White Paper

Hydropower & Biodiversity

Enabling Fish Mobility at Hydropower Plants

ETIP HYDROPOWER

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Intended Purpose: The present White Paper is intended to provide European decision-makers with background information on key issues that are and will be discussed in pending and upcoming EU and national legislation processes relevant to hydropower development. These are, among others, the methodology for the establishment of free-flowing rivers and updates on ecological flows under the process of the Common Implementation Strategy (CIS) under the Water Framework Directive (WFD), as well as the implementation of the revised Renewable Energy Directive (RED III) and the Nature Restoration Regulation (NRR).

Hydropower plays a key role for the EU goal to decarbonize Europe's energy systems providing renewable electricity and increasingly important flexibility services. This paper shows how hydropower can contribute to the achievement of EU environmental goals. It is part of a series of three papers on environmental topics; the other topics are E-Flows/Hydropower Peaking and Sediment Dynamics.

Executive Summary

Modern European River management balances hydropower generation, navigation, agriculture and tourism with fish migration requirements, sediment dynamics and instream flows. Effective fish passage solutions are essential to maintain the health of the river ecosystem while meeting the power system needs. The European regulatory frameworks driving fish passage implementation include the Water Framework Directive, Habitats Directive, Eel Regulation, and Nature Restoration Regulation, collectively requiring good ecological status/potential, habitat conservation, species protection, and river restoration.

Fish passage solutions must be tailored to each hydropower facility's unique characteristics and target species' specific requirements. Upstream, and in some cases, downstream migration solutions include nature-like fishways mimicking natural river courses, technical fishways with controlled flow conditions, and mechanical fish lifts. Downstream migration solutions encompass physical barriers such as screens and racks, behavioural guidance systems using sensory stimuli, collection and bypass systems, and fish-friendly turbine designs. To further optimise effectiveness, EU and national research programmes should support comparative studies of potential solutions, establish clear biological and hydraulic performance criteria, and implement long-term monitoring programmes.

Three priority areas require attention across Europe: (1) testing new and improved fish passage monitoring technologies (e.g. passive integrated transponders, camera and sonar-based fish detection coupled with machine learning for fish detection, species and size classification) with native fish species through streamlined approval processes for live animal studies; (2) developing standardised, science-based fish protection implementation guidelines for national and local authorities that enable a rapid and reliable cross-comparison between sites and watersheds and that support the transposition of EU legislation; and (3) investing in research and development to create advanced digitalised monitoring systems and computational modelling to enhance automated regulatory compliance reporting.

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Why is fish passage at hydropower plants needed?

Modern river management faces considerable challenges to address Europe's complex cultural landscape with the urgent need to support freshwater fish migration for multiple species and life stages [1]. The hydropower community is committed to maintain electricity generation and facilitate fish migration, while facing uncertain energy production and distribution scenarios, increasing urbanisation, and the increased challenges to fish posed by climate change [2]. Ensuring fish migration is therefore crucial to maintain and improve the quality of river ecosystems today and in the future [3].

Fish passage at hydropower plants encompasses hydrology, operating conditions, infra-structure and physical systems designed to enable safe fish migration considering upstream and downstream as required, through dams, turbines and hydraulic structures, including fishways, bypass channels, screens, and fish lifts that aid in maintaining river connectivity.

The need for fish passage at hydropower plants in Europe is primarily driven by legislative requirements and environmental protection goals. The EU Water Framework Directive (2000/60/EC) serves as the cornerstone of this regulatory framework, requiring all Member states to achieve "good ecological status" of natural water bodies and "good ecological potential" of heavily modified water bodies, respectively, which explicitly includes river continuity and fish migration. The Habitats Directive (92/43/EEC) focusses on the conservation of natural habitats and wild fauna and flora, including the protection of migratory fish species. The Eel Regulation (Council Regulation (EC) No 1100/2007) is specifically aimed at the recovery of European eel stocks and requires EU Member States to develop and implement Eel Management Plans. The EU Nature Restoration Regulation (2024/1991) is also closely related to fish migration, as it includes specific targets to restore 25,000 kilometres of European rivers to their free-flowing conditions by 2030 and may also affect hydropower operations and planning.

Which fish passage solutions exist for hydropower?

A key consideration when applying fish passage solutions is that **each hydropower facility is unique**, **and the biological responses of different fish species across their life stages can vary greatly** [4]. Due to these factors, the best results are typically found when multiple solutions are evaluated and implemented across the watershed [5], [6], [7].

Solutions for fish migration

Fishways are structures which allow upstream migrating fish to bypass hydropower facilities, and their designs vary from nature-like fishways mimicking the local conditions, to vertical slot fishways which are concrete structures with highly controlled flow conditions (Figure 1). In some cases, it is also possible to construct fishways which can facilitate both up- and downstream

migration. Hydraulic guidance systems use increased or augmented water flows to attract and guide fish towards the entrances of fishways, fish lifts, and collection systems.

Figure 1. Left: A large-scale nature-like fishway constructed at the Ruppoldingen run-of-river powerplant in Switzerland. On the right side of the powerhouse, a diversion river was implemented for ensuring fish migration (Source: ATEL). Right: The nature-like fishway at Baierbrunn in southern Germany illustrates how a well-designed structure can be integrated into the cultural landscape, providing native fish of different species and life stages an adequate variety of flow conditions for migration, resting, and shelter. (Source: C. Jähnel / University of Innsbruck)

Nature-like fishways include rough ramps, bed slides, and bypass channels, as illustrated in the Figure 1. These channels, constructed in a manner like natural river courses, meander through a wide expanse, circumvent obstruction and can provide new habitats for multiple species. Challenges can arise because of the large amount of space required and the higher discharges. An alternative form of bypass channel is the pond pass, which consists of a sequence of shallow ponds and tends to imitate small tributaries.

Technical fishways can be divided into basin-type and channel-type fish passes. In the case of basin-type fish passes, the difference in height between the upstream and downstream water is divided into several basins with smaller differences in height. The basins are connected to each other through holes or slot openings. The resulting smaller differences in water level can be overcome by fish. In channel-type fishways, the flow velocity is reduced by means of surface roughness, obstructions, or synthetic bristles, thereby creating passable conditions for fish. Basin and channel-type fishways require less space, can be adapted to fluctuating upstream and downstream water levels, but are associated with higher maintenance costs and do not provide additional habitat.

Fish lifts and elevators are mechanical transport systems that move migratory fish over dams by collecting them in a water-filled hopper at the base of the dam and lifting them to release points above the barrier. These systems are particularly useful at high dams where traditional fish ladders would be impractical, and they have proven especially effective for typical species such as brown trout as well as less common species such as shad and sturgeon, which may struggle with conventional nature-like and technical fishway designs.

Trap and transport for upstream fish migration works by capturing fish below hydropower barriers and relocating them above the obstruction when conventional fishways are not feasible.

Solutions for downstream migration

Physical barriers prevent fish from entering the hydropower turbine and include mesh screens, vertical, horizontal and angled bar racks, as well as floating booms and guidance walls near the intake region.

Behavioural guidance systems may include a variety of stimuli to attract or repel fish, including light, sound, bubbles, dissolved gases, and turbulence. They can be installed at fishways, both natural and technical to improve entrance guidance. These systems require greater knowledge of the species and environmental conditions present at each site and are commonly added to complement more conventional physical barriers such as bar racks. A potential drawback of these systems is that the short- and long-term effectiveness of behavioural guidance systems may undergo change as fish become accustomed to the stimuli.

Collection and bypass systems are used to prevent fish from entering turbine intakes. The collection system usually relies on hydraulic guidance measures, such as bar racks, to direct fish into the downstream bypass, which can range from closed pipes to nature-like channels, which can also be used for upstream fish migration.

Trap and transport is a proven method to move fish across multiple, nearby barriers, using targeted capture and relocation methods including trucks and barges.

Turbines with enhanced fish passage protection can improve downstream fish passage by reducing the blade strike speed and making the blade's leading edges thicker and slanted to reduce the risk of injury and mortality from collisions, as illustrated in the following figure. In most cases, turbine passage mortality is an important consideration in quantifying the overall success of downstream fish passage at hydropower plants. Turbines can be thoughtfully designed or retrofitted by modifying the runners and guide vanes to maximise survival rates of target fish species and life stages that enter and pass through them while maintaining power production at high efficiency.

Figure 2. Computational fluid mechanics models (left) provide engineers with the means to test several different turbine blade configurations and can be modelled to include site-specific features needed for both new and refurbished hydropower sites. Newer blade designs can be first tested as scale physical prototypes (middle), and once their efficiency has proven satisfactory, laboratory or in-situ tests with live fish such as eel (right, highlighted in blue) can be carried out to establish that fish passage has been enhanced. (Sources: J. Foust / Voith, H. Driscoll / Natel)

What are the best practices to evaluate and improve the effectiveness of fish passage solutions?

Conduct a comparative study to optimise on-site

Carrying out a comparative study of fish passage solutions at hydropower plants is essential to identify the most effective method/s for ensuring fish migration, minimizing environmental impact, and enhancing biodiversity. The study should include an overview of the strengths and weaknesses of existing solutions, focusing on site-specific characteristics and constraints. Learning from successful fish passage projects elsewhere can also help to define and refine local strategies. It is highly recommended that practitioners reach out directly to those who have completed successful projects to seek their advice and guidance.

Identify and establish biological and hydraulic performance criteria

Hydraulic and biological Performance criteria need to be species- and life-stage specific and consider downstream and upstream migration separately. For this reason, it is important to first identify the target species for fish passage and consider invasive species as well [8]. It is especially important to consider that the site-specific fishway design parameters and assessment methods often need to include both biological as well as hydraulic performance criteria. Recommended minimum biological criteria are the passage efficiency, period of delay, accumulation of fish and survival rates, and minimum hydraulic criteria are the min/max velocity, min/max discharge, pool turbulence, min depth for the target species, flow vectors, availability and suitability of the entrance discharge conditions for entry into the fishway [9]. Regarding longitudinal connectivity, a barrier with a fishway in a uniform part of the river may not always provide complete fish passage, and therefore such fishways may only partially restore migration for certain species and life stages [10].

Involve regulatory stakeholders early on

For most projects, permitting authorities are the key stakeholders for fish passage projects. Because site-specific requirements are highly differentiated for each hydropower facility, if regulatory requirements are clearly identified and discussed early in the design stage, fewer changes will be needed, substantially reducing the effort and costs required. Considering smaller hydropower plants (e.g. < 10 MW), technical standards for fish migration are often different than from large hydropower sites and thus monitoring activities may be reduced in coordination with permitting authorities.

Implement a long-term monitoring and reporting concept

Long-term continuous monitoring is key, because these data are needed to evaluate the performance criteria, and without them it is not possible to quantify the effectiveness of fish passage solutions, both upstream and downstream [11]. This is data would also be helpful to better understand the effects of climate change on aquatic species.

Common technologies to monitor fish migration are PIT tags, radio telemetry, sonar, and underwater video monitoring to track fish movements as they pass up- and downstream at hydropower facilities. As the long-term monitoring is in the public interest, EU and national funding schemes and programmes should be established.

What is needed to improve fish passage?

New and improved technologies for upstream and downstream passage are being developed and explored for use but remain largely untested at European sites with European native fish species.

Where knowledge gaps exist, European and national and research institutions should build up on earlier EU projects such as FitHydro, HYPOSO and RIBES and develop and evaluate new technologies supporting real-time monitoring at European hydropower installations [12]. In many cases, evaluation using live fish is still necessary to address key knowledge gaps that are species-specific. Consequently, processes should be streamlined for approving live animal testing to improve fish safety in the long term, such as when evaluating innovative new turbines for safe passage for eels, as shown in Figure 2.

Across Europe, fish protection requirements, such as the fish passage efficiencies for fishways and minimum survival requirements for turbines, should be developed using the best available science and be made openly available.

Fish survival and passage efficiency requirements for hydropower operators should be set in a way that is cross-comparable between sites and considers the turbine type, operating heads, discharges, regions, and specific Member state requirements. Monitoring methods and reporting should be carried out using scientifically proven, quantitative measures which are enforceable in the near term, and European research should continue to maximise fish survivability at population level in terms of short- and long-term challenges to maintain river ecosystem health and support resilience.

Conclusions

Although Europe is a world leader in the development of hydropower and fish passage solutions, further research is needed to close the gap in the use of computational fluid dynamics models to create new design concepts. Innovations in automation and digitalisation of fish passage monitoring and reporting have been put into practice. For example, the turbine industry has integrated the latest simulation and sensing technologies to deliver a first-generation of less damaging turbines at low-head European sites. Based on the commitment of European hydropower stakeholders, further research is needed to continue advancing designs that achieve levels of fish protection of aquatic populations higher than the current status. By supporting innovation in the design, monitoring, and reporting landscape, Europe can continue leading the creation of new solutions to improve and streamline environmental regulatory compliance locally and create new value-added solutions for fish passage which can be exported and used abroad.

Key Takeaways

- **Innovation Gap:** Despite Europe's leadership in hydropower and fish passage solutions, there is a significant need for advancements in the practical use of existing computational fluid dynamics models and the automation and digitalisation of fish passage monitoring and reporting.
- **Need for Improved Designs:** The turbine industry has made progress with less harmful turbines, but further advances are crucial to increase fish protection and support sustainable fish populations.
- **Strategic Vision:** Europe requires a long-term vision and coordinated strategy to develop, test, validate and implement effective fish passage and protection technologies, ensuring that hydropower remains a reliable and cost-effective renewable energy source.

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