Recommendations for fish protection and downstream fish migration at hydropower plants in the Rhine river basin

International Commission for the Protection of the Rhine

Technical Report 303

Disclaimer on accessibility

The ICPR strives to make its documents as accessible as possible. For reasons of efficiency, it is not always possible to make all documents in the four language versions completely accessible (for example with alternative texts for all graphics or in easy-to-read language). This report may contain figures and tables. For further clarification, please contact the ICPR secretariat on 0049261-94252-0 or by email to sekretariat@iksr.de.

Publisher:

International Commission for the Protection of the Rhine (ICPR)
Kaiserin-Augusta-Anlagen 15, D-56068 Koblenz
P.O. box: 20 02 53, D-56002 Koblenz
Telephone: +49-(0)261-94252-0
Email: sekretariat@iksr.de
www.iksr.org

Recommendations for fish protection and downstream fish migration at hydropower plants in the Rhine river basin

Table of contents

1. Introduction

1.1 The problem

Barriers to migration like barrages and weirs have many different adverse impacts on the ecological function and passability of watercourses (Vriese 2017). Fish can be harmed during downstream migration, particularly at transverse structures with hydropower plants (ICPR technical report no. 140):

- during passage through turbines:
  a. direct injury caused by the turbine (contact with fixed or moving parts, cuts due to high speeds)
  b. harm caused by shear forces (from fish losing scales to being completely torn apart) and pressure differences (barotraumas, for example damage to the swim bladder and vascular system caused by sudden decompression). Extreme drops in pressure can also lead to particularly dangerous cavitation damage (organ injury caused by implosion of gas bubbles)
- at the intake structure due to being pressed against fixtures (screens or inflow of the cleaning machine)
- when passing through spillways (especially on impact with the water or with obstacles during downstream passage over weirs)
- through secondary effects (indirect mortality resulting from disorientation, increased predation in the turbine tailwater and, if downstream migration is delayed, in the headwater as well)

Moreover, in the case of series-connected hydropower plants, the cumulative effect on migratory fish populations must be taken into consideration (direct and indirect mortality/injury, delayed migrations). This negatively impacts all migratory fish species, but especially affects diadromous long-distance migratory species such as salmon (anadromous) and eel (catadromous). This cumulative effect can be restrictive for species like salmon, if all juvenile salmon of a sub-basin have to negotiate several hydropower plants when migrating downstream. The body length of downstream migrating eels makes them especially vulnerable, and the cumulative mortality rate can be significant if there are several consecutive transverse structures, especially ones used for hydropower.

1.2 Mandate

The 16th Conference of Rhine Ministers in 2020 in Amsterdam requested the ICPR to draw up, by 2024, recommendations for fish protection and downstream migration at hydropower plants. ICPR Programme Rhine 2040 states that the recommendations will serve as the basis for the common setting of goals, depending on technical progress in this area, for sufficient population-preserving fish protection.

Since 2014, the ICPR has been discussing innovative technologies for downstream migration at transverse structures, with a view to reducing fish loss or injury (for example of salmon, eel), including at turbines. As part of these activities, in 2016 an international workshop on downstream fish migration took place in Roermond (NL), and in 2021 a webinar was held on “fish protection and downstream fish migration at large hydropower plants: sharing experiences and knowledge”.

Alongside those events, work was stepped up in the riparian states of the Rhine basin to

- implement fish protection and technologies for downstream migration in order to reduce fish mortality at small and medium-sized hydropower plants (discharge < 150 m^3/s)
- improve research and knowledge for large hydropower plants (discharge > 150 m^3/s) using pilot projects aimed at devising suitable technical solutions; trials of adapted turbine management, for instance during the transition period.

Some states in the Rhine basin already have best available technology for fish protection and downstream fish migration at hydropower plants of a certain size. In many places, transitional measures are being implemented in large hydropower plants. Some countries have already published their own recommendations or rules.

The platform on fish protection and downstream migration (http://forumfischschutz.de/), headed by the German Environment Agency (UBA), drew on the latest knowledge and technology to develop a nationwide uniform understanding of the requirements and solutions that should be taken as a basis for fish protection measures. The findings were published in a number of fact sheets http://forumfischschutz.de/factsheets).

In addition, some federal states in Germany have drawn up special guidelines identifying what fish ecology and fisheries science require for fish protection systems and downstream fishways at hydropower plants. These include Baden-Württemberg's guide to fish protection and fish descent ("Handreichung Fischschutz und Fischabstieg", https://pudi.lubw.de/detailseite/-/publication/89720) and North Rhine-Westphalia's guide to transverse structures ("Handbuch Querbauwerke", https://www.flussgebiete.nrw.de)

France also has a national dimensioning guideline based on empirical data:

- **a guide to dimensioning of fish-compatible intakes for small hydropower plants** (Courret & Larinier 2008)
- **a guide to dimensioning bypasses** (Raynal et al. 2013)
- **a guide on pressure losses** (Raynal et al. 2012)

Good progress was made through the implementation of the EU Eel Regulation, especially the research and development programme on eel-friendly structures, which was introduced in 2011 (https://www.trameverteetbleue.fr/programme-recherche-anguilles-ouvrages). A revised guideline is currently being draw up.

Drawing on national findings and recommendations already available, the ICPR formulated joint recommendations for fish protection and downstream fish migration at hydropower plants for the states of the Rhine river basin.

2. Objectives

The general aim is to protect populations of all migratory fish species in the Rhine system, with a view to the overarching goal of a biocoenosis that is as near-natural as possible. This relates to both diadromous and potamodromous fish species. However, priorities must be set in line with the threat level and habits of a species in the context of downstream migration. It is especially important to protect fish that migrate downstream over long distances, as their reproductive cycle hinges on river passability, and they are increasingly impacted by cumulative effects. For diadromous species such as salmon, sea trout, eel, allis shad, houting, sea lamprey and river lamprey, the particular focus is on the migratory life stages (for example silver eel and smolt). To date, most information on the technical feasibility of measures to promote fish protection and downstream migration has been collected on salmon and eel. These are indicator species representative of other fish species. To replenish eel stocks, the EU Eel Regulation specifies a target escapement of at least 40% of the silver eel biomass migrating from the eel river basin during the reference period. Fish protection measures in eel-frequented waters should be geared to this target.

3. Recommendations

3.1 General recommendations

Given their various adverse impacts on the ecological function and passability of watercourses and accessibility of remaining spawning grounds and juvenile fish habitats, the goal, wherever effects and uses allow, is to dismantle thresholds and weirs in tributaries and secondary waters of the Rhine, in line with the objectives of the Water Framework Directive. This will make it possible to restore functional habitats and reduce fish mortality during downstream fish migration (ICPR programme Rhine 2040). The restoration of free-flowing river stretches is also a key goal of the EU Nature Restoration Law that entered into force in 2024, the EU Biodiversity Strategy adopted in 2020 and the EU Eel Regulation for reducing eel mortality caused by hydropower plants.

If dismantling is not possible, obstacles to upstream and downstream migration must be equipped with well-functioning migration aids.

The construction of new obstacles to migration should not be permitted, especially in the programme waters of the Master Plan Migratory Fish (ICPR Technical Report no. 247); ICPR programme Rhine 2040.

The following recommendations apply to fish protection and downstream fish migration at existing hydropower plants, irrespective of the discharge at a site.

1) The following must be taken into consideration when determining the most suitable measures or combination of measures for a specific site:

- geographic location of the plant (for example, position in the river basin, features of the river)
- function and associated operational management of the plant
- design and position of potential downstream fish migration corridors
- hydraulic conditions (for example, flow structures and flow velocities in the inflow area of the river and near the hydropower plant)
- relevant laws and regulations

in addition,

- target fish species must be identified according to the fish fauna defined as the potential natural reference fish fauna, taking into account biological aspects such as seasonal presence or migration periods, behaviour, capabilities, age and size.

An evaluation of these factors enables minimum requirements and criteria to be derived that the measure must fulfill. Using these criteria, a measure can then be selected for a given site based on an assessment of the suitability and applicability of the options available.

2) Ideally, structural measures should be implemented in a way that allows them to be optimised subsequently at reasonable cost. They must be built to withstand extreme events and minimise wear and tear in the course of continuous operation. Structural measures must provide the same defined protection for the long term.

3) Innovative measures must be flanked with biomonitoring.

4) Exchange on research and the monitoring and evaluation of measures should be continued in the framework of the ICPR.

5) To maintain fish populations, effectiveness targets should be set for each arm or stretch of the river that proposed measures must achieve at the different bottlenecks. This is also required under various laws (EU Eel Regulation and the Water Framework Directive).

   Clear goals should be defined for individual sites and fish species, taking the overall situation of the river into account (see 4.4.) Combinations of measures for minimising cumulative mortality should also always be considered (see 4.2 HDX Wupper project), and where necessary monitored and evaluated.

   Even if targets cannot be set for individual sites, it must be ensured that efforts are made at every site to implement the best technical solution using best available technology.

3.2 Possible measures

From a fisheries science perspective, priority must be given to dismantling hydropower plants. The benefits of a hydropower plant for renewable energy generation must be weighed against the environmental costs of habitat loss and fragmented river systems. The greatest environmental benefit is achieved by dismantling hydropower plants or cancelling planned new plants.

Consequently, there is a general ban on constructing new migration obstacles in the programme waters of the Master Plan Migratory Fish (see ICPR programme Rhine 2040).

If new plants are built outside of these waters, more stringent targets can be set than those that apply to existing installations (see 4.4).

As outlined in 3.1, there is rarely a standard solution for fish protection and downstream fish migration at hydropower plants. The feasibility of the measures presented must therefore be reviewed for each site.

Generally speaking, the countries of the Rhine river basin have different views on the available measures (see also 4) and recommendations regarding particular measures.

However, there is consensus on the recommendation of horizontal or vertical fine screens with bypass (see also 3.3).

3.2.1 Proven measures: Horizontal or vertical fine screens with bypass

Physical measures, mostly in the form of mechanical (screen) barriers, are intended to stop fish swimming into the turbines (protective effect). To further facilitate migration, a bypass must be provided as an alternative fishway (Wagner 2020). Fine screens are an effective way of preventing fish from passing through turbines. Measures of this kind have already been implemented at numerous sites and experience gained in their construction and operation (for example, Cuchet et al. 2018, Ebel 2016, Ebel et al. 2018, Frey et al. 2020, Ingendahl et al. 2024, Tomanova et al. 2018a, Tomanova et al. 2018b, Tomanova et al. 2021). The measure's effectiveness hinges on suitable bar spacing in relation to the minimum size of the fish to be protected (both height and width of the fish are relevant, see Meister et al. 2022, Knott et al. 2023). There are different types of fine screens, both vertical and horizontal. These can be installed in various ways in the headrace channel. Unlike vertical screens, horizontal screens enable fish to reach the bypass without leaving their migration depth.

Inflow velocity plays a key role in the effectiveness of fine screens. If the velocity is too high (for example, 0.5 m/s)[1], fish are at risk of being forced against the screen. The angle or incline of a screen is also crucial. The inflow angle should be at least <45°, ensuring the screen not only blocks the path to the turbine, but also guides the fish away from the danger zone and towards the bypass. Inflow angles of under 26° have proved especially effective for vertical screens.

Irrespective of whether a screen is vertical or horizontal, it is important that the bypass connects up well, preferably directly, to the downstream end of the screen. This makes it easy to find (guiding effect) and minimises exploratory movements that delay the fish. To that end, the dimensions of the bypass (size and associated discharge and flow increase) and its position (as far as possible, directly at the downstream end of the fish protection screen) and configuration (one or more entry points throughout the entire water column) must all be adapted to the respective fish community (Ebel 2016).

To counter any deficiencies and make it easier for fish to find the bypass, Ebel (2016) recommends modifying the size of the screen in line with the discharge of the hydropower plant (2-5% Q_{WKA} with horizontal oblique inflow and 5-10% Q_{WKA} without horizontal oblique inflow). This is especially important in existing plants where the physical barrier is passable for specified target species, the inflow velocity is unsuitable or the bypass is positioned unfavourably relative to the barrier (bypass should be situated as close to the barrier as possible).

3.2.2 Other measures

Alongside conventional fine screens with bypass(es), other measures are being used temporarily or are being tested. These may become more important in future, possibly limited to particular sites. They include physical measures such as turbines with reduced potential to harm fish, operational measures and measures to influence fish behaviour. These measures are presented in the following sections.

Physical measures

Vertical guidance structures – type curved bar rack (CBR): these guidance structures (curved bar rack, vertical bar rack, louvers) have bar spacing that fish would normally be able to pass through. However, they generate turbulence which repels the fish and guides them towards a bypass. The advantage of CBR structures is that they do not incur the production losses associated with fine screens, require little maintenance and can protect and guide a range of species and sizes. Laboratory findings are promising, but little experience has been gained with CBR in the field, and the cost of installing them at existing hydropower plants is likely to be very high. This solution is probably less

[1] for example, guide on transverse structures of the German federal state North Rhine-Westphalia

expensive to implement in new hydropower plants.[2] At present, the potential of this technology to effectively prevent harm to fish is still unclear.

Coanda screens: These are intended as a more fish-friendly alternative to conventional Tyrolean weirs. The water flows over a weir to a downstream screen with a smooth surface and narrow-spaced, wedge-shaped bars. Fish and solid materials can be washed over the screen into the tailwater (BAFU 2022).

Steel cables: Steel cables are an alternative to the fixed structures described above. This system consists of cables braced between two anchor points over the headrace channel in the direction of the hydropower plant. This type of structure can be installed at reasonable cost. The advantage of these screens for plant operations is that they can be lowered during periods of high water to allow debris to pass through. However, this is not recommended as a means of deterring or guiding migrating fish. To achieve that, narrow cable spacing needs to be consistently maintained over a large area. It is not certain what potential these screens hold for future widespread use.

Partial depth guidance structures: These work on a similar principle to CBR guidance structures, but are restricted to the upper part of the water column. As there are no screens in the lower water column, fish are neither deterred nor guided there. Latest knowledge indicates that some fish species, for example salmonids, primarily migrate through the upper water column. For these species, partial depth guidance systems can be effective if migrating fish are guided directly towards the bypass and do not start seeking alternative routes. However, other species, such as the barbel, seem to migrate primarily along the river bed. Partial depth guidance systems are not effective for these species. Considerable savings could be made if structures were limited to the first few metres beneath the surface. However, it is not yet clear if such structures deliver satisfactory results. There have been no detailed studies on this to date.

Guidance structures near the banks such as screens and flow deflector (cf. Projekt FishPath, VAW): The idea behind this approach is to limit guidance structures to places where fish naturally congregate near the weir. Installing guidance structures at these locations substantially reduces the scale and cost of the measure. Prior to implementing such solutions, behavioural studies must be carried out to ascertain the places which migrating fish use naturally for orientation. These reviews may include telemetric studies to identify the search patterns and main congregation places. At present, it remains unclear whether all species display similar behaviour near a weir and whether this type of solution can be implemented effectively for a wide range of species and sizes. Moreover, fish behaviour can vary from year to year depending on abiotic factors such as flow regime and temperature. Observations must therefore be conducted over several years to verify that fish behaviour remains stable over time.

Moveable baffles (‘parois plongeantes mobiles’): This measure consists of a floating structure fitted with a baffle that extends a few metres below the surface. The structure is anchored to the banks and/or dam with cables, enabling it to be moved easily (for instance during high water or to optimise its position after installation). As this measure is only functional for the first few metres below the surface, its degree of effectiveness is not clear.

[2] M. Huber-Gysi, verbal communication

Turbines with reduced potential to harm fish

Fish mortality is heavily influenced by the type and operating mode of a turbine. Changes to the turbine or operating mode (see point 3 below) can reduce the risk of injury and mortality.

In low-head hydropower plants, the main cause of fish mortality is collision with turbine blades. Turbine characteristics relevant for fish mortality are blade thickness, the angle at which the fish comes into contact with the blades and leading edges and the rotational speed and number of the turbine blades (Berkel et al. 2016). Over time, turbines focussing on fish-friendliness were developed that can limit fish mortality to just a few percent. Natel Energy's Restoration Hydro Turbine (RHT) is one example. The manufacturer gives a survival rate for this turbine of 98-100% (see Amral et al. 2020, Watson et al. 2022 and Watson et al. 2023). Field studies have also been carried out on technologies such as Archimedes screw turbines (Kibel P. 2007; Kibel P. 2008), very low head (VLH) turbines (Courret & Larinier 2008; Lagarrigue T. 2013) and the mobile hydropower plant. A feasibility and cost assessment is currently being carried out for an RHT at a plant in Switzerland (under discussion for Eglisau power plant). Other studies looked at Fairbanks Nijhuis turbines (Winter et al., 2012; Bruijs & Vriese, 2013; Vriese, 2015) and the Voith Minimum Gap Runner (Robb, 2011).

Operational measures

Adapting hydropower plant operations can have an impact on fish mortality. Adjustments can be made, for example, to water distribution between power plant and weir, to water use and turbine settings. Turbines can even be powered down at times of increased fish migration (see examples in section 4).

Powering down turbines: Where other measures (physical and behavioural measures, turbines with reduced potential to harm fish) do not provide adequate protection for downstream migrating fish, powering down turbines can produce positive results. The turbine should be switched off when (downstream) fish migration is taking place. Early warning systems or predictive models can be used to determine the migration period. Their accuracy can vary according to location and may affect operations (shorter or longer shut down). While the plant is idle the fish can migrate downstream using alternative routes.

Adapted turbine management: Fish mortality at hydropower plants can depend on the volume of water flowing through the turbine. In turbines in which the discharge is regulated by the blade rotation, there needs to be more space between the blades when discharge is higher. This measure leads to lower fish mortality. Where there are several turbines, adapted management (aiming for maximum discharge at each turbine) can reduce fish mortality. The level of reduction depends on various factors. Well-known examples of adapted turbine management have reduced silver eel mortality by 25% (Bakker 2016).

Trap and transport: Measures for avoiding fish mortality during downstream migration can be supplemented by capturing fish in the upper reaches and releasing them downstream of the hydropower plant. Fish traps can be used to catch silver eel, for instance. This measure is relatively labour intensive. The extent to which trap and transport promotes fish survival depends on the extent of the catch and the effectiveness of the traps used (dependent on site). It must be noted that the efficacy of this measure is limited. Moreover, depending on how often the fishing gear is lifted from the water, it can delay fish migration.

Optimised weir and turbine management: The idea here is to lower the costs arising from production losses by optimising water use for downstream fish migration. This can be achieved through the targeted opening of the safe fish migration corridors (bypasses, sluices or other). These openings are pre-determined, based either on knowledge of the migration periods of the target species, or more flexibly on real-time monitoring of the fish at the weir (video, sonar). In the latter approach, the downstream fish migration corridors are only fed with water when fish are present. Solutions of this kind are currently being explored in a pilot study at the Stroppel power plant.

Behavioural measures

While physical measures prevent fish of a specified minimum size from swimming into turbines, behavioural measures focus on fish responses to different stimuli, and using fish behaviour to guide them to an alternative path. In practice, behavioural measures should be combined with an alternative route.

Various studies have shown that many of the sensory barriers are ineffective or of limited use only (for example, study on subsonic noise: Bau et al. 2011).

Turbulence-based guidance structures (see FishPath research project): The VAW research group (Laboratory of Hydraulics, Hydrology and Glaciology, VAW) of ETH Zürich is a partner in the FishPath Project, which aims to develop guidance methods based on fish response to turbulent eddies. The project is investigating which types of turbulence are most effective and which structures (such as cylinders or hydrofoils) can best produce the desired eddies. The project is currently in the research stage and is expected to conclude in 2026 (https://www.nina.no/fishpath).

Air bubble curtain or bioacoustic fish fence (BAFF): This type of barrier generates sensory stimuli (light, sound, bubbles) to induce fish to avoid certain areas and guide them to safe migration corridors (bypasses). In the past, the biological effectiveness of such systems was generally inadequate and they were only used in combination with existing mechanical barriers. However, the relatively new BAFF system, which combines acoustic stimuli with an air bubble curtain, appears promising and initial experience has been positive. The main advantage of such measures is that they obviate the need for physical barriers in the water column, making them relatively inexpensive. Moreover, as they do not impede flow to the turbine, they do not entail production losses.

Electric guidance and deterrence systems: some guidance systems use an electric field to repel the fish. For example, electrified steel cables with a far wider spacing than fine screens can guide fish to a bypass, thus minimising production losses. The cables can also be lowered during periods of high water to allow debris to pass through. However, in terms of fish protection this is not desirable, as fish migration tends to increase during periods of high water. This solution has not yet been tested at larger plants, and its effectiveness still needs to be evaluated. Another solution is to electrify the turbine’s protective screens or trash racks (prior to water abstraction). This helps minimise costs, as the use of the screens already in place saves extensive construction work on the dam. However, the alignment and position of existing screens in the watercourse is seldom ideal for guiding fish to an outlet or bypass. It has not yet been adequately proved that these guidance systems provide sufficient protection. Their effectiveness is debatable, especially during higher inflow velocities. Electric guidance and deterrence systems also raise concerns for human safety (September 2022: accident with two fatalities in the Arve near Geneva, in which an electrified fish fence may have played a role).

Induced drift application (IDA): the recently developed IDA technology also shows promise as a way of reducing harm to fish passing through a turbine. In this approach, an electric device mounted on the turbine gives the fish an electric shock immediately before they pass through. As an immobilised fish does not fight against the current, it is a lot less likely to be harmed during passage through the turbine. Fish pass through the turbine more quickly, thus lowering the probability of (lethal) collision. Initial findings show a 50% reduction in mortality and injury. This is still a very novel method and empirical data is lacking. It is important to note that passing through turbines which are not considered to have reduced potential to harm fish is far from ideal for fish. There is always a risk of injury or death, even if that risk is minimal for some species and/or age groups. Moreover, it is probable that the fish will still be immobilised and/or disoriented downstream of the turbine outlet and consequently more vulnerable to predation. It is therefore essential to consider the impacts of predation when deploying an IDA system.

3.3 Measures tailored to the size of the hydropower plant

The effect and suitability of measures depend on the size and design of the individual plant. For all hydropower plants, the option to dismantle must be explored first, taking into account energy efficiency and the disturbance effect of the power plant on the water body. Where dismantling is unfeasible, the measures set out below, depending on the discharge of the hydropower plant, can reduce harm to fish.

3.3.1 Small hydropower plants (discharge of total plant up to 50 m³/s)

State-of-the-art technology for downstream fish migration[3] is already available for small hydropower plants with a discharge of up to 50 m³/s, and experience has been gained with effective downstream fishways.

Small hydropower plants should favour technically proven structural/physical measures based on the latest research[4] over operational measures. These include:

- horizontal and vertical fine screens with bypass
- Coanda screens
- turbines with reduced potential to harm fish (various designs, such as Archimedes screw, VLH...)

It is relatively straightforward to install fine screens (10-15 mm bar spacing) that reliably ensure a high level of physical protection for fish above a certain size.

If physical measures cannot be implemented, operational measures can be used as an alternative, for example periodically powering down the plant during times of fish migration.

[3] in Germany: Forum Fischschutz findings (German Environment Agency 2023)
[4] in Germany: Forum Fischschutz findings (German Environment Agency 2023)

3.3.2 Medium-sized hydropower plants (discharge of total plant 50-100 m^3/s; depending on regional definition can also total up to 150 m^3/s)

In recent years, numerous studies and retrofitting measures have been carried out on medium-sized power plants (see examples in 4). Viable downstream migration systems have been installed at several power plants of this size.

For medium-sized power plants, physical measures are the preferred option (see 3.2). In power plants of this size, hydraulic conditions mean that in some cases fine screens with narrow bar spacing and a high level of physical protection cannot be implemented, or only at high cost. At these plants, greater use must be made of wider bar spacing and the guiding effect of angled screens. Fine screens are currently being planned at various sites.

A more in-depth study of operational and behavioural measures is needed to determine how effective and feasible they are (see 3.2). All measures must be selected with a view to the intended objective (for example, target species).

3.3.3 Large hydropower plants (discharge of total plant greater than 100 m^3/s)[5]

Further research and development is needed for large hydropower plants, especially for the large plants on the Rhine. In light of this, the ICPR Webinar ”Fish protection and downstream fish migration at large hydropower plants: sharing experiences and knowledge”, held on 15 and 16 September 2021, presented best-practice measures and the latest research findings on fish protection and downstream migration at large hydropower plants.

The webinar highlighted the broad spectrum of available measures to facilitate downstream fish migration at hydropower plants. These include:

- guidance systems (physical or behaviour-based)
- adapted turbine management (operational management combined with early warning system)
- use of turbines with reduced potential to harm fish
- structural modification of the position and layout of the inlet
- availability of an easy-to-find, passable alternative path (for instance, barrage/overflow, bypass, fishway)

The measures proposed here were tested at plants up to 450 m^3/s. The measures described above can be recommended for large hydropower plants, and the use of other measures described in 3.2 should also be reviewed. However, deploying screen systems is significantly more complex and costly here than in smaller plants, and is often not possible with current knowledge and technology.

Moreover, a distinction should be made between long-term and short-term solutions. Unlike structural solutions, operational measures such as optimised weir and turbine management are reversible and quick to implement. In principle, depending on the methods available for reviewing target achievement, species-specific survival rates should be laid down for river basins. These should draw on population biology and factor in the cumulative mortality of the power plant chains in the relevant section of the river. Steps towards this goal can be implemented gradually, whereby in the interests of fisheries science, priority should be given to measures with the best cost-benefit ratio (generally those in the downstream reaches).

[5] see 3.3.2

4. Practical examples from ICPR countries

Over the years, the countries of the Rhine river basin have gained considerable practical experience in fish protection and downstream migration aids aimed at reducing fish mortality at hydropower plants. Moreover, for large hydropower plants in particular (discharge > 150 m^3/s), pilot projects have enhanced research and raised the level of knowledge, enabling effective transitional measures to be implemented. Annex 1 contains a comprehensive overview of studies on fish protection and downstream fish migration in the countries of the Rhine and Meuse river basins.

The following presents examples of measures and regulations from ICPR countries.

4.1 Switzerland

<u>Dietikon hydropower plant</u>

The largest horizontal fine screen to date in the German-speaking region was installed at Dietikon power plant (discharge 95 m^3/s). The bar spacing is 20 mm. The screen has been in place since 2019 and according to the operator, there have been no issues with its operation or maintenance. Specific statements on its effectiveness are not yet possible as the biological impact assessment only starts in 2023.

<u>Stroppel and Rüchlig power plants</u>

The discharge is 40 m^3/s for Rüchlig dotation power plant and 33 m^3/s for Stroppel power plant. Both were fitted with a horizontal fine screen with bypass, 20 mm bar spacing and with a bed baffle. The inflow angle at Rüchlig power plant is close to 0° (parallel to flow), at Stroppel the angle is 38°. Impact assessments with detailed reports have been completed for Stroppel power plant on the Limmat and for Rüchlig dotation power plant on the Aare. Relative downstream migration figures were not collected for either plant (passage both through the turbines and various alternative migration corridors such as bypass, upstream fishway, weir overflow, for which no figures are available on downstream migration). For that reason, the biological impact assessment cannot make any detailed quantitative statements on the fish guidance and fish protection effect. In both cases, over 95% of the random samples in the fish traps downstream of the bypass consisted of fish < 10 cm in size. In theory, these should have been able to pass through the screen. The reports therefore concluded that only a very small number of fish can be assumed to migrate downstream through the screens via the turbine at either power plant. These assumptions are well-founded but cannot be quantitatively proven beyond doubt (the distribution of species and size of the downstream migrating fish can be compared to fish captured in the headwater). This comparison suggests that there is no selectivity of fish species or size at Stroppel power plant. Moreover, the high downstream migration figures indicate that the screens have a good guidance effect that enables the fish to find the bypass(es) at the two power plants. Videos taken at the Stroppel plant show that the fish easily found both entry points to the bypass.[6]

[6] https://plattform-renaturierung.ch/massnahmen-renaturierung/

Figure 1. The different sections of Rüchling power plant (ArcGIS, accessed 18 September 2018).

Legend: Hochwasserentlastung: spillway, Hauptkraftwerk: main power plant, Kraftwerkskanal: power plant channel, Fischaufstiegshilfen: upstream fish migration aids, Fischabstiegshilfe: downstream fish migration aid, Frey-Kanal: Frey channel, Stauwehr: weir, Dotierkraftwerk: dotation hydropower plant, Restwasserstrecke: residual waters

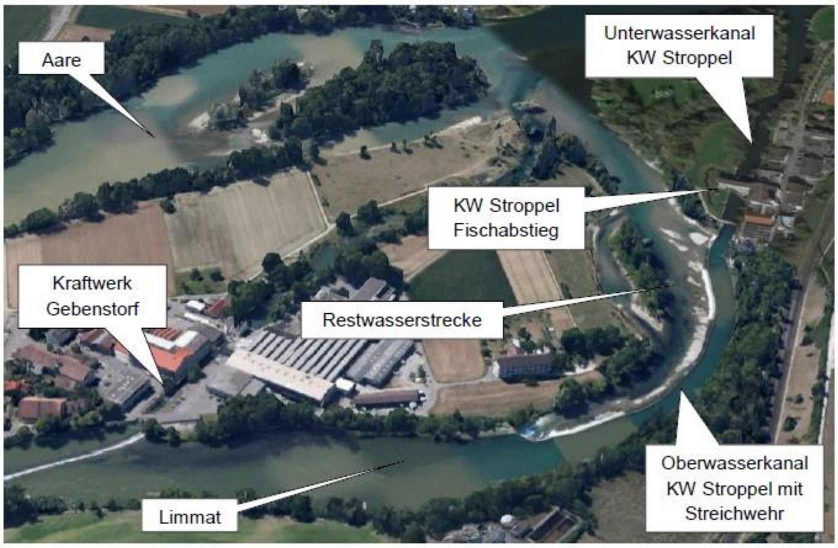

Figure 2. Stroppel small hydropower plant, including Gebenstorf power plant, upstream on the Limmat and Aare rivers (direction of flow from left to right, source Google Earth).

Legend: Aare: Aare, Kraftwerk Gebenstorf: Gebenstorf power plant, Limmat: Limmat, Oberwasserkanal KW Stroppel mit Streichwehr: Stroppel power plant headwater channel with gated weir, Restwasserstrecke: residual waters, KW Stroppel Fischabstieg: Stroppel power plant downstream fishway, Unterwasserkanal KW Stroppel: Stroppel power plant underwater channel

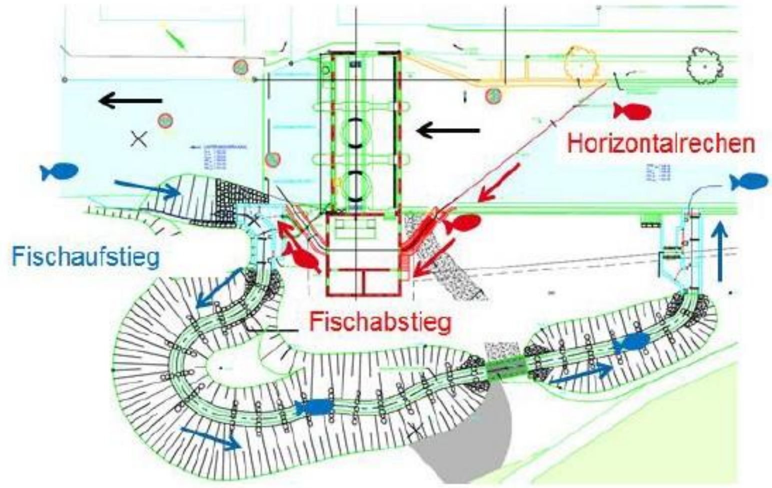

Figure 3. Downstream fish migration at Stroppel hydropower plant. The flow direction of the Limmat is from right to left.

Legend: Fischaufstieg: upstream fish migration, Fischabstieg: downstream fish migration, Horizontalrechen: horizontal screen

4.2 Germany

<u>Interim measures for fish protection and downstream fish migration at large hydropower plants on the river Main, illustrated with the examples of Offenbach and Kesselstadt sites (Mühlheim)</u>

There are 34 barrages along the river Main. The six barrages on the Lower Main before it discharges into the Rhine are in Hesse. Hydropower plants are operated at five of these barrages. They each have a capacity of 4 to 5 MW with discharges of 160-210 m³/s. Generally, only protective screens with wide bar spacing are installed at large hydropower plants like those on the Main. This prevents larger debris from entering the turbine, but means that most fish can pass through and end up in the turbines. Depending on their size and shape, a high percentage of these fish (up to 50%) are harmed or even killed by the turbine blades. Moreover, damage (for example to the swim bladder) can occur during passage through the turbine channel due to pressure conditions. This has to be considered in the context of the Main power plants, which are designed to allow the entire volume of the river (apart from the water in locks) to flow through the plant on around 240 days of the year. Generally speaking, there are no alternative downstream migration corridors.

One exception to this is the Kostheim barrage. Since it was commissioned in 2008, this barrage has been equipped with fine screens with a 20 mm bar spacing and an upstream and downstream fishway. Both passages are currently being optimised in a pilot project.

The hydropower plants at the Offenbach and Mühlheim barrages date from the mid to late 80s. Each plant has two turbines (each 90 m³/s). Until autumn 2018, there were no structural modifications, with only a coarse screen with 100 mm bar spacing in front of each turbine. During a licensing procedure required under water law for continued operation of the two plants, authorities and operators sought an interim solution that gave due consideration to both continued operation and fish protection.

Decisions of 2018 and 2019 granted a licence to continue operating the two hydropower plants for a limited period of five years, up to the end of June 2024. The main requirements for operation are:

- only turbines with 15 mm screens in front of them may be operated

- maximum permitted inflow velocity at the screen is 0.5 m/s
- only half of the Main discharge may be used for hydropower. This leads to continuous weir overflow which provides a potential downstream migration corridor for fish
- if the Federal Waterways and Shipping Administration is carrying out maintenance, monitoring, repairs or other work on or near the flap gates, more water from the Main can be discharged via the hydropower plants for a limited time
- this temporary higher admission means screenings must be monitored more intensively, as the higher discharge increases the speeds at the screen (> 0.5 m/s) and more harm to fish can be expected

The operating mode still in use today has proved its worth in terms of fish protection, notwithstanding the less than ideal downstream fishway available and the restricted operating capacity of the hydropower plant. However, this is only a temporary compromise until a permanent solution can be developed which combines the best possible fish protection with optimum operating capacity for the long term.

Figure 4. Mühlheim/Main barrage (photo: Darmstadt district administration).

<u>Project on fish protection and downstream fish migration at Unkelmühle pilot plant on the Sieg</u>

The Sieg is a designated water body for the target species salmon (*Salmo salar*) and eel (*Anguilla anguilla*) as well as one of the water bodies in a salmon repopulation programme in North Rhine-Westphalia (NRW). To improve passability and fish protection at Unkelmühle hydropower plant (discharge 27 m^3/s), a pilot project (2011) constructed a 10 mm vertical screen angled at 27°, several bypasses (six in the upper waters, a Bottom Gallery, three eel pipes at different depths) and an upstream fishway (new vertical slot pass). The aim was to achieve a balanced compromise between optimum fish protection and minimum energy losses. To that end, alongside biomonitoring of captured fish (radio-tagged and untagged, using telemetry) operations were also monitored. The latter found that a drop-profile screen leads to lower energy losses than a y profile screen. Biomonitoring showed significantly higher losses of downstream migrating salmon smolts in the deep and calm backwaters of the power plant compared to losses in the free-flowing upstream reference stretch (free flowing: 0.5%-1.6%; dam area: 4.4%-17.1%). For the fish sizes tested (from around 13 cm total length for salmon smolts, from 60 cm total length for eels), the 10 mm fine screen was 100% effective in protecting fish from passing through the turbine. Downstream migrating silver eels and salmon smolts use the surface bypasses and, if open, the flap gates as their main downstream migration corridors. Compared to a downstream weir without hydropower (Buisdorf weir), the migration speed directly at the structure was reduced by a factor of 10 (median: 0.4 km/h versus 5.6 km/h). The technical structures, bypass system, discharge of the various migration corridors and/or noises and pressure waves may cause the salmon to hesitate here (Ingendahl et al. 2019).

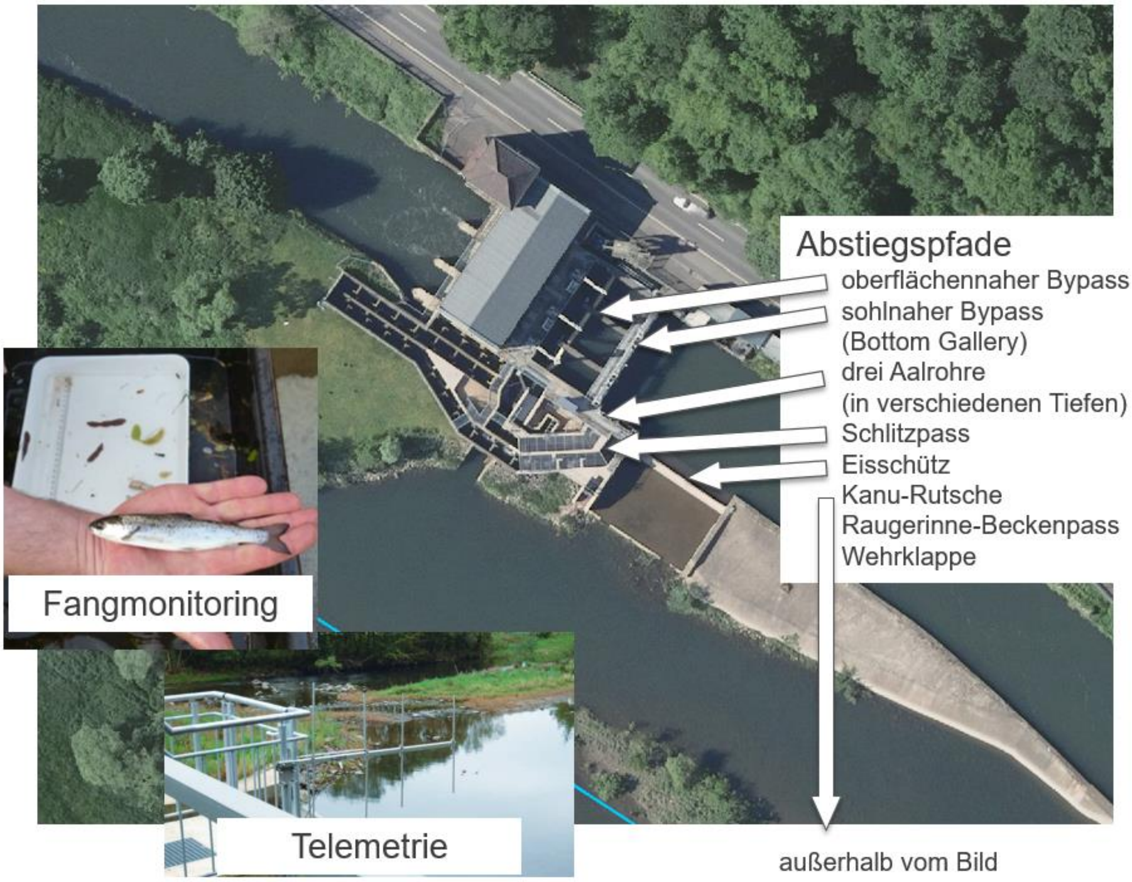

Figure 5. Unkelmühle hydropower plant on the Sieg (Lower Rhine tributary).

Legend: Fangmonitoring: fish monitoring, Telemetrie: telemetry, Abstiegspfad: downstream migration path, oberflächennaher Bypass: partial-depth bypass, sohlnaher Bypass (Bottom Gallery): bed baffle (Bottom Gallery), drei Aalrohre (in verschiedenen Tiefen): three eel pipes (at different depths), Schlitzpass: vertical slot pass, Eisschütz: ice guard, Kanu-Rutsche: canoe shoot, Raugerinne-Beckenpass: roughened-channel fishway, Wehrklappe: flap gate, außerhalb vom Bild: out of frame

<u>HDX-Wupper project</u>

The Wupper is a designated water body for the target species salmon (*Salmo salar*) and eel (*Anguilla anguilla*), as well as one of the water bodies in a salmon repopulation programme in North Rhine-Westphalia. Restoring upstream and downstream passability is therefore especially relevant. To establish passability, Auer Kotten diversion power plant (discharge 14 m^3/s) was equipped with three bypasses (bed baffle, partial-depth bypass for smolts, and a sluice gate). Two new upstream fishways were also constructed (at the hydropower plant and the diversion weir). In addition, a 12 mm horizontal screen was installed to protect downstream migrating fish. A study of the effectiveness of these measures was part of the HDX Wupper project (2013-2018), which evaluated the passability of the Wupper over a stretch of 65 km, including six hydropower sites, by monitoring fish tagged with HDX transponders (564 silver eels, 1,500 salmon smolts, 3088 "wild fish"). The results showed that the 12 mm horizontal screen at the Auer Kotten power plant fulfilled its protective function for downstream migrating eels and salmon smolts. 80% of downstream migrating fish followed the main current to the powerhouse, where the temporarily open sluice gate was the most efficient downstream migration corridor. The vertical slot pass and the partial-depth bypass were also commonly used for passage downstream. Regular opening of the sluice gate (at least every 30 minutes between 7 pm and 6 am) during the downstream migration period of salmon and eel (1 September to 31 May) increased the number of downstream migrating fish (Wölleke et al. 2020).

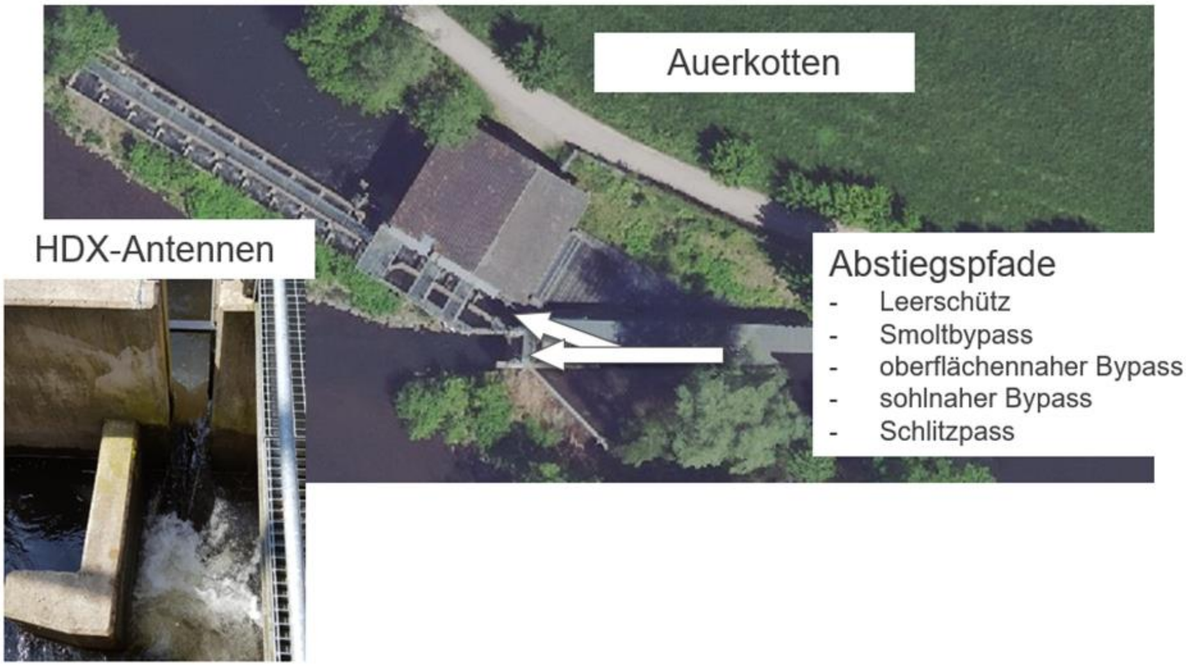

Figure 6. Auer Kotten diversion power plant on the Wupper (Lower Rhine tributary).

Legend: HDX Antennen: HDX antennas, Auerkotten: Auer Kotten, Abstiegspfade: downstream migration paths, Leerschütz: sluice gate, Smoltbypass: smolt bypass, oberflächennaher Bypass: partial-depth bypass, sohlnaher Bypass: bed baffle, Schlitzpass: vertical slot pass

4.3 France

On the Meuse:

Revin hydropower plant (turbine discharge 60 m^3/s) has a relatively fish-friendly intake structure consisting of a fine screen angled at 45 degrees with 20 mm bar spacing. The structure in question is a fine screen with 20 mm clearance and a 45 degree angle. The structure is designed to prevent fish migrating through the turbines and guide them uninjured to the downstream reaches of the plant.

 

The Givet, Hamm-sur-Meuse and Saint Joseph barrages (turbine discharge 50 m^3/s) were rebuilt in the framework of a public-private partnership (PPP) and equipped with turbines designed to allow fish to pass through uninjured. The turbines in question are VLH (very low head) turbines which are completely submerged, almost noiseless and rotate slowly. The partnership is equipping some twenty transverse structures with aids for downstream and/or upstream fish migration on the Meuse.

More information on the turbines can be found here:

https://www.vlh-turbine.com/fr/products/vlh-turbine

On the Ill:

Niederbourg hydropower plant near Illkirch-Graffenstaden (maximum turbine discharge 45 m^3/s) is equipped with a downstream fishway.

The upper reaches of the power plant are equipped with five horizontal screens angled at 33 degrees with 20 mm bar spacing. There is a bypass at the top of each screen. The angle of the screen and the flow velocity near the bypasses enable the fish to find them and swim towards the collection gallery behind the screens. From there, the fish are taken to the downstream reaches of the plant.

Photo credit: Association Saumon Rhin

4.4. The Netherlands

In the Netherlands, a distinction must be made between state and regional water bodies. State water bodies, which include the major rivers, are managed by Rijkswaterstaat. These water bodies are regulated by national policy on hydropower. Regional water bodies, such as tributaries of major rivers, are often managed by regional water management bodies (Dutch water associations) and are regulated by regional directives.

Legislation

The licensing of hydropower plants in state water bodies is regulated under the 2021 political guideline on the granting of concessions for hydropower plants in state waters (Staatscourant 2021). A concession may only be granted if the hydropower plant uses all options available to protect fish during downstream migration and if potential adverse impacts on upstream migrations are compensated.

On the Meuse (section from Eijsden to Lith), the Nederrijn (Dutch Lower Rhine) and the Lek, a concession may only be granted for a hydropower plant if its operation does not cause cumulative fish mortality of more than 10% for salmon (smolts) and silver eel. In the river sections mentioned above, a mortality rate of more than 10% is only permitted if the mortality of salmon (smolts) and silver eel caused by new hydropower plants does not exceed 0.1%. In addition, a concession for a hydropower plant may not be granted in the relevant area more than five times using the aforementioned percentages.

For state water bodies outside of these sections of the Meuse, Nederrijn and Lek rivers, a concession may only be granted for a hydropower plant if the maximum mortality rate it causes in salmon (smolts) and silver eel in the water body is 0.1%. Nor will a concession be granted if one has already been granted for a hydropower plant in the same water body. There are exceptions to this for a large number of water bodies, which are referred to in the 2021 political guideline on the granting of concessions for hydropower plants in state waters (Article 5(4)).

The various management bodies for regional waters have their own policies, many of which are based on the premise that the production of hydropower may not hinder upstream or downstream fish migration. In addition, a common requirement is that no harm or virtually no harm may be caused to fish. There is a limited number of small hydropower plants and old water mills in regional water bodies. The ECI hydropower plant in the Rur (tributary of the Meuse) is probably the most well known.

State water bodies

In the Netherlands there are three large hydropower plants in state water bodies (10-14 MW, ± 400 m^3/s). The plants are located in the Meuse (Linne and Lith) and in the Nederrijn (Maurik). These plants are regulated by the political guideline on the granting of concessions. In these rivers, the cumulative mortality caused by hydropower plants must therefore not exceed 10%. The two hydropower plants in the Meuse may only cause a maximum fish mortality of 5% (smolts and silver eel) each, the hydropower plant in the Nederrijn may only cause a maximum fish mortality of 10%.
The most recent review period included an investigation into whether a maximum mortality rate of 5% or 10% in smolts and silver eel is achievable. The Migromat® and early warning systems were among the technologies used for this study. Although the measures were effective to a degree, they were not enough to ensure a maximum mortality rate of 5% per hydropower plant in the Meuse. The review for the Nederrijn is still ongoing.

Additional measures

Additional measures are required (best available technology) to achieve a maximum mortality rate of 5% (Meuse) and 10% (Nederrijn). This often involves a combination of measures such as (periodically) powering down turbines, adapted turbine management and/or the trap and transport of silver eels.

- *Powering down hydropower plants*

The hydropower plants on the Meuse near Linne and Lith are temporarily powered down to make it easier for silver eels and smolts to migrate downstream. This is done to ensure mortality does not exceed 5%. The plants are powered down at night during the migration period of silver eel and smolts. This time frame varies slightly in the two plants, because one has a more complicated process to ensure sufficient reduction in fish mortality. When the Linne hydropower plant is powered down in spring, a Teichert model optimised for the Linne is used to predict smolt migration (Teichert 2020).
The powering down of the turbines at the Maurik hydropower plant is determined by variations in discharge. If the flow exceeds a certain limit value, the turbines are powered down for 48 hours. During the period 1 August to 30 November, the turbines may not be powered down more than once every three weeks. For the period 1 December to 31 January, the turbines are only powered down the first time the limit value is exceeded.

- *Adapted turbine management*

The turbines in the Meuse and Nederrijn are horizontal Kaplan turbines. Turbine discharge can be regulated by adjusting the blade settings. When discharges are low, there is less free space between the blades, leading to higher fish mortality. The goal of adapted turbine management is to lower fish mortality as much as possible. In practice this means using fewer turbines with a higher discharge. In the past it was calculated that the mortality of silver eels can be lowered by some 25% (Bakker 2016).

- *Trap and transport of silver eel*

In the period from 1 September to 1 December, as many silver eel as possible are captured in the upper reaches of the Maurik hydropower plant and released downstream of the plant. This prevents the eels from passing through the turbines. In general, it can be said that the effectiveness of this measure is relatively low. For instance, it was calculated for the Meuse that in the past about 1/30 silver eels were caught and released using these methods and in the Nederrijn about 1/6 (Bakker 2016). Practicability of trap and transport depends very much on local factors, the methods used to catch the fish, the number of fish traps and how they are used. This method has the further disadvantage of delaying the migration of silver eels.

Figure 7. Damming at Lith (Meuse). On the left the hydropower plant and fish pass, on the right shipping sluice (photo: Rijkswaterstaat).

References

Amaral, S. V.; Watson, S. M.; Schneider, A. D.; Rackovan, J. & Baumgartner, A. (2020). Improving survival: injury and mortality of fish struck by blades with slanted, blunt leading edges, Journal of Ecohydraulics, 5:2, 175-183, DOI: 10.1080/24705357.2020.1768166

BAFU (2022). Wiederherstellung der Fischwanderung. Gute Praxisbeispiele für Wasserkraftanlagen in der Schweiz), https://www.bafu.admin.ch/bafu/de/home/themen/wasser/publikationen-studien.html

Bakker, H. (2016). Lowering fish mortality at hydropower stations in Dutch rivers. Dead ends and new chances. Rijkswaterstaat. Presentation Fish market 2016, Roermond.

Bau et al. (2011). Test d'un dispositif de répulsion à infrasons au droit de deux ouvrages sur le Gave de Pau. 92 pages. https://hal.inrae.fr/hal-02596839/document

Berkel, J. van; Esch, B. van & Vriese, T. (2016). Fish safety of large, low-head turbines. HZ University of applied sciences, Eindhoven University of Technology & ATKB. Presentation Fish market 2016, Roermond.Cuchet, M., Geiger, F. & P. Rutschmann (2018): Zum Fischschutz und Fischabstieg an geneigten und horizontalen Rechen. WasserWirtschaft 9/2018, 36-40

Bruijs & Vriese: Workshop Fish Protection at Hydropower Stations in the River Meuse, the Netherlands, 2013

Courret & Larinier: Guide pour la conception de prises d'eau „ichtyocomptabiles" pour les petites centrales hydroélectriques. RAPPORT GHAAPPERA.08.04 : https://www.documentation.eauetbiodiversite.fr/notice/000000000189951d34aab740c6732a54, 2008

Cuchet, M; Geiger, F. & Rutschmann, P. (2018). Zum Fischschutz und Fischabstieg an geneigten und horizontalen Rechen. WasserWirtschaft 9/2018, 36-40

Ebel, G. (2016). Fischschutz und Fischabstieg an Wasserkraftanlagen - Handbuch Rechen- und Bypasssysteme. In: Mitteilungen aus dem Büro für Gewässerökologie und Fischereibiologie. 2. A. Band 4, Halle/Saale: Eigenverlag

Ebel, G.; Kehl, M. & Gluch, A. (2018). Fortschritte beim Fischschutz und Fischabstieg: Inbetriebnahme der Pilot-Wasserkraftanlagen Freyburg und Öblitz. WasserWirtschaft 9/2018, 54-62

Frey A. ; Tomanova S. ; Mercier O. ; Richard S. ; Courret D. ; Tetard S. ; Tissot L. ; Mataix V. ; Lagarrigue T. (2020). Etude d'efficacité de prises d'eau ichtyocompatibles pour les smolts de saumon atlantique – Projet EFFIGRI. Synthèse des résultats 2017-2018. Rapport OFB-Pôle Ecohydraulique, EDF R&D, ECOGEA.

Handbuch Querbauwerke (2005). Ministerium für Umwelt und Naturschutz, Landwirtschaft und Verbraucherschutz des Landes Nordrhein-Westfalen. ISBN 3-9810063-2-1

IKSR-Bericht Nr. 140. Auswirkungen von Wasserkraftanlagen in den Rheinzuflüssen auf den Wanderfischabstieg, IKSR, 2004, www.iksr.org

IKSR-Bericht Nr. 247. Masterplan Wanderfische Rhein 2018, IKSR, 2018, www.iksr.org

IKSR. Rhein 2040. Der Rhein und sein Einzugsgebiet: nachhaltig bewirtschaftet und klimaresilient, IKSR, 2020, www.iksr.org

Ingendahl, D.; Weimer, P.; Wilke, T. et al. (2019). Abschlussbericht zum Projekt Fischschutz und Fischabstieg an der Pilotanlage Unkelmühle, (www. flussgebiete.nrw.de/abschlussbericht-zum-projekt-fischschutz-undfischabstieg-der-pilotanlage-unkelmuehle-8039, (2019); Abruf 14.06.2023)

Ingendahl, D.; Burghardt, G.; Geist, S. J. (2024). Fischschutz an Wasserkraftanlagen durch Vertikal- oder Horizontalrechen, Wasser und Abfall, Ausgabe 9/2024

Kibel P. (2007). Fish Monitoring and Live Fish Trials. Archimedes Screw Turbine, River Dart. Phase 1 Report: Live fish trials, smolts, leading edge assessment, disorientation study, outflow monitoring. FISHTEK consulting, 38 p. + annexes.

Kibel P. (2008). Archimedes Screw Turbine Fisheries Assessment. Phase II: Eels and Kelts. FISHTEK consulting, 18 p. + annexes

Knott J., Mueller M., Pander J., Geist J. (2023). Bigger than expected: Species- and size-specific passage of fish through hydropower screens. Ecological Engineering. 188:106883. DOI: 10.1016/j.ecoleng.2022.106883

Lagarrigue T. (2013). Tests d'évaluation des dommages subis par les espèces piscicoles en dévalaison lors de leur transit à travers le groupe turbogénérateur VLH installé sur le Tarn à La Glacière (Millau). Principaux résultats des tests effectués en mai-juin 2013. https://www.vlh-turbine.com/wp-content/uploads/2019/01/vlh_fish_test_fr.pdf

Meister J., Selz O.M., Beck C., Peter A., Albayrak I., Boes R.M. (2022). Protection and guidance of downstream moving fish with horizontal bar rack bypass systems. Ecological Engineering 178 (2022) 106584.

Raynal S., Chatellier L., David L., Courret D., Larinier M. (2012). Définition de prises d'eau ichtyocompatibles - pertes de charge au passage des plans de grille inclines ou orientes dans des configurations ichtyocompatibles et champs de vitesse à leur approche. RAPPORT POLE RA11.02. 114 pages.

Raynal S., Chatellier L., David L., Courret D., Larinier M. (2013). Définition de prises d'eau ichtyocompatibles – Etude de l'alimentation en débit et du positionnement des exutoires de dévalaison au niveau des plans de grille inclinés ou orientés dans les configurations ichtycompatibles. Rapport Pôle RA.12.02. 112 pages.

Staatscourant 2021. Beleidsregel watervergunningverlening waterkrachtcentrales in rijkswateren Nr. 35745, 20 juli 2021

Teichert, N.; Benitez, J.P ; Dierckx, A.; Tétard, S.; Oliveira, E. de; Trancart, T.; Feunteun, E. & Ovidio, M. (2020). Development of an accurate model to predict the phenology of Atlantic salmon smolt spring migration. Aquatic Conservation, Marine and Freshwater Ecosystems. Volume 30, Issue 8. August 2020. Pages 1552-1565.

Tomanova S. ; Courret D. ; Alric A. ; De Oliveira E. ; Lagarrigue T. ; Tetard S. (2018a). Etude d'efficacité des exutoires associés à des grilles inclinées ou orientées pour la dévalaison des smolts de saumon atlantique. Etude 2016 et synthèse des résultats 2015-2016. Rapport AFB-Pôle Ecohydraulique, EDF R&D, ECOGEA.

Tomanova S. ; Courret D. ; Alric A. ; De Oliveira E. ; Lagarrigue T. ; Tetard S. (2018b). Protecting efficiently sea-migrating salmon smolts from entering hydropower plant turbines with inclined or oriented low bar spacing racks. Ecological Engineering. Volume 122: 143-152.

Tomanova S.; Courret D.; Richard S.; Tedesco PA.; Mataix V.; Frey A.; Lagarrigue T.; Chatellier L.; Tetard S. (2021). Protecting the downstream migration of salmon smolts from hydroelectric power plants with inclined racks and optimized bypass water discharge. Journal of Environmental Management 284 (2021) 112012.

Umweltbundesamt (2023). Abschlussbericht. Forum Fischschutz und Fischabstieg: Ergebnisse und Ausblick, https://forum-fischschutz.de/forum-dokumente.html

Vriese F. T.: Evaluation of Fish Injury and Mortality Associated with scale models of the Pentair Fairbanks Nijhuis Modified Bulb turbine and the Water2Energy Cross Flow turbine. Rapport Pro-Tide, 2015

Vriese, F. T., (2017). Vissterfte bij passage van stuwen. Rapport 20170587/01. ATKB, Waardenburg.

Wagner, S. (2020). „Wann ist ein Rechen ein Fischschutzrechen", https://forum-fischschutz.de/factsheets, Fact Sheet 05

Watson, S.; Schneider, A.; Santen, L.; Deters, K. A.; Mueller, R.; Pflugrath, B.; Stephenson, J.; Deng, Z. D. (2022). Safe passage of American Eels through a novel hydropower turbine, Transactions of the American Fisheries Society. 2022;151:711–724, DOI: 10.1002/tafs.10385

Watson, S. M.; Schneider, A. D.; Gardner, L. C.; Apell, B. R.; Thompson, P. C.; Cadman, G. B.; Gagnon, I. F.; Frese, C. R.; Wechsler, J. F. (2023). Juvenile Alewife Passage through a Compact Hydropower Turbine Designed for Fish Safety, North American Journal of Fisheries Management. https://doi.org/10.1002/nafm.10866

Winter, Bierman & Griffioen: Field test for mortality of eel after passage through the newly developed turbine of Pentair Fairbanks Nijhuis and FishFlow Innovations, 2012. http://www.fairbanksnijhuis.com/resources/images/3381.pdf

Wöllecke, B.; Adam, B. & Scheifhacken, N. (2020). Blankaale und Lachssmolts – Abwanderung aus der Wupper. Erkenntnisse aus der Freilanduntersuchung zur Abwanderung der Fischarten über mehrere Kraftwerksstandorte. Natur in NRW 4/2020, 34-38

Annex

Overview of studies on fish protection and downstream fish migration at hydropower plants (as at November 2024)

	Study	Discharge	Type of study	Hydraulic features of the fish protection system	Fish species studied	Results of study	Assessment of success/potential of the measure (+) positive (-) negative (0) no clear trend	Further research needed	Participating institutions / contact	Link	Status of study (ongoing or concluded)	Publication (yes/no)	Country
1	**Fish guidance system with vertical bars "mechanical behavioural barriers" Curved-bar rack bypass system (f-CBR-BS)**	Only laboratory experiments to date, but holds potential for large hydropower plants	Etho-hydraulic lab study	Clear bar spacing: 50 mm Screen angle ≥ 30° Inflow velocity 0.5 and 0.7m/s	Spirlin, barbel, common nase, brown trout, Atlantic salmon parr, European eel	FGE > 85% spirlin, barbel, nase and salmon parr FGE < 60% brown trout FGE < 40% eel FPE > 90% spirlin, barbel, nase and salmon parr FPE < 40% eel FPE < 60% brown trout Lower output losses due to optimised hydraulics	(+)	· Pilot project implementation f-CBR-BS at Herrentöbeli hydropower plant (< 50 m^3/s) in the Thur (CH), implemented 2023. Bar spacing 25 mm · Electrification of the f-CBR in a follow-up project increased FPE and FGE (up to 100% FPE and >60% FGE for eels, >70% FPE for trout and >50% FGE for trout). Data not yet published	VAW; Ismail Albayrak	publication on fish behaviour Publication Publication on hydraulic components: flow field	Concluded	Yes	CH
2	**Electrified fish protection system for downstream fish migration**	Only laboratory experiments to date, but holds potential for large hydropower plants and for retrofitting existing plants	Etho-hydraulic lab study	Intake racks with 90 mm bar spacing, f-CBR-BS and HBR-BS with 50 mm bar spacing with electrification	Chub, brown trout, eel	*Some findings published. Scheduled to conclude summer 2025*	(+)	See above study on Herrentöbeli pilot project: electrification option provided for when plant constructed. Problem of injury from electrification. VAW planning study for winter 2024	VAW; Anita Moldenhauer, Ismail Albayrak	doi://10.3850/IAHR-39WC2521716X202292	Ongoing	In part	CH
3	**FishPath: turbulent eddies to create corridors for downstream migration of salmon and eels at hydropower plants**	Only laboratory experiments to date, but holds potential for large hydropower plants	Etho-hydraulic lab study	Turbulent eddies caused by obstacles in front of the power plant. Vortex generator distance: 14.5 cm, system angle: 30°, flow velocity: 0.3, 0.6 and 0.8 m/s	Brown trout, salmon, eel	*Ongoing project, expected to conclude 2026.* Preliminary results of experiments with living fish (Atlantic salmon smolts) show up to 97% FGE	(+)	· Large-scale tests in Vattenfall laboratory in 2025, prototype-scale tests in 2026 in the Mandal, Norway	VAW; Ismail Albayrak	https://www.nina.no/fishpath	Ongoing	No	CH
4	**Feasibility study vertical bar rack (VBR) plus hydropower plant Bannwill (Aare)**	450 m^3/s (block-type thermal power station)	Feasibility study					–	BAFU; Martin Huber Gysi BKW Energie AG; Sandra Krähenbühl	https://www.swv.ch/fileadmin/user_upload/site/PDF/WKW_BAN_Technisches_Vorprojekt_final_240320.pdf	Concluded	Yes	CH
			Numerical studies			Extension of dividing pier in the headwater unavoidable			VAW, ETZ Zürich	https://www.swv.ch/fileadmin/user_upload/site/PDF/WKW_BAN_Technisches_Vorprojekt_final_240320.pdf	Concluded	Yes	CH
			Behavioural biology studies with radiotelemetry			108 fish (37%) migrated downstream 257 (88%) of 292 tagged fish were found again using manual tracking.			FishConsulting	https://www.swv.ch/fileadmin/user_upload/site/PDF/WKW_BAN_Radiotelemetrische_Untersuchungen_final_230330.pdf	Concluded	Yes	CH
			Sensor fish						Tallinn University of Technology	https://www.swv.ch/fileadmin/user_upload/site/PDF/WKW_BAN_Sensorfischuntersuchungen_v5_d_230520.pdf	Concluded	Yes	CH

	Study	Discharge	Type of study	Hydraulic features of the fish protection system	Fish species studied	Results of study	Assessment of success/potential of the measure (+) positive (-) negative (0) no clear trend	Further research needed	Participating institutions / contact	Link	Status of study (ongoing or concluded)	Publication (yes/no)	Country
5	**Feasibility study VBR plus Wildegg-Brüggen hydropower plant (Aare)**	420 m^3/s (diversion power plant)	Feasibility study (numerical investigations)	*Planned configuration:* Screen angled at 31° to the channel axis Clear bar spacing 50 mm					BAFU; Martin Huber Gysi Axpo Power AG; Ricardo Mendez	https://www.swv.ch/fileadmin/user_upload/site/PDF/KWWB_2024.03.27_H-17748_Technisches_Vorprojekt.pdf	Concluded	Yes	CH
			Behavioural biology study with acoustic telemetry		Barbel and other species					https://www.swv.ch/fileadmin/user_upload/site/PDF/KWWB_2024.03.27_H-18596_Akustische_Telemetrie.pdf		Yes	
6	**Pilot project Herrentöbeli power plant (Thur)**	11 m^3/s	Construction and impact analysis of curved bar rack	F-CBR-BS, 37° inflow angle, bar spacing 25 mm	Trout and greyling	Construction 2022, subsequent impact analysis	Underway	Electrification of the guidance system feasible (not currently planned, due to unfavourable electrical field with electrodes downstream and narrow bar spacing and because retrofitting of electrodes on the front of the bars is expensive)	0 BAFU; Martin Huber Gysi		Ongoing	No	CH
7	**Dietikon power plant (Limmat)**	95 m^3/s	Construction and impact analysis of horizontal fine screens	Horizontal guidance screen, 45° bar spacing 20 mm.	Diverse	In place for over a year, no problems with operation or maintenance. Biological impact analysis from 2023	(+) Operation Latest hydraulic measurements by VAW		EKZ, BAFU; Martin Huber Gysi VAW, ETZ Zurich		Ongoing	No	CH
8	**Rüchlig dotation power plant (Aare)**	40 m^3/s	Construction and impact analysis of horizontal fine scr	horizontal guidance screen almost parallel to flow direction, bed baffle (50 cm high), bar spacing 20 mm	Diverse, 22 species, high proportion of cyprinids and perch in downstream migration monitoring	In operation since 2015, biological impact analysis in 2017 using a fish trap at the bypass and Aris sonar. Unfortunately no relative surveys comparing fish migrating downstream through turbines or other downstream migration corridors. -minor risk of injury when migrating downstream via the bypass -good guidance effect of the screen to the bypass -majority (>95%) of downstream	(+) operation (0) biological impact analysis		Axpo Power AG; Ricardo Mendez, WFN (working group on water, fish and nature), Ökobüro; Martina Breitenstein	https://plattform-renaturierung.ch/wp-content/uploads/2019/01/20200714-Ru%CC%88chlig-Wiko-Fischabstieg.pdf			CH

	Study	Discharge	Type of study	Hydraulic features of the fish protection system	Fish species studied	Results of study	Assessment of success/potential of the measure (+) positive (-) negative (0) no clear trend	Further research needed	Participating institutions / contact	Link	Status of study (ongoing or concluded)	Publication (yes/no)	Country
9	**Stroppel power plant (Limmat)**	33 m^3/s	Construction and impact analysis of horizontal fine screens	Horizontal guidance screen, 38° inflow angle, bed baffle, bar spacing 20 mm	Diverse, 28 species, high proportion of cyprinids and perch in downstream migration monitoring	In operation since 2013/2014, biological impact analysis 2015-2017 using fish trap at the bypass, video recordings in front of the screen and Aris sonar in front of and behind the screen. Unfortunately no relative surveys comparing fish migrating downstream through turbines or other downstream migration passages: -majority (>95%) of downstream migrating fish <10 cm -good guidance effect of the screen -no species or size selectivity of the downstream migration corridor	(+) Operation, but modification of the bypass outlet (curve reduced) (+) biological impact analysis	https://www.mdpi.com/2073-4441/14/5/776/pdf?version=1646128343	Axpo Power AG; Ricardo Mendez	https://plattform-renaturierung.ch/wp-content/uploads/2019/04/KWKSt-2018.09.04Bericht-Erfolgskontrolle-Fischabstieg_inkl.-Anhang_final.pdf			CH
10	**Advanced Bypass System for Downstream Migration of European Key Umbrella Fish Species (ABSYS)**	Only laboratory experiments to date, but holds potential for large hydropower plants and for retrofitting existing plants	Etho-hydraulic lab study	Intake racks with 90 mm bar spacing f-CBR-BS and HBR-BS (curved and horizontal bar rack systems) with 50 mm bar spacing	Spirlin, barbel, brown trout, eel, salmon	*Scheduled to conclude autumn 2027*		See above study on Herrentöbeli pilot project: electrification option provided for during construction of plant	VAW; Ismail Albayrak, Yuhao Yan	https://vaw.ethz.ch/en/research/hydraulic-engineering/research-projects.html#absys	Ongoing	No	CH
11	**Downstream migration of silver eels from the Rur to Lith hydropower plant (Meuse)**	± 400 m^3/s	Behavioural study with NEDAP transponders	–	Silver eel	2018-2019: 91% of eels migrating downstream via Lith hydropower plant when the Migromat alert was triggered 2019-2020: 56% of eels migrating downstream when the Migromat alert was triggered Migromat does not predict eel migration with the same reliability every year Only 8 of 24 eels survived downstream migration via the Lith hydropower plant/weir	(+) (-)		Rijskwaterstaat; André Breukelaar ATKB; Tim Vriese		Concluded		NL
12	**Early warning system (Migromat) downstream migration of silver eels at Lith and Linne (Meuse) and Maurik (Rhine)**	± 400 m^3/s	Monitoring, telemetry (NEDAP transponder)		Silver eel	At Lith power plant 60% and 32% respectively of the eels would have been diverted over the weir (reduction of mortality) if it had been powered down for two nights following a Migromat alert. However, at least 85% need to be diverted to achieve the 5% maximum mortality standard. The experiment is therefore deemed a failure and the use of the Migromat will be discontinued in future. The project "Paling over de Dijk" (eel over the dike) also proved too ineffective and unreliable in the Meuse near Lith. Based on current knowledge, the conclusion is that the Migromat® is inadequate as an early warning system to meet the mortality standard for the Meuse every year.				Summarised in: Microsoft Word - 20200920_rap01_definitief_29_9_2021.docx (waterecologie.nl)	Published	Yes	NL

	Study	Discharge	Type of study	Hydraulic features of the fish protection system	Fish species studied	Results of study	Assessment of success/potential of the measure (+) positive (-) negative (0) no clear trend	Further research needed	Participating institutions / contact	Link	Status of study (ongoing or concluded)	Publication (yes/no)	Country
						The Migromat does not appear able to reliably predict the downstream migration of silver eel at Maurik, Lith and Linne power plants. That is the finding of the continuous monitoring of silver eels migrating via the power plant from 1 August to 31 January during the two years measurements were taken at each plant.							

	Study	Discharge	Type of study	Hydraulic features of the fish protection system	Fish species studied	Results of study	Assessment of success/potential of the measure (+) positive (-) negative (0) no clear trend	Further research needed	Participating institutions / contact	Link	Status of study (ongoing or concluded)	Publication (yes/no)	Country
13	**Early warning system downstream migration of salmon smolts at Lith (Meuse)**	± 400 m^3/s	Model development based on 2018/2019 monitoring data at Lith. Early warning system		Salmon smolt	Simple model based on three elements: water temperature of the Meuse, average duration of smolt migration in the Meuse and the observation that smolts mainly pass through the Lith power plant at night. A provisional conclusion would be that while the early warning system for smolts is sufficient for the present situation, it is probably not fit for the future (currently only effective for smolts from the Meuse border river, not for those from the tributaries Ourthe, Berwijn, Geul or Rur). As a long-term solution, the model by Teichert et al (2020a) Life4Fish seems to be more suitable.			Rijskwaterstaat; Marjoke Muller/Harriet Bakker ATKB; Tim Vriese	Vis, H., J.H. Kemper & T. da Graça 2020. Definitief Early Warning System en protocol voor de smoltmigratie bij WKC Alphen. VisAdvies BV, Nieuwegein. VA2019_31. 29 p Zusammengefasst in: Microsoft Word - 20200920 rap01_definitief_29_9_2021.docx (waterecologie.nl)	Concluded	Yes	NL
14	**Early warning system downstream migration of silver eels at Linne (Meuse)**	± 400 m^3/s	Model application		Silver eel	At Linne power plant a study explored whether an alternative predictive model for silver eel downstream migration, namely the LIfe4Fish model proposed by Teichert et al. in 2020, delivers better results than the Migromat. This model is based on the increase in river discharges, and this does seem to be apply. The calculation for the two measurement years shows that powering down the plant at night following an alert based on					?	?	?
15	**Protection of smolts and silver eels at hydropower plants in the Meuse (Wallonia)**		Behavioural studies		Silver eel Salmon smolt	46% efficiency of electric fence for eels It is possible that the fence had an adverse impact on salmon smolts 50% efficiency of the predictive model for silver eel downstream migration and powering down turbine Air bubble fence did not repel eels and was defective after a short time Weir overflow of 20-30 cm in Lixhe has a similar efficiency for smolts as the bypass in Namur	(-) (-)	Studies on the effect of electric fences on smolt behaviour Effect of adapted weir overflow on smolt downstream migration is being explored further	Luminus; P. Theunissen University of Lüttich; S. Erpicum Profish; Sonny Damien University of Namur; P. Kestemont EDF R and D; Eric De Oliveira LIFE4FISH project		Ongoing	Ongoing	BE

	Study	Discharge	Type of study	Hydraulic features of the fish protection system	Fish species studied	Results of study	Assessment of success/potential of the measure (+) positive (-) negative (0) no clear trend	Further research needed	Participating institutions / contact	Link	Status of study (ongoing or concluded)	Publication (yes/no)	Country
16	**Tuilières – partial-depth guide wall for downstream migration of salmon smolts**	320 m³/s	Behavioural studies with radiotelemetry	Guide wall (4.07 m), angle ~43° relative to the power plant • 3 fields divided by two pillars (phi 90 cm) • 3 bypasses: 2 in the pillars (2.5 m³/s + screens e=13 cm) and 1 flap gate (21 m³/s) Vertically attached to power plant (boomerang)	Salmon smolt	• Rate of downstream migration (via bypass) dependent on turbine discharge (75% for Q<175 m³/s, otherwise 20%) • Flap gate is chosen far more often than the secondary bypasses • 20% to 38% of smolts arrive directly at the flap gate • Smolts arriving at the guide wall use fields 2 and 3 • Guide wall very effective at diverting fish at Q<100 m³/s, but performs badly at Q>200 m³/s (74% of the smolts go deeper) • Smolts that swim under the guide wall do not turn back Conclusions • Behavioural barriers: not suitable for all species • The behaviour of species in any direction needs to be well known • It is essential to have an extremely good overview of the currents at the site and of all flows occurring during the downstream migration period • The geometry of the guide wall should ensure the following: • Depth of wall > swimming depth of the smolts, but a standard depth cannot be specified • Velocity under the guide wall < average speed of smolts (50- 60 cm/s) • On the surface, above the guide wall, tangential speed > normal speed (at Tuilières Vt=20 cm/s)		• Number, need for and efficacy of secondary bypasses • Debris management at the level of the bypasses, as the guide wall = blocking effect • Safety of fish downstream of the structure in the bypass spillway • Impacts on weir operation (estimated capacity loss 30 cm) • Interactions with upstream migration aids • Interactions with predators (catfish)	EDF Lionel Dumond		Concluded	?	FR
17	**Baigts-de-Béarn (64) – downstream fish migration facility – test of bypasses and fine screens**	90 (power plant) + 12 m³/s (small power plant)	Radiotelemetry: migration pathways (Several studies and facilities over the years 2001/2005/2010)	Bar screen with 30 mm spacing for main power plant; bar screen with 20 mm spacing for small power plant Deep bypass (7 m) and/or partial-depth bypass + 3 bypasses for small power plants (2 partial-depth; 1 deep)	Eel	Bypasses + fine screens +spillway structures: 92% diversion of large specimens (2006) Effectiveness depends both on size of specimens and on flow/hydraulics	+		ONEMA EDF R&D				FR
18	**Gave de Pau - eel and structures: downstream fish migration (2007-2010) report 2013**	28 to 110 m³/s (6 different power plants	fish biology study with radiotelemetry	Angled and vertical screens, different sizes and spacing (from 2 cm to 9.2 cm) Bypasses for different discharges	eel	Low use of bypasses Depending on size of specimens, some bar spacing restricts passage: physical barrier The design of the plant, especially the position and angle of the weir overflows, facilitate downstream migration of eels			ONEMA / IRSTEA EDF				FR
19	**Test to evaluate harm to juvenile salmonids and downstream migrating silver eel when passing through the group of VLH turbines in the Tarn near Millau (2008)**	20 m³/s	Study on the effects of a VLH turbine	Fish-friendly VLH turbines	Salmon	Deferred mortality rate negligible Smolt mortality estimated at 3.1%			ECOGEA				FR

	Study	Discharge	Type of study	Hydraulic features of the fish protection system	Fish species studied	Results of study	Assessment of success/potential of the measure (+) positive (-) negative (0) no clear trend	Further research needed	Participating institutions / contact	Link	Status of study (ongoing or concluded)	Publication (yes/no)	Country
20	**Downstream migration of diadromous fish at small power plants**	< 100 m^3/s	**<u>Notice</u>** <u>on solutions for</u> downstream fish migration to be implemented: based on current technical and biological knowledge (2012) + progress reports						ONEMA DIR Sud-Ouest & ONEMA Pôle Eco-hydraulique				FR
21	**HDX-Wupper-Monitoring**	14 m^3/s (Auerkotten)	Behavioural studies with radiotelemetry	Auer Kotten: horizontal screen with 12 mm clear bar spacing ; long angled screen 26.25 m; inflow angle 30°; 3 bypasses: bed baffle, partial-depth, smolt bypass	Silver eel, salmon smolt, "wild fish" (wild fish = brown trout, grayling, nase, barbel, chub, dace, perch, sea trout, river lamprey, pike, brook char, rainbow trout, roach)	• 80% of downstream migrating fish followed the main channel to the power house. The migration corridor over the diversion weir was used less often • The horizontal screen (bar spacing: 12 mm) fulfils its protective function for downstream migrating eels and salmon smolts. • The most efficient downstream migration corridor was the route over the opened sluice gate. • Opening the sluice gate to coincide with the downstream migration of salmon smolts increases downstream passage. • The slot pass and partial-depth bypass also frequently used for downstream migration Bed baffle and smolt bypass were less well used	(+)		Dusseldorf district government (North Rhine-Westphalia): Britta Wöllecke	https://www.brd.nrw.de/themen/umwelt-natur/wasserwirtschaft/oberflaechengewaesser-wasserbuch-und-wasserrahmenrichtlinie/durchgaengigkeit-fischschutz/fischmonitoring	Concluded	Yes	D
22	**Fish protection and downstream fish migration at Unkelmühle pilot plant**	27 m³/s	Monitoring of captured fish, telemetric studies	Vertical screen angled at 27°, 3 fish protection screens, spacing: 10 mm; 3 bypasses: partial-depth, 3 eel pipes and a bed baffle (eel pipe and bed baffle discharge into the monitoring station)	Salmon smolt, eel, "wild fish" (wild fish = brown trout, barbel, minnow, chub, nase, bleak, three-spined stickleback, spirlin, roach, gudgeon, dace, greyling, common perch, rainbow trout, tench, stone loach, carp, bitterling, bream, ruffle, lamprey, char, catfish, bluenose)	• A drop-profile screen causes lower energy loss than one with a y profile For the fish sizes tested (from around 13 cm total length for salmon smolts, from 60 cm total length for eels), the 10 mm fine screen proved to be 100% effective in protecting fish from turbine passage • Compared to the free flowing upstream reference stretch, there was a significantly higher loss of migrating salmon smolts in the deep and calm backwaters (free flowing: 0.5% - 1.6%; dam area: 4.4% - 17.1%). • The main downstream migration corridor for silver eels was the opened flap gate, for salmon smolts it was the partial-depth bypasses.		Further research is needed on the effects in the dam areas (predation, disorientation, loss of time on migration)	Cologne district government (North Rhine-Westphalia): Thomas Wilke		Concluded		D
23	**Vechte swimway**		Studies of fish behaviour using radiotelemetry aimed at improving fish migration from source to sea		Sea trout, ide, burbot, whitefish, river lamprey, silver eel	*Project ongoing (until 2023)*			State office for Nature, Environment and Consumer Protection: Karin Camara		Ongoing		D
24	**Classification of fish passability of water courses in North Rhine-Westphalia (NRW)**	-	Developing procedures for classifying fish passability of water courses in NRW (including study of the literature)			*Project ongoing, scheduled to conclude in mid-2024*			State Office for Nature, Environment and Consumer Protection: karin Camara, Sebastian Emde, Beate Bierschenk		Ongoing		D
25	**LAWA project: development and testing of criteria for assessing watercourse passability at sites with structures (LFP O 3.19; commissioned by the expert group on hydromorphology of the committee on surface and coastal waters of LAWA, the German Working Group on water issues of the Federal States and the Federal Government**	–	Developing a recommendation for action on classifying fish passability in watercourses			*Project ongoing, scheduled to conclude end 2022*			German Environment Agency (UBA): Stephan Naumann		Ongoing		D

FGE=fish guidance efficiency= N_{bypass}/N_{total}
FPE=fish protection efficiency=$(N_{bypass}+N_{refusal})/N_{total}$