4.3.5.2. Flow allocated to the downstream migrating compared to the maximum turbine flow.

The larger the flow allowed to the downstream migration [i.e., passing through the outfall(s)] compared to the turbine flow, the more attractive the outfall is.

<u>As regards the inclined bar racks</u>, the recommended proportion of flow allocated to the downstream migration in France varies between **5-6% for small facilities** and **2-3% for a turbine flow over 50 m^3/s**. In the case of facilities with a turbine flow over 100 m^3/s, the flow passing through the outfall(s) may be even lower.

<u>As regards the angled bar racks</u>, the criteria are not as precise as for the inclined bar racks, but it is recommended to allocate at least 2 **to 5% of the turbine flow** to the outfalls (Courret *et al.*, 2015)[15].

[15] 5-10% of the recommended turbine flow in Germany (Ebel, 2013), 2% minimum for the inclined bar racks in the USA (Environment Agency, 2005) and 5% for the inclined bar racks in the United Kingdom (Environment Agency, 2005).

It is possible to estimate the flow allocated to the downstream migration thanks to the following formula (Courret *et al.*, 2015) :

$$Q_b = N_b*B_b*H_b*V_b$$

where:
- Q_b : Flow allocated to the downstream migration (m^3/s)
- N_b : Number of outfalls
- B_b : Width of the outfalls (m)
- H_b : Height of the outfalls (m)
- V_b : Speed on entry to the outfall (m/s)

4.3.5.3. Size of the outfall

In France, a **width of around 1 m** is recommended for outfalls of inclined bar racks and the total width of the outfalls must be almost equal to **20-25% of the total width of the water intake**. The **depth** of the outfall must be at least **0.5 m**.

As regards the angled bar racks, the outfalls must be as deep as possible with a minimum of 0.5 m (Courret *et al.,* 2015)[16].

4.3.5.4. Speed on entry to the outfalls

In France, the recommendations are as follows[17] :

- **In the case of inclined bar racks**, the speed on entry to the outfalls (V_p) must be 1.1 times the approach speed (V_A)

- **In the case of angled bar racks** at 45º, the speed on entry to the outfalls (V_p) must be 1.7 times the approach speed (V_A); As regards the angled bar racks with bars positioned in the direction of the current or with horizontal bars, the speed on entry to the outfall (V_p) must be equal to the approach speed (V_A) (Courret *et al.,* 2015).

4.3.5.5. Sizing of the downstream migration chute and transfer of fish downstream

To avoid the fish being injured, the downstream migration chute must be sized in such a way that the speed inside does not exceed 5 to 6 m/s (Guensch *et al.*, 2002). The transition and changes in speed along the downstream transfer system must be gradual to avoid shearing, abrupt changes in pressure and strong turbulence, which are potential sources of injury for the fish.

In the case of the inclined bar racks, the downstream migration chute, which gather the fish that have crossed the outfalls, runs along the top of the bar rack. Ideally, **the same speed must be kept in the chute as in the outfalls**. One solution consists of increasing the width on the chute as the outfalls exit

[16] In the USA, the recommended width for angled bar racks is 0.4 to 0.6 m, with an outfall depth equal to the depth of the water intake (Rainey, 1985). In Germany, the recommended width is 0.4 to 0.6 m and the depth from 0.6 to 0.9 m (Ebel, 2013).

[17] In Germany, $V_p = 1.0\text{-}2.0*V_A$ (Ebel, 2013), the msot recent study in the USA recommends : $V_p = 1.0 - 1.5* V_A$ regardless of the type of bar rack (inclined or angled) (USBR, 2006).

into it (Figure 26). When there are a large number of outfalls, it is difficult to strictly respect this criterion. In that case, it is important to try **not to exceed 1m/s** in the chute.

Figure 26. *Chute at the top of an inclined bar rack. The outflow goes from the top to the bottom in the photo and the chute expands as the downstream migration outfalls run into it (photo D. Courret - OFB).*

Following the collective chute, the **fishway system** downstream (Example in Figure 27) must meet certain criteria in order to avoid the fish being injured:

- The transfer downstream must preferably use an **open channel**, rather than a pipe (more likely to become silted up and maintenance more difficult)
- The desirable **head** in the channel is **20-25 cm**, *minimum* 10-15 cm
- The **speed** in the structure must remain under **8-10 m/s**
- The **head** between the channel output and the water downstream must be ideally under 5 m (and always under 10-12 m)
- The discharge must be in **a sufficiently deep area** to avoid any risks of injury due to mechanical shock (in the same way as for the fish going over the weir cf. Paragraph 4.2).

Studies are currently underway in France to fine-tune these recommendations (OFB-EDF partnership).

Figure 27. *Transfer system of the downstream migrating fish, downstream of a bar rack and a collective chute (photo D. Courret - OFB).*

4.3.6. Examples of assessments of bar rack efficiency as determined by experts

If all the constituent parts of the downstream migrating system, described above, meet the proposed recommendations, the biological efficiency of the mechanism for the eels (i.e., the proportion of individuals reaching the water intake and which avoiding passage in the turbines) is considered close to 100%. Recent feedback has strengthened this conclusion for individuals over 55 cm in length (Tomanova *et al.*, 2019). However, when one or more parameter(s) are far removed from these recommendations (for example, too large a space between the bars), the efficiency may quickly be much less, or even none. Between these two extreme cases, **it is difficult to precisely assess this efficiency** other than by expertise. Thus, to help assess the efficiency of the water intakes whose design is not *a priori* optimal perspective, it is of interest to have several expert opinions in contrasting situations (Table 3).

Table 3. *Examples of assessing the efficiency of different bar racks, as per their characteristics, as determined by experts (according to ECOGEA, 2014). NR = no information. It should be noted that many of these bar racks have been subsequently modified, in order to improve this efficiency.*

Watercourse	Power plant name	Flow allocated to the downstream migrating compared to the turbine flow (%)	Outfall installation quality	Space between bars (mm)	Incline of the bar rack (º)	Comment	Estimate efficiency (%) for eels ≈ 70 cm in length
	Merville generating station	1,4	Poor installation	65	48		0
	Castet power plant	0	No outfall	80	70		0
	Ponsa generating station	NR	Poor installation	40	30	No tangential current	0

	Power plants of the stage	4-4.5% at the dam	Poor installation	20 at the dam and 50 at the generating station	20 at the dam and at the generating station		Near to 100 at the dam and 0 at the generating station
Gave d'Ossau	Tanneries power plant	NR	Poor installation	50 at the generating station and 20 at the dam	50 at the generating station and vertical at the dam		Near to 100 at the dam and 0 at the generating station
	Cau Upstream power plant	2,5	Good installation	40 out of 1/3 20 out of 2/3	NR		25
	Cau Downstream power plant	2,6	Good installation	33	30	Very high speed in the intake channel and slight tangential current	0
	Saint Cricq	3,3	Good installation	25	55	Outfall closed during eel downstream migration period	75
	Lailhacar generating station	1,9	Good installation	60	NR		0
	Abadie generating station	2.8 in theory but 2 times less in reality	Poor installation	30	60	The fishway plays the role of 2nd outfall	25
	Loubière generating station	5	Good installation	30	NR	Very fast approach speed	25
	Esquit power plant	7	Poor installation	40	54	No tangential current and outfall closed during eel downstream migration period	0
	Bedous water intake	1.6 to 3.9	Poor installation	30	NR		25
Gave d'Aspe	Gurmençon power plant	1,8	Poor installation	50	NR		0
	Sainte Marie power plant	3,5	Poor installation	35	70	Very fast approach speed and no tangential current	0
	Sainte Claire power plant	3,2	Poor installation	40	20		0

4.4. Calculating the mortality rate in different types of turbines

This paragraph sets out the way to use the data to carry out Stage 4 of Figure 9. The "R" code used for this calculation in SUDOANG is explained in the Annex.

4.4.1. Fish-friendly turbines

The two types of turbines recognised as fish-friendly in France are the VLH type turbines and the hydrodynamic screws. Exclusively in the case of these turbines, the **mortality** of the downstream migrating silver fish is considered to be **zero.**

N.B. : However, their impact on other species should be noted; for example, the mortality could be significant in VLH turbines for adult Atlantic salmon kelts[18].

4.4.2. Pelton Turbines

The morality rate of the fish (all species together) passing through a Pelton turbine is **100%**.

4.4.3. Kaplan Turbines

Ideally, the potential injuries suffered by the fish during their passage through a turbine must be assessed using experiments, particularly consisting of injecting fish into the turbine. However, these are very complex operations that can only be carried out on a very limited number of sites. Generally, these injuries are therefore estimated using **predictive formulas**, established by experiments conducted at other sites, or by **extrapolating the results** of tests on turbines with similar characteristics to the one studied.

Formulas have been proposed that allow an order of magnitude to be established of mortality percentages for downstream migrating eels according to their size and the characteristics of the Kaplan turbines (Gomes et Larinier, 2008). They are based on the gathering, assessment and analysis of the results of all the significant mortality tests carried out in Europe and in North America before 2008. Three expressions have thus been proposed that allow that mortality percentage to be estimated:

$$\mathbf{M1 = 4.67.TL^{1.53}.Dr^{-0.48}.N^{0.6}}$$
$$\mathbf{M2 = 6.59.TL^{1.63}.Q^{-0.24}.N^{0.63}}$$
$$\mathbf{M3 = 12.42.TL^{1.36}.Q^{-0.22}.Dr^{-0.10}.N^{0.49}}$$

where:
- M_i: Mortality percentage (%)
- TL: Fish length (m)
- Dr: Diameter of the wheel at mid-length (m)
- Q: Equipment flow (m^3/s)
- N: Rotation speed of each turbine (turns/min)

If all the parameters are available, the average is calculated for the mortalities obtained by the three formulas. If the value of a parameter is unknown, a single formula (M1 or M2) may be used.

These formulas allow a mortality rate to be obtained for different sizes of eels. This may be useful according to the characteristics of the local eel "population", for example, a majority of females, larger than the males, in the upstream areas. If the sizes of individuals are unknown, the mortality rate is generally estimated for three sizes of eels: 50, 70 and 90 cm.

[18] See ECOGEA (2013) and "https://patbiodiv.ofb.fr/fiche-methodologique/continuite-ecologique/turbines-ichtyocompatibles-140"

4.4.4. Francis Turbines

The number of experiments aimed at characterising eel mortality after their passage through Francis turbines is too limited to have a robust predictive relationship. Hence, a **formula to estimate mortality established for Atlantic Salmon smolts** (Bosc et Larinier, 2000) is generally used:

$$P = [SIN(-17.98 + 45.62 * H^{0.181} * D^{-0.207} * TL^{0.224})]^{2}$$

where:
- P : Mortality share (0<M<1)
- TL : Fish length (m)
- D : Turbine diameter (m)
- H : Net head (m)

4.4.5. Presence of several turbines in a single water intake

A single water intake can supply one or more turbines, which do not necessarily have the same characteristics. The turbine flows of each of them may be different. The portion of eels passing through each turbine should therefore be assessed. Therefore, the hypothesis is put forward that the eels are distributed proportionally to the turbine flow of each machine (Figure 28). In the case of multiple turbines, the **mortality rate** calculated for each turbine using the above equation shall therefore be **weighted by the flow proportion passing through each of them**.

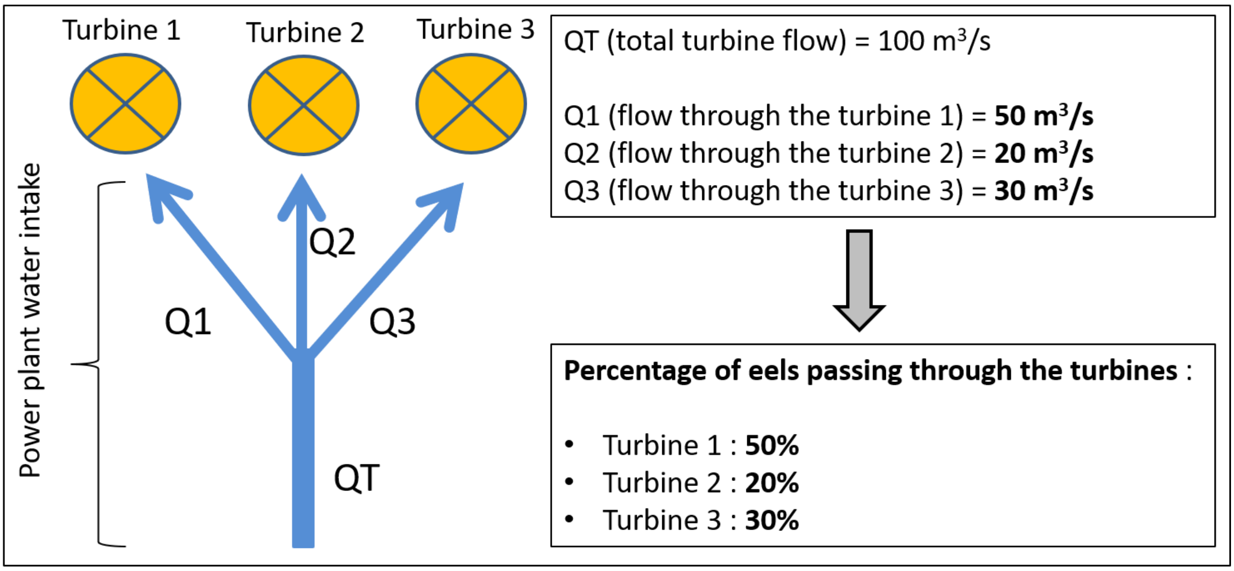


Figure 28. *Distribution of flows between three turbines supplied by a single water intake and deduction of the share of eels passing through each of them*

4.5. Mortality toll at the hydropower facility overall

Figure 29 recalls the different stages allowing the overall mortality rate for eels migrating downstream at a hydropower facility and which refers to Stage 5 of Figure 9. For the record, the overall mortality rate depends on the proportion of fish passing through spillway structures, on the efficiency of the downstream migrating devices installed upstream of the turbines (for example, a fine bar rack + associated outfalls) and on the mortality rate of the fish passing through the turbines.

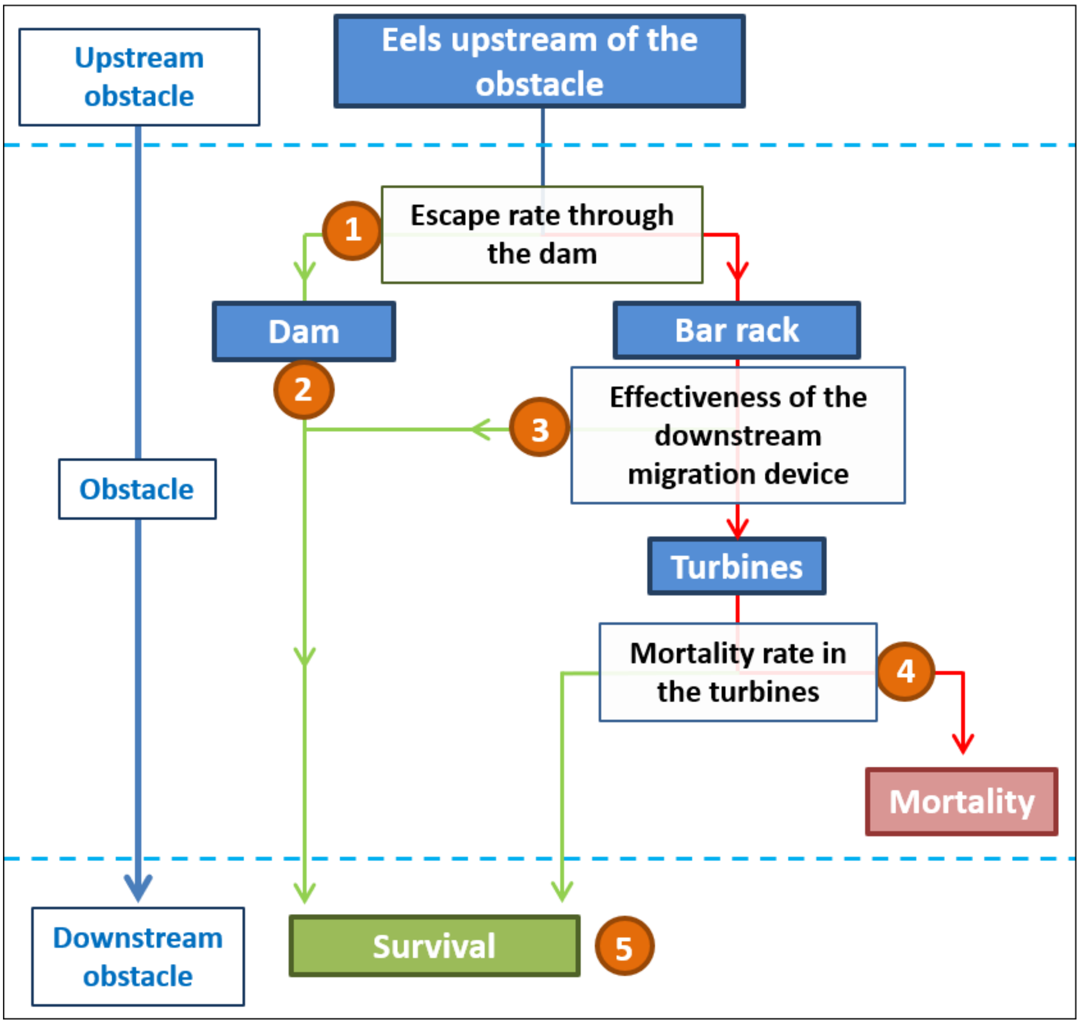


Figure 29. *Different stages allowing the overall mortality rate of fishing migrating downstream at a hydropower facility.*

4.6. Example of a diagnosis on the level of a hydropower facility

In order to better understand the proposed method, this paragraph describes the calculation methods for a specific example. The facility studied includes a power plant fitted with 2 Kaplan turbines and has a total equipment flow of 10 m^3/s (Table 4).

Table 4. *Characteristics of the hydropower facility studied.*

Characteristics of the facility		
Equipment flow (m^3/s)	10	
Reserved flow (m^3/s)	10	
Length of bypassed watercourse (m)	1000	
Free space between the bars (cm)	4	
Bar rack efficiency (%)	0	
Characteristics of the turbines		
	Turbine No. 1	**Turbine No. 1**
Type of Turbine	Kaplan	Kaplan
Head (m)	3.6 m	3.6 m
Turbine flows (m^3/s)	7	3
Number of vanes	4	4
Wheel diameter (m)	1.45	0.8
Rotation speed (turns/min)	196	212
Turbine flow proportion (%)	70	30

4.6.1. Stage 1: Proportion of individuals migrating downstream through spillway structures and lured in the water intake

4.6.1.1. Phase 1: Global downstream migration period and flows triggering downstream migration episodes

In this sector, the eel downstream migration period is from October to January. It has been determined thanks to different studies of the watershed area. In this watershed area, it has likewise been determined by fish monitoring that 20% of the individuals migrate downstream at a discharge of the 3rd quartile (Q_{75}), 20% at 90th percentile (Q_{90}), 20% at 95th percentile (Q_{95}), 20% at 97.5th percentile ($Q_{97.5}$) and 20% at 99th percentile (Q_{99}).

4.6.1.2. Phase 2: Calculating the daily flows at the facility

In order to produce a classified flow curve and to estimate flows of interest (Q_{75}, Q_{90}, Q_{95}, $Q_{97.5}$ and Q_{99}) during the eel downstream migration period in the sector in question (from October to January), in the absence of hydrological data immediately upstream of the facility, the daily average flow values of the closest hydrometric station were gathered. The daily average flows at the structure are then estimated using these data by performing a pro rata correction of the surface area of the watershed area (See Paragraph 4.1.2).

In this example, the watershed surface area at the facility and the hydrometric station are 1206 km^2 and 1120 km^2, respectively. The follow formula was therefore used to calculate the daily flows at the facility:

$$Q_{TOT} = Qs \times (1206 / 1120)^{0.8}$$

where:
- Q_{TOT}: flow immediately upstream from the facility (m^3/s)
- Qs: flow at the level of the hydrometric station used (m^3/s)

The classified flows of interest could then be estimated for each year for which the hydrological data were available (Table 5).

Table 5. *Classified flow values (m^3/s) at the facility studied, during the eel downstream migration period (October to January).*

Years	Non-exceedance frequencies				
	0,99	0,975	0,95	0,90	0,75
2008/2009	76.7	73.4	60.0	48.1	37.6
2009/2010	124.0	88.3	82.8	67.0	50.1
2010/2011	77.4	61.5	53.3	43.9	38.6
2011/2012	138.2	97.6	70.9	47.7	35.8
2012/2013	63.8	61.4	58.6	54.6	50.1
2013/2014	168.4	159.0	141.0	105.1	66.5
2014/2015	86.4	79.1	61.9	51.8	38.7
2015/2016	96.5	74.6	53.9	45.7	36.2
2016/2017	89.7	76.1	55.1	47.8	37.5
2017/2018	112.4	95.4	75.0	63.2	45.0
2018/2019	50.3	47.7	39.9	30.1	20.2

4.6.1.3. Phases 3 and 4: Estimating the overflow discharge at the weir and proportions of individuals using the different passageways

For this example, the formula proposed by Bau *et al.*, (2013) was used in order to calculate the passage probability through the spillway structures:

$$P = \exp(\eta)/(1+\exp(\eta))$$

avec : $\eta = -3{,}94 + 7{,}29 * (Q_{DEV}/Q_{TOT})$

where:

- P: Passage probability of the fish at the level of the spillway structures
- Q_{DEV}: Overflow discharge at spillway structures (m^3/s)
- Q_{TOT}: Flow of the watercourse immediately upstream of the facility (m^3/s)

The overflow discharge (Q_{DEV}) is the part of the total flow (Q_{TOT}) which is not turbined (See Paragraph 4.1.4).

In this example, the facility does not directly return the diverted flow to the bottom of the weir and creates a bypassed section of 1000 m (Table 4). A reserved flow of 10 m^3/s (minimum value) must here be discharged at the weir. As the maximum turbine flow is 10 m^3/s, the total flow upstream of the facility must therefore by over 20 m^3/s to allow the power plant to drive the turbines at their optimal power, which is the case in our example for all the classified flows of interest (see Table 5). During all the presumed eel downstream migration episodes at this facility, the following formula must therefore be applied:

$$Q_{DEV} = Q_{TOT} - Q_{TUR}$$

where:

- Q_{DEV} : Flow discharged at dam (m^3/s)
- Q_{TOT}: Flow of the watercourse immediately upstream of the facility (m^3/s)
- Q_{TUR}: Turbine flow (m^3/s)

A probability of eel passage at the spillway structures can then be calculated for each flow of interest and each year (Tableau 6). On the basis that a same proportion of eels, i.e., 20%, go downstream in each of the flows studied, an average of the passage probability may easily be determined for each year by calculating the passage probability average at each of the flows of interest (Table 6).

Table 6. *Probability of eel passage at the spillway structures at the facility studied, for different years and at different flows of interest (Q_{75} à Q_{99}).*

	Classified flows						**Downstream migration probability in the turbine flow part**
Years	Q_{99}	$Q_{97,.5}$	Q_{95}	Q_{90}	Q_{75}	Average	
2008/2009	0.92	0.92	0.91	0.88	0.84	0.89	0.11
2009/2010	0.94	0.93	0.93	0.91	0.89	0.92	0.08
2010/2011	0.92	0.91	0.90	0.87	0.85	0.89	0.11
2011/2012	0.94	0.93	0.92	0.88	0.83	0.90	0.10
2012/2013	0.91	0.91	0.90	0.90	0.89	0.90	0.10
2013/2014	0.95	0.95	0.94	0.94	0.91	0.94	0.06
2014/2015	0.93	0.92	0.91	0.89	0.85	0.90	0.10
2015/2016	0.93	0.92	0.90	0.88	0.84	0.89	0.11
2016/2017	0.93	0.92	0.90	0.88	0.84	0.90	0.10
2017/2018	0.94	0.93	0.92	0.91	0.87	0.91	0.09
2018/2019	0.89	0.88	0.86	0.79	0.59	0.80	0.20

This example shows that, for the eels, the passage probability through the spillway structures is greater during years of great hydrology (cf. Tables 5 and 6). The passage probability in the turbine flow part varies here from the simple to the triple according to the hydrology on the downstream migration period.

4.6.2. Stage 2: Mortality rate at the level of the spillway structure

For this example, there was no information available on the head and fish reception conditions when they crossed the facility by the spillway structure. The fish mortality was considered to be zero.

4.6.3. Stage 3: Efficiency of the bar rack

Due to a free space of 4 cm between the bars (Table 4), the efficiency of the bar rack has been considered zero. It is therefore considered that all the eel migrating downstream in the turbine flow passed through the turbines.

4.6.4. Stage 4: Calculating the mortality rate in the turbines

As the power plant in question was equipped for Kaplan turbines, the mortalities were estimated using the characteristics set out in Table 4 and by averaging the results obtained using the three formulas of Gomes & Larinier (2008), set out in Paragraph 4.4.3.

As the size of the eels migrating downstream at this facility are not known, the mortality was calculated for 3 lengths, representative of lengths of individuals migrating downstream: 50, 70 and 90 cm (Table 7).

Table 7. *Mortality rate caused by the two turbines of the facility studied, for eels measuring 50, 70 and 90 cm. The types of formulas are from Gomes & Larinier (2008) (see Paragraph 4.4.3).*

Type of formula	Turbine No. 1			Turbine No. 1		
	Eel size (m)					
	0.5	0.7	0.9	0.5	0.7	0.9
M1 (%)	32	54	79	45	75	100
M2 (%)	37	64	97	48	83	100
M3 (%)	40	64	90	54	85	100
Average (%)	37	61	88	49	81	100

Knowing that Turbine No. 1 accounts for 70% of the turbine flow (compared to 30% for Turbine No. 2) and that the number of fish passing through each turbine is considered to be proportional to the part of the turbine flow of each turbine, the average mortalities caused by the turbines at this facility can be easily calculated (Table 8). For example, for 50 cm eels, this average mortality will be: (37 x 0.7) + (49 x 0.3) = 40.6%.

Table 8 *Average mortality rate of eels of different sizes passing through the turbines of the facilities studied.*

	Eel size (m)		
	0.5	0.7	0.9
Average mortality rate (%)	40.6	67.0	91.6

4.6.5. Stage 5: Estimating the total morality on the scale of the facility

With it being taken that:

- There is no mortality at the spillway structures
- By definition, the eels that do not use the spillway structures migrate downstream in the part of the flow that goes through the turbines
- The efficiency of the bar rack is zero and all the eels migrating downstream in the turbine flow pass through the turbines

The mortality rate on the scale of this facility (Table 9) was estimated using the mortality rate caused by the turbines (Table 8), applied to the proportion of individuals migrating downstream in the turbine flow part (Table 6).

Table 9. *Estimating the year-on-year variability of the average mortality rate on the scale of the facility studied, for eels of different sizes.*

Years	Eel size (m)		
	0,5	0,7	0,9
2008/2009	4%	7%	10%
2009/2010	3%	5%	7%
2010/2011	4%	7%	10%
2011/2012	4%	7%	9%
2012/2013	4%	7%	9%
2013/2014	2%	4%	5%
2014/2015	4%	7%	9%
2015/2016	4%	7%	10%
2016/2017	4%	7%	9%
2017/2018	4%	6%	8%
2018/2019	8%	13%	18%
Average	4%	7%	10%

4.7. Mortality on the scale of a route or a territory

If the estimation of a mortality rate on the scale of a hydropower facility may be of interest to quantify the relative impact, that scale is not sufficient from the **perspective of large-scale fish management** and, *a fortiori*, of conserving an endangered species. It is therefore more advisable to **conduct this mortality diagnosis on the scale of a migration route,** in order to propose integrated and coherent impact reduction solutions, which are well prioritised between the sites and in time.

For example, facilities located upstream may have relatively small absolute mortalities due to a small number of fish in those areas compared to all the individuals in the watercourse. However, these upstream areas are ideal growth spots for the fattest females, who play a very important role in the breeding success, given that the number of eggs they can spawn is proportional to their weight. This has been particularly pointed out by Adam *et al.* (2008) : "*future recruitment seems to be more limited by* *the number of females spawning than by the number of males, even if the latter are essential for fertilising the eggs* ", and by the French Ministry for the Environment in an implementation report for the eel management plan (France, 2015) : *"if the densities drop according to the distance from the sea, taking the sex-ratio gradient into account show that mainly the large individuals that are impacted upstream of the basins. These individuals are females with great breeding potential.*" Thus, **a high mortality rate for an upstream facility, even it only applies to a small number of individuals, could have a significant impact on the number of eels produced in the following generation. It is there important to assess the impact of the facilities on the biomass, or even the amount of spawn produced *in fine*, and not only the number of individuals** (see, for example, CEREMA, 2016).

Moreover, the females that migrate upstream towards the sea are going to have to potentially cross a large number of facilities during their migration. If the aim is to give them a significant change of reaching their breeding ground, **actions to reduce the impacts** (i.e., reduce mortality in this case) must be put in place **at all the facilities** on the watercourse. In fact, just one of a set of successive facilities needs to have a high mortality rate to compromise the impact reduction efforts that could be made on another and for the global fish escapement rate on the migration route to be low.

Thus, the implementation of solutions[19] on a limited proportion of the structures on a route does not usually provide an effective solution for the mortality problems found along the downstream migration. That can be seen in Figure 30, which shows the evolution of the estimated total survival rates of the fish migrating downstream along the Grave de Pau, a watercourse with 27 hydropower facilities that must be crossed by some eels. This example first illustrates the considerable impact, in terms of total mortalities of fish migrating downstream from upstream areas, that can be recorded by a series of hydropower plants. Thus, the estimate survival rate is not more than around 30% after crossing eight facilities. Furthermore, it is noteworthy that making only certain structures compliant (installing fish-friendly bar racks on 7 out of the 27 facilities in the current case) does not dramatically reduce the global mortality rate along the migration route overall. In this example (Figure 30), the survival probability of an eel migrating downstream rises from 2% to 5%, after better solutions to limit mortality are put in place (in fact, it is estimated here that the fish-friendly water intakes installed at the 7 facilities in question allow 100% of the downstream migrating eels over 70 cm to survive).

[19] In France, the term "retrofitting" is sometime used, which is the action to make a facility comply with current regulation (cf. in particular, Article L214-17 of the Environment Code in France). More particularly here, it is about managing or fitting out a structure in order to allow the species to travel on the river sections with an "eel" issue.

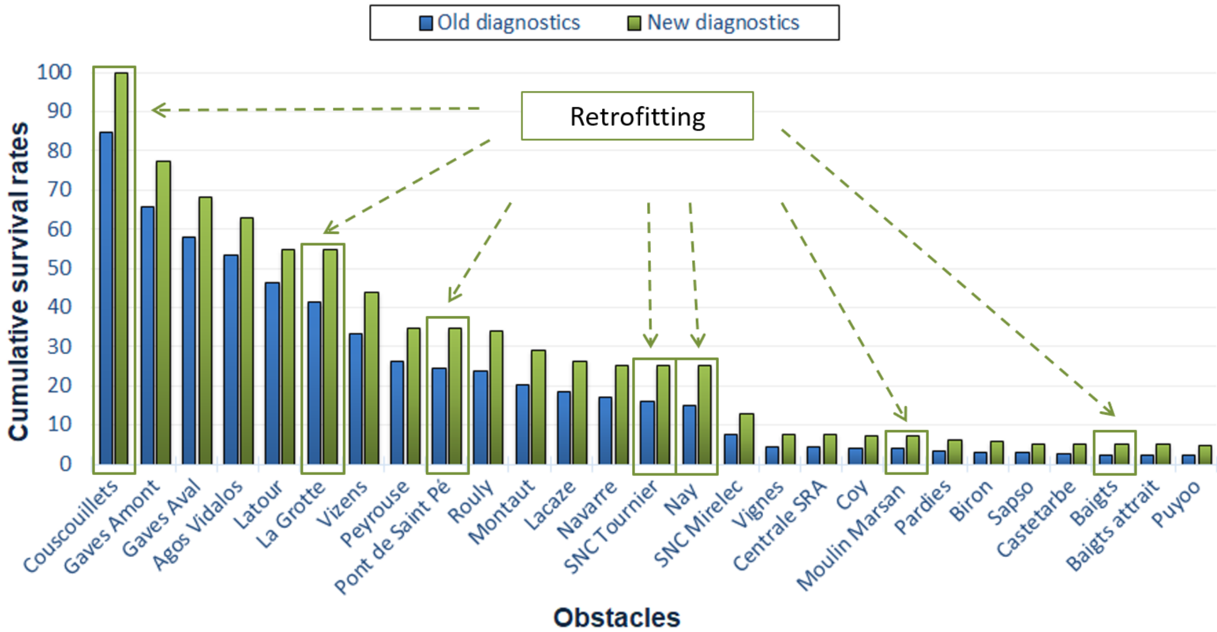


Figure 30. *Estimated total survival rate for eels migrating downstream from upstream of the Couscouillets facility (on the left of the figure), downstream (on the right) of Gave de Pau (the results given here are for 70 cm eels). Past assessments (in blue) were calculated prior to the installation of fish-friendly water intakes on the structures marked in green. Recent assessments (in green) take into account this retrofitting required by French law. Figure taken from SUDOANG Deliverable 2.2.2.*

When an "eel" issue (and more general, an "amphihaline migratory species") is present **along a route**, it therefore seems important and wise for the approach to be on a large geographical scale **limiting the impacts of each structure as far as possible**, rather than a structure-by-structure approach.

In fact, we must not forget that the solutions proposed here only allow the mortality of downstream migrating eels through turbines to be reduced, but they **do not solve the other ecological continuity problems potentially raised by the facilities**: bottlenecks or delays for the fish going up the watercourse, modifying habitats and sediment transport by creating a water-retention pound, mortality of other species during their passage in the turbines, mortality of yellow eels (smaller and therefore potentially badly stopped by the bars) which can also be travelling along the watercourse …

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ANNEX - R code: mortality in the turbines

1. Calculating mortality for a given turbine.

```
#' Calculation of turbines mortality for eel for Kaplan and Francis turbines.
#' For Kaplan Gomes et Larinier, 2008 propose three formulas given mortality
percentage (M) according to eel size
#'  size (TL in m), wheel diameter Dr (in m), nominal flow Q (in m3/s) and
turbine rotation speed N (in trn/min) :
#'  M1 : M (%) = 4.67 TL^1.53 Dr^-0.48 N^0.6
#'  M2 : M (%) = 6.59 TL^1.63 Q^-0.24 N^0.63
#'  M3 : M (%) = 12.42 TL^1.36 Q^-0.22 Dr^-0.10 N^0.49
#' For Francis, we use the formula developped for salmon by Bosc and Larinier
(2000)
#'  M4 : M(%) =  100*sin((pi/180)*pmin(90,-17.98 + 45.62 *  H^0.181 * Q^-0.207
* TL^0.224))^2
#' @param Size The fish size in meter : must be unique (not a vector) see
smolt_mortality_all_size to use several size
#' @param Dr Diameter of the wheel, in m
#' @param Q Flow in the turbine in m3 per second
#' @param N Rotation speed in turn per minute
#' @param H height of dam in m
#' @param QND A vector describing whether Q N and D are avalaible. Given data
availabilities, different formulas are used
#' see Gomez and Larinier, 2008
#' @param typ PARAM_DESCRIPTION, Default: c("Kaplan", "Francis", "Pelton",
"Ichtyocompatible")
#' @return A vector of mortalities
#' @examples
#' \dontrun{
#' if(interactive()){
#eel_mortality_size(Dr=1.78,Q=8,N=117,H=3,QND="QND",size=0.70, typ="Francis")
#21.49
#eel_mortality_size(Dr=1.3,Q=5.2,N=205,H=3,QND="QND",size=0.70, typ="Kaplan")
#70.35
#'  }
#' }
#' @rdname eel_mortality_size
#' @export
eel_mortality_size<-function(
             Dr,
             Q,
             N,
             H,
             QND,
             size,
             typ=c("Kaplan","Francis","Pelton","Ichtyocompatible"))
{
       # --- initial tests ----------------------------------------
       typ[is.na(typ)]<-"NA"
       if (! all(typ%in%c("Kaplan","Francis","Pelton","Ichtyocompatible")))
             warning(sprintf("typ %s not processed, should be one of 'Kaplan',
'Francis', 'Pelton', 'Ichtyocompatible'",
                                  unique(
typ[!typ%in%c("Kaplan","Francis","Pelton","Ichtyocompatible")])))
       QND[is.na(QND)]<-"NA"
       if (! all(QND%in%c("QND","QN","ND")))
```

```
            warning(sprintf("QND %s not processed, should be one of 
'QND','QN','ND'",
    
      unique(QND[!QND%in%c("QND","QN","ND")])))
      if (size>1) warning("Size >1 : size should be provided in meter")
      # --- Check types ----------------------------------------
      M <- rep(NA,length(typ))
      indexk <- typ=="Kaplan" & !is.na(typ)
      indexf <- typ=="Francis" & !is.na(typ)
      indexp <- typ=="Pelton" & !is.na(typ)
      indexi <- typ=="Ichtyocompatible" & !is.na(typ)

      # --- Kaplan -----------------------------------------------
      idxQND = QND=="QND"
      idxQN = QND=="QN"
      idxND = QND=="ND"
      if (sum(indexk&idxQND)>0)
            M[indexk&idxQND]<- pmin(100,12.42*size^1.36*Q[indexk&idxQND]^-
0.22*Dr[indexk&idxQND]^-0.10*N[indexk&idxQND]^0.49)
      if (sum(indexk&idxQN)>0)
            M[indexk&idxQN] <- pmin(100,6.59*size^1.63*Q[indexk&idxQN]^-
0.24*N[indexk&idxQN]^0.63)
      if (sum(indexk&idxND)>0)
            M[indexk&idxND] <- pmin(100,4.67*size^1.53*Dr[indexk&idxND]^-
0.48*N[indexk&idxND]^0.6)
      # ---  Francis ---------------------------------------------
      if (sum(indexf)>0)
            M[indexf] =
                        100*sin((pi/180)*pmin(90,-17.98 + 45.62 *
H[indexf]^0.181 * Dr[indexf]^-0.207 * size^0.224))^2
      # --- Pelton -----------------------------------------------
      if (sum(indexp)>0)
            M[indexp]=100
      # --- ichtyocompatible ---------------------------------------
      if (sum(indexi)>0)
            M[indexi]=0
      return(M)
}
```

2. Calculating mortalities of a size class matrix

```
#'  eel mortalities for a matrix of size class and abundance, Applies the 
eel_mortality_size to a matrix of size
#'
#' This function takes the matrix of size class and the matrix of size number
(these can vary from one turbine to the next)
#' and return either a vector of the average mortality (weighted by proportion
of the different size) or
#' the matrix of mortality to get the detail of mortality per size
#' @param size_table A table containing the proportion of size per turbine (the
sum of row must be one, if NA a warning will be issued.)
#' @param middle_class A table containing the "average" size to which the
proportion applies, this
#' can be the center of the class or the average value of the class center
derived from the population structure if available
```

```
#' @param return_type One of vector or matrix, if matrix the class will return a
list with the mortality per size class
#' otherwise it will return,  Default: c("vector", "matrix")
#' @param ... Other parameters passed to the smolt_mortality_size function
EXCEPT the size
#' @return Either a matrix with size in column and turbine in line or a vector
of mortalities per turbine
#' @author Cédric Briand, Mathilde Labedan
#' #' @examples
#' \dontrun{

#' if(interactive()){
#eel_mortality_allsize(
#            size_table=data.frame(
#                         "s0.50"=rep(1/3,3),
#                         "s0.70"=rep(1/3,3),
#                         "s0.90"=rep(1/3,3)),
#            middle_class = c(0.5,0.7,0.9)    ,
#            Dr = c(1.78,1.3,1.5,0,1.5),
#            H = c(3,   3,   4.4,0,5.2),
#            N = c(117,205,122,0,223),
#            Q = c(8,5.2,5.5,0,12),
#            QND=c(NA,"QND",NA,NA,"QND"),
#            typ = c("Francis","Kaplan","Francis","Pelton","Kaplan"),
#            return_type="matrix")
#[,1]      [,2]      [,3]
#[1,]  16.94863  21.49516  25.39744
#[2,]  44.52102  70.35569  99.02292
#[3,]  23.47612  29.11836  33.86979
#[4,] 100.00000 100.00000 100.00000
#[5,]  38.05057  60.13057  84.63145
#'   }
#' }
#' @rdname eel_mortality_allsize
#' @export
eel_mortality_allsize <-function(size_table,
middle_class,return_type="vector",...) {
      if (length(return_type)>1) stop("Return type choose one value, vector or
matrix")
      if (!return_type %in% c("vector","matrix")) stop("return_type should be
one of vector or matrix")
      if (ncol(size_table)!=length(middle_class)) stop("the number of column of
size_table and the length of middle_class have to match")
      # apply the smolt mortality size to each size class center
      mortality_table<-
mapply(eel_mortality_size,size=middle_class,MoreArgs=list(...))
      if (return_type=="vector"){
            return(round(rowSums(mortality_table*size_table),2))
      } else {
            return(round(mortality_table,2))
      }
}
```