LIFEEL

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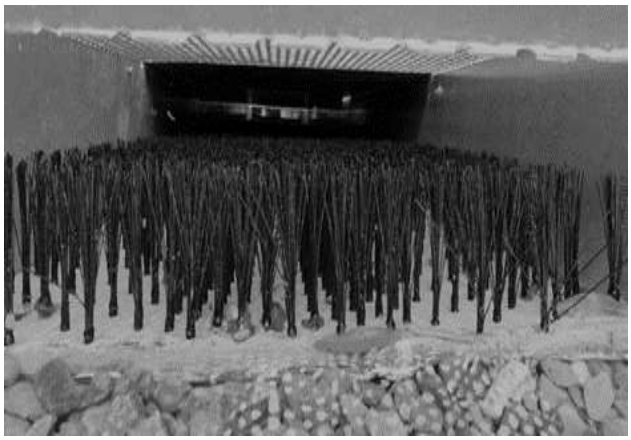
Urgent measures in the Eastern Mediterranean for the long-term conservation of endangered European eel (Anguilla anguilla)



DELIVERABLE

Action A.5.2

Guidelines for the compliance of hydro structures with downstream migration of silver eels

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Abstract

Downstream-migrating silver eels face multiple barriers, including turbines and pumps associated with water abstraction, hydropower generation and water-level control infrastructures, while attempting to leave freshwater systems and reach the Sargasso Sea spawning grounds. This issue affects the European eel (*Anguilla anguilla*) throughout its distribution range and represents one of the key threats to the completion of its life cycle.

Action A5 of the LIFEEL project addresses river fragmentation and the compatibility of hydraulic infrastructures with eel migration. These Guidelines, developed under Sub-action A5.2, focus specifically on downstream migration of silver eels and on the technical and management measures that can reduce turbine-related mortality.

The document first provides an overview of the conservation status of the European eel at European scale and summarises the main threats and conservation measures currently recognised for the species. It then examines the effects of river fragmentation, with particular attention to mortality associated with downstream passage through hydropower turbines, including the main injury mechanisms, the difficulties in estimating mortality and the different levels of risk associated with turbine types.

The Guidelines subsequently describe the biological and behavioural traits of downstream-migrating silver eels that are relevant to mitigation design, including migration timing, swimming performance and responses to hydraulic structures. Fish-friendly operational management, fish-friendly turbine solutions and retrofitting options are then reviewed.

A substantial part of the document is devoted to deterrent systems aimed at preventing or reducing eel entry into hydropower intakes. Physical barriers and behavioural deterrents are analysed, including screen-based systems, vertical-bar barriers, labyrinth, overflow and Coanda systems, moving-belt and drum-screen systems, floating rod barriers, chemical, louvre, bubble, hydrodynamic, electric, acoustic and light-based deterrents.

Particular attention is given to light-based and LED deterrent systems, which currently appear to provide one of the most promising options for downstream-migrating eels, especially when designed according to site-specific hydraulic and ecological conditions. The LIFEEL experience with the design, implementation and monitoring of an experimental light-based deterrent system is used as a technical reference to support the assessment of this approach, without limiting the applicability of the Guidelines to a single site or river basin.

The conclusions highlight that no single deterrent can be considered universally effective. Successful mitigation requires site-specific assessment, baseline monitoring, careful consideration of hydraulic conditions and, where appropriate, the integration of multiple stimuli within multimodal guidance systems. Within this framework, LED-based behavioural deterrents emerge as a particularly promising, flexible and transferable solution for reducing turbine-related mortality and improving the ecological compatibility of hydropower infrastructures with the conservation needs of the European eel.

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Introduction

Project Action A5 (*Plans of the Priority Interventions to Restore River Connectivity for Eel Conservation and Guidelines for the Compliance of Hydro Structures with Downstream Migration of Silver Eels*) addresses one of the major global threats affecting the European eel (hereinafter referred to as "eel"): **river fragmentation**. The construction of transverse barriers across watercourses hinders the upstream migration of juvenile individuals towards growth habitats. Once fully grown, sexually mature individuals undertake a downstream reproductive migration; during this migration they may encounter water intakes connected to hydropower turbines, resulting in high mortality rates. Technical solutions capable of mitigating these impacts are currently being studied and developed, and their further investigation is one of the objectives of this document.

These guidelines, developed under Sub-action 5.2, constitute an update of those previously drafted within Action A4 and have therefore been developed on the basis of the experience gained during Sub-action A.4.2 (concerning the design of the first demonstrative deterrent/guidance device) and, in particular, through the activities aimed at monitoring its effectiveness (Deliverable D.2.2).

The guidelines are primarily addressed to hydropower plant operators, as well as to engineers, biologists and public authorities involved in the planning, design, management and authorisation of hydropower facilities. The document places particular emphasis on downstream eel migration and proposes mitigation measures, specifically deterrent systems, aimed at reducing turbine-related mortality and improving the ecological sustainability of hydropower infrastructures.

The introductory section provides an overview of the conservation status of the European eel at the European scale and outlines the conservation measures currently recognised for the species. The following section examines the impacts of river fragmentation on eel populations, with particular focus on the risks associated with downstream migration through hydropower facilities and on the mortality rates associated with different turbine types.

The guidelines then present the main biological and behavioural traits of silver eels relevant to downstream migration and review the currently available approaches for reducing turbine-related mortality, including fish-friendly management practices, fish-friendly turbines, physical barriers and behavioural deterrent systems.

Particular attention is devoted to light-based deterrent systems, which currently represent one of the most promising approaches for reducing the entry of migrating silver eels into hydropower intakes. The recommendations presented in these guidelines also draw upon the experience gained within the LIFEEL project through the design, implementation and monitoring of an experimental light-based deterrent system.

1 Conservation Status of the European Eel and Threats to its Conservation

1.1 Conservation status of the species

Current conservation status of the species, defined by IUCN:

Pike, C., Crook, V. & Gollock, M. 2020. Anguilla anguilla. The IUCN Red List of Threatened Species 2020: e.T60344A152845178. Accessed on 22 January 2026.

Since 2013, *Anguilla anguilla* has been classified by the International Union for Conservation of Nature (IUCN) as **Critically Endangered (CR)**, both in the global Red List and in several national assessments, as the population has declined dramatically over recent decades.

This severe decline cannot be attributed to a single factor, but rather results from the cumulative effects of multiple pressures acting simultaneously on the species. A particularly important role is played by the eel's long and complex life cycle, which exposes it to a wide range of environmental threats throughout its development and migration phases.

The principal causes of the decline of the European eel can be identified as follows:

- River fragmentation caused by transverse barriers across watercourses;
- Hydraulic infrastructures that are not fish-friendly, including the absence or inadequacy of fish passes and the lack of deterrent systems preventing eel entry into hydropower intakes;
- Water pollution;
- Alteration of river ecosystems and habitat loss;
- Presence of invasive alien fish species;
- Overfishing.

The species is also subject to a specific European conservation framework established by Council Regulation (EC) No. 1100/2007. This Regulation requires Member States to adopt and implement Eel

Management Plans aimed at defining and applying the most effective conservation and management measures for the recovery of the species.

Despite the implementation of conservation measures in several European countries and the occurrence of local improvements in some river basins, available evidence still does not indicate a substantial recovery of the species at the continental scale. In particular, both the escapement of mature silver eels and the natural recruitment of juvenile stages remain far below historical levels.

1.1 Species vulnerability and conservation measures

The distribution range of the European eel extends throughout Europe, from Scandinavia to the Mediterranean coasts of Morocco and Tunisia.

The species is a catadromous migrant and therefore, between autumn and early winter, mature “silver eels” migrate downstream towards the sea and subsequently undertake a long-distance migration to the Sargasso Sea, where reproduction takes place. During this journey, individuals may travel approximately 15–40 km per day and ultimately cover a distance of several thousand kilometres before reaching the spawning grounds located in the central Atlantic Ocean.

The distribution of the species throughout Europe is a consequence of its larval dispersal mechanism. Following hatching in the Sargasso Sea, larvae are transported towards European and North African coasts by Atlantic oceanic currents, particularly the Gulf Stream.

The European eel is a euryhaline species capable of adapting to a wide variety of habitats, ranging from marine and brackish environments to freshwater rivers and lakes. Its ecological plasticity allows it to colonise a broad range of aquatic ecosystems throughout its distribution area.

During upstream migration, juvenile eels are often capable of overcoming natural and artificial obstacles, sometimes even leaving the water and moving across wet surfaces when suitable conditions are present. The species is generally associated with benthic habitats and shows a preference for sheltered environments offering refuges and hiding places.

The eel possesses a highly developed olfactory system and is predominantly nocturnal, carrying out most of its feeding activity from dusk until the early hours of the morning. It generally avoids highly illuminated environments and tends to prefer turbid waters and habitats offering protection from predators.

Despite its remarkable ecological adaptability, the species depends critically on river connectivity. Free longitudinal connectivity is essential both for the upstream migration of juvenile stages towards growth habitats and for the downstream migration of mature silver eels towards the sea. For this reason, river fragmentation is widely recognised as one of the most significant threats affecting the species.

An additional threat derives from excessive fishing pressure, particularly considering the high commercial value historically associated with the species.

Conservation Strategies

The conservation of the European eel requires action on multiple fronts.

First and foremost, habitat restoration measures are essential in order to mitigate the alterations affecting river ecosystems and to improve environmental conditions for the species. Equally important is the implementation of monitoring programmes aimed at assessing population status, evaluating the effectiveness of conservation actions and identifying opportunities for adaptive management.

Direct actions targeting the species may also be necessary, particularly where population recovery requires active intervention. At the same time, the social dimension should not be neglected. Continuous communication and awareness-raising activities targeting stakeholders, fishers and the general public remain fundamental components of any successful conservation strategy.

Priority Conservation Measures

Among the most important conservation measures are:

- Restoration and renaturalisation of river channels and riparian habitats;
- Improvement of environmental flow regimes;
- Construction of fish passage facilities at barriers that are impassable to migratory fish species;
- Population reinforcement and restocking actions, where scientifically justified;
- Regulation or suspension of fishing activities when required for conservation purposes;
- Control of invasive alien species that may negatively affect eel populations.

Monitoring programmes should include:

- Periodic assessment of population abundance, structure and health status;
- Evaluation of habitat suitability and ecological conditions;
- Monitoring of water quality through chemical and biological indicators.

Public engagement measures should include:

- Local environmental education initiatives;
- Broad-scale information and awareness campaigns.

What Should Be Avoided

The presence of impassable barriers along rivers represents one of the most critical threats to the species. Whenever barrier removal is not feasible, appropriate fish passage facilities should be provided to ensure both upstream and downstream migration of eels and other fish species.

Critical Factors

The principal limiting factors for eel conservation are barriers that prevent or restrict access to growth habitats during upstream migration and impede the successful downstream migration of mature individuals towards their spawning grounds.

The European eel presents exceptional conservation challenges due to its unique biological characteristics. It is catadromous, semelparous and panmictic, meaning that all European breeders belong to a single reproductive population. Its generation time is particularly long, typically exceeding a decade, and its life cycle involves several developmental stages and extensive migrations through environments affected by both natural and anthropogenic pressures.

On the one hand, the biology of the species makes it highly vulnerable to environmental alterations, including migration barriers, habitat degradation and climate change. On the other hand, its high commercial value continues to expose it to exploitation for fisheries and aquaculture purposes.

These factors highlight the need for conservation measures that are both effective and applicable across the species' entire European range. Despite ongoing efforts, the recovery objectives established under European conservation policies have not yet been fully achieved, reinforcing the urgency of implementing coordinated and transferable conservation strategies throughout the distribution area of the species..

2 Effects of river fragmentation on European Eel

River fragmentation is globally recognised as one of the most significant threats affecting the conservation status of the European eel. The presence of barriers within river networks, many of which are impassable, prevents upstream migrating individuals from reaching suitable growth habitats, thereby disrupting the normal completion of the species' life cycle.

As a diadromous species, eels are particularly vulnerable to obstacles located along watercourses, since they may need to pass these barriers multiple times during their lifetime in order to complete their biological cycle (Liermann *et al.*, 2012; Cairns *et al.*, 2013; Reid *et al.*, 2019).

Numerous studies conducted throughout the species' distribution range have documented the accumulation of individuals downstream of migration barriers, where they are unable to continue their upstream movements. The interruption of migration routes may increase mortality rates through greater exposure to predation and fishing pressure.

Under conditions of high density, competitive and cannibalistic behaviours may also emerge (Sinha and Jones, 1967; Knights, 1987; Lamothe *et al.*, 2000). Furthermore, chronic stress associated with migration blockage may influence population structure and favour the development of male individuals.

In general, elvers and young yellow eels migrating upstream are capable of climbing wet vertical surfaces when sufficient substrate roughness is available, or of passing barriers through specifically designed eel passes (Haro, 2013; EPRI, 2018; Vowles *et al.*, 2017; Kerr *et al.,* 2015).

The present guidelines focus specifically on downstream migration. The successful completion of the reproductive migration towards the sea is also threatened by hydropower barriers, as physical injuries associated with passage through water intakes and turbines may be lethal.

Facilitating the downstream migration of mature silver eels remains a major challenge (Hadderingh and Bruijs, 2002; Versar Inc., 2009; Piper *et al.*, 2013; EPRI, 2018; Verhelst *et al.*, 2018; Pratt *et al.,* 2021). This is due to several biological characteristics of the species, including limited burst-swimming performance (Bruijs and Durif, 2009; Russon and Kemp, 2011), preference for relatively high flow velocities (Bruijs and Durif, 2009; Piper *et al.*, 2013), and body morphology (Calles *et al.*, 2010).

These characteristics make eels particularly vulnerable to entrainment into pumps and turbines, often resulting in mortality rates higher than those observed for many other fish species under similar conditions (Hadderingh and Bruijs, 2002).

At the global scale, river fragmentation and turbine-related mortality have been associated with substantial population declines in eel populations (Liermann *et al.*, 2012; Piper *et al.*, 2013; Jacoby *et al.*, 2015; Verhelst *et al.*, 2018).

2.1 Mortality associated with downstream passage through turbines

2.1.1 Mechanisms of mortality and difficulties in quantification

What are the mechanisms underlying fish mortality during downstream passage through hydropower turbines?

For the purposes of these guidelines, the principal types of injuries affecting fish during turbine passage are briefly presented (Pracheil *et al.*, 2016). These injuries are summarised in the figures below.

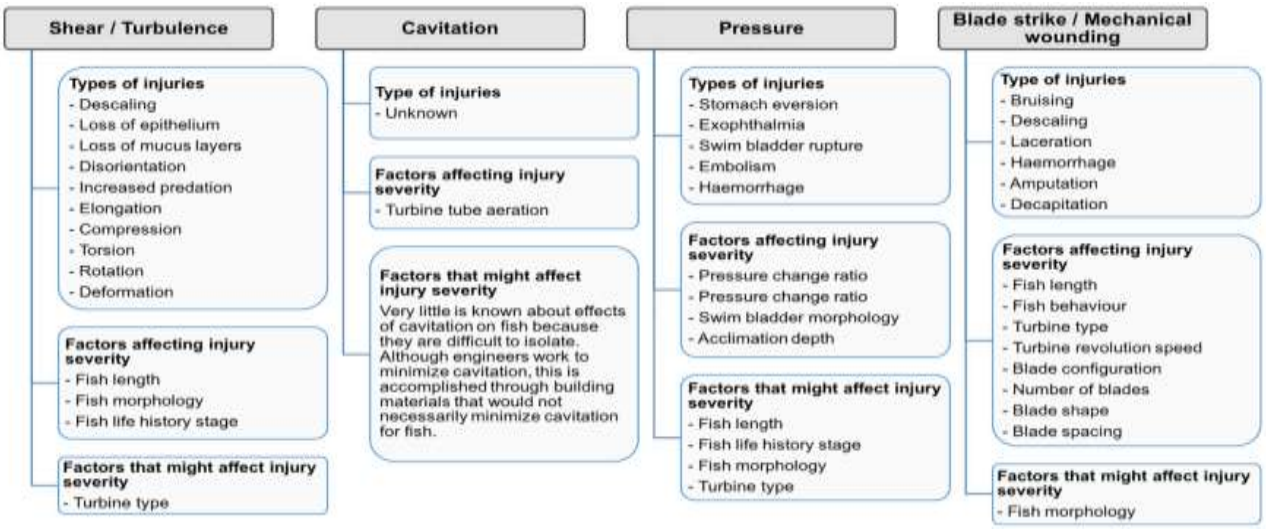


Figure 2-1. Overview of the known injury types and potential factors contributing to increased mortality of fish passing through hydropower turbines (Pracheil *et al.*, 2016).

Injury type	Description	Body parts
Fractures	Interruption of the continuity of skeleton elements and /or a loss of skeletal symmetry; disruption of outer skeletal contour	Skull, vertebrae, ribs, spines, pterygiophores
Deformations	Shift of vertebra resulting in a S-shape of the spine as well as unnatural turnaround or distortion of other bony structures	Skull, vertebrae, ribs, spines, pterygiophores
Compressions	Vertebra of the spine heavily squeezed together, also resulting in a deformation of ribs and spinous processes in the same area	Vertebrae
Emphysema	Blackish, often circular bubbles which are more radiolucent compared to fluid accumulations, with a clearly defined margin. Emphysema can appear in all soft parts of the fish body, often close to skeletal parts	Soft tissue
Free intraperitoneal gas	Blackish, often circular bubbles which are more radiolucent compared to fluid accumulations with a clearly defined margin, appearing in the body cavity	Body cavity
Fluid accumulations	Greyish areas which are more radiopaque compared to emphysema and free intraperitoneal gas, differing in shape and in contrast to emphysema and free intraperitoneal gas non-circular and with a less clearly defined margin	Soft tissue, body cavity
Swim bladder anomalies	Deflated or overinflated swim bladder with decreased size compared to natural conditions or no swim bladder visible anymore (rupture). Swim bladder anomalies often co-occur with free intraperitoneal gas due to tearing, rupture or gas exchange through the *ductus pneumaticus* in physostomes	Swim bladder
Radiopaque materials	Very bright areas on the X-ray film indicating material which is impermeable for radiation (e.g., pebbles taken up with the food)	Soft tissue, body cavity

Note:
List of the assessed injury types with description of their appearance and the body parts in which they were recorded.

Table 2-1. Potential internal injuries associated with fish passage through hydropower turbines. (Mueller *et al.*, 2020).

Most injuries affecting downstream migrating fish at hydropower facilities appear to occur in the immediate vicinity of the turbine (Čada *et al.*, 1997; Montén, 1985; Turnpenny, 1998; McEwen and Scobie, 1992). Injury mechanisms can generally be classified into four categories:

- Mechanical injuries;
- Pressure-related injuries (barotrauma);
- Shear stress injuries;
- Cavitation injuries.

Klopries and Schüttrumpf (2019) identified mechanical injuries as the most important source of mortality for eels, accounting for approximately 22–37% of observed deaths. These findings are consistent with earlier observations reported by Von Raben (1957) for several fish species. Nevertheless, significant mortality rates, reaching up to 18%, have also been associated with barotrauma and shear stress. Consequently, none of these injury mechanisms should be overlooked when assessing turbine impacts.

Fish may be exposed simultaneously to several stressors during a single passage event, increasing the probability of severe or lethal injuries compared with situations in which only one stressor is present (Richmond *et al.*, 2014a,b). Given the complexity associated with multiple interacting injury mechanisms, most studies have analysed individual mechanisms separately in order to evaluate their specific effects on fish survival.

In general, the principal cause of mortality during turbine passage is the interaction between fish and the rigid structural and operational elements of the turbine rotor and stator.

Mechanical injuries are commonly classified into three categories:

- Collisions resulting from impacts against solid surfaces;
- Crushing injuries resulting from fish becoming trapped within narrow gaps;
- Friction and abrasion injuries.

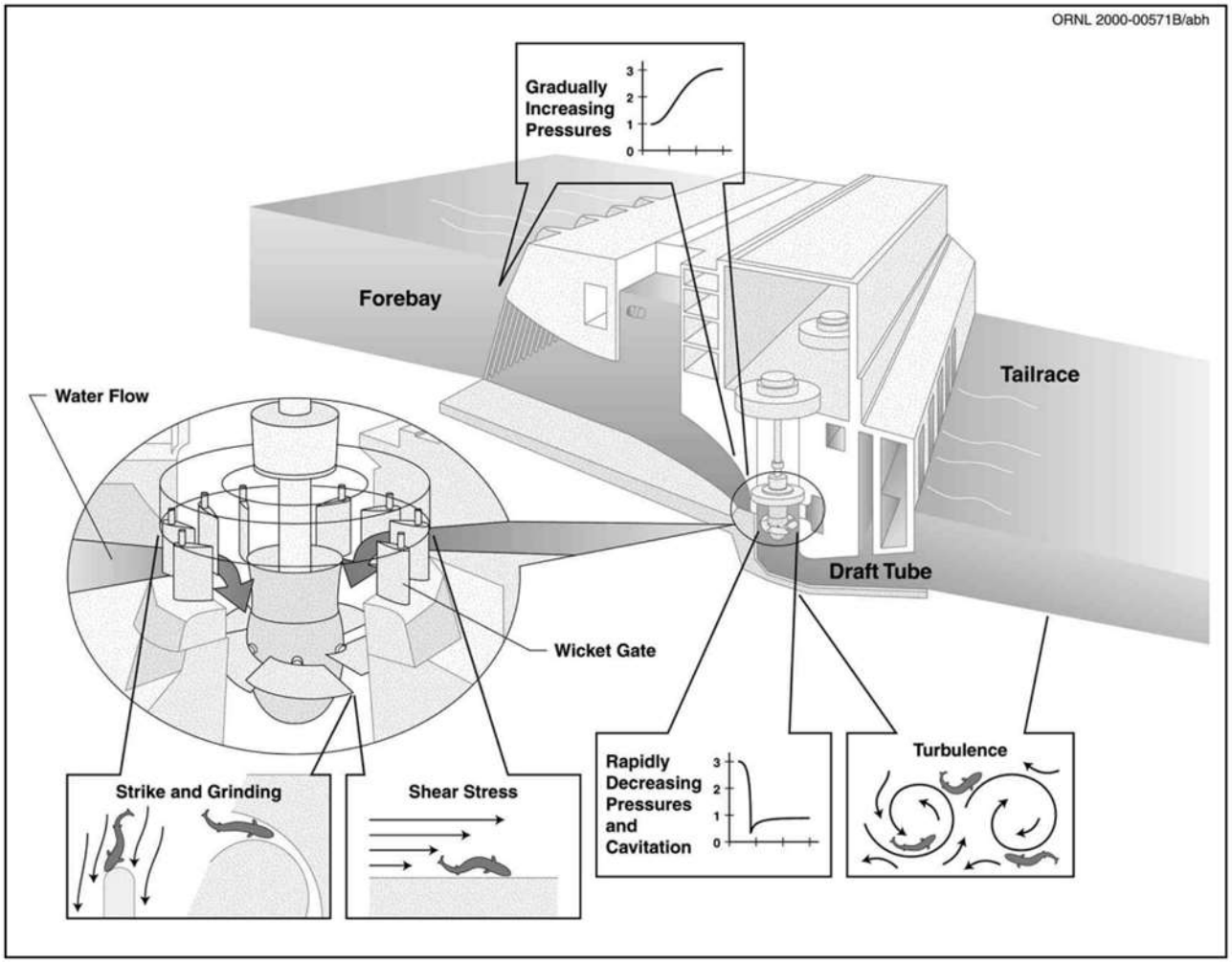


Figure 2-2. Main mortality causes related to fish passage through a Kaplan turbine.

Among collision-related injuries, blade strike is widely recognised as one of the principal causes of immediate fish mortality (Coutant and Whitney, 2000; Pracheil *et al.*, 2016). Additional impacts may occur against stationary structures such as wicket gates and other turbine components. Fish may also become trapped in gaps located near blade tips or hub regions (Radinger *et al.*, 2021).

The risk of mechanical damage increases when water flow is diverted within the turbine and does not strike the blades according to the optimal rotor direction (Cramer and Oligher, 1964), thereby increasing the probability of collisions with turbine structures.

The number of injured fish is generally inversely proportional to discharge. As flow decreases, guide vane openings become narrower in order to maintain flow velocity, increasing the likelihood of collision events (Von Raben, 1955).

Under low-flow conditions, small guide vane opening angles appear to increase collision probability due to sharper flow direction changes and more abrupt hydraulic transitions.

Turbine type, runner design, operational conditions, blade geometry and fish characteristics all influence both the probability and severity of impacts (Bevelhimer *et al.*, 2017). Fish size, physiological condition and species-specific traits may strongly affect susceptibility to injury (Čada, 2001).

Crushing injuries have received considerably less attention in the scientific literature. These injuries are directly associated with the presence of narrow gaps where fish may become trapped, particularly when influenced by secondary flow patterns.

In Kaplan turbines, gaps may occur between blade roots and the hub, between blade tips and the discharge ring, and sometimes between guide vanes and distributor walls (FIThydro, 2018).

In addition to the risk of physical entrapment, these areas may generate strong velocity gradients, elevated shear stress, vortex formation and local pressure reductions.

Optimisation of turbine clearances and gap dimensions can therefore contribute not only to improved hydraulic performance but also to increased fish survival during downstream passage.

A general guideline recommends the elimination of gaps, as they should be minimised to a size of less than 2 mm in order to prevent fish injuries caused by crushing (Cook *et al.*, 1997).

Friction and abrasion refer to the shear stress experienced by fish along the turbine walls; in practice, it is rather difficult to distinguish friction/abrasion from other types of physical damage (Odeh, 1999). Efforts are underway to devise techniques to quantify and distinguish abrasion from shear stress (Harding *et al.*, 2019). In any case, the presence of irregularities within the draft tube, such as protrusions resulting from welding or bolts used for pipe connections, considerably increases the potential risk of abrasion (Odeh, 1999).

Cavitation, turbulence, shear stress and pressure may also cause injuries or mortality (Abernethy *et al.*, 2001, 2002; Čada *et al.*, 1997; Carlson, 2000; Neitzel *et al.*, 2000; Wittinger *et al.*, 1995; Turnpenny, 1998).
Cavitation occurs when water pressure is equal to or lower than vapour pressure and gas bubbles form within the water (Kumar *et al.,* 2010). Studies have suggested that the collapse of gas bubbles may generate violent shock waves and that fish may be injured as a consequence (Turnpenny *et al.*, 2000; Muir, 1959).
Pressure waves of up to 10,000 kPa (Pavlov *et al.,* 2002) develop during bubble implosion, producing very high-velocity micro-jets (Franc and Michel, 2005) that may perforate tissues (Krizek *et al.,* 2020) and even metallic surfaces (Reuter *et al.*, 2022), as well as emit powerful shock waves (Koukouvinis *et al.,* 2017). Despite the severity associated with cavitation collapse, experimental investigations have shown contrasting results since Muir (1959), with mortality rates ranging from 0 to 60% when fish are exposed to cavitation conditions. Studies indicate that mortality caused by cavitation is approximately 2–6%, whereas mortality caused by pressure changes is approximately 19% (IRENA, 2022; International Energy Agency, 2021).
Laboratory studies have demonstrated that shear stress can cause various types of injuries to fish (Deng *et al.,* 2005); it results from the variation of velocity with distance, or from the strain rate of the fluid. It occurs, for example, between walls and moving fluid. If the flow is parallel to the walls, shear stress is low, but if it is not (as in the case of sudden changes in curvature), shear stress may be significant.
As an indication, shear stress in streams and rivers may be on the order of 100 Pa, whereas in turbines it may reach 5,000 Pa (Pflugrath *et al.*, 2020). Although these values are much lower than the pressure variations described below, fish are considerably more sensitive to shear stress, since it may be compared to the exposure to frictional forces generated by two solid surfaces striking and rubbing against one another

(Čada *et al.*, 2006). Common injuries associated with high levels of shear stress include loss of the mucus layer, tissue lacerations or haematomas, and even decapitation (Čada, 2007).

A fish passing through a turbine is subjected to substantial pressure variations (Koukouvinis and Anagnostopoulos, 2023). After passing through the intake screens and entering the penstock, pressure gradually increases as a consequence of hydrostatic pressure (Stephenson *et al.*, 2010).

Subsequently, in the vicinity of the blades, pressure rapidly decreases, much more quickly than it had previously increased. Gauge pressure may even fall below zero (vacuum conditions) near the suction side of the blades (Guo *et al.,* 2021; Kumar and Saini, 2010).

Typically, the pressure nadir occurs immediately downstream of the blades, with the lowest values observed near the blade tips and just below the leading edge. The lowest pressure experienced by a fish during turbine passage may range approximately from 2 to 200 kPa (Carlson *et al.*, 2008), depending on turbine design, operating conditions, hydraulic head and passage route. An indicative diagram of this pressure variation is shown below.

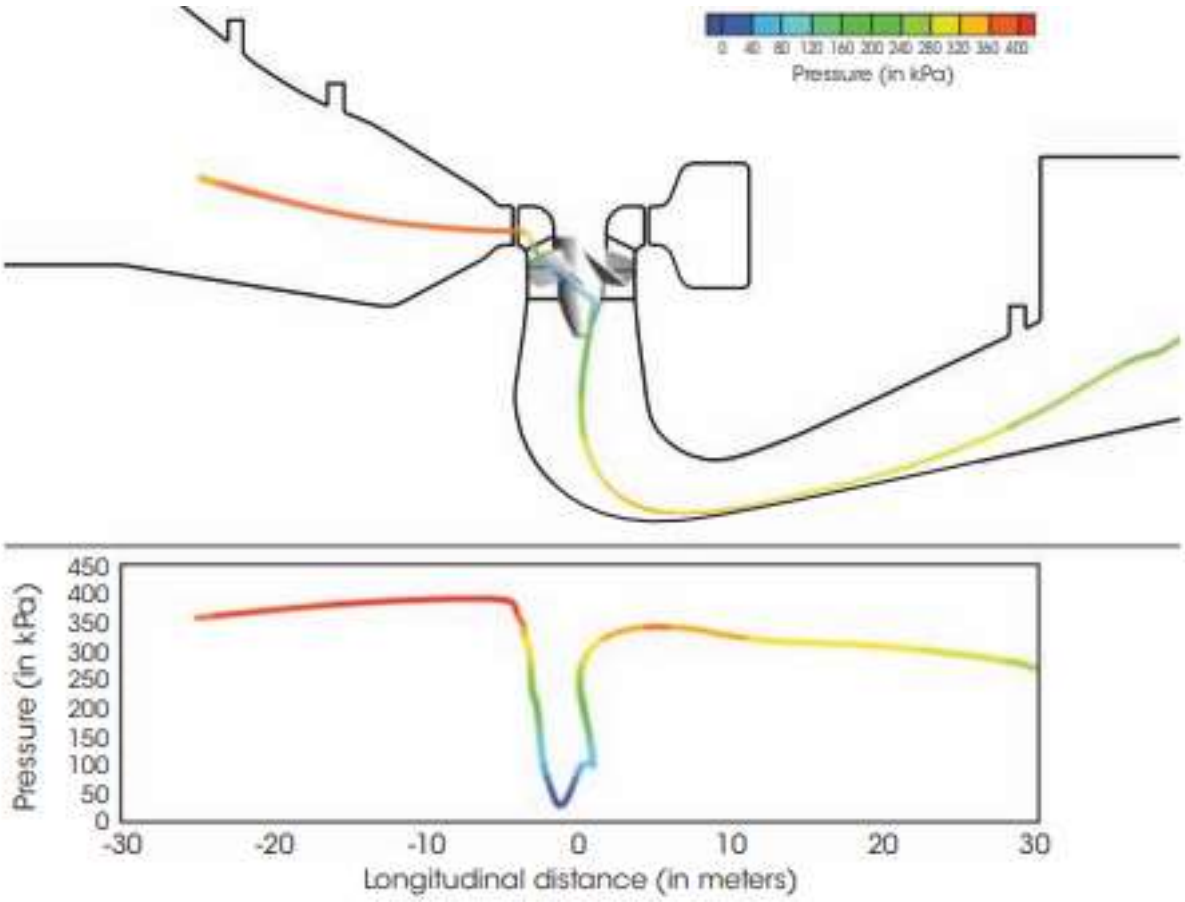


Figure 2-3. The Pressure-Nadir stressor computed by BioPA helps estimate fish exposure to pressure changes during turbine passage (source: Richmond *et al.*, 2014)

According to the USACE study, the pressure range to which fish are exposed varies from the absolute pressure found in a low-head hydropower plant (146 kPa) to the absolute pressure found in a high-head hydropower plant (605 kPa).

Such information can help engineers focus on critical areas in the design of new turbine runners that are more fish-friendly than existing units (Twardek *et al.*, 2022).

In any case, once released downstream, pressure gradually recovers to conditions close to atmospheric pressure.

Damage resulting from pressure changes ("barotrauma") depends on the rate and magnitude of pressure variation, on the fish species involved (DWA, 2005), and on their acclimation status. Injuries caused by barotrauma are common among fish passing through hydropower turbines (Cramer and Oligher, 1964; Čada, 1990, 2001; Brown *et al.,* 2009).

Although research on barotrauma is fundamental for fisheries management, relatively few studies have been conducted on this topic (Carlson *et al.*, 2010).

Extensive research has shown that pressurisation is generally well tolerated, since damage to fish is minimal and no direct mortality has been observed (Čada *et al.*, 1997); conversely, barotrauma occurs in fish subjected to rapid depressurisation (indicative mortality values are on the order of 90 kPa/s; Tsvetkov *et al.*, 1972).

The gases contained in fish swim bladders expand during decompression and may cause rupture of the swim bladder and exophthalmia. Furthermore, as fish undergo decompression, gas may come out of solution from the blood and tissues, resulting in the formation of bubbles within the bloodstream and tissues (embolism and emphysema), as well as vascular rupture or haemorrhage (Cramer and Oligher, 1964; Tsvetkov *et al.,* 1972; Beyer *et al.*, 1976; Rummer and Bennett, 2005; Brown *et al.,* 2009).

Physostomous fish possess a pneumatic duct connecting the swim bladder to the oesophagus, which, together with the mouth, is used to rapidly absorb or release gas (Lagler *et al.,* 1962). Physoclistous fish do not possess a pneumatic duct and must regulate their internal gas content through diffusion into the bloodstream. Since this diffusion process may require several hours, these fish are more susceptible to injuries caused by rapid pressure decreases (Pompeu *et al.*, 2002).

In addition, fish inhabiting deeper portions of the water column are required to absorb greater amounts of gas in order to maintain neutral buoyancy and may therefore be at greater risk of barotrauma during rapid decompression (Colotelo, in EPRI, 2011).

What Are the Difficulties in Estimating Mortality?

When fish pass through turbines, they are exposed to severe hydraulic conditions capable of causing injury or death (Bell and DeLacy, 1972; Bell, 1981; Čada *et al.*, 1997; McEwen and Scobie, 1992; Montén, 1985; Pavlov *et al.*, 1999; Ruggles and Murray, 1983; R2 Resource Consultants, 1998; Turnpenny *et al.*, 1992; Turnpenny, 1998). This risk has been a persistent focus of research on the impacts of hydropower generation (Montén, 1985; Mueller *et al.*, 2017; Von Raben, 1957).

Numerous studies (Ploskey and Carlson, 2004; van Esch and Spierts, 2014; Vikström *et al.*, 2020; Deng *et al.*, 2007) have attempted to identify correlations for estimating the effects of various factors on fish mortality; however, simplifying assumptions are commonly involved, and therefore the results are generally highly heterogeneous (Čada, 1997). The first mortality models developed in this field were those of Larinier and Dartiguelongue (1989), Larinier and Travade (2002), and Headrick (1998).

Mortality rates may be overestimated because of injuries occurring before turbine entry, harmful sampling methods and fish handling, or other sources of injury unrelated to turbine passage (Mueller *et al.*, 2017; Pander *et al.*, 2018). Furthermore, in small samples, the effect of false positives or false negatives (i.e., the

incorrect classification of fish as suffering lethal or sublethal injuries) on mortality estimates is greater than in large samples.

Mortality caused by turbine passage also depends on the specific operating conditions of the facility. Although turbines are designed for a specific design flow, they may be operated under a range of discharge conditions, thereby creating conditions that are more or less favourable to fish survival.

Estimates may also be biased by the behaviour and biological characteristics of the fish species involved. For example, fish behaviour influences the outcome of impacts, as some species tend to move through the turbine as a rigid body, whereas others actively react and avoid collisions (Čada, 1997).

In addition, fish size may influence the outcome of impacts, since smaller fish have less inertia and therefore tend to be carried around the blades by the flow rather than colliding with them. As an indication, one study identified 20 g as the weight below which fish are unlikely to experience blade strikes (Turnpenny, 1992).

Other aspects associated with turbine-related mortality, such as swimming path and reactive behaviour within a turbine (Coutant and Whitney, 2000), appear to be less predictable.

It should also be noted that fish injuries and mortality depend on the trajectory followed through the turbine. For example, mortality among fish passing close to the hub is approximately 5% lower than among fish passing through the central blade region (cited in Mohammadi, 2014).

These are some of the reasons why empirical in situ assessments of mortality rates provide the most realistic estimates when compared with physical models (Deng *et al.*, 2007; Montén, 1985) or in situ experiments involving sensor technologies (Carlson and Duncan, 2003; Deng *et al.*, 2014).

Empirical in situ assessments implicitly account for differences in swimming behaviour (Pracheil *et al.*, 2016), swimming performance, body size and shape, and resistance to injury among species, life stages and individual fish.

More subtle effects, such as temporary impairment and disorientation, are known to make fish more vulnerable to predation by birds and piscivorous fish downstream of turbine outlets. A distinction should therefore be made between mortality directly resulting from turbine passage and mortality indirectly associated with passage through subsequent predation on fish impaired by turbine passage (Carlson and Duncan, 2003).

Consequently, if only immediate mortality is considered, overall mortality may be underestimated because of delayed mortality effects (Ferguson *et al.*, 2006).

Ultimately, due to the high variability of empirical estimates of turbine-related fish mortality both among and within species and turbine types, meaningful comparisons among sites have rarely been possible, and simple general conclusions have not been established.

The effects of turbine-related injuries on fish populations are still not fully understood, but they are undoubtedly linked to turbine injury potential, the maturity stage and size of migrating individuals, and the proportion of migrating fish relative to the total population.

To date, research on downstream migration has focused primarily on diadromous fish species, and several models have been developed to estimate injury and mortality rates for eels and salmonids (Benigni, 2019).

What Are the Future Perspectives?

In the past, studies using live fish have been conducted at hydropower plants to assess turbine-related mortality and the effects of different operating conditions. These studies are costly and can only be carried out after turbines have been put into operation.

In addition to studies using live fish, analytical models can be used to evaluate mortality at hydropower plants. These are black-box models that describe the relationship between the input and output parameters of a complex system without providing information on the internal functioning of the system.

Both approaches can be used to estimate mortality rates, but neither provides detailed information on the mechanisms and locations of injury within a turbine.

More recent approaches, based on sensor fish studies, laboratory experiments and Computational Fluid Dynamics (CFD) modelling, promise deeper insights into and improved quantification of turbine-induced mortality.

The general concept behind this approach is to describe flow conditions using a CFD model and to identify potential hazards for fish by simulating fish passage through the turbine. Therefore, CFD modelling typically consists of three main components: flow modelling, fish passage modelling and mortality assessment.

The hydraulic and physical stressors present along the modelled fish trajectories can reasonably be assumed to be those acting on fish during turbine passage and consequently causing injury or mortality.

It is therefore possible to calculate the probability of exposure to a given stressor experienced by fish. By combining the probability of exposure with the probability of lethal injury (dose-response relationship) associated with each stressor, a performance score can be obtained for the turbine being evaluated (Richmond, 2014).

This performance score may be expressed either as a survival rate or as a mortality value and can be used to compare different turbine types or different turbine operating conditions.

2.1.2 Mortality Associated with the Main Turbine Types

The hydraulic turbine is the most important component of a hydropower plant. Its function is to convert the energy of water into mechanical energy, which is subsequently transformed into electrical energy through the presence of a generator. A turbine consists of two fundamental elements:

- a fixed component, the distributor, whose function is to direct and regulate the water flow towards the runner;
- a moving component, the runner, which receives the water jet coming from the distributor and converts it into rotational (mechanical) energy of the drive shaft on which it is installed.

Different types of turbines exist, depending essentially on the hydraulic head and discharge available for energy production. They are mainly classified into impulse turbines and reaction turbines.

The **Pelton** turbine was introduced in 1879 by the American carpenter and inventor Lester Allan Pelton. Its operating principle reflects that of the traditional water wheel used in old mills, redesigned to increase efficiency: water is conveyed through a penstock which terminates in a nozzle, a restriction that increases and directs the velocity of the water.

The water jet leaving the nozzle strikes the runner blades, which are shaped like specially designed buckets. The Pelton turbine is used for high hydraulic heads (between 300 and 1,400 metres) and flow rates below 50 cubic metres per second, allowing very high water velocities to be achieved.

In impulse turbines such as the Pelton turbine, pressure energy is entirely converted into kinetic energy within one or more nozzles located upstream of the runner. These nozzles direct the water onto the blades, causing the runner to rotate.

The Pelton turbine was invented in 1879 and remains the impulse turbine with the highest efficiency currently available. It is a relatively slow-running turbine and is mainly used for high-head applications. Its blades are shaped as paired buckets that are struck centrally by the water jet, which is then discharged laterally.

Figure 2-4. Examples, from left to right, of a Francis turbine, a Pelton turbine and a Kaplan turbine (source: ENEL Green Power, official website: www.enelgreenpower.com).

In reaction turbines, the conversion of pressure energy into kinetic energy takes place partly in the stator and partly in the runner.

The **Francis** turbine is a medium-speed hydraulic turbine with a medium degree of reaction (0.4–0.8). Developed in 1848 by the Anglo-American engineer James B. Francis, it remains the most widely used type of hydraulic turbine to this day. It is an inward-flow reaction turbine: water reaches the runner through a spiral casing, after which adjustable guide vanes in the stationary part direct the flow towards the runner blades. It is used for medium hydraulic heads (from 10 up to 300–400 metres) and flow rates ranging from 2 to 100 cubic metres per second.

The Francis turbine is a centripetal-flow reaction turbine in which water reaches the runner through a spiral casing. Water first encounters a stationary distributor and then the runner blades before being discharged through the centre of the turbine. A draft tube is located downstream and is used to reduce pressure at the outlet. The turbine is reversible and can therefore operate as a pump. It is used in watercourses with hydraulic heads ranging from 10 m to 300–400 m and flow rates from 2–3 m^3/s up to 40–50 m^3/s.

The **Kaplan** turbine, invented in 1913 by the Austrian professor Viktor Kaplan, follows the operating principle of a ship's propeller. It is an axial-flow turbine: the water flow that drives the propeller blades enters and exits in an axial direction with respect to the runner axis.

Thanks to the possibility of adjusting the blade pitch angle, it provides excellent efficiency under low-head conditions and can also accommodate substantial flow variations (from approximately 200 cubic metres per second upwards).

The Kaplan turbine is a fast-running reaction turbine (high degree of reaction > 0.8) designed for low hydraulic heads, generally up to a few tens of metres, but with high flow rates, starting from approximately 2–3 m^3/s.

A spiral casing and guide vanes are located around the runner, while the runner itself occupies the central section of the turbine. A draft tube is located downstream and is used to reduce outlet pressure and consequently increase power output.

The turbine consists of a propeller whose blades can be adjusted according to flow conditions, ensuring high efficiency even when discharge is substantially reduced, down to 20–30% of the nominal flow rate.

Water is conveyed through the spiral casing, which distributes flow around the entire circumference. It then passes through a stationary distributor that imparts a swirling motion to the water. The flow is subsequently deflected by 90° and enters the runner axially.

If neither the distributor nor the runner blades are adjustable, as in the Kaplan turbine, the machine is referred to as a **propeller turbine**.

Given the high mortality associated with downstream fish passage through Pelton and Francis turbines, Kaplan turbines generally exhibit significantly lower mortality rates and can also be modified to further reduce this undesirable effect. For this reason, the following discussion will focus on this turbine type.

From a conceptual perspective, Francis and Pelton turbines should ideally be replaced by fish-friendly turbines (or at least by Kaplan turbines modified according to fish-friendly design principles). Alternatively—and preferably in combination with such interventions—the installation of downstream deterrent systems aimed at preventing fish from entering turbines is proposed later in these guidelines.

2.1.3 Mortality Associated with Kaplan Turbines

References are available in the scientific literature regarding the survival rates of fish passing through Kaplan turbines. These values vary according to operating conditions and the specific turbine model employed, but they are nevertheless sufficiently indicative at a general level.

1. **For small-sized fish (length < approximately 20 cm):**

- 88% survival (Mohammadi, 2014);
- 80–95% survival (FAO, 2001);
- 80–100% survival for salmonids (Therrien and Bourgeois, 2000);
- 78.5% survival for *Alosa sapidissima* at Holyoke Dam, Connecticut River, Massachusetts (Bell and Kynard, 2011);
- 88% survival (Čada, 1999; Odeh, 1999; Bickford and Skalski, 2000);

- 80–98% survival for juvenile salmonids (Larinier and Travade, 2011);
- 94% survival for juvenile salmonids at Bonneville Dam (Peltier, 2008);
- 91.4–97.1% survival for juvenile Coho salmon at Wanapum Dam, Columbia River (Normandeau *et al.*, 1996c);
- 97.1% survival for juvenile Chinook salmon at McNary Dam, Columbia River (Normandeau *et al.*, 1999);
- 94.8% survival for juvenile Chinook salmon at Lower Granite Dam, Snake River (Normandeau *et al.*, 1995);
- 95.8% survival for juvenile Chinook salmon at Rocky Reach Dam (Normandeau and Skalski, 1996);
- 96.1% survival for juvenile Chinook salmon at Rock Island Dam (Normandeau and Skalski, 1997);
- 88.5–100% survival (Čada *et al.*, 2007);
- 85–96% survival for juvenile salmonids (Franke *et al.*, 1997);
- 93.8–97.5% survival for Kaplan MGR (Minimum Gap Runner) turbines (Peltier, 2008);
- 86% survival for Kaplan MGR (Minimum Gap Runner) turbines (Workshop on Rehabilitation of Hydropower, 2011).

2. **For fish in general:**

- 97,5% survival (Normandeau Associates, 2000);
- 85-96% survival (Franke *et al.*, 1997);
- 81-98% survival (Whitney *et al.*, 1997).

Despite the generally high survival rates reported for many fish species, European eel appears to be particularly vulnerable to turbine passage because of its elongated body shape and behavioural characteristics. Klopries and Schüttrumpf (2020), using CFD-based modelling, estimated mortality attributable to specific injury mechanisms as follows:

- collision mortality: 22–37%;
- shear-stress mortality: 7–14%;
- barotrauma mortality: 0–18%.

The impact of downstream migration through hydropower facilities on European eel has been the primary focus of several telemetry studies investigating either direct mortality (Dainys *et al.*, 2018; Pedersen *et al.*, 2012) or total mortality (including delayed mortality) associated with turbine passage (Calles *et al.*, 2013; Dębowski *et al.*, 2016; Økland *et al.*, 2019; Trancart *et al.*, 2018).

Recent reviews and reports suggest mortality rates of 10–20% in large low-head Kaplan turbines (Larinier, 2008), 20–38% in other large Kaplan turbines (Bruijs and Durif, 2009; Klopries and Schüttrumpf, 2020), an average mortality rate of 41% (International Council for the Exploration of the Sea – ICES, 2019), and 50–100% in small turbines, such as CINK turbines (Dainys *et al.*, 2018; Larinier, 2008).

Furthermore, silver eels may encounter multiple hydropower plants (HPPs) during their downstream migration. Larinier (2008) suggested that cumulative mortality may increase dramatically from 2–5% to 19–40% after passage through 10 hydropower plants and from 33–74% after passage through 20 facilities, potentially threatening the conservation status of entire eel populations.

The following images illustrate examples of turbine-related mortality observed in European eels during downstream migration.

Figure 2-5. Examples of European eels injured during passage through a hydropower plant.

3 Guidelines for Ensuring Compatibility of Hydropower Plants with the Reproductive Migration of the European Eel

The adaptation of hydropower plants to reduce fish mortality associated with turbine passage, and particularly the mortality of European eels, depends on the specific characteristics and operating conditions of each facility. As discussed previously, Francis and Pelton turbines should, whenever feasible, be replaced by fish-friendly turbines, or at least by next-generation Kaplan turbines incorporating fish-friendly design features.

Following a brief overview of the behaviour of downstream-migrating silver eels and their swimming performance, these guidelines provide general fish-friendly operational recommendations aimed at facilitating the reproductive migration of the species. The main types of fish-friendly turbines, as well as fish-friendly retrofitting solutions applicable to existing Kaplan turbines, are subsequently described in order to improve their environmental performance.

The document then presents a state-of-the-art review of deterrent systems designed to prevent downstream-migrating fish from entering turbine intakes. The review concludes with a case study developed within the framework of the LIFEEL project.

For optimal fish protection, the deterrent systems presented in these guidelines should be considered complementary to the installation of fish-friendly turbines. From a more practical perspective, where turbine replacement is not feasible, such systems should at least be implemented as an alternative measure to reduce turbine-related mortality..

3.1 Behaviour and Swimming Performance of Downstream-Migrating European Eels

Improving our understanding of eel behaviour, particularly that of downstream-migrating adult individuals, is essential for the development of effective conservation measures. The design and operation of deterrent systems may depend on the seasonality of migration. For example, at Backbarrow (River Leven, Cumbria), silver eels are protected through the installation of dedicated intake screens that are deployed only during the autumn migration period, thereby avoiding unnecessary head losses during periods of lower relevance for eel downstream migration.

Knowledge of the swimming performance of the target species is also fundamental for designing effective deterrent systems without creating a risk of mortality caused by fish becoming trapped against the structures themselves.

3.1.1 Behaviour

The migration periods associated with the different life stages of the European eel are summarised below. For the purposes of these guidelines, particular attention is devoted to downstream-migrating silver eels.

Table 3-1 - Migration periods associated with the life stages of the European eel.

LIFE STAGE	MIGRATION TYPE	PERIOD
Glass eel	Passive transport by tidal currents	Spring
Elver	Active upstream migration	Throughout the year
Yellow eel	Active upstream and downstream movements	Throughout the year
Silver eel	Downstream migration	Throughout the year, but primarily in autumn

In temperate regions, it is still not possible to identify with certainty the factors that trigger downstream migration in adult eels. However, it is generally accepted that large-scale migration events are closely associated with synergistic hydrological factors, such as flow conditions (high-flow events and floods) and water temperature (Vøllestad *et al.*, 1994; EELREP, 2005).

With regard to temperature, recent studies suggest that no specific threshold directly triggers migration. Rather, temperature appears to play a greater role in the physiological preparation for migration than as a direct trigger for downstream movement.

Rainfall and the associated increase in river discharge have a significant influence on downstream eel migration (Frost, 1950; Deelder, 1984; Vøllestad *et al.*, 1986; Teichert *et al.*, 2020; Knott *et al.*, 2020). Since migration peaks generally occur when water levels rise substantially, this phenomenon typically takes place between September and January in temperate regions (Tesch, 2003; Behrmann-Godel and Eckmann, 2003). Nevertheless, migration peaks may also occur during spring, particularly when environmental conditions during the preceding autumn were unfavourable.

The nocturnal behaviour of eels is well documented in the scientific literature. However, the timing of peak activity varies among studies, with most reporting maximum activity during the first half of the night (Aarestrup *et al.*, 2008; Breukelaar *et al.*, 2009; Brown *et al.*, 2009; Gosset *et al.*, 2005; Lennox *et al.*, 2018; Stein *et al.*, 2016; Verhelst *et al.*, 2018).

The eels investigated by Kjaeras *et al.* (2022) exhibited peak activity during the hours preceding midnight. In that study, downstream-migrating eels were observed near the water surface at night and during periods of elevated discharge. This behaviour is typical of fish species that avoid exposure to surface predators during daylight hours while taking advantage of favourable surface conditions during the night.

Another well-established behavioural characteristic of European eels is their tendency to migrate predominantly during the new moon phase of the lunar cycle. In the study conducted by Carter *et al.* (2023), most downstream-migrating eels moved during the night and in correspondence with the new moon phase (2018 = 90.5%; 2020 = 100%), despite the fact that suitable discharge conditions were also provided during daytime.

Under these conditions, most eels passed rapidly through the sluice gate of the Hobhole pumping station, even though the gate remained open for only 2.8–2.9% of the study period. This information is summarised in the figure below.

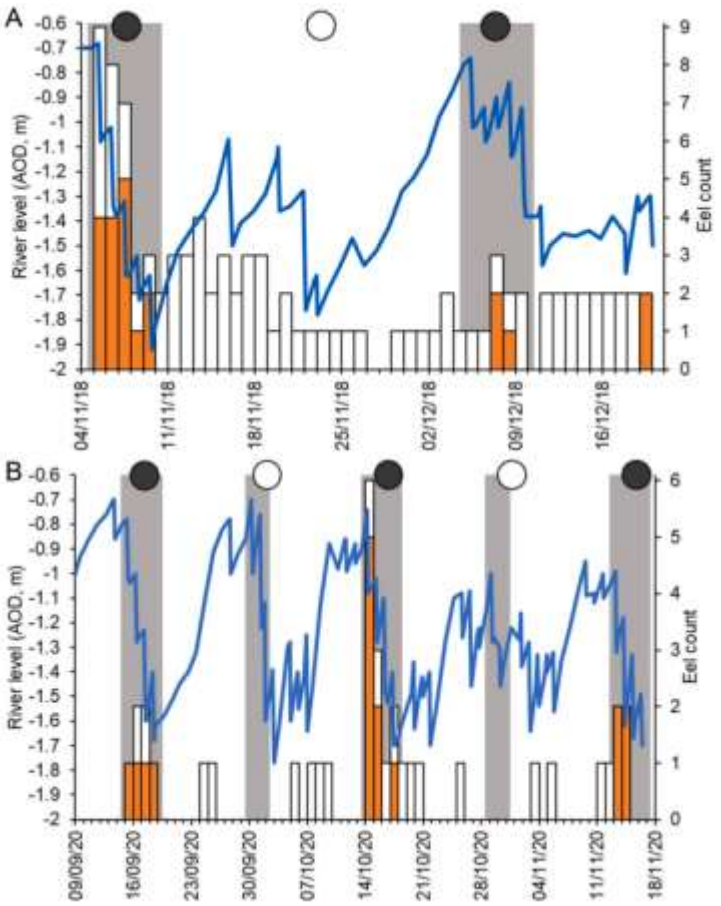


Figure 3-1. Number of eels approaching (white bars) and successfully passing (orange bars) the Hobhole pumping station in 2018 (top) and 2020 (bottom), in relation to water level (blue line). Grey shaded areas indicate periods during which the sluice gate was open at night; black circles indicate the new moon phase, while white circles indicate the full moon phase (source: Carter *et al.*, 2023)

While eels remain in continuous movement during their oceanic migration, their migration within river systems is more intermittent, as individuals may rest on the riverbed for up to four days. This finding is consistent with previous studies documenting resting periods of 4–5 days (Durif *et al.*, 2002).

Thermal stratification in rivers is generally weak, except in deep pools; therefore, the advantage of swimming in the mid-water column is likely related to the higher current velocities found in surface layers. This hypothesis is further supported by the absence of significant variations in visibility throughout the water column during the study.

The lateral distribution of downstream-migrating eels was predominantly concentrated in the central part of the river, where current velocities were highest. In contrast, during upstream migration, eels tended to move through low-velocity areas and along the riverbed, particularly near the banks, regardless of visibility conditions (Carter *et al.*, 2025).

The average migration speed recorded by Huisman *et al.* (2022) was relatively low (0.14 m/s), whereas average migration speeds reported for the Meuse River (Belgium and the Netherlands), the River Finn (Ireland) and the River Gudenaa (Denmark) were 0.62, 0.45 and 0.27 m/s, respectively (Aarestrup *et al.*, 2008; Barry *et al.*, 2016; Verbiest *et al.*, 2012). Progression rates measured along the river reach investigated by Huisman *et al.* (2022), including movement through the navigation lock, were even lower (0.07 m/s). This

value is comparable to the low swimming speeds (<0.06 m/s) reported by Verhelst *et al.* (2018) for eels migrating through a navigation canal in Belgium.

In general, however, downstream migration speeds of eels are higher in river habitats characterised by continuous flow than in habitats where flow is artificially reduced or naturally intermittent (Lenihan *et al.*, 2019).

When approaching hydraulic structures, eels are known to exhibit exploratory behaviour, actively searching for downstream passage routes (Piper *et al.*, 2015). They typically retreat upstream when a downstream route is rejected or unavailable (Bolland *et al.*, 2019; van Keeken *et al.*, 2020).

In the study by Kjaeras *et al.* (2022), when approaching the intake protection screen, eels primarily explored the deeper portions of the structure, although surface areas were also investigated. Most individuals subsequently migrated downstream through the bottom outlet, although nearly 30% used the surface outlet. In agreement with recent studies (Egg *et al.*, 2017; Økland *et al.*, 2017), these observations suggest that effective downstream passage may occur even without an exclusive dependence on bottom bypass systems.

3.1.2 Swimming performance

The design of effective deterrent systems must take into account the swimming performance of the target species, as there is a risk that water velocities in the vicinity of the deterrent may be too high for the deterrent effect to be effective. Under such conditions, fish may be entrained into turbine flows or become trapped against the deterrent structures described later in these guidelines.

For the purposes of this document, a deterrent system is defined as any barrier (for example, a screen) installed at the entrance to a water intake structure and intended to prevent downstream-migrating fish from entering the turbine.

The European eel is generally considered a species with relatively limited swimming capabilities, which are strongly influenced by body morphology and water temperature. When designing water intakes, deterrent systems and bypass channels, it is therefore necessary to take into account the swimming performance values summarised in Table 3-2.

Table 3-2 - Velocità di scatto e di nuoto sostenuto (cm/s) di anguille gialle in relazione alla taglia e alla temperatura dell'acqua, con mediana e valori del 90° percentile (da SWIMIT v3.3).

Water temp. °C	**Parameter and percentile**	**Body length (cm)**							
		10cm		30cm		50cm		70cm	
		Sust.	Burst	Sust	Burst	Sust	Burst	Sust	Burst
<10	Mean	9	101	19	109	38	119	58	126
	90	<5	80	6	88	18	98	31	105
10-15	Mean	13	104	23	112	43	123	62	129
	90	<5	83	9	91	22	102	35	108
>15	Mean	18	107	27	115	47	125	66	132
	90	6	86	13	94	26	104	38	111

Note: By definition, burst swimming speed can be sustained for up to 20 seconds. Sustained swimming speed, on the other hand, can be maintained for at least 200 minutes. Intermediate swimming speeds may be maintained for periods falling between these two limits (EA, 2014).

With regard to fish escape speed, the literature reports the following values:

- maximum swimming speeds ranging between 1.2 and 1.5 m/s (Clough, 2004);
- maximum velocity that can be overcome by elvers (approximately 20 cm in length): 1.15 m/s (Beach and Solomon, 2004);
- maximum velocity that can be overcome by yellow eels (approximately 40 cm in length): 1.25 m/s (Beach and Solomon, 2004);
- maximum velocity that can be overcome by adult eels (>60 cm in length): 1.35–1.40 m/s (Beach and Solomon, 2004);
- maximum burst swimming speed of the species: exceeding 2.40 m/s (Travade *et al.*, 1998).

Entrapment of eels against deterrent structures may result in injury or death by asphyxiation. To avoid these consequences, water velocity within the intake channel (and especially in the vicinity of deterrent systems) must remain below the escape swimming speed of eels.

As previously mentioned, the angle of the deterrent structures relative to the flow direction must also be appropriately designed.

Table 3-3. Maximum water velocity that may be imposed at 10 cm from a deterrent structure, according to eel life stage (EA, 2014).

Life stage	Screen angle Φ 21 to 90°	Screen angle Φ ≤ 20°
Elver/glass eel	10 cms^{-1}	25 cms^{-1} (screen length <10 m)
Yellow >14cm	15 cms^{-1}	30 cms^{-1}
Yellow >30cm/silver eel	20 cms^{-1}	40 cms^{-1}
Silver eel	40 cms^{-1}	50 cms^{-1}

3.2 “Fish-friendly” operational management

According to Carter *et al.* (2023), existing infrastructure associated with river barriers, such as gravity outlets and bypass channels, has the potential to provide a low-cost solution for facilitating downstream fish migration, although such structures are rarely considered for this purpose. Migrating eels have been observed using spillways to move downstream at hydropower facilities (Travade *et al.*, 2010; Økland *et al.*, 2019; Baker *et al.*, 2020). For example, Egg *et al.* (2017) documented 214 eels passing downstream through a bottom outlet at a hydropower plant. A study by Kroglund (2019) found that eels used a bottom outlet when discharge through that route represented at least 5% of turbine discharge, although the author also noted that this solution required manual regulation of river water levels and was therefore considered impractical.

Fish-friendly operational management refers to a management approach in which turbine operation is reduced or suspended during time windows that coincide with fish migration periods, in order to minimise

attraction towards intake structures and maximise safe downstream passage through alternative release routes (Schwevers and Adam, 2019).

Fish-friendly operational management may not always be economically desirable for hydropower facilities because of the associated reduction in energy production. However, it may still prove more cost-effective than turbine replacement or the installation of dedicated deterrent systems. In order to minimise operational losses, management measures should be aligned with the seasonal, lunar and circadian rhythms of eel migration, so that turbine shutdowns occur only when necessary.

In particular, European eels are known to migrate between late summer and early winter in response to lunar cycles (especially the new moon phase) and increased rainfall, which results in higher river discharge and turbidity, predominantly during nighttime hours (Tesch, 2003; Jansen *et al.*, 2007; Piper *et al.*, 2013; Bolland *et al.*, 2019).

As reported by Eyler *et al.* (2016), the seasonal shutdown of turbines at five hydropower dams reduced cumulative mortality of the American eel (Anguilla rostrata) from 63.3% to 37.3%.

The results presented by Carter *et al.* (2025) suggest that, in order to facilitate eel migration, the duration of water releases could be reduced in favour of shorter releases with higher discharge volumes. However, the amount of water released through sluices is generally determined by climatic conditions and the specific characteristics of the river system. The study therefore recommended that water managers develop site-specific compromises designed to optimise eel migration while maintaining operational requirements.

3.3 Fish-friendly turbines

The first step in reducing fish injury and mortality associated with downstream passage through hydropower facilities is to prevent fish from entering the intake structure through the installation of appropriate deterrent systems (discussed in the following sections). However, in the absence of such systems, or where their effectiveness is only partial, fish injury and mortality rates vary according to the technical and operational characteristics of the turbine.

Identifying the locations and hydraulic conditions within a turbine where injuries occur is essential for the effectiveness of mitigation measures, since injury and mortality rates can be reduced through the selection of appropriate turbine types, particularly in the case of new hydropower developments.

Fish-friendly turbines are specifically designed to facilitate the safe passage of fish. In addition, existing turbines may be adapted to improve their fish-friendliness through modifications to selected technical components that reduce their impact compared with standard configurations (Becker *et al.*, 2009).

In general, however, the scope for modification remains limited, as modern turbine designs already operate close to their maximum hydraulic efficiency and any alteration may result in a reduction in energy production.

According to Mohammadi (2014), the leading edge of the stay vanes is one of the most critical components, since variations in discharge have only a limited influence on the opening angle of the guide vanes. Optimisation should therefore aim to achieve a local reduction in flow velocity followed by a gradual acceleration of the flow.

In addition to the leading edge, factors such as misalignment, minimum clearance between stay vanes and guide vanes, vane profile geometry, blade tip design and protrusion of movable blades may also represent sources of injury to fish.

More generally, the alignment between stay vanes and guide vanes, as well as their optimal operation, depends respectively on design specifications and the operating range of the machine.

In advanced guide vane design, pressure gradients are reduced and velocity profiles are optimised according to both hydraulic and mechanical considerations.

At the same time, Computational Fluid Dynamics (CFD) modelling can be used to optimise the positioning of stay vanes and guide vanes, minimising fluid turbulence and reducing collision risks associated with different vane opening configurations.

The figure below illustrates the correct positioning of guide vanes relative to stay vanes. Under this configuration, hydraulic efficiency is maximised while the risk of collision is minimised.

Surface roughness associated with welded components represents an additional source of risk for fish. This risk can be reduced by polishing these surfaces, including stay vanes, guide vanes and draft tube cones. In low-velocity zones, however, surface polishing may not be necessary, as it could lead to unnecessary additional costs.

Draft tube piers are structural elements for which surface smoothness is particularly important. Although they cannot be eliminated for structural reasons, their design should incorporate fully smoothed and rounded profiles in order to minimise both collision risk and flow separation.

A lower number of runner blades reduces the probability of fish strikes and maximises the available flow passage area, thereby also reducing the likelihood of abrasion injuries. This configuration generally requires longer blades, which allow the turbine to maintain the same hydraulic capacity and power output while simultaneously minimising cavitation.

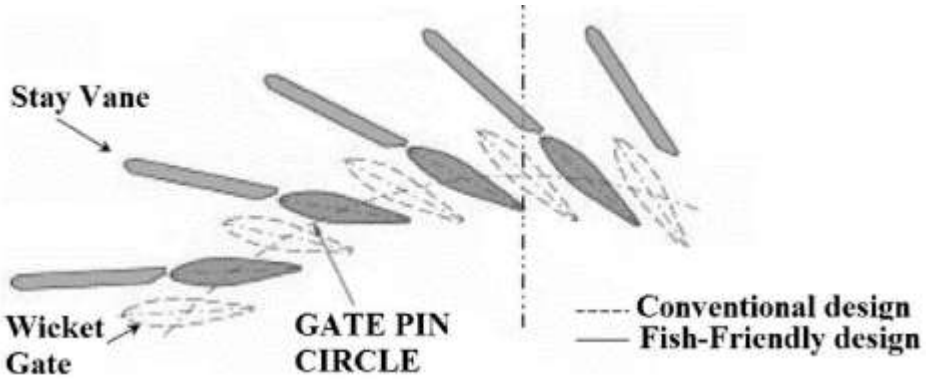


Figure 3-2. Configuration of stay vanes and guide vanes (Mohammadi *et al.*, 2014).

The following conclusions can be drawn with regard to reducing the risk of fish injury during turbine passage (Čada *et al.*, 1997; Franke *et al.*, 1997; Čada, 1998; Erzinger, 1999; Schilling *et al.*, 2000; DWA, 2005; Nelson and Freeman, in EPRI, 2011):

- Construction of new hydropower facilities with low hydraulic heads and large-diameter turbines (in the case of Kaplan turbines).
- Reduction of turbulence in the flow approaching the stay vanes through the addition of leading-edge extensions; improvements in flow quality within the draft tube may be achieved through modifications to runner geometry and by adding material to the bottom of the draft tube.
- Reduction in the number of runner blades (thereby increasing the spacing between blades) in order to decrease the probability of fish strikes.
- Rounding and thickening of blade leading edges to reduce both the frequency and severity of injuries.
- Reduction of rotational speed by lowering turbine rotational frequency, thereby reducing collision velocity and consequently the frequency and severity of injuries.
- Minimisation of clearances between blades and the hub, as well as between all stationary and moving components.
- Development of turbine designs that guide fish away from the distal portion of the blades and towards the proximal region, thereby reducing collision velocity through lower peripheral blade speeds and consequently decreasing injury frequency and severity.
- Smoothing of hydraulic boundary surfaces in order to minimise abrasions and lacerations.
- Optimisation of turbine operation in order to identify settings that maximise fish survival probabilities. Peak turbine efficiency should coincide with optimal hydraulic conditions, under which stay vanes and guide vanes are properly aligned and flow remains as uniform as possible throughout the turbine.
- Development of blade designs that minimise cavitation.
- Reduction of pressure drops occurring within the turbine..

In summary, the objective of fish-friendly turbine design is to maintain high energy efficiency while minimising injuries to fish passing through the turbine. This objective is achieved primarily through a reduction in the number of runner blades and the minimisation of clearances between moving and stationary components. Such modifications also improve blade profile flushing conditions: firstly, cavitation

risk is reduced; secondly, areas characterised by high turbulence levels, which can further increase fish injury rates, are minimised (Benigni *et al.*, 2023).

A comprehensive review of fish-friendly turbine technologies is provided by Koukouvinis and Anagnostopoulos (2023).

One of the best-known fish-friendly turbine designs is the **Minimum Gap Runner (MGR).** In this design, the runner blades, hub and discharge ring are characterised by more rounded profiles that minimise clearances. As a result, improved performance is expected in terms of reducing mechanically induced fish injuries. This design modification also removes part of the blade leading edge, thereby reducing local pressure gradients and shear stress while simultaneously improving turbine efficiency (Hogan *et al.*, 2014).

MGR turbines are characterised by large runner diameters, relatively low rotational speeds, low hydraulic heads and only minimal negative pressure zones. Tests performed on MGR turbines have demonstrated improved fish survival compared with conventional Kaplan turbines, with only 1.4% of fish injured compared with 2.5% recorded for fish passing through a conventional Kaplan turbine (Normandeau Associates, 2000).

Similarly to the MGR, the **Very Low Head (VLH)** turbine can also be considered a Kaplan-type turbine specifically designed to allow safe fish passage (Quaranta *et al.*, 2022). Originally developed in France for installation at existing low-head hydropower facilities, it is suitable for hydraulic heads between 1.4 and 4.2 m and discharges ranging from 10 to 30 m^3/s. The turbine is installed at an inclined angle (30–50° relative to the horizontal axis) and equipped with an eight-bladed Kaplan runner.

The unit is designed to be compact and easily integrated into existing facilities, reducing the dimensions of intake and tailrace structures through the maximisation of runner diameter. The large turbine diameter contributes to low rotational speeds, which are considered essential for safe fish passage. Field tests conducted in Europe have indicated mortality rates below 5% (Quaranta *et al.*, 2022).

Another Kaplan-derived concept is the **Vaneless Vortex Injector System** (Airody *et al.*, 2017). In this design, the conventional inlet stay-vane system is replaced by a vaneless casing coupled with a fish-friendly Kaplan turbine. The system is suitable for hydraulic heads of up to 6 m.

The vaneless casing generates the tangential velocity component required by the runner by guiding the flow along a spiral path. Because no inlet vanes are present, fish mortality caused by impacts is substantially reduced.

An innovative turbine concept developed during the same period as the MGR is the **Alden turbine** (Čada, 2001; Cook *et al.*, 2003). This low-head turbine ($H \approx 25$ m) was jointly developed by Alden Research Laboratory, Inc./Northern Research and Engineering Corporation (ARL/NREC) and Voith Hydro, Inc. in 1995.

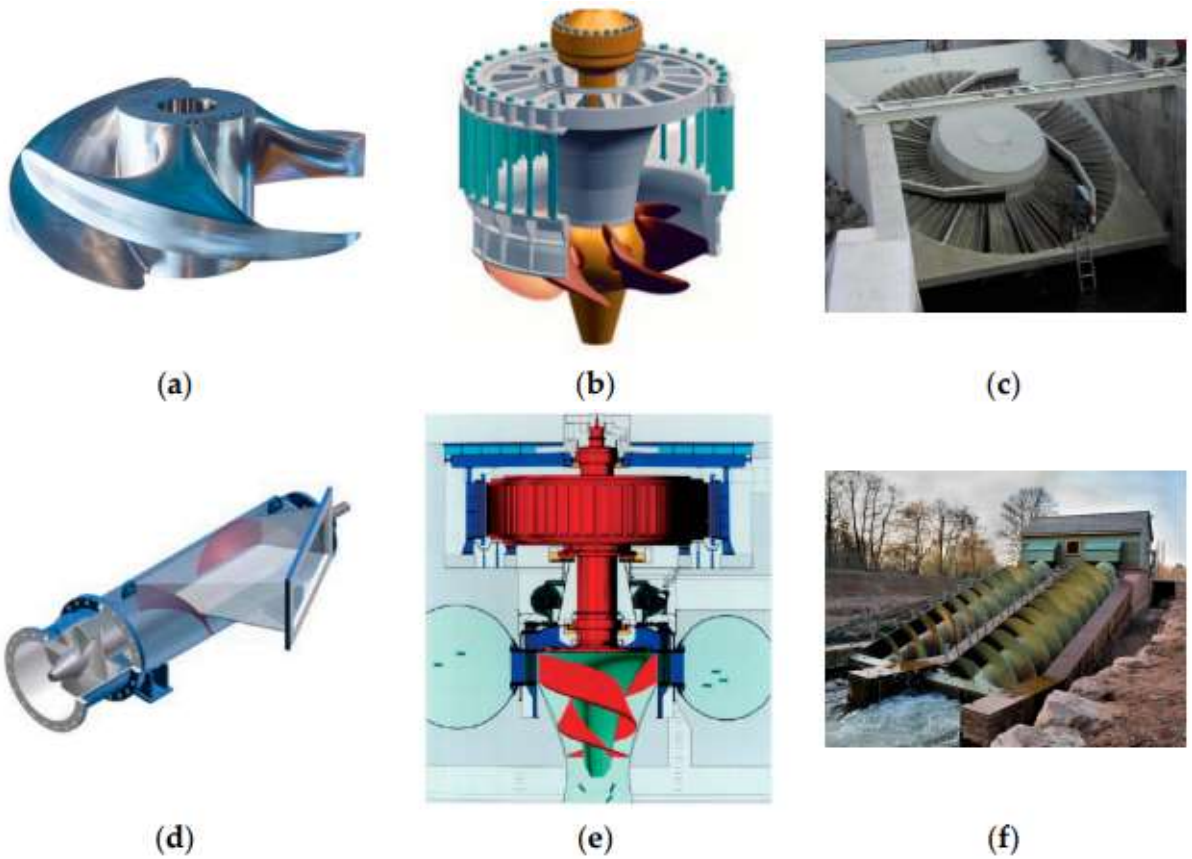
The final design incorporates three helical blades connected both to the hub and to a rotating outer shroud, thereby eliminating gaps and preventing pinch-related injuries. The turbine casing follows a conventional spiral configuration that directs flow through a radial passage equipped with a limited number of elongated guide vanes (wicket gates), before gradually redirecting the flow towards the runner inlet.

The elongated helical blade geometry was specifically developed to reduce pressure fluctuations and improve fish survival by minimising barotrauma during turbine passage. Furthermore, the Alden turbine incorporates thick leading edges, which have been shown to reduce injuries caused by blunt impacts.

These design features—including a reduced number of blades, lower operating speeds, minimised pressure differentials and thickened leading edges—have demonstrated significant improvements in fish survival.

The hydraulic characteristics of the Alden/Concepts NREC turbine were evaluated against biological criteria identified as important for safe fish passage through turbines (Cook *et al.*, 1997). The original design criteria were essentially as follows (note that the units have been converted from those used in the original publication):

- maximum runner peripheral speed: 12.20 m/s;
- minimum pressure: 68.9 kPa;
- maximum pressure change rate: 551.5 kPa/s;
- maximum shear stress: 180 s^{-1} (180 cm/s/cm);
- minimum number and total length of blade leading edges;
- maximum spacing between runner and guide vanes, while minimising all other clearances;
- maximum passage dimensions.



(g) (h) (i)

Figure 3-3. Conventional Kaplan runner (a) and two-tilt-angle Minimum Gap Runner (MGR) (b). Unlike fixed-blade propeller runners, the blades of Kaplan and MGR runners are hinged to the hub in order to maintain high efficiency under varying flow conditions. In conventional Kaplan turbines, the clearances between the blade tip and the discharge ring, as well as between the blade and the hub, are substantially reduced in the MGR through modifications of the geometry towards a more spherical profile. Modified from Odeh (1999).

3.4 Deterrent systems

The studies presented thus far have focused on understanding the mechanisms affecting fish that enter turbines and on identifying their likely fate during turbine passage. This knowledge supports the development of fish-friendly technologies aimed at minimising injuries and mortality associated with turbine passage.

However, because it is not always feasible to implement all available technological improvements or to retrofit existing facilities, and because even fish-friendly turbines may still cause some degree of mortality, specific deterrent systems are often employed to prevent fish from entering turbine intakes. These systems are typically installed at intake structures or immediately upstream of the turbine.

These guidelines provide an overview of the deterrent systems currently available, which should be regarded as alternatives to, or preferably complementary measures alongside, the installation of fish-friendly turbines.

To prevent fish from entering channels subject to frequent dewatering or leading to turbine intakes, either passive barriers (i.e. physical barriers that prevent fish passage) or active barriers (i.e. behavioural barriers that exploit positive or negative sensory stimuli) may be used. Active barriers either discourage fish from moving in a particular direction or attract them towards a preferred route without relying on a permanent physical structure. In some cases, both approaches are combined.

Physical barriers primarily prevent fish from entering intake structures or redirect them elsewhere, but they do not discourage fish from approaching the structure itself. Consequently, fish may become trapped against these barriers if local water velocities exceed their swimming capabilities.

Furthermore, physical barriers may generate operational problems associated with debris accumulation and clogging of intake channels.

Although behavioural barriers generally involve higher installation and operational costs than physical barriers, their effectiveness varies considerably according to the target species, life stage, physiological condition (Hocutt, 1980) and environmental conditions.

Although the threats associated with downstream migration are similar worldwide, effective solutions are often highly site-specific (Fjeldstad *et al.*, 2018). Laboratory and field studies conducted during the last

decade on deterrent systems for downstream fish migration have produced variable results (Russon *et al.*, 2010; Calles *et al.*, 2013, 2021; Fjeldstad *et al.*, 2018; Økland *et al.*, 2019).

Successful downstream passage is important not only in terms of survival but also in terms of migration timing. Delays caused by hesitation at barriers may negatively affect reproductive success by slowing migration progress (Verhelst *et al.*, 2018).

In 2015, the scientific community generally considered available and experimental downstream fish protection solutions to be either unsatisfactory or still under development ("Fish Passage 2015 – International Conference on River Connectivity Best Practices and Innovations", Groningen). At that time, physical barriers included screen systems, vertical-bar screens, labyrinth barriers and overflow barriers, while behavioural barriers included louvre systems, light-based deterrents, bubble curtains, electric barriers and acoustic guidance systems.

The present document has also considered the most recent scientific literature published between 2022 and 2025 in order to provide an updated overview of the current state of knowledge.

Considerable individual variability exists in the time required for silver eels to pass through bypass systems (Behrmann-Gödel & Eckmann, 2003; Pedersen *et al.*, 2012; Calles *et al.*, 2013). Although the causes of this variability remain poorly understood, they may be related to individual traits such as morphology, degree of sexual maturation and behavioural characteristics.

Morphological metrics such as body mass and girth directly influence swimming performance and the ability of fish to overcome deterrent systems (Calles *et al.*, 2010; Travade *et al.*, 2010b). Migratory motivation may also be described by the degree of silvering, which can be estimated using indices based on eye size and pectoral fin development (Durif *et al.*, 2009).

Behavioural types—that is, behavioural traits that remain consistent over time and across different contexts (for example, bold, exploratory, aggressive or shy behaviour)—have been characterised in laboratory studies involving glass eels and elvers (Geffroy & Bardonnet, 2012; Geffroy *et al.*, 2014, 2015). Comparable information for adult eels remains limited, largely because adult eels are difficult to study under laboratory conditions.

The importance of behavioural type during downstream migration remains poorly understood. Nevertheless, adult eels have been shown to display a wide range of responses when encountering physical barriers, including following the channel, colliding with screens, retreating upstream or exhibiting combinations of these behaviours (Amaral *et al.*, 2003; Behrmann-Gödel & Eckmann, 2003; Russon *et al.*, 2010; Russon & Kemp, 2011; Verhelst *et al.*, 2018).

Body mass has been found to be positively correlated with the probability of successful passage (Calles *et al.*, 2013, 2021; Økland *et al.*, 2019). Larger eels may be more effective swimmers because of their greater muscle mass, allowing them to move more rapidly along screens and locate bypass entrances more efficiently.

Furthermore, because most eels larger than 500 mm are females, owing to the well-documented sexual dimorphism of the species (Tesch, 2003), effective deterrent and bypass systems may contribute disproportionately to the survival of highly fecund migrating females. If confirmed, this would have important conservation implications and could partially offset the opposite trend observed for turbine passage survival, which is negatively correlated with body size (Calles *et al.*, 2010).

Motyka *et al.* (2025) found no relationship between either of the two morphometric variables examined (eye index and pectoral fin index) and passage rates through deterrent systems, providing no evidence that the degree of sexual maturation influences passage success. In previous studies, these indices had

generally been used descriptively (Durif & Elie, 2008; Calles *et al.*, 2013; Mordenti *et al.*, 2013) rather than as explanatory variables in analyses of deterrent-system performance.

3.4.1 Physical Barriers

Physical barriers such as screens are commonly installed at hydropower facilities, primarily to prevent debris from entering water intake structures. These installations can also guide downstream-migrating fish towards preferred migration routes (bypass systems) by mechanically preventing access to undesirable pathways.

However, their effectiveness generally decreases in larger facilities and river systems. In addition, maintenance can become problematic due to biofouling and debris accumulation (EPRI, 2018; Schwevers and Adam, 2019; Bruijs, 2021; Mensinger *et al.*, 2021).

The design of effective screening, deterrence and bypass systems requires a thorough understanding of fish behaviour under different hydraulic conditions, as well as of the relevant flow dynamics. Turbulence intensity and structure significantly influence fish behaviour, and certain screen configurations have been shown to improve guidance efficiency towards bypass systems for several species, including European eel (Meister *et al.*, 2022).

3.4.1.1 SCREEN-BASED DETERRENTS

Screen systems represent the most widely used method for protecting fish from entering water intakes and can also be effective for European eels, provided that appropriate bar spacing is selected and water velocity in the vicinity of the screen remains sufficiently low.

One or more screen panels are typically installed within guide rails incorporated into the supporting structure, allowing easy removal from above for maintenance purposes. In some cases, screens may also be designed to rotate for maintenance and cleaning operations; however, this is not considered an optimal solution because fish may pass through the structure while it is rotating.

Ideally, screens should be positioned parallel to the flow direction or at an angle that facilitates fish guidance towards a collection channel or bypass located downstream of the screen. The installation angle should be selected so that the component of flow velocity perpendicular to the screen remains lower than the swimming speed of the target species. An angled configuration also exposes the screen to tangential flow velocities that contribute to self-cleaning.

The dimensions of the screen system clearly depend on intake size and handling requirements. Appropriate bar spacing varies according to the target species and the period of the year. During eel downstream migration periods, relatively wide bar spacing may be sufficient. A reduction in effective spacing can also be achieved through the installation of a second parallel screen offset from the first.

The optimal spacing depends both on screen orientation and eel size. Where screens are installed at angles lower than 20° relative to the main flow direction, current velocities along the screen increase, inducing avoidance behaviour in eels and allowing the use of relatively wide bar spacing.

Stainless steel is generally considered the most suitable and durable construction material. Upstream of the fish-guidance screen, the installation of an additional coarse screen is often recommended. This arrangement helps maintain the guidance screen in a cleaner and more efficient condition but may require the construction of an additional passage route for larger fish.

Alternatively, sufficient spacing may be incorporated to allow the passage of larger fish individuals.

The principal **advantages** of screen-based deterrent systems are:

- no electrical power supply is required;
- installation costs are relatively low, particularly at small facilities.

The principal **disadvantages** are:

- frequent cleaning is required to prevent clogging;
- limited resistance to flood events;
- head losses may become significant when fine-mesh screens are used (for glass eels and elvers, mesh sizes of approximately 2 mm may be required).

Many facilities currently employ screens with bar spacings of 80–100 mm in order to reduce the risk of blockage by debris. Numerous studies have investigated eel behaviour in front of such structures. Bolland *et al.* (2019) and van Keeken *et al.* (2020) found that most eels turned around and moved upstream after physical contact with the screen. However, other studies observed exploratory behaviour that sometimes resulted in successful passage through the screen (Piper *et al.*, 2015; Bruijs and Durif, 2009). Consequently, complete removal of the screen or an increase in bar spacing may significantly increase downstream passage rates.

Evans *et al.* (2024b) reported that eels were generally reluctant to pass through a screen, but the probability of passage increased significantly from 36% to 52% when bar spacing was increased from 100 mm to 190 mm.

According to Kjaeras *et al.* (2022), a screen installed at a 30° angle relative to the flow direction, with horizontal bars spaced 15 mm apart and combined with a bottom outlet bypass, can achieve a downstream migration efficiency of 72% among fish entering the intake area, and 100% when additional bypass routes, such as surface outlets, are also available.

Beck *et al.* (2020) investigated a horizontal bar rack with bypass section (HBR-BS). Their results showed that velocity and pressure gradients between the horizontal bars, and up to approximately 40 mm upstream of the screen, were particularly high, causing most tested fish species to avoid the structure. European eel, however, exhibited significantly weaker responses to these hydrodynamic stimuli.

Consequently, the deterrent system demonstrated high protection and guidance efficiencies (>75%) for five European freshwater fish species, but only limited or negligible behavioural effects on brown trout and European eel.

In experiments conducted by Moldenhauer-Roth *et al.* (2024), a 90-mm spacing screen was modified by installing an electric deterrent system immediately downstream (142-mm spacing, 44 V). The screen alone provided little deterrence, whereas electrification increased eel guidance efficiency to 92% at a flow velocity of 0.3 m/s and 76% at 0.6 m/s.

Laboratory studies indicate that both inclined and angled screens can successfully deter eels (Amaral *et al.*, 2003; Russon *et al.*, 2010), and these findings have been confirmed under field conditions (Calles *et al.*, 2013,

2021; Økland *et al.*, 2019). Proposed screen designs typically incorporate bar spacings between 10 and 20 mm and are installed at angles ranging from 26° to 45° relative to either the vertical or horizontal plane.

For example, in the River Sieg, a screen inclined at 27° with 10-mm bar spacing achieved a deterrence efficiency exceeding 92% (Økland *et al.*, 2019), while a 30° inclined screen with 15-mm spacing in the River Ätran achieved efficiencies between 95% and 100% (Calles *et al.*, 2021; Kjærås *et al.*, 2023).

Results further indicate that angled screens with bar spacings of 15 mm and 30 mm achieved relatively high deterrence efficiencies (81.3% and 70.8%, respectively). These values are consistent with earlier studies. For example, Amaral *et al.* (2003) reported efficiencies of approximately 85–95% for screens installed at 15° relative to the current with 50-mm spacing, and approximately 60% for screens installed at 45° with 25-mm and 50-mm spacing. Another laboratory study demonstrated high efficiencies for screens with 12-mm spacing installed at 15°, 30° and 45° (Russon *et al.*, 2010).

Among the most advanced screen-based deterrent technologies are the Modular Inclined Screens (MIS) developed by the Electric Power Research Institute (EPRI), which are highly versatile and suitable for a wide range of environmental conditions and target species (Amaral *et al.*, 1999).

The system consists of a wedge-wire screen installed at an angle of 10–20° relative to the flow, with bar spacing of approximately 1.9 mm and an open area ratio of approximately 50%. The installation can rotate into a position parallel to the flow, allowing self-cleaning. A diversion channel is located downstream of the screen. The entire structure measures approximately 9 m × 3 m and can accommodate flow rates of 2.8–3 m^3/s with approach velocities ranging from 0.6 to 3 m/s.

In laboratory simulations conducted by Amaral *et al.* (1999), this system achieved deterrence efficiencies of approximately 96% across a range of flow conditions and species. The same study reported efficiencies of approximately 95% during tests conducted at operational water-intake facilities.

Carter *et al.* (2023) evaluated the influence of wedge-wire screens with different mesh sizes (1, 2, 3 and 5 mm) and water velocities (0, 0.1, 0.15 and 0.2 m/s) on the passage behaviour of juvenile eels measuring 60–80 mm and 100–160 mm.

Mesh sizes of 1 mm and 2 mm were used to exclude eels measuring 60–80 mm and 100–160 mm, respectively.

At a flow velocity of 0.2 m/s, up to 90% of the 60–80 mm eels and 100% of the 100–160 mm eels were prevented from passing through the screen. This velocity also increased both the number of contacts with the screen and the time required for fish to establish contact with it.

A small proportion (9.2%) of the 60–80 mm eels did not approach the screen at all, while eels small enough to pass through the mesh did not always do so, suggesting that factors other than body size may influence screen-passage behaviour.

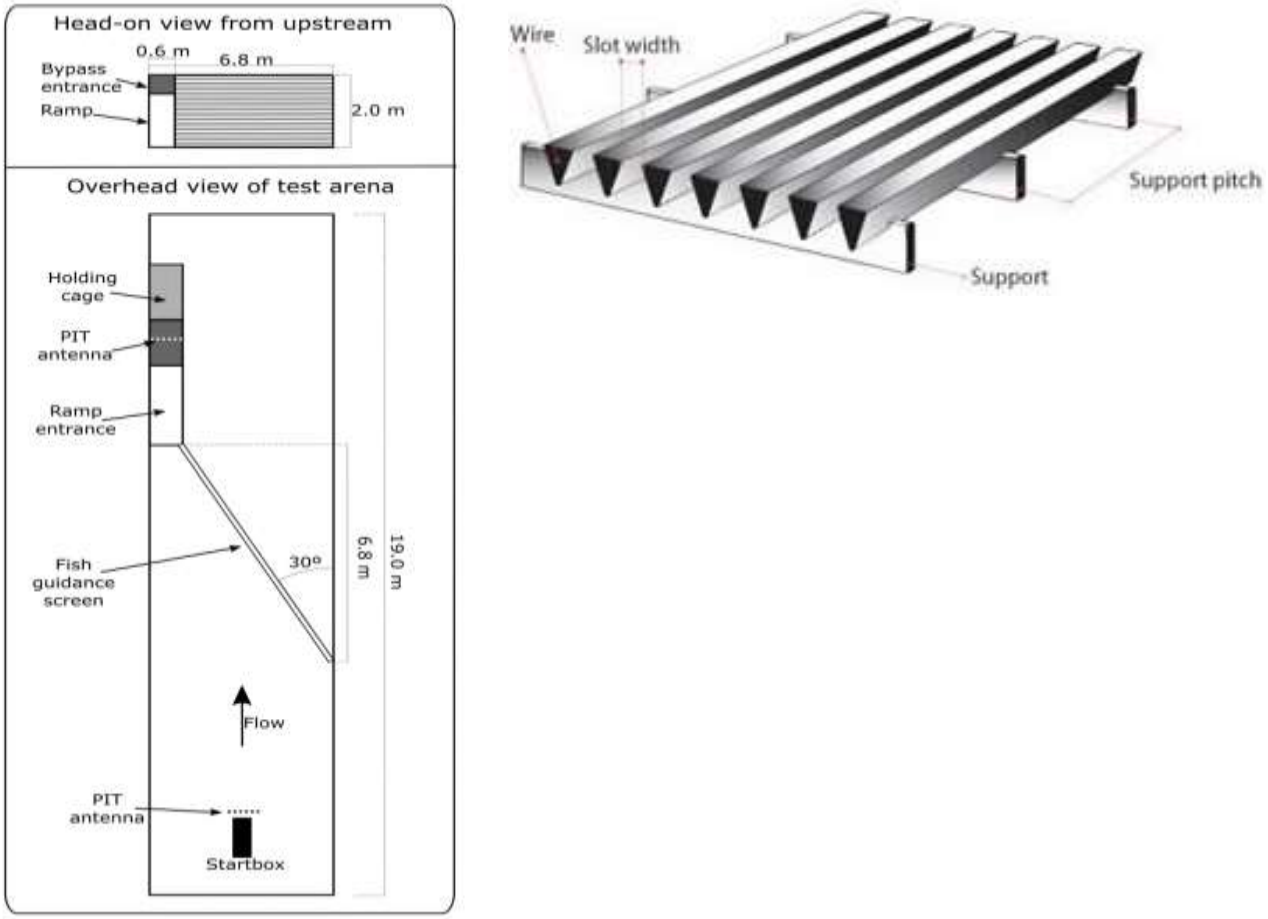


Figura 3 4. Experimental model of a hydropower intake, screen barrier and bypass system (left; source: Motyka *et al.*, 2025). Wedge-wire screen (right; source: http://www.euroslotkdss.com/dissuasoration/wedge-wire).

The geographical location of a water intake determines the size classes of eels likely to occur in its vicinity. Due to the peculiar life cycle of the European eel, glass eels and elvers are generally found only within the final 30 km of river systems before they enter the sea. Beyond this zone, upstream-migrating eels typically reach or exceed a length of 30 cm. Consequently, technical solutions adopted for fish protection in these areas should be designed for eels of at least this size.

Water intakes located in the lower and middle reaches of river systems therefore generally require finer screen spacing than those located in upper river reaches (Environment Agency, 2014).

When adapting these guidelines to a specific river basin, screen design should therefore be selected according to the expected size classes of eels present at the site and the distance from the sea.

3.4.1.2 VERTICAL-BAR DETERRENTS

Vertical-bar deterrents were originally developed for debris diversion. Some designs incorporate movable teeth or rake-cleaning systems to remove accumulated material from the exposed surface. Depending on the specific application, bar spacing may range from 38 mm to 150 mm. An inclination of approximately 10° from the vertical helps maintain contact between the rake mechanism and the bars during cleaning operations.

The most commonly used construction materials are mild steel and stainless steel. In some facilities, horizontally oriented bars have also been tested, allowing the current itself to contribute to automatic cleaning (Ebel, 2008). As with the conventional screen systems described previously, modern installations

generally employ two rows of panels: an upstream row for debris diversion and a downstream row for fish guidance.

Rectangular-section bars are recommended because they are more effective at repelling fish, including eels, than cylindrical bars (Travade *et al.*, 2009). A spacing of 20 mm between rectangular bars produces a deterrent effect on eels comparable to that obtained with a spacing of 15 mm between wedge-shaped bars.

This solution, whose primary target remains adult eels, represents an alternative to conventional mesh-screen systems.

3.4.1.3 LABYRINTH DETERRENTS

Labyrinth deterrents are a variation of conventional screen systems or vertical-bar barriers. In this configuration, vertical-bar screens are arranged in a series of V-shaped sections that guide fish towards a bypass channel located downstream.

A typical installation consists of 14 screens arranged to form seven V-shaped guidance structures. Such a configuration generally occupies approximately 40 m of channel length, whereas a single V-shaped structure designed to achieve comparable guidance performance would require substantially more space.

An impermeable ramp positioned downstream on the bottom of each V-shaped section and inclined at approximately 45° promotes local flow acceleration, thereby attracting fish towards the bypass channel.

3.4.1.4 OVERFLOW DETERRENTS

An overflow deterrent consists of a parallel-bar screen installed in a sloping configuration along the downstream side of a weir. Water passes through the screen and is directed towards the turbine intake, while debris and fish are carried downstream by the overflow discharge (Turnpenny, 1998).

3.4.1.5 COANDA DETERRENTS

The Coanda deterrent is based on the Coanda effect, first described by Henri Coandă in 1910.

In this system, the water layer in direct contact with the screen experiences friction and slows down, entering the intake channel located beneath the screen. Meanwhile, the upper water layer continues to flow along a specially designed spillway surface incorporating an ogive-shaped curvature with a radius of approximately 3 m.

The bars, generally of the same type recommended previously for glass eels and elvers, are spaced according to both the size of debris to be diverted and the dimensions of the target fish species. Their orientation promotes flow separation, slowing and diverting the lower flow component towards the intake while accelerating the upper flow component (Turnpenny, 1998).

This solution has been adopted primarily at small hydropower facilities, although there is no technical reason preventing its application at larger installations.

The most important consideration when designing a Coanda intake is the quantitative balance between diverted water and overflow discharge. If bar spacing is too large, insufficient flow may remain in the river channel downstream of the intake. During low-flow periods, it may therefore be necessary to cover part of the screened area in order to ensure the release of adequate residual flow to the river.

3.4.1.6 MOVING-BELT AND DRUM-SCREEN DETERRENTS

Many water-intake facilities employ moving-belt or drum-screen filtration systems to remove debris from the water supply. These installations are typically located within pumping stations rather than directly at the intake structure itself.

Several design improvements have been developed to minimise physical injury to fish, including:

- collection baskets capable of lifting and returning fish and debris to the receiving water body;
- low-pressure washing and backwashing jets (≤1 bar), which are considered non-injurious to fish and are used to direct fish and debris towards collection baskets;
- high-pressure washing and backwashing jets (≥3 bar), which are applied only as a secondary treatment once fish have already been separated and returned to the water body.

The rotational speed of drum screens, which depends on the operation of the cleaning jets, is an important factor affecting fish survival. Nozzle systems can be programmed so that high-pressure cleaning is activated only when excessive clogging occurs. Following low-pressure washing, fish are directed through dedicated openings into return conduits leading back to the water body.

The use of chlorine for antifouling purposes within these systems may be toxic to fish returned to the aquatic environment. However, chlorine treatments are generally applied during summer and therefore do not normally coincide with the migration period of glass eels and elvers. Fish survival is inversely related to both chlorine concentration and exposure duration. Nevertheless, antifouling treatments should be applied exclusively downstream of the fish collection and return system.

Fish survival rates vary considerably, but values of up to 80% have been reported for relatively resilient species returned to the receiving water body (Turnpenny and O'Keeffe, 2005).

Technical improvements that have been introduced over the years for this type of system include:

- non-metallic collection baskets;
- smooth construction materials;
- optimisation of washing and backwashing jet configurations.

Particular attention has been devoted to the design of collection baskets (Turnpenny *et al.*, 2010). Standard basket designs appear poorly suited to elongate fish species such as lampreys and eels. Indeed, survival rates of eels passing through these systems are generally relatively low (Clough *et al.*, 2003). The principal issue appears to be either the ability of eels to escape from the baskets or injuries sustained during escape attempts.

The main recommendations for improving the survival of fish returned to the water body are:

- continuous operation of the screening system to ensure the transfer of fish into return conduits;
- use of smooth, fish-friendly screen surfaces with mesh sizes smaller than 6 mm;
- ensuring that basket designs prevent eel escape;
- applying chemical treatments only downstream of fish recovery systems;
- ensuring that return conduits have a minimum diameter of 30 cm;
- discharging fish back to the receiving water body at water level;

- maintaining continuous water flow within return conduits;
- maintaining a constant screen rotational speed of at least 1.5 m/min in order to minimise fish stress;

This type of deterrent system is most commonly used at estuarine facilities, although it may also be applied at drinking-water abstraction plants.

The effectiveness of these systems is generally high for benthic and demersal species but remains uncertain for pelagic species. In the specific case of European eel, the effectiveness of current collection-basket designs is relatively low. For the protection and recovery of juvenile life stages, screen mesh sizes should not exceed 2–3 mm.

3.4.1.7 FLOATING ROD BARRIERS

Stoilova *et al.* (2023) investigated a deterrent system consisting of a series of floating polyethylene rods arranged parallel to one another at regular spacing and anchored to the riverbed. The structure oscillates under the action of the current, creating a permeable barrier intended to divert fish away from the turbine intake of a hydropower facility.

A pilot study conducted on 106 downstream-migrating juvenile Atlantic salmon demonstrated the deterrent effectiveness of the system. Only 5.7% of the fish passed downstream through the barrier. Most individuals remained upstream of the structure (51.9%), while the remaining fish followed the barrier downstream towards a bypass ramp (39.6%).

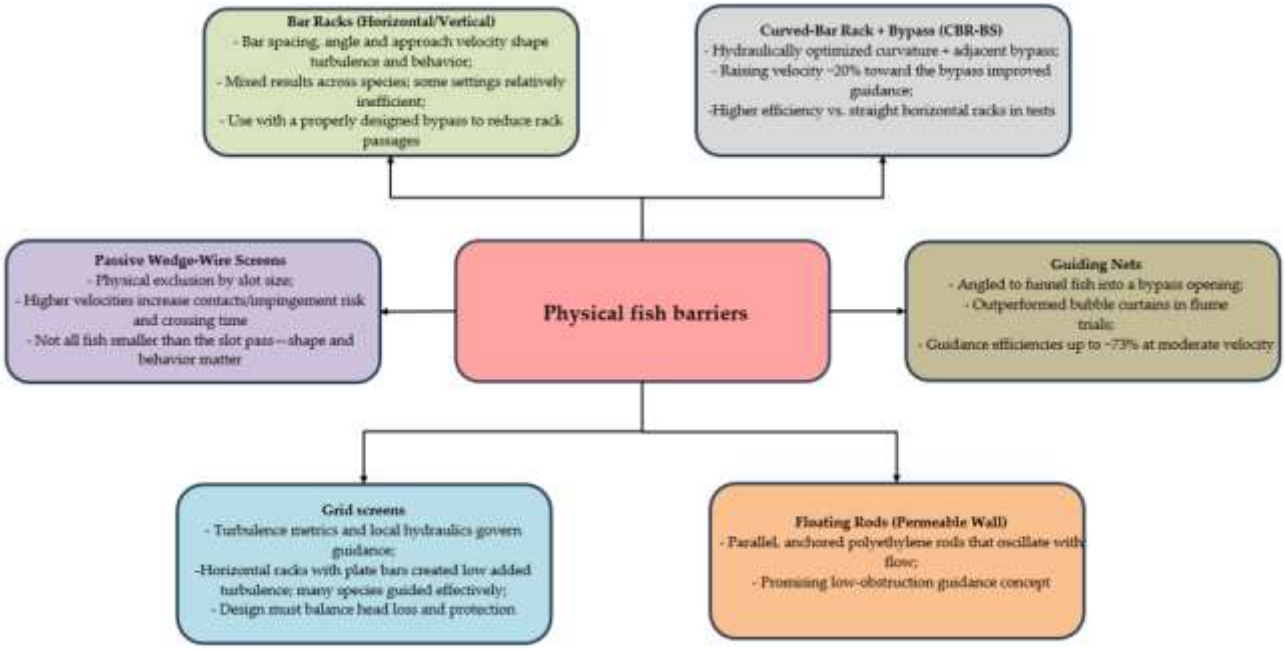


Figure 3-5. Overview of the main characteristics of the principal physical barrier systems used for fish protection and guidance (source: Nicula and Lungulescu, 2025).

3.4.2 Behavioural Barriers and Deterrent Methods

In light of the limitations associated with physical barriers, considerable interest has emerged in the development of behavioural solutions capable of modifying fish migration routes, either as alternatives to or in combination with physical barriers (Hadderingh *et al.*, 1999; Versar, Inc., 2009; Piper *et al.*, 2015, 2019; EPRI, 2018; Elvidge *et al.*, 2018; Popper *et al.*, 2020; Pratt *et al.*, 2021).

In some situations, the installation of physical barriers at water intakes is not feasible, mainly because of navigation requirements, high sediment transport loads or a strong tendency for biofouling development.

Behavioural barriers are deterrent systems designed to guide fish away from hazardous areas. These barriers rely on behavioural rather than physical mechanisms, using acoustic, visual, chemical or multimodal stimuli to modify the probability and direction of fish movement, thereby reducing exposure to high-risk areas or periods (Jesus *et al.*, 2021).

Noatch and Suski (2012) reviewed a range of behavioural deterrent methods, highlighting their flexibility and adaptability for fish-movement management and their potential to improve the effectiveness of fish migration control strategies.

Fish possess a variety of highly developed sensory systems and are able to perceive and respond to numerous stimuli, including sound, vibration, temperature, taste, odour, pressure changes, hydraulic shear, acceleration, electric fields and magnetic fields. Sensitivity and behavioural responses naturally vary among species and life stages. Behavioural deterrents exploit one or more of these stimuli to discourage fish from approaching water intakes and, in some cases, to guide them towards safer migration routes.

In general, stimulus intensity must be calibrated carefully so as not to create a complete barrier to fish movement within the watercourse while remaining effective under varying environmental conditions.

European eels respond to environmental cues such as hydrodynamic conditions, light and sound (Evans and Claiborne, 2006; Trischitta *et al.*, 2013), although responses vary according to life stage and immediate behavioural priorities (Horodysky *et al.*, 2022). Although eels do not possess a specialised electro-sensory anatomy (England and Robert, 2022), their nervous system can be directly influenced by electrical stimulation, and they may respond either voluntarily or involuntarily to such stimuli (Cowx and Lamarque, 1990; Sharber and Sharber Black, 1999; Noatch and Suski, 2012).

Eels are also capable of perceiving magnetic fields (Moore and Riley, 2009; Durif *et al.*, 2022), temperature, odours and pressure changes (Evans and Claiborne, 2006). However, chemical stimuli are strongly influenced by local hydrodynamic conditions and therefore tend to disperse irregularly and unpredictably within downstream flows (Allen *et al.*, 2012).

Several hydrodynamic aspects are particularly relevant for the development of behavioural guidance systems. At higher flow velocities, the effectiveness of any stimulus may be reduced, requiring greater stimulus intensity to elicit a behavioural response (Hadderingh *et al.*, 1999; Versar, Inc., 2009; Putland and Mensinger, 2019; Miller *et al.*, 2021).

Even when stimulus intensity is sufficient to induce the desired response, eel behaviour may become physically constrained when flow velocities approach or exceed their burst swimming capabilities (1.35–2.12 m/s; Russon and Kemp, 2011), or, in the case of downstream migration, once the eel has reached a “point of no return” (Bruijs, 2021).

Eels also tend to avoid objects present in the water column, particularly when these create hydrodynamic disturbances (Piper *et al.*, 2017), a characteristic that may prove useful in the design of behavioural guidance systems.

A common limitation affecting all behavioural deterrent technologies is that naturally occurring background levels of similar stimuli may reduce the relative intensity of artificial signals. This is of particular concern at

sites affected by light pollution or elevated ambient noise levels (Popper and Carlson, 1998; Noatch and Suski, 2012; Popper *et al.*, 2020).

The following sections present the principal deterrent systems that have been tested and for which practical application potential has been identified..

3.4.2.1 CHEMICAL DETERRENTS

Chemical stimuli and kairomones may be used as behavioural deterrent barriers by exploiting the intrinsic sensitivity of fish to chemical cues in the aquatic environment. Alarm signals released by injured conspecifics can rapidly reduce activity levels, increase shelter-seeking behaviour or alter shoaling patterns, thereby discouraging fish from entering areas perceived as dangerous (Li *et al.*, 2023; Mesch *et al.*, 2022; Sitvarin *et al.*, 2015).

Kairomones released by predators can induce behavioural responses such as reduced exploratory activity, increased vigilance and changes in spatial positioning, which may decrease the attractiveness or accessibility of specific areas (Jesus *et al.*, 2021; Mensch *et al.*, 2022; Robison *et al.*, 2017).

More generally, the chemical landscape of a water body can be manipulated to create behavioural barriers by generating chemically mediated risk environments. Such chemical cues may be used either as stand-alone deterrents or in combination with other behavioural stimuli (Jesus *et al.*, 2021; Pereira *et al.*, 2017; Goldman *et al.*, 2020; Mensch *et al.*, 2022).

Winter *et al.* (2023) investigated the influence of wastewater treatment plant effluent plumes on eel migratory behaviour. The authors monitored the behavioural responses of 40 tagged eels encountering an effluent plume discharged from a wastewater treatment facility during downstream migration within the Ems Canal, Netherlands.

The results indicated that the presence of the effluent plume induced significant behavioural changes. The eels actively avoided the plume, in some cases causing potentially substantial delays to downstream migration. These findings suggest that chemically distinct effluent plumes may possess some potential as deterrent stimuli, although their practical application for fish guidance remains to be further evaluated..

3.4.2.2 LOUVRE DETERRENTS

Louvre deterrents have been used since the 1950s and consist of a semi-physical guidance system capable of diverting up to 90% of fish approaching the structure (Aitken *et al.*, 1966; Solomon, 1992).

In general, the efficiency of this type of deterrent ranges from 80% to 100%, depending on louvre spacing and installation angle. The operating principle is based on the avoidance response exhibited by fish when encountering vortices generated by water flowing along the louvre blades. Fish are consequently guided, through the orientation of the structure, towards a collection channel or bypass route.

Maximum efficiency is achieved when the individual louvre blades are positioned perpendicular to the flow direction. The overall structure is typically installed at an angle ranging from 10° to 30° relative to the flow, although optimum performance is generally obtained at approximately 10–15°. Efficiency tends to decrease as this angle increases.

The optimum installation angle results in a total louvre-system length approximately 3.86–5.76 times the width of the channel being protected (Solomon, 1992).

Appropriate spacing between louvre blades varies from 2.5 cm to 30 cm depending on the target species (Therrien and Bourgeois, 2000). Most fish that pass through the structure do so near its downstream end, close to the entrance of the collection channel. For this reason, blade spacing should be reduced to approximately 5 cm in this area whenever upstream spacing is larger.

Water depth does not appear to significantly affect the performance of louvre systems, as their effectiveness has been demonstrated even in channels up to 4 m deep (Ducharme, 1972).

Although relatively few studies have investigated the use of louvre systems specifically for diverting eels from water intakes, promising results have been reported for silver American eels (Anguilla rostrata) with an average length of approximately 56 cm. A diversion efficiency of approximately 60% was achieved using louvre blades spaced 5 cm apart, oriented at 45° from the vertical and installed at 15° relative to the flow direction, under flow velocities of 0.3, 0.6 and 0.9 m/s.

When a 30-cm-high bottom guidance plate was added along the base of the structure, diversion efficiency increased to approximately 90%, largely independent of flow velocity.

Although louvre systems are considered semi-physical barriers, they may still be affected by debris accumulation and associated maintenance requirements. These issues can be mitigated through the installation of a coarse debris screen upstream of the louvre system.

Louvre barriers are particularly suitable for canalised or regulated watercourses characterised by relatively uniform discharges and flow velocities. Because they generate only limited head losses, they are also well suited to large water bodies and low-head hydropower facilities.

This type of deterrent is less suitable for rivers characterised by substantial transport of floating vegetation and organic debris.

Louvre systems are generally considered most appropriate for adult eels exceeding 50 cm in length.

3.4.2.3 BUBBLE DETERRENTS

Bubble barriers represent an innovative fish-deterrence solution based on the artificial generation of a continuous wall of bubbles rising from the riverbed.

Their advantages include relatively low installation and maintenance costs, ease of removal, reduced obstruction of water intakes and lower ecological impacts compared with conventional physical barriers.

On the other hand, their effectiveness may vary considerably depending on hydrological conditions, flow velocity and the target species. In rivers characterised by moderate to high discharges and strong turbulence, the deterrent effect may be substantially reduced. Energy consumption and access to reliable power sources may also represent limiting factors (Leander *et al.*, 2024; Circiumaru *et al.*, 2022). Furthermore, bubble barriers are generally species-specific solutions and are therefore difficult to apply effectively across entire fish communities.

In a nighttime experimental study involving PIT-tagged eels, a physical barrier (Kevlar net) consistently outperformed a bubble-deterrent system in terms of guidance efficiency (Stoilova *et al.*, 2025). The physical barrier achieved an average guidance efficiency of 68%, reaching a maximum value of 73% at a flow velocity of 0.7 $m \cdot s^{-1}$. The barrier successfully diverted eels away from the protected area, with relatively few

successful penetrations and a stronger avoidance response, reflected by a greater number of swimming reversals.

By contrast, the bubble-deterrent system did not show any significant effectiveness compared with control conditions and allowed numerous downstream penetrations. In this study, flow velocity (0.1–1.0 m/s) had no detectable influence on deterrent performance, whereas larger eels were less likely to enter the bypass route.

The results therefore indicated that the physical barrier provided effective deterrence for downstream-migrating eels, whereas the bubble barrier did not.

Turnpenny and O'Keeffe (2005) suggested that bubble barriers may be more suitable for migratory species, as resident species can gradually become habituated to the disturbance generated by the bubbles, reducing the effectiveness of the system over time.

Because of the relatively limited visual capabilities of eels, individuals must generally come into direct contact with the bubble curtain before detecting its presence. Available evidence suggests that the sensory stimulus generated by bubbles alone may be too weak to trigger the desired avoidance response.

The effectiveness of bubble barriers could potentially be improved through adjustments to bubble size and density or through integration with acoustic and visual stimuli. Such modifications may increase the reliability of bubble barriers as tools for the protection of aquatic ecosystems (Dennis and Suski, 2025; Leander *et al.*, 2021).

3.4.2.4 HYDRODYNAMIC DETERRENTS

Early experimental investigations into hydrodynamic manipulation as a fish-guidance mechanism produced inconclusive results. These included the concept of using "sweeping flows" to direct eels towards one side of a channel (Coutant, 2003) and studies suggesting a preference of eels for acceleration corridors (Hadderingh *et al.*, 1999).

Consistent with these findings, EPRI (2016) unsuccessfully attempted to exploit increased flow velocity within a channel to guide downstream-migrating eels towards a collection facility.

Hydrodynamic manipulation remains the only deterrent approach with the potential to attract or redirect eels through modifications of flow velocity. However, excessively high velocities may become ineffective or even detrimental.

Piper *et al.* (2015) investigated the responses of downstream-migrating eels to channel constriction and flow acceleration. The study found that eels tended to avoid narrow sections characterised by accelerated flow and required significantly longer times to pass through these areas compared with control individuals. Nevertheless, all tested eels eventually traversed the experimental section.

Vowles *et al.* (2025) further clarified the role of channel constriction and the resulting flow acceleration. Their results confirmed that accelerated flows act as a deterrent to downstream-migrating eels and additionally demonstrated that turbulence associated with vortices and recirculation zones exerts a stronger deterrent effect than flow acceleration alone.

These observations suggest that accelerated flows may have potential as deterrent stimuli capable of directing eels towards preferred migration routes, particularly when combined with other deterrent

modalities. Although further research is required, it appears plausible that manipulated hydrodynamic conditions could be used to guide downstream-migrating eels under specific circumstances, provided that the relevant parameters and behavioural responses are more clearly understood.

The findings of Piper *et al.* (2015) and Vowles *et al.* (2025) highlight the largely unexplored potential of accelerated and recirculating flow fields as components of multimodal fish-guidance systems.

In very large rivers, it may be preferable to modify hydrodynamic conditions only within selected portions of the channel in order to influence a useful proportion of downstream-migrating eels (Pratt *et al.*, 2021). Consequently, if supported by further research, hydrodynamic manipulation may be most appropriately applied in relatively small channels characterised by low to moderate flow velocities.

3.4.2.5 ELECTRIC DETERRENTS

Electric current directly stimulates fish, including eels, and most responses are probably involuntary or due to proximity to an aversive stimulus (Cowx and Lamarque, 1990; Sharber and Sharber Black, 1999; Noatch and Suski, 2012).

Electric fish barriers consist of a series of metallic anodes and cathodes arranged throughout the water column. Electric current flows from the anode to the cathode, creating an electric field that acts as a barrier to fish species (Britton *et al.*, 2011; Katopodis *et al.*, 1994).

Fish may exhibit a gradient of potential responses when exposed to an electric field, depending on the field intensity and distance from the device:

- Direct current (DC): spasmodic movements, galvanotaxis, galvanonarcosis;
- Alternating current (AC): spasmodic movements, oscillotaxis, oscillonarcosis;
- Pulsed or intermittent current: spasmodic movements, galvanotaxis, galvanonarcosis.

In reality, these effects vary among species (Dolan and Miranda, 2003), according to water conductivity (Hill and Willis, 1994; Dettmers *et al.*, 2009), and depending on electrode design and arrangement (Copp, 1989), although they generally represent a source of stress for fish.

The effects of electroshock are not always externally visible in fish (Nielsen, 1998). Individuals showing no evident external injuries may nevertheless suffer severe internal injuries that can be fatal (Kocovsky *et al.*, 1997).

The use of direct current generally results in higher survival rates of fish exposed to electroshock (McLain, 1957; Palmisano and Burger, 1988) compared with alternating current (EPA, 2000), although the latter appears to be more effective as a deterrent according to Svoboda and Hutcherson (2014).

Hadderingh and Jansen (1990) described detrimental effects associated with early attempts to guide or deter eels using electric fields, and a study reviewed by Versar, Inc. (2009) reported thousands of dead individuals after an electric deterrent trapped fish within an area characterised by excessively high flow velocities, resulting in their impingement against the intake protection screen. Even if the eels had been able to overcome the flow velocity, they would not have been able to leave the intake area by swimming upstream through the electric field.

More recent results from the LIFE4FISH project (2020) are more encouraging. The installation of an electric guidance device upstream of a hydropower plant resulted in a greater number of eels being diverted away from the intake compared with previous years, while simultaneously reducing the number of eels trapped against the protection screen. However, this outcome was only possible because flow velocities were sufficiently low to allow the eels to move away from the electric field.

A laboratory study provided additional behavioural context to these observations by examining the responses of mature eels to two electric fields of different intensities under two flow-velocity conditions (low and high; Miller *et al.*, 2021). Seventy-four percent of eels exhibited a response to the electric field under low-flow conditions, compared with only 31% under high-flow conditions.

Of those individuals that responded under both hydrodynamic conditions, the number that reacted by accelerating through the electric field was almost twice the number that altered their downstream migration trajectory.

As may be inferred from the above, generating an electric field capable of acting as a fish deterrent is a particularly delicate undertaking, not only because of the impacts it may exert on fish fauna, but also because of:

- human safety concerns, since the barrier must be calibrated so as to be effective in achieving its purpose without posing a risk to human health (USACE, 2009);
- concerns relating to the presence of non-fish aquatic species, particularly waterbirds and amphibians;
- limitations associated with the size-dependent response of fish to electric fields (EPRI, 1994). Larger fish are exposed to higher voltage gradients than smaller fish and therefore react more intensely (Dolan and Miranda, 2003). Nevertheless, larvae and juvenile stages have also been shown to be sensitive to certain voltage levels (Henry *et al.*, 2003). Consequently, an electric field sufficiently strong to deter small fish may be excessively intense for larger fish, which may become temporarily paralysed and subsequently swept into the intake by the current (Turnpenny, 1998). Conversely, an electric field that does not cause trauma to large fish may be insufficient to deter smaller individuals (Reynolds, 1996). A study conducted by the Great Lakes Fisheries Commission (Brammeier *et al.*, 2008) demonstrated that an electric barrier was ineffective against carp at the larval stage;
- limitations resulting from the inability of fish to identify the source of the electric field and therefore escape in the appropriate direction (Bullen and Carlson, 2003);
- limitations related to the spatial extent of the electric field, which is generally most effective in shallow waters and confined areas (Bullen and Carlson, 2003);
- limitations in operational reliability, including power fluctuations, lightning damage, insufficient fuel supply for generators, inadequate maintenance and malfunction of monitoring systems used to verify barrier functionality (Clarkson, 2004; Marsden, 2010);
- limitations in overall effectiveness, which may in some cases be relatively low. For example, an efficiency of only 15% (range 8–28%) was reported in diverting juvenile salmon along a 20-m guidance screen towards a bypass channel (Halsou, in Larinier and Travade; International Fish Screening Conference, Southampton, 29–30 March 2011). Such limitations may also result from inadequate design of the entire deterrent system, including flow velocity, characteristics of the electric barrier and the presence, absence or inappropriate design of any associated bypass channel.

Over recent decades, electric barriers have primarily been employed to prevent non-native fish populations from colonising upstream areas or reaching suitable spawning habitats (Conover *et al.*, 2007).

Examples include:

- electric barriers installed to limit the spawning migration of sea lamprey (*Petromyzon marinus*) into tributaries of the North American Great Lakes (Katopodis *et al.*, 1994);
- electric barriers installed within the Central Arizona Project to prevent the upstream movement of non-native species from the Colorado River into the Gila River (Clarkson, 2004);
- the series of electric barriers installed in the Chicago Sanitary and Shipping Canal (CSSC) to prevent the upstream spread of silver carp (*Hypophthalmichthys molitrix*) and bighead carp (*Hypophthalmichthys nobilis*) (Parker *et al.*, 2015; Holiman *et al.*, 2015; Holiman, 2010; Barner *et al.*, 2010).

The results reported in the literature are generally satisfactory; however, it should be noted that in these cases the barrier is positioned upstream of the migrating fish. Under conditions of galvanonarcosis, the current carries the fish away from the electric field (i.e. downstream), thereby preventing further physical injury. Conversely, when an electric barrier is positioned downstream of the fish to be diverted, the current may carry fish experiencing swimming impairment or galvanonarcosis directly towards the electric field itself.

The use of electric current as a deterrent barrier initially attracted only limited interest and attention (EPRI, 1998; EPRI, 2002; Burger *et al.*, 2012). More recently, however, low-frequency electric barriers with short pulse durations have proven highly effective in guiding downstream-migrating eels (Stoot *et al.*, 2018).

Turnpenny and O'Keeffe (2005) advised against the use of electric barriers as downstream-migration deterrents, particularly in the presence of elongated fish species such as eels, suggesting instead that they may be more appropriate as deterrent systems located downstream of discharge structures.

Parker *et al.* (2016) observed that fish frequently attempt to actively cross electric barriers, demonstrating a strong motivation to continue their movement despite the associated risks, including injury or death. This finding is consistent with other studies showing that fish, especially those exhibiting a strong migratory drive, often make repeated attempts to overcome such barriers until they either succeed or suffer physical damage.

The implications of this behaviour are significant, as they suggest that, although electric barriers may be effective in achieving their intended purpose, they may also increase stress levels and mortality within fish populations (Nicula and Lungulescu, 2025).

Miller *et al.* (2021) further demonstrated that low-frequency electric fields with short pulse durations can induce a reliable behavioural response while presenting a limited risk of tetany, thereby offering a gentler deterrence approach.

The available evidence suggests that electricity is generally not suitable as a primary deterrent unless flow velocities are very low (Life4Fish, 2020; Miller *et al.*, 2021). Nevertheless, further optimisation of barrier placement and electrical parameters may reveal additional potential applications. For example, low-frequency electricity with short pulses could be used to alter eel swimming trajectories (Miller *et al.*, 2021), while electrically induced galvanotaxis could potentially be exploited to guide eels into collection facilities for downstream transport operations.

3.4.2.6 ACOUSTIC DETERRENTS

Acoustic barriers are among the most extensively developed behavioural deterrent systems for influencing fish behaviour. They can discourage movement and modify habitat use without requiring the installation of physical barriers, selectively guiding fish away from sensitive areas or towards safer habitats.

Signals associated with disturbance or predators may also function as early-warning cues, modifying feeding and shelter-seeking behaviour before direct encounters occur and thereby reshaping movement patterns (Goldman *et al.*, 2020). Unlike many other stimuli, sound possesses the distinct advantage of transmitting information over long distances without being substantially affected by factors such as discharge, turbidity or light conditions, making it a potentially effective tool for aquatic ecosystem conservation.

Thanks to this characteristic, acoustic deterrent systems have been deployed at strategic locations such as locks, dams and water-intake channels to prevent biological invasions and protect aquatic ecosystems.

Furthermore, loudspeakers are relatively inexpensive and require less power than electric deterrent systems. In the event of a power failure, they can be operated using small backup generators or batteries. Their lower cost also allows the installation of independent redundant systems, ensuring continued operation if one set of speakers becomes damaged (Murchy *et al.*, 2017).

The hearing range of most fish species overlaps broadly with that of humans, with maximum sensitivity generally occurring below 3 kHz and extending into the infrasonic range (Hawkins, 1981; Sand and Karlsen, 1986). Many fish species exhibit avoidance responses to intense sounds, a characteristic that can be exploited to create effective acoustic barriers preventing fish from entering water-intake structures.

Considerable progress has been made in the field of acoustic guidance, particularly for pelagic species and large water-intake facilities (Turnpenny and O'Keeffe, 2005).

The known hearing range of anguillids (<1–300 Hz; Jerkø *et al.*, 1989) is relatively narrow and substantially lower than that of humans (20–20,000 Hz; Purves *et al.*, 2001), although it is broadly comparable to that of many other fish species. Audiogram measurements have demonstrated that eels are sensitive to frequencies around 90 Hz and to vibrations near 40 Hz (Jerkø *et al.*, 1989).

Between 100 and 300 Hz, direct detection may become more difficult, whereas resonance of the swim bladder induced by sound pressure—functionally analogous to the tympanic membrane of mammals (Popper *et al.*, 2019)—may contribute to sound detection (Jerkø *et al.*, 1989). Unlike some other fish species, however, eels lack specialised anatomical structures that enhance this mechanism, meaning that such secondary signals are likely to attenuate substantially before being detected (Popper *et al.*, 2003; Ladich and Schulz-Mirbach, 2016; Popper and Hawkins, 2018).

Consequently, the frequency range below 100 Hz, including frequencies within the infrasonic spectrum (<20 Hz), may represent the optimal hearing range for anguillids.

Nevertheless, much uncertainty remains regarding these conclusions. Recent evidence suggests that audiogram measurements may not accurately reflect the frequencies that produce the strongest

behavioural responses (Holgate *et al.*, 2023), while additional concerns have been raised regarding the validity of many earlier aquatic audiology studies (Leighton *et al.*, 2020).

Relatively recent experimental studies have observed eels exhibiting the strongest avoidance responses to three low-frequency stimuli (10, 50 and 100 Hz). Among these frequencies, the strongest response was recorded at 10 Hz and the weakest at 100 Hz, supporting the hypothesis that lower frequencies may be more effective for behavioural guidance purposes (EPRI, 2016).

There are, however, cases in which the use of infrasonic sources (12 Hz) proved ineffective. Although the stimulus altered the movement behaviour of European eels, it did not significantly reduce the number of individuals passing through a given opening (Piper *et al.*, 2019).

Historically, both laboratory and field experiments assessing the effectiveness of broadband sound (60–1000 Hz) and low-frequency sound have generally produced poor to moderate results, with reported success rates ranging from 0% to 57% (Sand *et al.*, 2000; Bau *et al.*, 2011; Piper *et al.*, 2019; Deleau *et al.*, 2020a).

Sand *et al.* (2000) demonstrated that eel migration appears to be influenced by ultrasonic sound sources. Advances in acoustic mapping and acoustic telemetry have subsequently enabled more detailed analyses and a more targeted approach to acoustic guidance.

Although infrasound was again shown to be ineffective as a direct deterrent in Piper *et al.* (2019)—reducing the number of passing eels by only 28%—the authors demonstrated that exposed eels exhibited hesitation, erratic movements and required more than twice as much time to traverse the insonified area compared with control individuals.

These findings suggest that infrasound may still have value as a secondary stimulus within a multimodal guidance system (Putland and Mensinger, 2019; Pratt *et al.*, 2021; Piper *et al.*, 2019). This conclusion is consistent with the hypothesis proposed by Versar, Inc. (2009), which suggested an enhancing effect of vibrating moorings within the light-guidance system described by McGrath *et al.* (2003).

To date, infrasound does not appear to have been tested within a truly multimodal experimental framework. However, Deleau *et al.* (2020b) investigated whether either continuous broadband sound (60–1000 Hz) or low-frequency pulsed sound (100 Hz) could improve the guidance of downstream-migrating eels within a channel equipped with a physical vertical-bar barrier and a bypass route.

Responses to the acoustic stimuli were compared with control trials in which the physical barrier remained present but no acoustic signal was emitted. Most eels ultimately reached the bypass under all conditions; however, a greater number of individuals were successfully diverted during the acoustic-treatment trials.

Both acoustic treatments enabled eels to reach the bypass more rapidly than under control conditions, although the 100-Hz pulse generated a stronger effect than broadband sound. It is possible that an even greater effect could be achieved if a similar experiment were conducted using infrasound (EPRI, 2016).

Further investigation of sound as a secondary deterrent is required, although several limitations are already evident. High levels of background noise are common around hydropower facilities, and existing infrastructure at some sites may interfere with the ability of eels to detect acoustic stimuli. Furthermore, particularly shallow or wide rivers may generate complex acoustic fields, especially at lower frequencies (Noatch and Suski, 2012; Pratt *et al.*, 2021).

Nevertheless, if the predominant migration pathways of eels at a given site could be identified in advance, it might be possible to equip only a relatively small portion of the channel with acoustic devices while still influencing a sufficient proportion of downstream-migrating individuals (as suggested by EPRI, 2018).

Additional studies are required to provide detailed quantification of eel responses to both natural and anthropogenic sounds, particularly across different sites characterised by well-defined soundscapes (Popper *et al.*, 2020).

Available evidence also indicates that multimodal approaches may be even more effective. The combination of acoustic and visual stimuli has been shown to elicit stronger anti-predator responses than either stimulus applied independently (Lucas *et al.*, 2021).

3.4.2.7 LIGHT DETERRENTS

Visual signals provided by light barriers, whether through targeted lighting patterns, threatening silhouettes or high-contrast optical cues, represent powerful tools for influencing fish behaviour. Such stimuli may independently elicit pronounced anti-predator or exploratory responses.

It is important to note that visual effects are strongly modulated by ambient light conditions, background risk levels and previous predation experience, all of which influence both the intensity and direction of behavioural responses (Cohen-Rengifo *et al.*, 2023; Pereira *et al.*, 2017; Alund *et al.*, 2022).

Substantial preliminary evidence suggests that light may be effectively used to deter or guide eels. Numerous studies on the spatial and temporal ecology of eels describe them as predominantly nocturnal migrants, exhibiting negative phototaxis or generally higher activity levels during darkness or in low-light environments (Smith and Saunders, 1955; Helfman *et al.*, 1983; Vøllestad *et al.*, 1986; Stahl *et al.*, 2023).

Downstream-migrating eels are known to avoid artificial illumination. For example, illumination of a section of a dam resulted in reduced eel captures in fishing nets deployed nearby (Cullen and McCarthy, 2000).

In captive studies, adult silver eels undertaking downstream migration were successfully diverted by fluorescent lighting (Hadderingh *et al.*, 1999) as well as by light-emitting diode (LED) illumination (Elvidge *et al.*, 2018; Vowles and Kemp, 2021).

Table 3-4. Bibliographic references investigating the effectiveness of light-based deterrent systems for European eel (*Anguilla anguilla*) (source: MacLeod, 2025).

	Field		Laboratory/flume	
Sensory modality (*n* studies)	**Published**	**Grey literature**	**Published**	**Grey literature**
Light ($n=11$)	Cullen and McCarthy (2000), Lenihan et al. (2025)	Hadderingh and Smythe (1997), McGrath et al. (2003), Bowen (2014), Kruitwagen (2014), Bruijis and Vriese (2013), EPRI (2024)	Hadderingh et al. (1999), Elvidge et al. (2018), Vowles and Kemp (2021)	
Sound ($n=6$)	Piper et al. (2019), Deleau et al. (2020a)	Sand et al. (2000), Bau et al. (2011)	Deleau et al. (2020b)	EPRI (2016)
Hydrodynamics ($n=4$)	Piper et al. (2015), Vowles et al. (2025)		Hadderingh et al. (1999)	EPRI (2016)
Electric fields ($n=4$)	Hadderingh and Jansen (1990)	Versar, Inc (2009) (review; describes studies within), Life4Fish (2020)	Miller et al. (2021)	

Light, and more recently LED technology in particular, has in several cases been considered effective for guiding adult downstream-migrating eels at hydropower infrastructures (Hadderingh and Smythe, 1997; Bowen, 2014; Kruitwagen, 2014). However, the same systems have proven ineffective for other fish species despite using identical equipment (Bruijs and Vriese, 2013).

In one notable example, submerged halogen lamps installed in the St. Lawrence River (North America) were designed to create a "wall of light" (McGrath *et al.*, 2003). Although the system produced substantial deterrent effects, significant problems related to debris accumulation and maintenance ultimately discouraged its further application. Moreover, because the device itself constituted a physical obstacle, eels avoided the structure even during control nights when the lights were switched off.

The specific contribution of light beyond these hydrodynamic and physical barrier effects was not clearly quantified, as the results were based primarily on visual observations. Furthermore, the complete results of several studies (e.g. Hadderingh and Smythe, 1997; Kruitwagen, 2014; Bruijs and Vriese, 2013; Bowen, 2014) are not publicly available.

Nevertheless, it has been suggested that the failure of some light-guidance systems may be attributable to site-specific factors, including channel morphology, water turbidity, environmental variables such as turbulence and background noise, and suboptimal positioning of the light sources (Bruijs and Vriese, 2013).

A second study conducted upstream of the Iroquois water-control dam, at the same site investigated by McGrath *et al.* (2003), employed acoustic telemetry to describe in situ behavioural responses in greater detail than previous field studies (EPRI, 2024).

In this case, an above-water light-guidance structure equipped with downward-facing white LED lights was installed upstream of the dam at an angle of 30° relative to the river axis. The system was designed to divert eels horizontally towards one side of the river, where they could be collected and transported downstream. The configuration was based on previous telemetry studies that had identified the principal migratory pathways used by downstream-migrating eels.

The eels swam in close proximity to the illuminated guidance structure without being diverted as intended. However, compared with control individuals, they exhibited reduced swimming speeds and tended to dive deeper in the water column (EPRI, 2024; Piper *et al.*, 2017).

These findings suggest that underwater illumination may be more effective than above-water lighting and, more generally, highlight the importance of device configuration in achieving the desired behavioural response.

The objectives of applying light stimuli are essentially twofold:

- To illuminate physical or behavioural barriers, making them more visible to fish;
- To provide either a deterrent or an attraction effect.

Research into the use of light as a fish deterrent began in the 1950s. Brett and MacKinnon (1953) demonstrated that responses to light stimuli are highly species-specific and that intermittent lighting (or flashing lights) generally elicits stronger behavioural reactions in fish.

Most fish impingement against barriers and entrainment into water intakes occurs during nighttime. The appropriate placement of light sources near physical barriers can significantly reduce, or even completely eliminate, fish impingement and entrainment into water intakes. The effectiveness of light-based deterrent systems has been reported to reach 100% for species such as European perch and ruffe (Hadderingh, 1982).

To minimise light pollution while maximising effectiveness, the light source should ideally be submerged, although this entails additional maintenance and cleaning requirements. In most applications, lights are arranged in an arc along the riverbed near the intake structure, at a sufficient distance to allow approaching

fish to detect the stimulus, alter their swimming trajectory, and move away from the hazardous area (Turnpenny, 1998).

The orientation of the light beam is equally important. An angle of 40–45° relative to the horizontal plane has been recommended as optimal (Johnson *et al.*, 2001).

Light barriers are generally most effective when integrated into a multimodal guidance system designed to maximise deterrence and minimise habituation, particularly for species that rely on multiple sensory cues for threat assessment (Cohen-Rengifo *et al.*, 2023; Alund *et al.*, 2022).

CONTINUOUS LIGHTING

Although continuous lighting is not considered the most effective deterrent method for many fish species, it appears to be particularly effective for eels, and its use has been extensively tested in the Netherlands (Hadderingh and Smythe, 1997). Eels exhibit strong phototactic and positive rheotactic behaviour; therefore, light can be used to discourage them from following the flow of water entering a hydropower intake.

The light source may consist of incandescent, mercury-vapour or fluorescent lamps.

Experimental studies have generally employed fluorescent lamps (36 W, Philips PL-L, spectrum with peaks at 440, 550 and 610 nm), achieving deterrence efficiencies of up to 74% at hydropower facilities..

INTERMITTENT LIGHTING

Recently, the first published field study using broad-spectrum white stroboscopic LEDs reported an 80% deflection rate of downstream-migrating eels in the River Shannon (Lenihan *et al.*, 2025). The lights were installed underwater, spaced 1.08 m apart and positioned at a 45° angle to the river axis. Eels that were not deflected were generally smaller than those that were, suggesting that larger eels were better able to alter their migratory trajectory to avoid the light array (Lenihan *et al.*, 2025). As also observed by McGrath *et al.* (2003), the authors noted that the strong behavioural response was probably the result of a combination of the eel's negative phototaxis and the hydrodynamic and physical effects associated with the lighting support structure.

Lenihan *et al.* (2025) investigated the effectiveness of an intermittent lighting system (broad-spectrum white LEDs emitting between 425 and 725 nm) as a guidance barrier for eels during downstream migration, with the aim of reducing mortality associated with anthropogenic barriers such as dams.

The results demonstrated that intermittent lighting effectively redirected eels towards safer migration routes, confirming previous findings regarding the influence of light on other eel species (Elvidge *et al.*, 2018).

Experimental observations clearly showed a strong negative phototactic response when the intermittent lighting system was activated. The system proved highly effective, successfully diverting 80.6% of the monitored individuals.

A significant difference in eel size was also observed: individuals captured during test nights were generally smaller than those captured during control nights. This finding suggests that smaller eels may have a reduced ability to avoid illuminated areas, whereas larger individuals appear more capable of detecting and circumventing the light field (Lenihan *et al.*, 2025).

Patrick *et al.* (1982) tested stroboscopic lights as a deterrent for eels near the intake of a non-operational turbine. In a subsequent study, Patrick *et al.* (2001) used stroboscopic lighting within a fish passage facility. In both cases, eel movements were reduced by 65–92%. In the latter study, flashing frequencies ranging from 66 to 1,090 flashes per minute were tested, consistently producing positive deterrent effects.

Stroboscopic lighting may be even more effective when combined with other behavioural or physical deterrent systems. For example, the combination of a bubble curtain and stroboscopic lighting has proven particularly effective for species such as Alewife (*Alosa pseudoharengus*), Rainbow Smelt (*Osmerus mordax*) and Gizzard Shad (*Dorosoma cepedianum*) (Patrick *et al.*, 1985), although this approach has never been tested on eels.

Although stroboscopic lights are generally considered to be more effective in highly transparent waters (Turnpenny and O'Keeffe, 2005), the experiment conducted by McIninch and Hocutt (1987) reported an increase in deterrence efficiency with increasing turbidity, ranging from clear water conditions to 39–45 and 102–138 NTU. This phenomenon is probably attributable to the refraction of light by suspended particles, creating a more visible illuminated zone that is easier for fish to detect.

Elvidge *et al.* (2018) also investigated the effects of colour and strobe frequency. Blue LED light (480 nm) elicited the strongest avoidance response, consistent with the ontogenetic shift in retinal photoreceptor sensitivity observed in eels (Pankhurst and Lythgoe, 1983), followed by full-spectrum white light. In both cases, stroboscopic illumination (30 Hz) proved more effective than flashing light at 1 Hz.

Elvidge *et al.* (2018) therefore suggested that these colours and settings should be prioritised in future field evaluations of light-based deterrent systems. Field trials have often reported promising results, although most of the available evidence remains within the grey literature (Hadderingh and Smythe, 1997; McGrath *et al.*, 2003; Kruitwagen, 2014; Bruijis and Vriese, 2013; Bowen, 2014).

Recommended installation practices include:

- selecting target environments where water turbidity is not excessively high;
- mounting lamps on sliding mechanisms to facilitate cleaning and maintenance;
- conducting appropriate trials to optimise flash frequency, as unsuitable flashing rates may attract fish rather than repel them and may also pose risks to human health; consequently, a flashing rate below 240 flashes per minute is generally considered safe;
- activating the lights only when required, to minimise energy consumption and reduce the likelihood of equipment failure;
- installing monitoring systems capable of detecting and promptly reporting lighting malfunctions.

Light-based deterrent techniques are particularly suitable where large volumes of water must be diverted without significant head differences, such as at thermal power station intakes. These techniques are especially effective when combined with other deterrent systems, whether behavioural or physical, and ongoing advances in stroboscopic lighting technology are delivering increasingly promising performance in terms of reliability and operational lifespan.

For eels, effective behavioural barriers have been developed using fluorescent lamps. When positioned underwater near the obstacle to be avoided, these systems have been shown to divert more than 65% of the individuals tested towards darker areas, influencing migratory trajectories far more strongly than flow velocity, which is normally the primary factor governing swimming routes in natural environments (Hadderingh *et al.*, 1999).

The currently available evidence is therefore cautiously encouraging. However, relatively few peer-reviewed field studies exist, while the methods and outcomes reported across the broader evidence base

remain highly variable and, in some cases, difficult to access. The most promising results appear to be achieved through a multimodal approach, combining light with physical barriers, as demonstrated by Lenihan *et al.* (2025) and McGrath *et al.* (2003).

3.4.2.8 Specific Technical Recommendations for the Implementation of LED Behavioural Barriers

Recent attempts to use LEDs as a light source appear considerably more promising than earlier approaches. Modern LED systems may also incorporate anti-biofouling UV diodes to reduce maintenance and cleaning requirements. They can be programmed to operate either continuously or in flashing mode, thereby improving visibility and potentially reducing habituation by fish (EPRI, 2018a).

The use of LED lighting allows easy programming of light intensity, flashing frequency and wavelength, potentially enabling the selection of highly effective deterrent combinations, even in real time. The most advanced systems are equipped with variable-cycle programming capabilities.

Adult eels undertaking their spawning migration have shown particular sensitivity to blue (480 nm) and green (520 nm) light (Pankhurst & Lythgoe, 1983), with sensitivity to blue wavelengths increasing with sexual maturation (Carlisle & Denton, 1959). Under dark conditions, eel retinal cells are most sensitive to wavelengths around 520 nm, whereas under illuminated conditions sensitivity shifts towards longer wavelengths, such as 550 nm (Gordon *et al.*, 1978).

Stroboscopic lighting has proven to be an effective deterrent for eels (Kruitwagen, 2014), although only white and red lights were evaluated in that study, with the latter proving ineffective.

An experimental system developed by Elvidge (2018) consisted of 162 LED modules capable of producing red, green and blue light at variable intensities and frequencies of up to 40 Hz, allowing approximately 16 million different colour and intensity combinations (ATET-Tech, www.atet-tech.com). The system was programmed to emit blue light (480 nm), yellow light (550 nm), and full-spectrum white light, operating either at 1 Hz or 30 Hz flashing frequencies. Eels exhibited the strongest avoidance response to blue light flashing at 30 Hz.

LED lighting systems are less expensive than xenon-based systems and can incorporate anti-biofouling diodes, making them less demanding in terms of maintenance. They can operate continuously or intermittently and can be flexibly programmed to reduce habituation or minimise impacts on non-target species. Furthermore, LEDs have a substantially longer operational lifespan than alternative light sources, such as mercury-vapour or incandescent lamps, which were commonly used in earlier field trials (EPRI, 2017).

State of the Art and Future Perspectives of Behavioural Deterrents

Fish rarely rely on a single sensory modality; rather, they integrate and process information from multiple sensory systems within the constraints imposed by local hydraulic conditions. Mechanosensory input, detected through the lateral line system, governs responses to flow changes, barriers and bypass structures (Mussen and Cech, 2018). The combination of mechanosensory and acoustic stimuli often enhances deterrence effectiveness (Jesus *et al.*, 2021). Because behavioural responses are highly context- and species-dependent, multimodal approaches are generally more effective at reducing access to sensitive areas (Jesus *et al.*, 2021; Pereira *et al.*, 2017).

In the early 2000s, the use of a single behavioural barrier alone was generally considered insufficient to prevent fish passage through turbines, and it was recommended that such systems be combined either with physical barriers (ATV-DVWK, 2005) or with additional behavioural deterrents. For example, Taylor *et al.* (2003) reported an effectiveness of 53% for a standalone electric barrier, increasing to 84% when combined with an acoustic barrier.

According to recent reviews (MacLeod, 2025; Nicula and Lungulescu, 2025), no effective and practical deterrent method based on a single sensory modality has yet been developed. Multimodal approaches combining visual and acoustic stimuli currently appear to be the most promising (e.g. McGrath *et al.*, 2003; Deleau *et al.*, 2020b; Lenihan *et al.*, 2025).

The development of behavioural deterrent systems must account for substantial inter- and intra-specific variability driven by multiple factors, including sex, maturation stage and behavioural state (Putland and Mensinger, 2019; Elmer *et al.*, 2021).

Hydroacoustic stimuli and substrate-borne signals, particularly particle motion and sound pressure, may further modify movement patterns and deterrent effectiveness (Lukas *et al.*, 2021; Thomsen *et al.*, 2022). Because all these cues are filtered by the hydraulic context (velocity gradients, turbulence and recirculation zones), linking behaviour to flow conditions requires dedicated experimental studies and modelling approaches. Recent research has begun to formalise downstream migration triggers under hydraulic conditions comparable to those occurring within water intake structures (Roth *et al.*, 2024) and has demonstrated why the integration of tracking technologies with three-dimensional numerical modelling is essential for effective system design (Machiels *et al.*, 2019).

Engineered stimuli have been shown to influence fish shoal movements (Bonnet *et al.*, 2018), but how these concepts can be successfully transferred to real-world conditions and hydropower intakes remains uncertain. This highlights the need for field-tested devices capable of maintaining their effectiveness across multiple species and flow conditions (Beck *et al.*, 2020). Evidence suggesting that visual illusions and habitat-related stimuli may be exploited (Paxton and Smith, 2018) must also be validated under dynamic environmental conditions (e.g. variable light regimes, turbidity and diel cycles) to avoid overestimating laboratory performance (de Bie *et al.*, 2021; Jones and Hale, 2020; Paxton and Smith, 2018).

Behavioural uncertainty is further amplified by inter- and intra-specific differences in learning ability, memory and responses to novel structures. Captive experiments have shown that species differ in how rapidly they learn to avoid or utilise new microhabitats and visual cues, implying that guidance effectiveness may change over time as fish gain experience (Arsin *et al.*, 2018).

A widely accepted trait-based decision framework capable of systematically matching guidance solutions to the dominant species present at a site, while also accounting for variability within species, is still lacking (Silva *et al.*, 2017; Jones and Hale, 2020; Luiz *et al.*, 2019). Another major knowledge gap concerns long-term durability. While immediate responses to light, flow manipulation and visual stimuli are often documented, far less is known about how these responses persist across repeated encounters, seasons or life stages, despite the obvious implications for long-term system performance (Beck *et al.*, 2020; Roth *et al.*, 2024).

Overall, predicting how multisensory guidance systems will perform across different species and environments remains challenging, limiting the development of reliable and broadly applicable designs.

Addressing these challenges will require a comprehensive framework that explicitly incorporates learning, memory, ontogenetic development and social behaviour, and that is tested under real-world conditions across a wide range of species and hydraulic settings (Putland and Mensinger, 2019; Wu *et al.*, 2024; Mensch *et al.*, 2022).

There is a clear need for harmonised protocols capable of quantifying behavioural responses, such as approach rates, bypass acceptance and hesitation time, under comparable hydrodynamic conditions and across different species (Mussen and Cech, 2018; Arsin *et al.*, 2018). In the absence of such standards, comparisons among sites and devices remain largely qualitative, slowing knowledge synthesis and policy transfer. Telemetry and tagging technologies can reveal detailed movement patterns and behavioural triggers in the vicinity of deterrent systems, but their application remains uneven and analytical approaches differ among studies, making it difficult to establish a coherent evidence base.

Passive acoustic tracking offers a promising method for estimating fish movements over larger spatial scales; however, field applications require careful calibration, adequate receiver density and standardised workflows capable of linking high-resolution movement trajectories to device-specific performance metrics across different river systems (Mouy *et al.*, 2017; Crossin *et al.*, 2017).

Stress and animal welfare represent another area that remains poorly understood. Acute and chronic stress associated with capture, handling, confinement and exposure to artificial structures can alter fish behaviour and consequently influence guidance outcomes. Depending on the context, stress may increase avoidance of deterrent systems or, conversely, lead to maladaptive behaviours. Animal welfare should therefore be regarded as a key behavioural factor requiring evaluation through both field testing and long-term monitoring (Arsin *et al.*, 2018). Water quality, physiological stress responses and environmental conditions more generally all influence fish behaviour.

Research on fish welfare has also shown that species-specific risk profiles affect responses to captivity and handling, highlighting the importance of integrating welfare considerations into system design. Structures that minimise stress are more likely to elicit predictable behaviours and achieve greater acceptance of prescribed migration routes (Saraiva *et al.*, 2019).

In conclusion, electric fields represent a considerable risk for endangered species migrating downstream with the current. However, these systems could potentially be configured differently to provide softer guidance of swimming trajectories, either as deterrents under very low-flow conditions (Life4Fish, 2020; Miller *et al.*, 2021) or as tools for fish collection and downstream transport following successful diversion.

The addition of acoustic or light-based stimuli to existing physical barriers may offer a cost-effective solution compared with the potential benefits obtained, particularly in retrofit applications. Such measures may deliver immediate marginal improvements in passage efficiency, which, when applied at larger scales, could result in substantial overall gains (Miller *et al.*, 2022).

Overall, deterrence appears to be a more achievable—and perhaps more realistic—management objective than attraction.

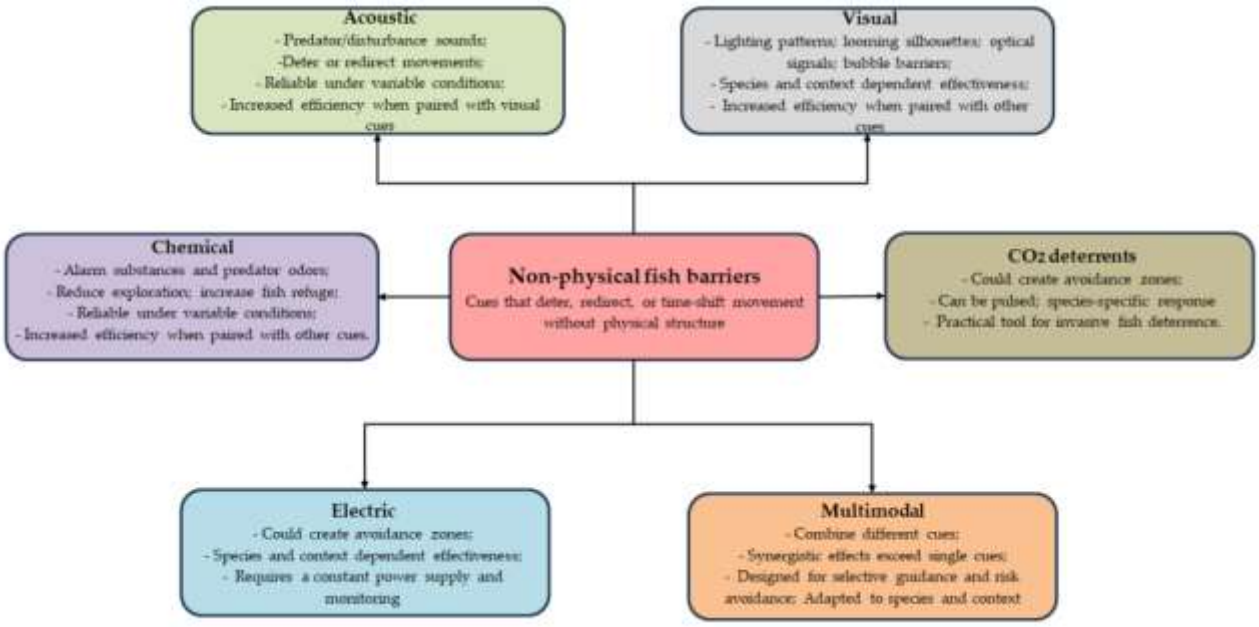


Figure 3-6. Characteristics of the main behavioural deterrent systems (source: Nicula and Lungulescu, 2025).

The considerations presented above are generally applicable to all fish species, including eels. However, eels represent a particularly challenging taxon in the context of fish passage facilities, which is one of the reasons why anguillid populations are globally endangered.

The diagram presented below summarises the potential applications and the most significant considerations associated with the principal behavioural stimuli—and therefore the corresponding deterrent systems—for downstream eel migration.

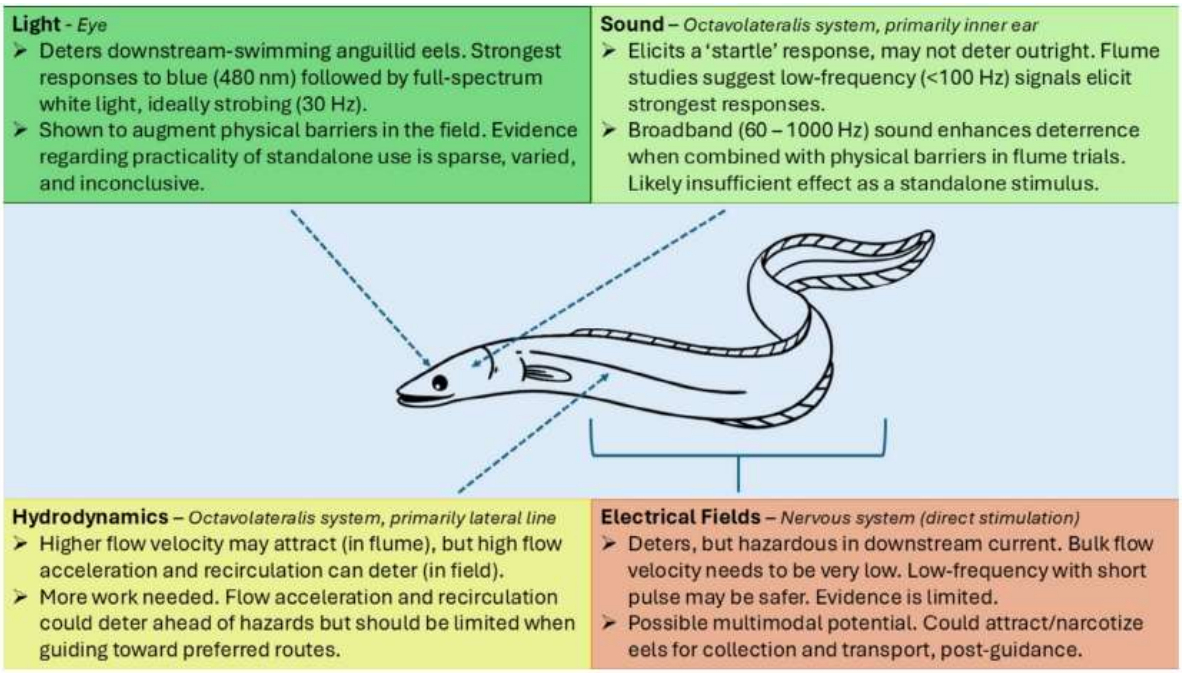


Figure 3-7. Schematic feasibility diagram of the use of different stimuli as deterrents for downstream-migrating eels (source: MacLeod, 2025).

3.5 Conclusions and recommendations

The literature reviewed clearly indicates that no universally effective deterrent currently exists for downstream-migrating eels. Fish responses are strongly influenced by local hydraulic conditions, environmental context, individual behavioural variability, life stage, motivational state and species-specific sensory ecology. Consequently, successful mitigation measures must be designed on a site-specific basis and supported by detailed monitoring of fish behaviour and flow conditions (Noatch and Suski, 2012).

Baseline monitoring provides a fundamental understanding of how fish naturally move through a site. Identifying preferred downstream migration routes may reveal that the required range of influence of a deterrent is smaller than initially expected (EPRI, 2024). Furthermore, these natural movement patterns can be compared with experimental data to isolate the effect of the deterrent itself and determine whether the structure exerts a significant hydraulic influence on fish behaviour.

In situ monitoring enables detailed observation of fish behaviour in the field rather than relying solely on post hoc outcomes. This approach has been adopted in many of the recent studies discussed herein (Noatch and Suski, 2012; EPRI, 2018, 2024; Piper *et al.*, 2013, 2015, 2017, 2019). Tracking wild fish also makes it possible to identify peak migration periods, providing information that is highly relevant from a management perspective, allowing cost-effectiveness to be maximized by restricting deterrent operation to critical periods while minimizing impacts on non-target species.

The effectiveness of deterrent systems depends on how fish perceive and interpret their surrounding environment. Vision and other sensory systems, flow conditions, microhabitat cues, stress levels, learning processes and decision-making mechanisms are all species-specific factors. Despite considerable progress, several key limitations still affect the reliability and transferability of results obtained from both physical and behavioural deterrent systems. These knowledge gaps concern sensory and behavioural ecology, hydraulic and structural constraints, monitoring approaches, the selection of performance metrics (including welfare indicators), governance issues and knowledge transfer.

Particularly important is the interaction between deterrent stimuli and local hydraulic conditions. Flow velocity, turbulence, recirculation zones and hydraulic gradients can amplify, mask or even reverse behavioural responses. As a result, deterrents that perform effectively at one site may prove ineffective elsewhere, even when the same species and technology are involved. Understanding these interactions remains one of the main challenges in the development of reliable fish-guidance systems.

For this reason, increasing attention is being devoted to multimodal guidance systems combining physical, hydraulic, visual and acoustic stimuli. Current evidence suggests that integrated approaches are generally more effective than single-stimulus systems, while also providing greater flexibility under varying environmental conditions. The combination of multiple sensory cues more closely reflects the way fish naturally perceive their environment and may reduce habituation while increasing overall deterrence efficiency.

Among behavioural deterrents, light-based systems currently appear to offer one of the most promising solutions for the protection of downstream-migrating silver eels. A substantial body of evidence indicates that eels exhibit a pronounced negative phototactic response during downstream migration and that artificial illumination can significantly alter their movement trajectories, delay passage, or divert individuals away from hazardous areas. Recent studies employing LED technology, particularly blue-spectrum and stroboscopic lighting systems, have reported encouraging results under both experimental and field conditions.

Light, sound and electricity each present unique advantages and limitations for behavioural guidance. High turbidity can attenuate light transmission and reduce the distance at which fish perceive visual stimuli (Hamel *et al.*, 2008; Putland and Mensinger, 2019). Sound does not suffer from this limitation, but very wide or shallow channels may generate acoustic fields that are unsuitable for effective guidance (Noatch and Suski, 2012; Pratt *et al.*, 2021). Electrical deterrents can induce strong behavioural responses but may also cause injury, physiological stress, tetany or delayed mortality, particularly when applied to downstream-migrating fish moving with the current. Furthermore, their effectiveness depends strongly on hydraulic conditions, fish size and species-specific sensitivity.

Overall, currently available evidence suggests that no single behavioural stimulus can provide a universally effective deterrent under all environmental conditions. Nevertheless, among the individual stimuli investigated to date, light-based deterrents appear to provide one of the best compromises between efficacy, operational simplicity, safety for fish, ease of retrofitting and practical applicability at existing hydropower facilities.

From an operational perspective, light-based systems offer several advantages. They can be integrated into existing infrastructures with limited civil engineering requirements, do not expose fish to the risks associated with electrical fields, can be activated only during migration periods, and generally involve lower maintenance requirements than many physical barriers. The rapid technological development of LED systems further increases their attractiveness by allowing precise control of wavelength, intensity, flashing frequency and operating schedules.

It was within this scientific framework that the LIFEEL project selected a LED-based behavioural deterrent as the focus of its experimental activities. This choice was supported by the growing body of scientific evidence available at the time of project design, indicating that light represented one of the most mature, scalable and environmentally sustainable behavioural guidance technologies for downstream-migrating eels. The objective was not only to verify its effectiveness under real operating conditions, but also to assess its feasibility as a transferable mitigation measure applicable to hydropower facilities throughout the Po River basin and potentially across other European river systems affected by eel migration barriers.

Further research is still needed to develop multispecies syntheses of light preferences and adaptation mechanisms, to better understand how visual stimuli interact with other sensory modalities, and to establish quantitative design criteria capable of maintaining effectiveness under varying turbidity conditions, residence times and diel cycles. Field validation linking behavioural responses to deterrent performance remains essential (Tetard *et al.*, 2019; Jesus *et al.*, 2021; Keep *et al.*, 2021; Lin *et al.*, 2019; Crawford *et al.*, 2024; Nyqvist *et al.*, 2024).

Moreover, terminology and monitoring protocols should be standardized to facilitate quantitative comparisons among studies (Popper *et al.*, 2020). Common shortcomings include insufficient reporting of contextual data, inadequate descriptions of behavioural responses, misrepresentation of response magnitude, poor stimulus characterization and the use of inappropriate performance metrics (Putland and Mensinger, 2019; Popper *et al.*, 2020).

From a practical perspective, deterrent systems offer the advantage of being less permanent than structural modifications and can be temporarily deactivated or remotely controlled to coincide with peak migration periods. Such flexibility allows managers to optimize conservation outcomes while minimizing operational constraints and costs.

In conclusion, behavioural deterrence appears more readily achievable, and often more realistic, than attraction as a management strategy for downstream-migrating eels. While no single solution can yet be

considered universally effective, recent advances in LED-based systems, combined with their operational flexibility, relatively low environmental impact and compatibility with existing infrastructures, justify continued research and large-scale field validation. At the same time, the evidence reviewed highlights that future progress will likely depend on the development of site-specific and increasingly multimodal guidance systems capable of integrating fish behaviour, sensory ecology and hydraulic engineering into a coherent management framework. The results obtained within LIFEEL contribute to this growing body of knowledge and provide a valuable basis for future applications aimed at reducing turbine-related mortality and restoring ecological connectivity for the European eel.

Table 3-5. Comparison of the main advantages and disadvantages of physical and behavioural deterrent systems (source: Nicula and Lungulescu, 2025).

Table 1. Main advantages of physical vs non-physical fish barriers.

Aspect	Physical barriers	Non-physical barriers
Structural permanence	Long-term, fixed infrastructure with continuous operation and high reliability once installed [1,7].	Typically, less permanent; performance depends on equipment and power supply.
Species coverage/selectivity	Can simultaneously guide many species and life stages when appropriately designed [1,7].	Stimuli can be tuned for target taxa or life stages, allowing more selective guidance [17].
Hydraulics and infrastructure integration	Modern designs maintain low head losses and integrate well into hydropower intakes [1].	Can be retrofitted to existing dams/intakes with minimal structural modification [6,7].
Environmental impact on flow	Can be optimized to limit additional hydraulic disturbance, though still alter morphology locally [1].	Do not block flow; preserve natural hydraulic regimes and reduce fragmentation relative to dams [7].
Operational predictability/adaptability	Performance governed by well-understood hydraulic/mechanical relations (bar spacing, velocity, angle) enabling predictable design [8].	High flexibility: stimulus parameters (frequency, intensity, wavelength) can be adjusted adaptively in response to monitoring [17].
Capital investment and structural requirements	High initial civil works and integration costs, but potentially low operational complexity once optimized [7,8].	Lower permanent infrastructure and site alteration; often lower upfront cost and easier deployment in resource-limited settings [6].

Table 2. Main disadvantages of physical vs non-physical fish guidance barriers.

Aspect	Physical barriers	Non-physical barriers
Injury/welfare risks	Screens and racks can cause impingement, abrasion and entrainment if poorly designed or operated [8].	Generally, avoid mechanical injury, but some electric systems can harm non-target organisms [18].
Migratory delay/behavioral disruption	Turbulence and high velocities near racks and bypasses may delay migration and disrupt timing [8].	Strong deterrent fields may redirect fish into suboptimal areas if not carefully configured [19].
Flow alteration and navigation	Gravity dams and similar structures obstruct flow, alter sediment transport and hinder navigation [7].	Do not obstruct flow, but effectiveness can be constrained where hydrodynamic cues dominate behavior [17].
Maintenance and monitoring	Require debris management, inspection and structural maintenance, especially in complex configurations [7].	Depend on continuous functioning of electronics, cabling and power; require calibration and protection from fouling/damage [18].
Consistency/species specificity	Typically provide relatively consistent mechanical guidance across species when dimensioned correctly [1].	Effectiveness is strongly species- and context-dependent; no single modality works reliably across taxa [6,20].
Environmental context dependence	Performance mainly affected by hydraulics and debris rather than sensory background [7].	Strongly influenced by ambient noise, light and turbidity, which can mask deterrent stimuli [17,19].
Habituation and long-term efficacy	Structural effect does not decline through habituation [8].	Fish can habituate to repeated stimuli, reducing deterrent effect over time [6,9].
Non-target/ecosystem effects	Large structures can drive broad habitat and community changes via hydromorphological alteration [7].	Acoustic/electric systems may interfere with communication and orientation of non-target species [6,19].
Invasive species management	Often form the primary, robust control for invasive species where full physical exclusion is feasible [7].	Efficacy for invasive species is variable and context-dependent; some taxa show weak or inconsistent responses [20].

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