SPECIAL ISSUE

CSIRO PUBLISHING

Marine and Freshwater Research, 2018, **69**, 1834–1847
https://doi.org/10.1071/MF18120

Review

Safe two-way migration for salmonids and eel past hydropower structures in Europe: a review and recommendations for best-practice solutions

Hans-Petter Fjeldstad[A,D], *Ulrich Pulg*[B] and *Torbjørn Forseth*[C]

[A]SINTEF Energy Research, Postboks 4761 NO-7465 Torgarden, Norway.
[B]Norwegian Research Centre NORCE LFI, Nygårdsgaten 112, NO-5006 Bergen, Norway.
[C]Norwegian Institute for Nature Research, Postboks 5685 Torgarden, 7485 Trondheim, Norway.
[D]Corresponding author. Email: hans-petter.fjeldstad@sintef.no

Abstract. This review provides a summary of knowledge on two-way fish migration of salmonids and eels past hydroelectric plants in Europe. On the basis of a summary of international literature, general designs and recommendations for best practices for fish-pass facilities are provided. The review is part of the Norwegian SafePass project, which focuses on Atlantic salmon, brown trout, grayling and European eel. According to recent international recommendations, many existing European fishways for upstream migration do not have an optimal design. This is especially evident for denil and pool-and-weir fishways in inland areas with species such as grayling and brown trout. Based on the review, we generally recommend (1) using ramps, nature-like channels and vertical-slot fishways for these species and (2) reducing water drop between the pools in pool-and-weir fishways and reducing energy dissipation compared with the design of traditional Atlantic salmon ladders. There are few well-functioning passages for downstream migration of fish in Europe and significant progress has been made in the past decade to improve technology and knowledge. Several international studies have shown that physical structures, such as fine-mesh trash racks with alternative escape routes and bypass arrangements, provide >90% passage efficiency for downstream migration, especially for brown trout and salmon, and have, in recent years, shown good results also for silver eels.

Received 23 March 2018, accepted 6 August 2018, published online 7 November 2018

Introduction and objectives

Many fish species migrate in rivers to utilise different habitats at different life stages for spawning, growth and wintering. The migration of Atlantic salmon (*Salmo salar*) from its spawning grounds and rearing habitats in rivers to the feeding grounds in the ocean (anadromous behaviour) is well known. For many species, migrations occur within the same river, which is the case for inland brown trout (*Salmo trutta*) and grayling (*Thymallus thymallus*). The European eel (*Anguilla anguilla*) displays a catadromous behaviour, with its spawning area being located in the Sargasso Sea, whereas it feeds along the coasts and in rivers and lakes in Europe.

Delay and blocking of fish migration as a consequence of hydropower structures leads to fragmentation of habitats and fish populations and may limit dispersal of fishes. This may eventually lead to a significant reduction and, in some cases, extirpation of fish populations and species. Passability for fish in rivers is an important prerequisite for maintaining the fish population and for achieving good ecological status or potential according to the EU Water Framework Directive (WFD). Restoration of ecological connectivity (river segments without migration barriers between important habitats) has a high priority in water management, in accordance with the WFD and national water regulations.

Internationally, research on fish-pass facilities has become a major and multidisciplinary field of expertise (Katopodis and Williams 2012; Silva *et al.* 2018). In Norway, the SafePass project is a major effort funded by the Norwegian Research Council, the Norwegian hydropower industry and Norwegian river management and environment authorities, to develop and recommend best practices for upstream and downstream migration past hydropower structures in Norway. The project consists of a literature review, laboratory studies and field experiments, and has research partners from Norway, Sweden, Denmark, Austria, Canada and France. This review is based on the literature review part of the project and the objective is to summarise the migration behaviour, demands and suitable migration facilities for the target species of Atlantic salmon, brown trout, grayling and European eel.

The aim of the study has been to identify and recommend the best-practice solutions for safe two-way fish migration in European regulated rivers, and we advocate that existing knowledge should be used, instead of waiting for an 'ultimate solution' which might never come. In general, 'two-way fish-migration facilities' do not imply combined solutions for both up- and downstream migration, but, rather, separate solutions that ensure migration in both directions past barriers.

As part of this review, relevant literature has been reviewed from both Norway and elsewhere in Europe and the USA, particularly from Sweden, Germany, Austria, UK, the Netherlands, Denmark and France. Scientific papers, books, reports and guidelines in different languages have been collected from research partners in the SafePass project and other sources, so as to define best practices (Clay 1995, Jungwirth *et al.* 1998; Larinier and Travade 2002; Larinier *et al.* 2002; Fjeldstad 2012; Williams *et al.* 2012; Emanuelsson *et al.* 2017; Greenberg *et al.* 2017; Nyqvist *et al.* 2017; Økland *et al.* 2017; Silva *et al.* 2018). We have included knowledge from 'grey literature', because there is a lot of technical experience and solutions developed in different countries, which have not been published in peer-reviewed international journals (Katopodis 1992; Food and Agriculture Organisation of the United Nations 2002; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2005, 2014; Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft 2012; Gough *et al*. 2012; Calles *et al.* 2013*a*; International Commission for the Protection of the Danube River 2013; Seifert 2016; Brink *et al.* 2018; Pulg *et al.* 2018).

Several European countries have introduced general requirements and guidelines for best practice for fish-pass solutions, which, in this context, correspond to 'best practice' (e.g. Austria, Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft 2012). Gough *et al.* (2012) and Brink *et al.* (2018) discussed such guidelines on a global scale. In best practices, the goal is that all migrating fish should be able to pass with a minimum of delay. However, the use of 100% of the fish as a target for passage efficiency may not be reasonable because there is also natural mortality during migration, surveillance mortality and because some fish may have reached their migration target when they reach the barrier. Internationally, therefore, it has become customary to use 'at least 90%' as a metric for passage efficiency (Calles *et al.* 2013*a*; Nyqvist *et al.* 2017; Silva *et al.* 2018). The solutions recommended as best practices in the present review have in common that they can achieve 90% fish-pass efficiency, provided that the necessary design criteria, dimensioning and proper locations are met. However, in each situation, target passage efficiency should be defined, and may deviate from 90% on the basis of conditions and factors, such as initial connectivity before the barrier was installed, habitat distribution in the river system, other barriers on the river and the accumulated mortality, or whether it is sufficient to make a passage for parts of the population (e.g. spawning fish). In practice, no global standard for fishways exists or is in use. Hence, the function or efficiency of a fishway, upstream and downstream, needs to be verified through monitoring measures (Travade and Larinier 2002).

To what extent best practice is required for a given hydroelectric structure is typically a management decision based on cost–benefit assessments. We do not emphasise costs in this review, because they depend strongly on the types of barriers and local conditions. However, although retrofitting migration solutions in old installations is often particularly costly, we advocate the use of best-practice solutions in case of new hydropower installations.

Fragmentation of rivers as a result of hydropower regulation is a main reason for the decline and reduced distribution of freshwater fishes (Hart and Poff 2002; Fahrig 2003; Nilsson *et al.* 2005; Poulet 2007). Construction of dams can lead to reduced water flow on fish-migration reaches and lack of migration possibilities for fish past the structures (Kraabøl *et al.* 2008; Calles and Greenberg 2009; Haltunen 2011). In recent years, there has been a strong focus on achieving sustainable fish population by restoring the connectivity of the rivers and, in particular, with the aim to reduce damage and mortality as a consequence of turbine passage (Coutant and Whitney 2000; Čada 2001; Čada *et al.* 2006; Östergren and Rivinoja 2008; Electric Power Research Institute–US Department of Energy 2011; Katopodis and Williams 2012; Pedersen *et al.* 2012). International studies have shown that the function of many of fishways of today is not satisfactory (Noonan *et al.* 2012; Fjeldstad *et al.* 2013), with the typical target for passage efficiency at over 90% for migratory fish not being reached (Lucas and Baras 2001; Ferguson and Williams 2002; Quigley and Harper 2006; Noonan *et al.* 2012). Low efficiencies at fish-passage facilities are linked to both technical design and fish behaviour in relation to stimuli and environmental variables (Clay 1995; Arnekleiv *et al.* 2007; Roscoe and Hinch 2010). Furthermore, many of the fish-passage solutions that are regarded as well functioning often work poorly for smaller fish or fish with low swimming capacity (Food and Agriculture Organisation of the United Nations 2002; Jansen *et al.* 2007; Mallen-Cooper and Brand 2007; Kraabøl 2012; Williams *et al.* 2012). For downstream fish migration, efficient passage past hydroelectric turbines can be achieved both with behavioural measures and by physical blocking, but behavioural measures are often species specific (Katopodis and Williams 2012). Effective blocking structures (Larinier *et al.* 2002; Calles *et al.* 2012; Greenberg *et al.* 2017) in the form of fine-mesh trash racks are often technically challenging to construct and operate and imply head losses (Chatellier *et al.* 2011; Raynal *et al.* 2014; Tsikata *et al.* 2014; Szabo-Meszaros *et al.* 2018). This applies especially when the trash racks and downstream migration corridors are retrofitted to established hydropower plants and intakes. However, successful retrofitting of projects has been reported, particularly for smaller plants (Økland *et al.* 2017). These experiences have led to the recognition that effective migration in fish, and especially in the presence of multiple migratory species, should be based on a combination of behavioural and physical barriers (Larinier and Travade 2002; Liao 2007; Thorstad 2010; Allen *et al.* 2012; Noatch and Suski 2012).

Migration patterns depend on both biological factors and abiotic habitat conditions. Biologically motivated movements and migration, such as spawning or feeding migrations, define the period during which the fish migrate and the migration target habitat. Hydromorphological (e.g. water velocities, turbulence) conditions determine whether the fish can pass a river reach, and both river flow and temperature are trigger variables that can influence when fish migrate. Re-establishment of connectivity, therefore, requires knowledge on fish species communities, habitat distribution, water-discharge patterns and temperature regime in a river system (Gough *et al.* 2012; Seifert 2016).

Below, we first present important design criteria and 'best-practice' solutions for upstream migration. Then, we address similar topics for downstream migration.

Upstream fish migration and European passage facilities

In most European rivers and streams, there are artificial migratory obstacles and barriers, such as culverts, weirs, dams and power stations. In Norway alone, more than 500 fishways have been constructed (Fjeldstad *et al.* 2013), increasing the production reaches for Atlantic salmon by more than 2000 km of river habitat. Although numerous fishways have been constructed in Europe, no general guideline has been developed for how to design fishways past hydropower structures. However, existing examples have demonstrated that with adequate design of fishway entrances and exits as well as favourable hydraulic conditions in the passage, the efficiency of fishways can be within the 90% target (Dumont *et al.* 2005; Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft 2012; Calles *et al.* 2013*a*; Nyqvist *et al.* 2017).

The following sections present solutions that are considered as best practice for migration of eel, grayling, brown trout and Atlantic salmon in Europe with regards to upstream migration past hydropower plants, on the basis of current knowledge. We begin with a summary of current knowledge on general upstream fishway characteristics such as entrance, attraction flow, water-discharge solutions and bed substrates in fish passages, followed by the concept for assessing the suitability and prioritisation of different fish-passage solutions.

Fish-passage entrance and water flow

Upstream-migrating salmonids generally seek the most powerful water flow and, at hydroelectric dams, water velocities are often higher in the turbine tailrace than at fishway entrances (Linløkken 1993; Laine *et al.* 1998; Williams 1998; Thorstad *et al.* 2003, 2008; Rivinoja 2005). The entrance to a fish ladder, a nature-like bypass or a ramp can be crucial for the function of the fishway and should be placed in the area where the fish stop at the migration barrier, and, generally, by the foot of a waterfall or the outlet of a hydropower plant. The entrance should not, under any circumstances, be placed too far downstream from the migration barrier, so that the entrance is not detected where the fish gather (Grande 2010; Fjeldstad *et al.* 2013). If the water supply from the entrance of the fishway (attraction flow) is small compared with the water flow in the river, it is an advantage to guide the attraction flow towards the main stream of the river, whereas in the case of a large attraction discharge, the attraction flow should be more parallel to the main flow (National Oceanic and Atmospheric Administration 2012).

According to the International Commission for the Protection of the Danube River (2013), to attract fish (salmonids, percids and cyprinids of the Danube system) into a fishway, water flow in the fishway relative to river flow should follow the discharge values in Table 1.

The values in Table 1 correspond with recommendations from, among others, Larinier *et al.* (2002), which generally recommended that the attraction flow should represent 2–5% of the river flow. Other studies have indicated that even more water is required to attract fish to the fishway entrance. Arnekleiv and

Table 1. Orientation values for discharge in upstream fishways

River discharge ($m^3 s^{-1}$)	Discharge in fishway ($m^3 s^{-1}$)	Proportion of river discharge in fishway (%)
5	0.25	5
10	0.5	5
20	0,8	4
50	1	2
100	1.5	1.5
200	2	1

Kraabol (1996) found that brown trout stopped their migration when the attraction flow was less than 9% of the turbine discharge. In the fish ladder at Marieberg in the Swedish Mørrumsån, the discharge is $\sim$1 $m^3 s^{-1}$; however, when river discharge exceeded 20 $m^3 s^{-1}$, the fishway did not attract Atlantic salmon and brown trout effectively. The discharge in the fishway then represented 3.5–5% of the total flow. The recommendations and studies above have shown that water flow in European fishways is, in many cases, too small, being often $<$0.5 $m^3 s^{-1}$ (Fjeldstad *et al.* 2013; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014). This can be remedied by releasing an increased amount of water through separate pipes next to the existing fishway, thus providing additional attraction water near the fishway entrance. At dams in large rivers ($Q_{Mean} > \sim 100$ $m^3 s^{-1}$), many studies have shown that site-specific studies are necessary to find a satisfactory amount of attraction flow from fishway entrances. Clay (1995) and Grande (2010) suggested that large dams may require multiple entrances to the fishway or several fishways, such as one fishway on either side of the river. The International Commission for the Protection of the Danube River (2013) stated that rivers wider than 100 m should at least be provided with two fishways, but, for Atlantic salmon, it has been shown that a single fishway may work well (Fjeldstad *et al.* 2013). Typical situations where multiple entrances or fishways are required include the following: (1) when downstream water level at the migration barrier varies greatly with river discharge, where the fish move along the banks and have difficulties crossing the main course of the river by high water flow; (2) when the river is so wide that fish does not detect the attraction flow from a fishway on one side of the river (Washington Department of Fish and Wildlife 2000); and (3) when the fish species in question move at different depths, such as, for example, eels and salmonids (Rosten *et al.* 2013).

Ferguson *et al.* (2005) suggested that adult Atlantic salmon (Pacific), once at a dam, will search across the river for passage routes and that entrance preferences were for deep and wide openings with a significant attraction flow. Similar behaviour and recommendations have been observed for salmonids (Calles *et al.* 2013*a*; Fjeldstad *et al.* 2013). The water velocity, which is also a function of discharge, was considered to be essential. Pavlov (1989) determined through field studies on a large number of fish species that attraction flow velocity should be $\sim$60–80% of the individual's maximum swimming speed. The Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall (2014) indicated that, at the entrance of the fishway (not inside the actual fishway), the water speed should be at least 1 m s^{-1}, and even higher for salmonids such as grayling, brown trout and Atlantic salmon. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall (2014) recommended, generally, a gradual transition between the river bottom and the bottom of the fishway entrance, and that it should be a natural type of roughness on the bottom of this transition (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014).

Hydropower-plant outlets (also applies to outlets directly to a lake) should be provided with a physical barrier in the form of a bar rack, with a gap opening adapted to the smallest fish assumed to be present on its upstream migration. Many examples of powerplant outlets where bar racks have been omitted have shown that the fish migrate into the tailrace tunnel and remain there (Thorstad *et al.* 2003). By blocking the fish from swimming into the outlet channel, the migration delay is reduced and, in addition, the fish are prevented from moving into potentially hazardous areas that can cause physical damage or where they can be exposed to gas saturation and barotrauma. Furthermore, to efficiently guide fish past the power-plant outlet, an attractive migration option must be established in the form of an attraction flow with sufficient water velocity, and discharge as close as possible to the outlet, or in the area where fish are stopping as described above. If fish cannot be guided with attraction flow, it may be appropriate to establish a physical guide wall or fence. This has been used with some success downstream of hydropower plants in Denmark (Koed *et al.* 1996) and in the United Kingdom (Gowans *et al.* 1999). A disadvantage of such constructions is that they can be filled up with debris or destroyed by flood and ice.

Water intake (fishway exit) for fish passages

A suitable discharge in the fishway is determined by the upstream water level or some sort of technical flow-regulation device. Ramps, cell-shaped weirs and partly nature-like bypasses are flexible with regards to variation in river discharge and nature-like bypasses can withstand water-flow variation to a certain extent. However, it is acknowledged, as a general issue, that the water flow in fishways can be either too small or too large, particularly for pool and weir ladders, which basically need a certain water level for optimal functionality. If the water level upstream of a dam varies widely, one should generally prefer vertical-slot fishways rather than pool-type ladders with surface notches, because the vertical slots between the pools will regulate water flow in relation to the upstream water level, while the slope between the pools remains constant (Katopodis 1992). The discharge in the fishway not only affects the migration within the fishway but also the attraction flow at the fishway entrance. It is generally recommended to establish some sort of a sluice or gate in the upper end of the fishway to control the water intake. With this, the water flow can be optimised in relation to the size of the fishway and the water flow can be completely closed to perform maintenance or inspection of, for example, the fishway or fish counter. However, the gate must not be a barrier itself, which sometimes is the case. Dimensions, position and regulation must, therefore, be adapted to the fishway type and it is recommended to regulate the intake from the side, rather than performing a horizontal adjustment (Pulg *et al.* 2018).

The exit of the fishway should be located far enough from the hydropower-plant intake or the migration barrier, so that fish do not fall back over spill gates or get sucked into the intake (Seifert 2016). This is a site-specific metric that depends on local hydromorphological conditions. In general, water velocities in the river next to the fishway exit should be lower than those inside the fishway, so that fish can easily continue their upstream migration. Water velocities below 0.5 m s^{-1} are referred to as safe (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014). As for the fishway entrance, there should be a gradual transition between the river bottom and the bottom of the fishway exit. (Dumont *et al.* 2005; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014; Seifert 2016).

Slope, height and energy dissipation in upstream fish passages

Ramps and nature-like bypasses are generally designed to mimic natural watercourses (Calles *et al.* 2013*b*). The design is based on natural morphological models (Pulg *et al.* 2018). Drop height (DH) between the pools depends on the type of watercourse and the migrating fish species. It is recommended to follow the overview given in Table 2. That is, the DH should be between 10 and 20 cm for silver eel, grayling and inland brown trout, and between 20 and 50 cm for Atlantic salmon and anadromous brown trout. The gradient should be at most 0.1 (salmon) and 0.08–0.05 for trout and grayling. A coarse bottom substrate generally gives adequate opportunities for migration because a network of corridors of different scale occurs.

It should be noted that, (1) according to the Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (2012), no further documentation is required on the function of the passage if the fish passage is constructed according to the guidelines. If the guidelines are not met, the function should be tested by additional monitoring and if necessary the fishway needs to be adjusted.

It should also be noted that (2) the recommendations for the maximum height between the pools have been significantly reduced over the past 20 years, on the basis of experience with many hundred fish passages in Austria, Switzerland and Germany. Although a DH of 30–50 cm was recommended by the Deutcher Verband für Wasserwirtschaft und Kulturbau (1996) guidelines and the Food and Agriculture Organisation of the United Nations (2002) guidelines, the recommendations in the latest guidelines are between 13 and 20 cm for brown trout, eel and grayling, and up to 30 cm for trout and Atlantic salmon (Dumont *et al.* 2005; Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft 2012; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014; Seifert 2016).

Pool and weir ladders and other concrete pool structures (so-called technical fishways) have been shown, in many cases, and with a proper design, to be effective for adult Atlantic salmon and anadromous brown trout. Besides the fact that fish can migrate in such ladders, they have the advantage that they do not require as much space as do nature-like bypasses and can flexibly be adapted to the terrain. However, on the basis of this review, many European fishways do not have an optimal design, particularly for smaller fish and fish species with a low

Table 2. Design criteria for fishways for upstream migration, based on guidelines from Germany, Austria and Norway (Dumont *et al.* 2005; Grande 2010; Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft 2012; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014; Seifert 2016; Pulg *et al.* 2018)

Well suited, full connectivity possible; with correct design, all year classes of the fish species can pass with efficiency higher than 90%. Partly suited, selective connectivity; with correct design, only some size classes can migrate at certain periods of the year. Not suited, no connectivity; fish can only occasionally pass

Measure/fishway type	Fish species				
	Atlantic salmon, large brown trout	Resident brown trout	Grayling	Silver eel	Glass eel
Removal of barrier	Well suited	Well suited	Well suited	Well suited	Well suited
Nature-like ramps and cell-shaped weirs	Well suited	Well suited	Well suited	Well suited	Well suited
Nature-like bypass	Well suited	Well suited	Well suited	Well suited	Well suited
Vertical-slot ladder	Well suited	Well suited	Well suited	Well suited	Not suited
Pool-and-weir ladder with surface notch	Well suited	Partly suited	Partly suited	Not suited	Not suited
Pool-and-weir ladder with bottom orifice	Well suited	Partly suited	Partly suited	Partly suited	Not suited
Denil fishway	Partly suited	Partly suited	Not suited	Not suited	Not suited
Hydraulic characteristics in technical fishways					
Recommended maximum drop between pools (DH) (cm)	20–50; 20–30 in vertical slot passes	18–20	15–20	13–15	Glass-eel passage required
Recommended maximum energy dissipation ($W\,m^{-3}$)	160–250	160–250	120–200	100–150	
Minimum pool length (cm)	280–400	210–310	150–250	150–250	
Minimum pool width (cm)	170–225	140–150	170–185	140–180	
Minimum depth (cm)	50–105	50–105	60–70	75	
Minimum slot width in vertical-slot fishways (cm)	30	15	20	25–30	
Pool-and-weir ladders					
Minimum notch height (cm)	50–60	30–50	30–50	30–60	
Minimum width (cm)	40–60	20–50	25–50	35–60 bottom orifice	

swimming capacity (Fjeldstad *et al.* 2013; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014; Seifert 2016). This is especially evident for the drop between the pools (DH). Adult Atlantic salmon in Norway has been shown to pass in traditional pool-and-weir ladders with a drop of 0.5–1 m between the crests (Fjeldstad *et al.* 2013); however, monitoring data have indicated that this may be too high for efficient passage (Grande 2010), especially at low water temperatures, which reduce the metabolism and, consequently, the ability of the fish to swim. This can explain why fishways can cause delays under the fish migration. Calles *et al.* (2013*a*) recommended that the vertical water drop between the pools should not exceed 30 cm for Atlantic salmon and this has been supported especially by Degerman (2008), Dumont *et al.* (2005) and Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall (2014). However, the broad Norwegian experience with Atlantic salmon fishways has suggested that the drop could be increased to 50 cm (Fjeldstad *et al.* 2013, 2018; Pulg *et al.* 2018) for pool-and-weir ladders, whereas it should not exceed 30 cm in vertical-slot ladders. Nevertheless, it is expected that the fishways would work better if the water drop between the pools were reduced, with a longer period of good efficiency throughout the season, and less delay. For inland brown trout, and not the least for grayling, the water drop between the pools should be halved and, for grayling, there must be slots between the pools because grayling does not jump during their migration. In vertical-slot ladders for grayling, a coarse bottom substrate should also be established, which would ensure low water velocities along the bottom. Limited drop between the pools is also required for the grayling to be able to migrate at low water temperatures during its spring migration period.

Pool size in fishways is determined by the drop between the pools, the water discharge and the fish species and size. For Atlantic salmon and large trout, the energy dissipation in the pools should not exceed 200–250 $W\,m^{-3}$ (see Table 2), and, for smaller inland trout and grayling, it should not exceed 150–200 $W\,m^{-3}$. For vertical-slot ladders, the slot width should be at least three times the width of the largest fish to pass through the fishway. Similarly, the pool length in such ladders should be at least 10 times the width of the slot or three times the length of the longest fish (Katopodis 1992; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014) and the pool width at least eight times the slot width. Fishway slope is given by the pool size and the drop between the pools, and typical slopes in many European fishways are 7–10%.

Adult and large juvenile eels can swim upstream vertical-slot fishways as long as the bottom substrate is consistently rough. In pool-and-weir fishways, these eel stages can migrate upstream if there are bottom openings in the weirs. These should have a brush structure at least on one side, so that even the juvenile eels can ‘crawl’ through. However, the youngest stages (<8 cm, glass eels) and small juvenile eels require a different type of passage, because their behaviour is different from that of older eels. Glass eels (also called elvers) migrate near the surface and can overcome only low water velocities. They can migrate past obstacles by moving directly on the substrate surface, also outside the water, as long as the surface is moist and rough, such as, for example, on moss-clad rocks. So as to imitate such conditions, special eel passages have been developed. These consist of a channel with brushes, artificial turf or other structures with continuous voids that are kept moist (Armstrong *et al.* 2010; Environment Agency UK 2011; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014). For hydraulic details for design and dimensioning of eel passages, the English Guide for Eel Passages (Environment Agency UK 2011) is recommended.

Light condition

Light conditions can be important in fish passages. In Norway, there are examples where Atlantic salmon, trout and eel have passed several-hundred-metre long dark tunnels and culverts (e.g. River Apeltunelva, brown trout, 200 m; River Akerselva, Atlantic salmon and brown trout, 580 m; Pulg *et al.* 2018). In the River Lærdalselva, it was documented that the migration of Atlantic salmon was not delayed in a 200-m-long tunnel in full darkness (Romundstad 1991) and Fjeldstad *et al.* (2013) showed that migration in completely dark tunnels can work well at some sites, whereas, elsewhere, it is necessary to have artificial light. Migratory fish will not expose themselves unnecessarily, but, at the same time, they prefer to have a good view. Lindmark and Gustavsson (2008) found that more trout passed through a fish channel when it was painted dark. Turnpenny *et al.* (1998) showed that salmonids evaded a nature-like fishway without daylight. Several international guidelines (e.g. from the USA and Australia) recommend lighting for a variety of species, including salmonids. This also includes the entrance and exit of passages, to avoid steep transitions in light intensity. It is generally recommended that fishways should have daylight (during daytime) and no sudden changes in lighting conditions (International Commission for the Protection of the Danube River 2013).

The following is recommended for European conditions (Pulg *et al.* 2018): (1) sharp light changes compared with the river should be avoided; shadow and indirect light is preferred at entrances and inside fish passages; (2) in the case of simple hydraulic passages, such as natural river bed in culverts and low gradients (<0.05, E <150–300 W m^{-3}), no artificial light is usually required; and (3) for steep passages with complex hydraulics, moderate lighting is recommended during the day (artificial, gradient >0.05–0.1; E >150–300 W m^{-3}).

Other types of upstream fish passage

Denil fishways consist of special deflectors that produce spiral-shaped countercurrent, high-energy dissipation and reduced water velocities in the main stream of the fish pass. Studies have shown that denil passages are unsuitable for most species of fish and young fish, including all carp fish, eel, white fish and grayling (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014). Denil passages have not been shown to work in practice. Armstrong *et al.* (2010) stated that specifically designed denil passages with a low gradient may work for several species, but they require certain hydraulic conditions and are, therefore, not suitable at varying water levels (Armstrong *et al.* 2010). Denil fish passages can be used in special situations and can be suitable for adult Atlantic salmon and brown trout at limited space and in steep terrain.

Sluices and lifts have been used especially at large height differences and in limited available space (Croze *et al.* 2008). The solutions are often selective because one and the same capture device rarely works for all species and age groups. Moreover, the installation itself can have a deterrent effect on some fish. In England, Germany and France, the functional capacity of such facilities has been rated as low, because only a small part of the fish found their way up (Armstrong *et al.* 2010).

Tank and truck of migrating fishes has been used in the case of large migration barriers, and especially where there are a series of barriers after each other. Tank and truck systems are basically selective, labour consuming and require repetitions in the long term, but can still contribute to occurrence or fish production of a species when other solutions are not realisable.

The authors advocate that the solutions mentioned above as ‘other types’ should not be chosen as a primary solution for efficient upstream fish passage.

A concept for prioritisation of fishway types

On the basis of experiences from the past decades of measures implemented in Europe for improved river connectivity (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft 2012; Calles *et al.* (2013*a*); Seifert 2016; Pulg *et al.* 2018), we recommend the following priority list (see also Table 2):

- If connectivity is to be restored, it should initially be considered whether the migration barrier can be removed. This is the best long-term solution if the goal is to recreate connectivity. This study focused on regulated rivers where dams will basically be maintained; however, also in regulated rivers there are possibilities for removing obstacles. Particularly on residual flow reaches or in spill channels, weirs or smaller dams have successfully been removed (Fjeldstad *et al.* 2012*a*).
- If barrier removal is not possible, fish passages can make the barrier passable for fish. The best solutions reach across the entire river transect and include the whole river discharge at site, which, again, makes it suitable both for up- and downstream migration. Examples of such solutions are ramps and cell-shaped weirs. Fish will find the migration corridor quickly and can use it in both directions. If such solutions are nature-like, re-establish full connectivity, and if they do not require maintenance, these are considered as full restoration of connectivity (Pulg *et al.* 2018).
- If the situation allows only parts of the water flow to be used in the fish pass, or the total drop is too large for ramps and weirs, different types of bypass fishways are used instead. These are different construction types that are chosen for the specific purposes and local topographic conditions. The entrance must be located where the fish naturally search for a migration corridor. Therefore, multiple entrances should be considered at large rivers and when species diversity is high. The bypass must have a sufficiently good hydraulic design, as well as regular maintenance. Technical fishways and nature-like

Table 3. Priority of solutions for upstream migration

Priority	Fish-passage type	Fish migration potential if properly designed	Remarks
1	Removal of barrier	All native freshwater species in Europe	Restores connectivity. Works for up- and downstream migration. Low or no selectivity and delay of fish. May affect economic usage of water.
2	Nature-like ramps and cell shaped weirs	All native freshwater species in Europe	Potentially restores connectivity. May work for both up- and downstream migration. Low or no selectivity and delay of fish. Length of the ramp will vary with the drop of the barrier and the solution is usually used for barriers below 5-m drop.
3	Nature-like bypass	All native freshwater species in Europe	Fish-pass efficiency of >90% for upstream migration may be reached if designed properly. Needs maintenance and usually a form of operation. Needs more space than do technical fishways, but can also provide habitat function, such as, for example, spawning grounds
4	Vertical-slot pass	All native freshwater species in Europe	Fish-pass efficiency of >90% may be reached for upstream migration if designed properly. Needs maintenance and usually a form of operation. Needs less space than does a nature-like bypass.
5	Pool-and-weir ladder	Atlantic salmon and large brown trout; also subadult eels if bottom orifice is installed and kept open.	Fish-pass efficiency of >90% may be reached for upstream migration if designed properly, but only for selected species. May be even shorter than vertical-slot fishways, but is best suited for species with a high swimming capacity
6	Other solutions (such as lifts, sluices and denil fishways)	Often selective for a few species and fish sizes	Fish-pass efficiency of >90% not likely to be reached, even if designed properly. Should be used only in special cases and under special circumstances

bypasses are artificial facilities and require regular maintenance and some form of operation and are, therefore, not considered as complete restoration measures.

On the basis of the above (Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft 2012; Calles *et al.* 2013*a*; Seifert 2016; Pulg *et al.* 2018), a conceptual priority list for solutions to ensure efficient upstream migration is proposed (Table 3).

Downstream migration and migration facilities

The focus on downstream migration is a result of the increased awareness and knowledge that entrainment in Kaplan, Pelton and Francis turbines often involves high fish mortality (Larinier and Travade 2002; Calles and Greenberg 2009; Kroglund *et al.* 2011; Calles *et al.* 2012; Fjeldstad *et al.* 2012*b*). Safe downstream migration past hydropower structures and intakes is complicated because the fish tend to follow the bulk water flow, which often enters diverting tunnels and turbine intakes. At the same time, downstream migration is essential for fish to complete all stages of its life cycle, and effective downstream migration passages should be provided if fish can pass upstream a hydropower barrier (Čada *et al.* 2006).

The risk of injury and mortality from blade strike is particularly great for adult fish (Montén 1985; Čada 1990) because the likelihood for blade strike increases with an increasing fish length and, hence, turbine injuries and mortality depend on both the size of the fish and the turbine specifications, such as number of blades and pressure drop. The highest survival rate has been observed for small fish in large low-pressure Kaplan turbines in North America, with direct blade-strike mortality being in the range of 2–20% (Hogan *et al.* 2014). This corresponds with the results of studies in Norway and Sweden where the probability of blade strike has been both modelled and studied in the field (see e.g. Montén 1985; Ferguson *et al.* 2005). Blade-strike probability increases linearly with the fish length and can reach 100% for large fish. Fish-friendly turbines have been designed, which generally imply a larger turbine size and runner-gap minimisation (see https://voith.com/corp-en/VH_Product_Brochure_Environmentally-friendly-turbine-design_14_vvk_t3360e_en.pdf, accessed 28 October 2018), and, thus, lower water velocities through the runners (Hogan *et al.* 2014). Mortality increases with the power plant's total head and is larger in small turbines. In addition, there may be delayed mortality, mainly owing to cavitation, turbulence, pressure drop (barotrauma) and shear stress and scratches (Brown *et al.* 2014). Although there is ongoing innovation and research on 'fish-friendly turbines, we advocate that, in general, fish should not enter turbines, considering both the immediate risk of injuries and mortality (particularly for large fish), and the delayed effects for surviving fish after passage (Deng *et al.* 2011; Skalski *et al.* 2002; Brown *et al.* 2014).

Fish migration delay at power-plant reservoirs and forebays is problematic because a swift and synchronised migration is often essential for the fish to complete the most favourable migration. Such delay can cause increased predation, energy loss and, at worst, fish may choose not to migrate, which in turn results in ecological effects (Čada 1997; Acou *et al.* 2008).

The challenge of safe downstream migration is global, and several authorities have developed manuals and guidelines to prevent migration into intakes and, in some cases, also to ensure migration for fish past water intakes and dams (see e.g. Calles *et al.* 2013*a* for Sweden; Environment Agency UK 2011 for England; and Dumont *et al.* 2005 for North Rhine–Westphalia, Germany).

Although traditional trash racks or Eicher screens themselves are not effective as complete fish barriers, downstream migration past the barrier can be significantly increased if a fish-adapted bypass is designed close to the intake (Arnekleiv *et al.* 2007). Other solutions that also have been shown to increase downstream fish survival past hydropower plants are guiding screens, such as louvres, wire screens and partial-depth fine-screen fish collectors, combined with transport and spill of water (Fjeldstad *et al.* 2012*b*).

Until recently, many of these solutions were regarded as premature, costly and with uncertain passage efficiency (Larinier and Travade 2002; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2005). Gough *et al.* (2012) concluded that there is little to no experience with downstream migration facilities in most European countries, with some exceptions. Indeed, several national fishway guidelines (Armstrong *et al.* 2010; Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft 2012; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014; Seifert 2016) have avoided or paused downstream solutions as a topic, although fish migration is 'a two-way street' (Calles and Greenberg 2009). Recent research and full-scale testing have demonstrated that downstream-migration facilities can indeed reach high passage efficiency (>90%). This is especially true for fine screens (Greenberg *et al.* 2017; Emanuelsson *et al.* 2017; Nyqvist *et al.* 2017) and has found the way into recent national guidelines (Calles *et al.* 2013*a*; Pulg *et al.* 2018). Although retrofitting of existing hydropower plants may be challenging, case studies have shown that it has been realised (Nyqvist *et al.* 2017; Økland *et al.* 2017).

The knowledge on downstream migration and the challenges related to passage of hydropower facilities vary among fish species. Studies on eels are increasing, but the general situation for downstream migratory eels in Europe is largely unknown. On the basis of several field experiments, significant mortality in a major part of hydroelectric turbines in Europe must be assumed (Thorstad 2010; Kroglund *et al.* 2011; Thorstad *et al.* 2011). For resident brown trout, the situation is similar, with knowledge being poor on both the extent of the problem and solutions, and for European grayling, the knowledge is particularly limiting.

For Atlantic salmon, extensive research has shown that both smolts and kelts migrate through turbines and, although we often do not know the exact consequences, mortality rates probably follow the pattern demonstrated in several international surveys (Montén 1985; Larinier and Travade 2002; Deng *et al.* 2011; Brown *et al.* 2014). Promising experiments on fine-mesh trash racks have been conducted and are currently under way in Sweden and Denmark (Calles *et al.* 2012; Greenberg *et al.* 2017; Nyqvist *et al.* 2017). Coanda intakes, although not initially used as fish barriers, are increasingly being applied to smaller intakes with the presence of inland trout and grayling. However, for most migrating fish, especially for anadromous fish and eel, it is not sufficient to block the migration in front of the intake. Alternative migration corridors or bypasses must be established for the fish to complete the migration past the barrier (escape openings and bypasses). A range of technical solutions has been studied (Larinier and Travade 2002; Calles *et al.* 2013*a*), and, at many installations, they have been proven to be efficient (Nyqvist *et al.* 2017; Økland *et al.* 2017). However, solutions are largely site-specific (Kroglund *et al.* 2011) and it may be particularly challenging to achieve high efficiency if the escape-route entrance is located too far from the water intake or barrier (Larinier and Travade 2002).

Although knowledge on salmonid smolt and eel downstream migration facilities has increased in recent years, little is known about downstream migration facilities for grayling. Because of lack of experience, it is generally assumed that grayling behaves similarly to trout or Atlantic salmon smolts, because they belong to the same family and overlap partly in size (Pulg *et al.* 2018). However, there may be significant differences because of differences in habitat use over life, timing of migration and body size (Linløkken 1993). Grayling fry is known to drift downstream after swim-up (Linløkken 1993; Jungwirth *et al.* 1998) and little is known about how these early life stages are influenced by dams, hydroplants or downstream passage facilities. Owing to their small size (15–30 mm), they are likely to pass even through 10-mm-fine screens, but it remains unexplored to what extent they tolerate turbine passage and spill over dams.

In some studies, repulsion measures using light and sound have shown some effect (Johnson and Ploskey 1998; Welton *et al.* 2002; Johnson *et al.* 2005; Fjeldstad *et al.* 2012*b*), whereas in other experiments, no effect has been observed (Johnson and Ploskey 1998; Ploskey *et al.* 1998; Welton *et al.* 2002). This may be related to the general behaviour of different fish species, as well as the local conditions and the time of day when the fish migrate. In the River Mandalselva in Norway, strobe lights gave a repulsing effect on migratory Atlantic salmon smolt at night, but not during daytime (Fjeldstad *et al.* 2012*b*). Repulsion measures (electric fields, light, sound, air bubbles) in front of hydropower intakes may, thus, have some effect, but are recommended only in combination with other measures, or if trash racks or other physical barriers are not feasible. Combined solutions with repulsion and attraction measures (such as extra spill of water) have been shown to be rather successful in guiding fish towards a bypass route (Økland *et al.* 2013).

Both traditional trash racks and the inclined passive-pressure Eicher screen are known to guide fish into bypass systems, but the total fish-guidance efficiency differs from site to site (Winchell and Sullivan 1991; Calles *et al.* 2013*a*). Electrical field barriers have successfully been used to prevent eels from entering industrial water inlets (www.profish-technology.be, accessed 14 September 2018); however, for downstream migration, the technology is challenging, both in terms of human safety and the risk that fish can be paralysed and drift into the intake. Other physical behavioural barriers, such as partial-depth fine screens and guiding fences, or so-called louvres, have increased bypass migration significantly in some locations, when combined with bypass structures (Scruton *et al.* 2008).

A significant part of artificially induced mortality during downstream fish migration at hydropower plants does not happen during turbine passage but in impoundments upstream and pools downstream of the barriers, owing to increased predation (Jepsen *et al.* 2000; Koed *et al.* 2002, Økland *et al.* 2017). Jepsen *et al.* (1998) showed that this mortality may be higher than turbine mortality for Atlantic salmon and brown trout smolt. Changes in river morphology, water velocity and turbulence induced by dams and hydroelectric plants may decrease migration speed and lead to disorientation of the migrating fish. At the same time, these changes often improve habitat and hunting conditions for predators such as pike (*Esox Lucius*) and cormorant (*Phalacrocorax carbo sinensis*; Jepsen *et al.* 2000). It is, therefore, recommended to look beyond the barriers and turbines of hydropower plants and to include their effects on river morphology, habitat and predation when designing downstream passages, such as placement of bypass intakes and outlets. Predation can be reduced by facilitating rapid downstream migration with steady and fast water flow. Stopping points, such as pools or back eddies in downstream migration corridors, should therefore be avoided. Also, at the downstream end of a bypass (the exit), the fish should be guided directly into fast-flowing water downstream, not into a turbulent pool at the tail race (Ebel 2013). When entering or leaving a bypass system, physical protection, such as a netting against birds, may be considered. Bypass solutions through flood gates (<10-m drop) and pipe transport (water velocity <12 m s^{-1}) have been shown to function for juvenile salmonids (Johnson and Dauble 2006) and these techniques can be helpful to transport fish to safe areas.

Many authors underline the accumulative effects of several barriers on the downstream migration routes of fish (Jungwirth *et al.* 1998; Larinier 2008; Kroglund *et al.* 2011; Norrgård *et al.* 2017). High passage efficiency per barrier (90%) may accumulate to low total efficiency after several barriers (e.g. 35% efficiency after 10 passages). Efficiency targets, passage design and method should, therefore, take accumulative effects into account. Norrgård *et al.* (2017) recommended considering trap and transport at multiple barrier routes.

In conclusion, safe downstream migration past hydropower intakes is obtained by preventing fish from entering the hydropower stations and directing the fish quickly and safely past the power-plant structures. If only small fish migrate and the alternative migration route is risky, fish friendly turbines may be an alternative. Solutions that are regarded as best practices for downstream migration past power-plant structures for eel, grayling, brown trout and Atlantic salmon are presented below.

Best-practice solutions and recommendations

Downstream migration facilities past hydropower plants must be designed differently from upstream migration bypasses because the fish largely follow the main water flow, which, at the power station, most often enters the water intake to the turbines. For downstream passages, it is therefore recommended to use a trash rack and guiding structure, together with a bypass, so as to defer and guide the fish to one or more escape routes where they can enter safely into a bypass system past the power plant (Larinier and Travade 2002; Calles *et al.* 2013*a*; Pulg *et al.* 2018). The gap between the bars in the trash rack must be so small that the fish cannot pass between them. Additionally, fish should not be in direct contact with the trash rack or guiding unit, to prevent them from being injured or impinged. The probability of good function of trash racks increases as the angle between the rack and the main flow towards the rack is reduced. The angle contributes to a lower velocity vector through the rack and to guiding the fish to a bypass at the end of the rack. Dumont *et al.* (2005) and Calles *et al.* (2013*a*) recommended an angle of 35° or lower relative to the main flow and velocities lower than 0.5 m s^{-1} through the screen. For eels and salmonids, the location of escape-route entrances is particularly important. The general recommendation is close to the river bottom for eels and at the surface for salmonid fishes. A particularly successful downstream passage facility for both Atlantic salmon and eel was installed at a hydroplant in Sweden (Härting in River Ätran). The facility consists of an angled (30°) β-screen (15 mm) and a bypass intake formed as a vertical slot covering the whole water column, and provides high passage efficiency for silver eels (95%), salmon kelts (96%) and salmon smolt (91–98%; Calles *et al.* 2015; Nyqvist *et al.* 2017). The solution is considered as best practice in Sweden. The bar rack is 40 m long, and has hydrodynamic, horizontal bars made of composite. The angle to the main flow is 30°. Long trash tracks or screens should be equipped with multiple escape openings. Calles *et al.* (2013*a*) recommended openings every 10 m at α-screens. To ensure that fish that enter a bypass do not stop or return, turbulence or rapid changes in water velocity should be avoided (Ebel 2013).

The only safe solution to prevent fish from entering hydropower intakes is fine-mesh trash racks, with a gap opening smaller than the width of the fish. For smolt of Atlantic salmon and brown trout, the recommended gap is a maximum of 15 mm, which corresponds to practice in Sweden (Calles *et al.* 2013*a*), whereas German guidelines requires even smaller gaps (10 mm; Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2014). Such racks will also be a barrier to migratory eel, as well as adult grayling, brown trout and Atlantic salmon. Both horizontal and vertical bars can be used, and the decision depends on the design of a bypass system and practical maintenance and installation. High water velocity towards a bar rack implies a risk of fish impingement on the rack and reduces the ability for fish to escape into safe bypasses. Hence, the perpendicular force from the water flow to the rack should not exceed a respective perpendicular component of the water velocity at 0.5 m s^{-1} for salmon and trout smolts, adult eel and grayling. To reduce the water velocity normally to the rack and to guide the fish towards an escape opening and the bypass, it is recommended that the angle of the rack is less than 35–40° on the main direction of flow, and preferably less than 30°, both for horizontally sloping or inclined racks being used (so-called β-rack and α-rack; Fig. 1). Dumont *et al.* (2005) recommended similar angles and water velocities but 10-mm bar spacing in racks for smolts and eels, on the basis of experiments in Germany and France. Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall (2005) recommended 12-mm bar spacing for Atlantic salmon smolts.

A recently published study from three run-of-river hydropower plants with downstream migration measures in Germany described a high passage efficiency for silver eels (Økland *et al.* 2017). At the Unkelmuehle power station (Sieg River), 96 and 92% of the eels in 2014 and 2015 respectively passed safely. The power plant has an α-rack, 10-mm bar spacing, one surface escape opening and multiple escape openings at the bottom. Most of the eels passed over the dam and into the spillway next to the trash rack. In the study of Økland *et al.* (2017), the bottom

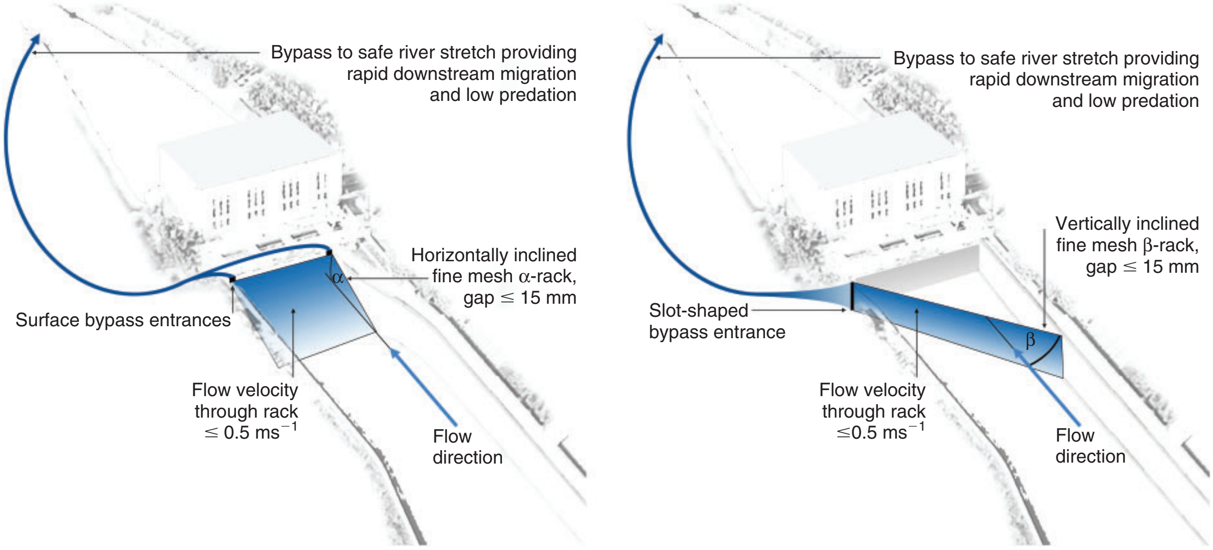

Fig. 1. Illustration of two different configurations of fine-mesh fish screens with the so-called α-rack to the left and the β-rack to the right.

openings were seldom used as a migration route, probably because of turbid water. No eels were drawn into the turbine. The turbine at the Gengenbach power plant on the River Kinzig is adjustable and is located within a chamber protected by a 15-mm curved trash rack. Here, at least 84% of the eels passed safely. At the Kuhlemuehle power plant on the River Diemel, a fish-friendly screw turbine (Archimedess screw) was installed. Here, 76% of the silver eels passed safely. For the remaining fish, it could not be verified whether they stayed upstream, were taken by predators or died in the turbine. The results confirmed that more than 90% passage efficiency can be reached for eels using migration measures, especially with fine-mesh bar racks and bypass possibilities.

Successful migration depends on the fish continuing their migration past the location of the dam or power plant. Danish studies have shown that as few as 10–20% of adult eels migrate safely past single dams and down to the sea (Pedersen *et al.* 2012), despite the fact that the intakes were provided with fine-mesh trash racks. This emphasises the importance of properly designed bypass systems. The bypass can either (1) be immediately aside the power plant intake or it can (2) be located at the dam, which may be located downstream of the intake. The first situation provides the best opportunity for an effective solution because the fish can easily find the alternative route (bypass), and the entrance to the bypass should in such cases be located near the place where the fish are most likely to search. A fault of few metres in the location has been shown to reduce the efficiency significantly (Kroglund *et al.* 2014). For Atlantic salmon and brown trout smolts, this means that the entrance to the bypass should be placed near the surface and, for the eel, at the bottom immediately near the power plant intake. The most common recommendation is that the opening should be successively tapered and have rounded sides and bottom to achieve water acceleration less than 1.0 m s^{-1} per metre of outlet channel, and with the least possible turbulence. The width of the escape opening should be 0.5–1.0 m, and the depth should not be less than 0.4 m (Calles *et al.* 2013*a*). With limitations on design, depth should be prioritised over width (Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall 2005). Depending on the location and trash-rack design, it is recommended that the water flow in the bypass should be 2–10% of the total river discharge on site.

Conclusions

In this paper, relevant literature mainly from Europe but also from North America has been reviewed to advise river managers, water authorities and hydropower industry of best-practice solutions for safe two-way migration for Atlantic salmon, brown trout, grayling and eel past hydroelectric structures. The reviewed studies have highlighted that many existing fishways for upstream migration are not designed according to existing knowledge and many hydroelectric structures are not provided with any sort of facilities for safe downstream passage for fish past turbines. Consequently, large parts of migrating fish populations are delayed or blocked, or experience large mortality during their migration upstream or downstream past such structures. The studies have shown that potential solutions with a passage efficiency larger than 90% exist for both up- and downstream passage for Atlantic salmon, brown trout and European eel. However, for European grayling, it remains unclear whether the downstream solutions can reach this efficiency and further research is needed.

The traditional technical fishways for upstream migration, such as pool-and-weir fishways, have been shown to serve as an appropriate solution for adult Atlantic salmon and large brown trout with a high swimming capacity, but they are not recommended as a best-practice solution for smaller trout, grayling and eel. For these species, a suite of different fishway facilities is suggested, including dam removal, nature-like bypasses, ramps and vertical-slot passes and a smaller drop between the pools. Glass eels demand specially designed glass-eel passages.

Turbine passage as a downstream migration corridor where salmonids and eels are present is problematic because of the risk of both direct injuries and delayed mortality effects. Recent studies have shown that it is possible to reach 90% downstream passage efficiency by physically blocking the turbine intake for fish with fine-mesh trash racks, combined with escape routes and bypass corridors, and we recommend this approach as the best practice. The latest fish-friendly turbines such as minimum-gap runners and screws have shown that high fish survival can be obtained under certain circumstances. Large Kaplan turbines can also pass small fishes, such as salmon smolts, at high survival rates. If only small fish migrate and if any other migration route is risky, fish-friendly turbines may be used as an alternative. This might be the case at very large dam sites, where screening systems have been shown to be difficult because of high cost, energy loss and low turbine-passage mortality rates. If complete blocking of the water intake for fish is not feasible, a combination of attraction and repulsion measures can be used, in combination with physical guiding structures and a bypass, to reduce mortality. However, 90% efficiency is not likely to be reached with attraction and repulsion alone. None of these solutions is yet common standard in Europe.

Conflicts of interest

The authors declare that they have no conflicts of interest.

Acknowledgements

This study is supported by the Norwegian Research council and the Norwegian hydropower industry (project number 244022).

References

Acou, A., Laffaille, P., Legault, A., and Feunteun, E. (2008). Migration pattern of silver eel (*Anguilla anguilla*, L.) in an obstructed river system. *Ecology Freshwater Fish* **17**, 432–442. doi:10.1111/J.1600-0633.2008.00295.X

Allen, G., Amaral, S., and Black, J. (2012). Fish protection technologies: the US experience. In 'Operational and Environmental Consequences of Large Industrial Cooling Water Intakes'. (Eds S. Rajagopal, H. A. Jenner, and V. P. Venugopalan.) pp. 371–390. (Springer Nature Switzerland AG.)

Armstrong, G., Aprahamian, M., Fewings, G., Gough, P., Reader, N., and Varallo, P. (2010). 'Environment Agency Fish Pass Manual.' (Environment Agency: Bristol, UK.)

Arnekleiv, J., and Kraabol, M. (1996). Migratory behaviour of adult fast-growing brown trout (*Salmo trutta* L.) in relation to water flow in a regulated Norwegian river. *Regulated Rivers: Research and Management* **12**, 39–49. doi:10.1002/(SICI)1099-1646(199601)12:1<39::AID-RRR375>3.0.CO;2-#

Arnekleiv, J. V., Kraabøl, M., and Museth, J. (2007). Efforts to aid downstream migrating brown trout (*Salmo trutta* L.) kelts and smolts passing a hydroelectric dam and a spillway. *Hydrobiologia* **582**, 5–15. doi:10.1007/S10750-006-0547-8

Brink, K., Gough, P., Royte, J., Schollema, P. P., and Wan-ningen, H. (2018). 'From Sea to Source 2.0. Protection and Restoration of Fish Migration in Rivers Worldwide.' (World Fish Migration Foundation: Groningen, Netherlands.)

Brown, R. S., Colotelo, A. H., Pflugrath, B. D., Boys, C. A., Baumgartner, L. J., Deng, Z. D., Luiz, G. M., Silva, L. G. M., Brauner, C. J., Mallen-Cooper, M., Phonekhampeng, O., Thorncraft, G., and Singhanouvong, D. (2014). Understanding barotrauma in fish passing hydro structures: a global strategy for sustainable development of water resources *Fisheries* **39**(3), 108–122. doi:10.1080/03632415.2014.883570

Bundesministerium für Land- und Forstwirtschaft, Umwelt und Wasserwirtschaft (2012). 'Leitfaden zum Bau von Fischaufstiegshilfen.' (BMLFUW: Wien, Austria.)

Čada, G. F. (1990). A review of studies relating to the effects of propeller type turbine passage on fish early life stages *North American Journal of Fisheries Management* **10**(4), 418–426. doi:10.1577/1548-8675(1990)010<0418:AROSRT>2.3.CO;2

Čada, G. F. (1997). Shaken, not stirred: the recipe for a fish-friendly turbine. In 'Waterpower '97. Proceedings of an International Conference & Exposition on Hydropower'. pp. 374–382. (American Society of Civil Engineers: New York, NY, USA.)

Čada, G. F. (2001). The development of advanced hydroelectric turbines to improve fish passage survival. *Fisheries* **26**(9), 14–23. doi:10.1577/1548-8446(2001)026<0014:TDOAHT>2.0.CO;2

Čada, G. F., Loar, J. M., Garrison, L., Fisher, R. K., and Neitzel, D. (2006). Efforts to reduce mortality to hydroelectric turbine-passed fish: locating and quantifying damaging shear stresses. *Environmental Management* **37**(6), 898–906. doi:10.1007/S00267-005-0061-1

Calles, O., and Greenberg, L. (2009). Connectivity is a two-way street: the need for a holistic approach to fish passage problems in regulated rivers. *River Research and Applications* **25**(10), 1268–1286. doi:10.1002/RRA.1228

Calles, O., Karlsson, S., Hebrand, M., and Comoglio, C. (2012). Evaluating technical improvements for downstream migrating diadromous fish at a hydroelectric plant. *Ecological Engineering* **48**, 30–37. doi:10.1016/J.ECOLENG.2011.05.002

Calles, O., Degermann, E., Wickstrøm, E., Christiansson, J., Wickstrøm, H., and Næslund, I. (2013*a*). Anordningar för upp- och nedströmspassage av fisk vid vattenanläggningar. Havs- og Vattenmyndigheter. Report 2013:14. Available at https://www.havochvatten.se/download/18.5f66a4e81416b5e51f73113/1383209282924/rapport-hav-2013-14-anordningar-passage-fisk.pdf [Verified 14 September 2018].

Calles, O., Karlsson, S., Vezza, P., Comoglio, C., and Tielman, J. (2013*b*). Success of a low-sloping rack for improving downstream passage of silver eels at a hydroelectric plant. *Freshwater Biology* **58**(10), 2168–2179. doi:10.1111/FWB.12199

Calles, O., Christiansson, J., Kläppe, S., Alenäs, I., Karlsson, S., Nyqvist, D., and Hebrand, M. (2015). Slutrapport Hertingprojektet: förstudie och uppföljning av åtgärder för förbättrad fiskpassage 2007–2015. Technical report. Naturresurs Rinnande Vatten, Biologi, Karlstads Universitet, Karlstad, Sweden.

Chatellier, L., Wang, R.-W., David, L., Courret, D., and Larinier, M. (2011). Experimental characterization of the flow across fish-friendly angled trashrack models. In 'Proceedings of the 34th World Congress of the International Association for Hydro- Environment Research and Engineering: 33rd Hydrology and Water Resources Symposium and 10th Conference on Hydraulics in Water Engineering', 26 June–1 July 2011, Brisbane, Qld, Australia. (Eds E. M. Valentine, C. J. Apelt, J. Ball, H. Chanson, R. Cox, R. Ettema, G. Kuczera, M. Lambert, B. W. Melville, and J. E. Sargison.) pp. 2776–2783. (Engineers Australia: Barton, ACT, Australia.)

Clay, C. H. (1995). 'Design of Fishways and other Fish Facilities.' (Lewia Publishers: Boca Raton, FL, USA.)

Coutant, C. C., and Whitney, R. R. (2000). Fish behaviour in relation to passage through hydropower turbines: a review. *Transactions of the American Fisheries Society* **129**, 351–380. doi:10.1577/1548-8659(2000)129<0351:FBIRTP>2.0.CO;2

Croze, O., Bau, F., and Delmouly, L. (2008). Efficiency of a fish lift for returning Atlantic salmon at a large-scale hydroelectric complex in France. *Fisheries Management and Ecology* **15**, 467–476. doi:10.1111/J.1365-2400.2008.00628.X

Degerman, E. (2008). Ekologisk restaurering av vattendrag. Naturvårdsverket & Fiskeriverket. (Fiskeriverket och Naturvårdsverket.) Available at https://

www.havochvatten.se/download/18.64f5b3211343cffddb2800022567/1348912824990/ekologisk-restaurering-av-vattendrag.pdf [Verified 14 September 2018].

Deng, Z., Carlson, T. J., Dauble, D. D., and Ploskey, G. R. (2011). Fish passage assessment of an advanced hydropower turbine and conventional turbine using blade-strike modeling. *Energies* **4**(1), 57–67. doi:10.3390/EN4010057

Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall (2005). 'Fish Protection Technologies and Downstream Fishways. Dimensioning, Design, Effectiveness Inspection.' (DWA: Hennef, Germany.)

Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall (2014). 'Merkblatt M-509: Fischaufstiegsanlagen und Fischpassierbare Bauwerke: Gestaltung, Bemessung, Qualitätssicherung.' (DWA: Hennef, Germany.)

Deutcher Verband für Wasserwirtschaft und Kulturbau (1996). Fischaufstiegsanlagen – Bemessungen, Gestaltung, Funktionskontrolle. In 'Merkblätter zur Wasserwirtshaft, Vol. 232'. (Wirtschafts- und Verlagsgesellschaft Gas und Wasser: Bonn, Germany.)

Dumont, U., Danderer, P., and Schwevers, U. (2005). 'Handbuch Querbauwerke.' (MUNLV: Düsseldorf, Germany.)

Ebel, G. (2013). 'Fischschutz und Fischabstieg an Wasserkraftanlagen: Handbuch Rechen- und Bypasssysteme.' (BGF, Mitteilungen aus dem Buro fur Gewasserokologie und Fischereibiologie Dr. Ebel (Band 4): Halle (Saale), Germany.)

Electric Power Research Institute–US Department of Energy (2011). 'Conference on Environmentally Enhanced Hydropower Turbines: Technical Papers.' (EPRI: Palo Alto, CA, USA; and DOE: Washington, DC, USA.)

Emanuelsson, A., Christensen, P., Mikaelsson, F., Böjer, M., Göransson, F., Östberg, J., Öhrfeldt, U., Hemfrid-Schwartz, Y., Noren, P., and Calles, O. (2017). Fysiska avledare för uppsamling av blankål vid vattenkraftverk. Tekniska utmaningar och kostnadseffektiviseringar. Report 2017: 458, Energiforsk, Stockholm, Sweden.

Environment Agency UK (2011). Screening at intakes and outfalls: measures to protect eels. Available at http://www.therrc.co.uk/MOT/References/EA_Eel_Manual.pdf [Verified 28 October 2018].

Fahrig, L. (2003). Effects of habitat fragmentation on biodiversity. *Annual Review of Ecology and Systematics* **34**, 487–515. doi:10.1146/ANNUREV.ECOLSYS.34.011802.132419

Ferguson, J. W., and Williams, J. (2002). 'Recommendations for Improving Fish Passage at the Stornorrfors Power Station on the Umealven, Umea, Sweden.' (Northwest Fisheries Science Center: Seattle, WA, USA.)

Ferguson, J. W., Matthews, G. M., McComas, R. L., Absolon, R. F., Brege, D. A., Gessel, M. H., and Gilbreath, L. G. (2005). Passage of adult and juvenile salmonids through federal Columbia River power system dams. NOAA Technical Memorandum NMFS–NWFSC 64, pp. i–xx. National Technical Information Service, Springfield, VA, USA.

Fjeldstad, H.-P. (2012). Atlantic salmon migration past barriers. Ph.D. Thesis (NTNU thesis number 128-2012), Norwegian University of Science and Technology, Trondheim, Norway.

Fjeldstad, H.-P., Barlaup, B. T., Stickler, M., Gabrielsen, S.-E., and Alfredsen, K. (2012*a*). Removal of weirs and the influence on physical habitat for salmonids in a Norwegian river. *River Research and Applications* **28**, 753–763. doi:10.1002/RRA.1529

Fjeldstad, H. P., Uglem, I., Diserud, O. H., Fiske, P., Forseth, T., Kvingedal, E., Hvidsten, N. A., Økland, F., and Järnegren, J. A. (2012*b*). A concept for improving smolt migration past hydropower intakes. *Journal of Fish Biology* **81**, 642–663. doi:10.1111/J.1095-8649.2012.03363.X

Fjeldstad, H.-P., Alfredsen, K., and Forseth, T. (2013). Atlantic salmon fishways: the Norwegian experience. *Vann* **2**, 191–204.

Fjeldstad, H.-P., Pulg., U., and Forseth, T. (2018). Sikker toveis vandring forbi vannkraftverk: kunnskapsoppdatering og mønsterpraksis. SINTEF report 2017, 00723, SINTEF Energy, Trondheim, Norway.

Food and Agriculture Organisation of the United Nations (2002). 'Fish Passes: Design, Dimensions and Monitoring.' (FAO: Rome, Italy.)

Gough, P., Philipsen, P., Schollema, P. P., and Wanningen, H. (2012). From sea to source; international guidance for the restoration of fish migration highways. (Regional Water Authority Hunze en Aa's: Veendam, Netherlands.) Available at http://www.fromseatosource.com/?page=DOWNLOAD&version=2012 [Verified 30 October 2018].

Gowans, A. R. D., Armstrong, J. D., and Priede, I. G. (1999). Movements of adult Atlantic salmon in relation to a hydroelectric dam and fish ladder. *Journal of Fish Biology* **54**(4), 713–726. doi:10.1111/J.1095-8649.1999.TB02028.X

Grande, R. (2010). 'Håndbok for Fisketrapper.' (Tapir Akademiske Forlag: Trondheim, Norway.) [Summary and figure captions in English.]

Greenberg, L., Nyqvist, D., Bergman, E., and Calles, O. (2017). Förbättrad nedströmspassage för vild laxfisk I Klarälven. Report, University of Karlstad, Sweden.

Haltunen, E. (2011). Staying alive: the survival and importance of Atlantic salmon post-spawners. Ph.D. Thesis, Univesitetet i Tromsø, Norway.

Hart, D. D., and Poff, N. L. (2002). Introduction to special issue. *Bioscience* **52**(8), 653–655. doi:10.1641/0006-3568(2002)052[0653:ASSODR]2.0.CO;2

Hogan, T. W., Čada, G. F., and Amaral, S. V. (2014). The status of environmentally enhanced hydropower turbines. *Fisheries* **39**(4), 164–172. doi:10.1080/03632415.2014.897195

International Commission for the Protection of the Danube River (2013). 'Measures for Ensuring Fish Migration at Transversal Structures.' (ICPDR Secretariat: Vienna, Austria.)

Jansen, H. M., Winter, H. V., Bruijs, M. C. M., and Polman, H. J. G. (2007). Just go with the flow? Route selection and mortality during downstream migration of silver eels in relation to river discharge2007. *ICES Journal of Marine Science* **64**, 1437–1443. doi:10.1093/ICESJMS/FSM132

Jepsen, N., Aarestrup, K., Økland, F., and Rasmussen, G. (1998). Survival of radiotagged Atlantic salmon (*Salmo salar* L.) – and trout (*Salmo trutta* L.) smolts passing a reservoir during seaward migration. *Hydrobiologia* **371/372**, 347–353. doi:10.1023/A:1017047527478

Jepsen, N., Pedersen, S., and Thorstad, E. (2000). Behavioural interactions between prey (trout smolts) and predators (pike and pikeperch) in an impounded river. *Regulated Rivers: Research and Management* **16**, 189–198. doi:10.1002/(SICI)1099-1646(200003/04)16:2<189::AID-RRR570>3.0.CO;2-N

Johnson, G. E., and Dauble, D. D. (2006). Surface flow outlets to protect juvenile salmonids passing through hydropower dams. *Reviews in Fisheries Science* **14**, 213–244. doi:10.1080/10641260600864023

Johnson, P. N., and Ploskey, G. R. (1998). Behavioral technologies for bypass channels, phase 2: evaluation of infrasound and strobe lights for redistributing migrant salmon smolts in the McNary Juvenile Bypass. Technical report, US Department of Energy, Office of Scientific and Technical Information, Vicksburg, MS, USA.

Johnson, P. N., Bouchard, K., and Goetz, F. A. (2005). Effectiveness of strobe lights for reducing juvenile salmonid entrainment into a navigation lock. *North American Journal of Fisheries Management* **25**, 491–501. doi:10.1577/M04-073.1

Jungwirth, M., Schmutz, S., Weiss, S. (Eds) (1998). 'Fish Migration and Fish Bypasses. Fishing News Books.' (Blackwell Publications: Oxford, UK.)

Katopodis, C. (1992). Introduction to fishway design. Working document, Freshwater Institute, Fisheries and Oceans Canada, Winnipeg, MB, Canada.

Katopodis, C., and Williams, J. G. (2012). The development of fish passage research in a historical context. *Ecological Engineering* **48**, 8–18. doi:10.1016/J.ECOLENG.2011.07.004

Koed, A., Rasmussen, G., Holdensgård, G., and Pedersen, C. (1996). Tangetrappen 1994–95. DFU-rapport 8-96, Danmarks Fiskeriundersøgelser, Silkeborg, Denmark.

Koed, A., Jepsen, N., Aarestrup, K., and Nielsen, C. (2002). Initial mortality of radio-tagged Atlantic salmon (*Salmo salar* L.) smolts following release downstream of a hydropower station. *Hydrobiologia* **483**, 31–37. doi:10.1023/A:1021390403703

Kraabøl, M. (2012). Reproductive and migratory challenges inflicted on migrant brown trout (*Salmo trutta* L.) in a heavily modified river. PhD Thesis, NTNU, Institut for Biologi, Trondheim, Norway.

Kraabøl, M., Arnekleiv, J. V., and Museth, J. (2008). Efforts to aid downstream migrating brown trout (*Salmo trutta* L.) kelts and smolts passing a hydroelectric dam and a spillway. *Fisheries Management and Ecology* **15**, 417–423.

Kroglund, F., Haugen, T., Güttrup, J., Hawley, K., Johansen, J., Rosten, C., Kristensen, T., and Tormodsgard, L. (2011). Effekter av å passere en kraftverksturbin på smoltoverlevelse og atferd. Betydningen av tiltak. Report 6139, NIVA, Oslo, Norway.

Kroglund, F., Haraldstad, T., Güttrup, J., and Hegeland, P. V. (2014). Evaluering av tiltak for nedvandrende blankål ved elvekraftverk. Resultater fra forsøk ved Fosstveit kraftverk, 2010–2013. Report 6722–2014, NIVA, Oslo, Norway.

Laine, A., Kamula, R., and Hooli, P. (1998). Fish and lamprey passage in a combined denil and vertical slot fishway. *Fisheries Management and Ecology* **5**(1), 31–44. doi:10.1046/J.1365-2400.1998.00077.X

Larinier, M. (2008). Fish passage in small-scale hydro-electric power plants in France. *Hydrobiologia* **609**, 97–108. doi:10.1007/S10750-008-9398-9

Larinier, M., and Travade, F. (2002). Downstream migration: problems and facilities. *Bulletin Francais de la Peche et de la Pisciculture* **364**, 181–207. doi:10.1051/KMAE/2002102

Larinier, M., Travade, F., and Porcher, J. P. (2002). Fishways: biological basis, design criteria and monitoring. *Bulletin Francais de la Peche et de la Pisciculture* **364**, 1–208.

Liao, J. C. (2007). A review of fish swimming mechanics and behaviour in altered flows. *Philosophical Transactions of the Royal Society of London – B. Biological Sciences* **362**, 1973–1993. doi:10.1098/RSTB.2007.2082

Lindmark, E., and Gustavsson, L. H. (2008). Field study of an attraction channel as entrance to fishways. *River Research and Applications* **24**, 564–570. doi:10.1002/RRA.1145

Linløkken, A. (1993). Efficiency of fishways and impact of dams on the migration of grayling and brown trout in the Glomma River system, southeastern Norway. *Regulated Rivers: Research and Management* **8**, 145–153. doi:10.1002/RRR.3450080117

Lucas, M. C., and Baras, E. (2001). 'Migration of Freshwater Fishes.' (Blackwell Science: Oxford, UK.)

Mallen-Cooper, M., and Brand, D. A. (2007). Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? *Fisheries Management and Ecology* **14**, 319–332. doi:10.1111/J.1365-2400.2007.00557.X

Montén, E. (1985). 'Fish och Turbiner. Om Fiskars Möjligheter att Oskadda Passere Genem Kraftverksturbiner.' (Vattenfall: Stochholm, Sweden.)

National Oceanic and Atmospheric Administration (2012). 'Diadromous Fish Passage: a Primer on Technology, Planning, and Design for the Atlantic and Gulf Coasts.' (NOAA: Silver Spring, MD, USA.)

Nilsson, C., Reidy, C. A., Dynesius, M., and Revenga, C. (2005). Fragmentation and flow regulation of the world's large river systems. *Science* **308**, 405–408. doi:10.1126/SCIENCE.1107887

Noatch, M. R., and Suski, C. D. (2012). Non-physical barriers to deter fish movements. *Environmental Reviews* **20**(1), 71–82. doi:10.1139/A2012-001

Noonan, M. J., Grant, J. W. A., and Jackson, C. D. (2012). A quantitative assessment of fish passage efficiency. *Fish and Fisheries* **13**(4), 450–464. doi:10.1111/J.1467-2979.2011.00445.X

Norrgård, J., Greenberg, L. A., Piccolo, J. J., Schmitz, M., and Bergman, E. (2017). Multiplicative loss of landlocked Atlantic salmon *Salmo salar* L. smolts during downstream migration through multiple dams. *River Research and Applications* **10**, 1306–1317.

Nyqvist, D., Nilsson, P. A., Alenäs, I., Elghagen, J., Hebrand, M., Karlsson, S., Kläppe, S., and Calles, O. (2017). Upstream and downstream passage of migrating adult Atlantic salmon: remedial measures improve passage performance at a hydropower dam *Ecological Engineering* **102**, 331–343. doi:10.1016/J.ECOLENG.2017.02.055

Økland, F., Kvingedal, E., Lamberg, A., Kroglund, F., Forseth, T., Diserud, O., and Uglem, I. (2013). Smoltutvandring forbi Laudal Kraftverk i Mandalselva i 2013. Report 1067, NINA, Trondheim, Norway.

Økland, F., Teichert, M. A. K., Havn, T. B., Thorstad, E. B., Heermann, L., Sæther, S. A., Tambets, M., and Borcherding, J. (2017). Downstream migration of European eel at three German hydropower stations. Report 1355, NINA, Trondheim, Norway.

Östergren, J., and Rivinoja, P. (2008). Overwintering and downstream migration of sea trout (*Salmo trutta* L.) kelts under regulated flows: northern Sweden. *River Research and Applications* **24**, 551–563. doi:10.1002/RRA.1141

Pavlov, D. S. (1989). Structures assisting the migration of non-salmonid fish. Technical Paper 308, Food and Agriculture Organisation of the United Nations, Rome, Italy.

Pedersen, M. I., Jepsen, N., Aarestrup, K., Koed, A., Pedersen, S., and Økland, F. (2012). Loss of European silver eel passing a hydropower station. *Journal of Applied Ichthyology* **28**, 189–193. doi:10.1111/J.1439-0426.2011.01913.X

Ploskey, G. R., Johnson, P. N., Burczynski, M. G., Nestler, J. M., and Carlson, T. J. (1998). 'Effectiveness of Strobe Lights, Infrasound Devices, and a Sound Transducer for Eliciting Avoidance by Juvenile Salmon.' (US Army Engineer District: Portland OR, USA.)

Poulet, N. (2007). Impact of weirs on fish communities in a Piedmont stream. *River Research and Applications* **23**, 1038–1047. doi:10.1002/RRA.1040

Pulg, U., Barlaup, B. T., Velle, G., Gabrielsen, S.-E., Stranzl, S., Olsen, E. E., Lehmann, G. B., Wiers, T., Skår, B., Normann, E., and Fjeldstad, H.-P. (2018). Tiltakshåndbok for bedre fysisk vannmiljø: god praksis ved miljøforbedrende tiltak I elver og bekker. Report number 296, Uni Miljø Research, Bergen, Norway.

Quigley, J. T., and Harper, D. J. (2006). Effectiveness of fish habitat compensations in Canada in achieving no net loss. *Environmental Management* **37**, 351–366. doi:10.1007/S00267-004-0263-Y

Raynal, S., Chatellier, L., Courret, D., Larinier, M., and David, L. (2014). Streamwise bars in fish-friendly angled trashracks. *Journal of Hydraulic Research* **52**(3), 426–431. doi:10.1080/00221686.2013.879540

Rivinoja, P. (2005). Migration problems of Atlantic salmon (*Salmo salar* L.) in flow regulated rivers. Ph.D. Thesis, number 2005: 114, Swedish University of Agricultural Sciences, Umeå, Sweden.

Romundstad, A. T. (1991). Biologiske og fiskeokonomiske forutsetninger for fisketrapper. Norske erfaringer. In 'Villaksseminaret Kompendium', 31 May–1 June 1991, Lærdal, Norway. (Eds F. E. Krogh and L. M. Sattem.) pp. 65–83. [In Norwegian].

Roscoe, D. W., and Hinch, S. G. (2010). Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. *Fish and Fisheries* **11**, 12–33. doi:10.1111/J.1467-2979.2009.00333.X

Rosten, C., Gozlan, R. E., and Lucas, M. C. (2013). Diel and seasonal movements of the critically endangered European eel. *Vann* **1**, 89–95.

Scruton, D. A., Pennell, C. J., Bourgeois, C. E., Goosney, R. F., King, L., Booth, R. K., Eddy, W., Porter, T. R., Ollerhead, L. M. N., and Clarke, K. D. (2008). Hydroelectricity and fish: a synopsis of comprehensive studies of upstream and downstream passage of anadromous wild Atlantic salmon, *Salmo salar*, on the Exploits River, Canada. *Hydrobiologia* **609**, 225–239. doi:10.1007/S10750-008-9410-4

Seifert, K. (2016). 'Fischaufstiegsanlagen in Bayern. Hinweise und Empfehlungen zur Planung Bau und Betrieb', 2nd edn. (Landesfischereiverband Bayern e.V. und Bayerisches Landesamt fuer Umwelt: Munchen.

Germany.) Available at https://lfvbayern.de/download/fischaufstiegsanlagen-in-bayern [Verified 28 October 2018].

Silva, A. T., Lucas, M. C., Castro-Santos, T., Katopodis, C., Baumgartner, L. J., Thiem, J. D., Aarestrup, K., Pompeu, P., O'Brien, G. C., Braun, D., Burnett, N. J., Zhu, D. Z., Fjeldstad, H. P., Forseth, T., Rajaratnam, N., Williams, J. G., and Cooke, S. (2018). The future of fish passage science, engineering, and practice. *Fish and Fisheries* **19**, 340–362. doi:10.1111/FAF.12258

Skalski, J. R., Mathur, D., and Heisey, P. G. (2002). Effects of turbine operating efficiency on smolt passage survival. *North American Journal of Fisheries Management* **22**, 1193–1200. doi:10.1577/1548-8675(2002)022<1193:EOTOEO>2.0.CO;2

Szabo-Meszaros, M., Navaratnam, C. U., Aberle, J., Silva, A. T., Forseth, T., Calles, O., Fjeldstad, H.-P., and Alfredsen, K. (2018). Experimental hydraulics on fish-friendly trash-racks: an ecological approach. *Ecological Engineering* **113**, 11–20. doi:10.1016/J.ECOLENG.2017.12.032

Thorstad, E. B. (2010). Ål og konsekvenser av vannkraftutbygging – en kunnskapsoppsummering. Miljøbasert Vannføring 1–2010. (Norges Vassdrags- og Energidirektorat: Oslo, Norway.) Available at http://www.nina.no/archive/nina/PppBasePdf/rapporter%20i%20ekstern%20rapportserie/2010/Thorstad%20%C3%85l%20Milj%C3%B8basert%20Vannf%C3%B8ring%201%202010.pdf [Verified 30 October 2018].

Thorstad, E. B., Økland, F., Kroglund, F., and Jepsen, N. (2003). Upstream migration of Atlantic salmon at a power station on the River Nidelva, southern Norway. *Fisheries Management and Ecology* **10**, 139–146. doi:10.1046/J.1365-2400.2003.00335.X

Thorstad, E. B., Økland, F., Aarestrup, K., and Heggberget, T. G. (2008). Factors affecting the within-river spawning migration of Atlantic salmon, with emphasis on human impacts. *Reviews in Fish Biology and Fisheries* **18**(4), 345–371. doi:10.1007/S11160-007-9076-4

Thorstad, E. B., Larsen, B. M., Finstad, B., Hesthagen, T., Hvidsten, N. A., Johnsen, B. O., Næsje, T. F., and Sandlund, O. T. (2011). Kunnskapsoppsummering om ål og forslag til overvåkingssystem i norske vassdrag. Report 661, NINA, Trondheim, Norway.

Travade, F., and Larinier, M. (2002). Chapter 12. Monitoring techniques for fishways. *Bulletin Francais de la Peche et de la Pisciculture* **364**, 166–180. doi:10.1051/KMAE/2002101

Tsikata, J. M., Tachie, M. F., and Katopodis, C. (2014). Open channel turbulent flow through bar racks. *Journal of Hydraulic Research* **52**(5), 630–643. doi:10.1080/00221686.2014.928805

Turnpenny, A. W. H, Struthers, G., and Hanson, K. P. (1998). 'A UK Guide to Intake Fish Screening Regulations, Policy and Best Practice.' (Fawley Aquatic Research Laboratories Ltd & Hydroplan: Fawley, UK.)

Washington Department of Fish and Wildlife (2000). 'Fish Passage Barrier and Surface Water Diversion Screening and Prioritization Manual.' (WDFW: Olympia, WA, USA.)

Welton, J. S., Beaumont, W. R. C., and Clarke, R. T. (2002). 'The efficacy of air, sound and acoustic bubble screens in deflecting Atlantic salmon, *Salmo salar* L., smolts in the River Frome, UK. *Fisheries Management and Ecology* **9**(1), 11–18. doi:10.1046/J.1365-2400.2002.00252.X

Williams, J. G. (1998). Fish passage in the Columbia River, USA and its tributaries: problems and solutions. In 'Fish Migration and Fish Bypasses'. (Eds M. Jungwirth, S. Schmutz, and S. Weiss.) Fishing News Book, pp. 180–191. (Cambridge University Press: Cambridge, UK.)

Williams, J. G., Armstrong, G., Katopodis, C., Larinier, M., and Travade, F. (2012). Thinking like a fish: a key ingredient for development of effective fish passage facilities at river obstructions. *River Research and Applications* **28**, 407–417. doi:10.1002/RRA.1551

Winchell, F. C., and Sullivan, C. W. (1991). Evaluation of the Eicher fish diversion screen at Elwha dam. In 'Waterpower '91: Proceedings of the International Conference on Hydropower', 24–26 July 1991, Denver, CO, USA. (Ed. D. D. Darling.) Vol. 1, pp. 93–102. (American Society of Civil Engineers: New York, NY, USA.)

Handling Editor: Daniel Deng