Ecological Engineering 105 (2017) 262–275

Contents lists available at ScienceDirect

Ecological Engineering

journal homepage: www.elsevier.com/locate/ecoleng

Research paper

Downstream migration of Atlantic salmon smolts past a low head hydropower station equippped with Archimedes screw and Francis turbines

T.B Havn[a,*], S.A Sæther[a], E.B Thorstad[a], M.A.K. Teichert[b], L. Heermann[b], O.H. Diserud[a], J. Borcherding[b], M. Tambets[c], F. Økland[a]

[a] Norwegian Institute for Nature Research - NINA, P.O. Box 5685 Sluppen, NO-7485 Trondheim, Norway
[b] University of Cologne, Institute for Zoology, General Ecology & Limnology, Zülpicher Str. 47b, Köln, 50674, Germany
[c] Wildlife Estonia, Veski 4, Tartu 51005, Estonia

ARTICLE INFO

Article history:
Received 10 November 2016
Received in revised form 23 March 2017
Accepted 27 April 2017
Available online 15 May 2017

Keywords:
Mortality
Migration speed
Fishway
Radio tag
Telemetry
Salmo salar

ABSTRACT

Downstream migration of 112 radio-tagged Atlantic salmon smolts was studied in the Diemel, Germany, to examine 1) mortality and migration speeds during riverine migration and at a hydropower station, 2) choice of migration routes at the power station, and 3) survival and transit speed through Archimedes screw and Francis turbines. Mortality was not elevated in the impounded stretch above the dam compared to a free-flowing control stretch (1.9 and 2.5% loss per km, respectively). Migration speeds did not differ among the control stretch, impounded stretch and in passing the power station, but there was large individual variation. Smolts reaching the power station (n = 101) could choose between six possible passage routes. Most smolts passed through the Archimedes screw (43%), or via a route where Francis turbines were installed (33%). Three percent migrated over the dam, 14% used a fishway at the Archimedes screw and 8% used a fishway at the Francis turbines. The smolts used the fishways (instead of the Archimedes and Francis turbines) more often than expected from the proportion of water discharge, especially larger smolts at lower discharge. Smolts passed the power station mainly in the evening and early night. Migration speed past the power station was faster for smolts passing via the Archimedes screw and associated fishway than for those using other routes. Smolts were not markedly delayed in their downstream migration by using the Archimedes screw. Immediate mortality of smolts passing through the Archimedes screw and Francis turbines was probably below 10% and 13%, respectively.

1. Introduction

Hydropower is the largest renewable electricity source, and a doubling of global capacity is foreseen by 2050 (International Energy Agency, 2012). Most of the growth is foreseen from large hydropower projects, but some also from smaller run-of-the-river projects, including installing turbines in existing mill sites and weirs (International Energy Agency, 2012; Okot 2013). Run-of-the-river hydropower stations have limited water storage and often small head differences, and may have less impact on the environment than projects involving large dams, high heads and large reservoirs (*e.g.*, Okot 2013; Benejam et al., 2016). Run-of-the-river power stations still have negative impacts on the environment, such as impacts on migrating fishes that have to pass barriers at hydropower stations during their life cycle (*e.g.*, Coutant and Whitney 2000; Haro et al., 2000; Kynard and Horgan 2001; Haro and Castro-Santos 2012). It is therefore necessary to improve mitigation measures for migrating fishes by reducing injury, mortality and migration delays caused by hydropower installations.

Atlantic salmon (*Salmo salar*) is an anadromous species with spawning and juvenile stages in freshwater and a migration to marine feeding areas (Thorstad et al., 2011a). During downstream migration towards the sea, Atlantic salmon are termed smolts. The smolt migration was previously believed to be a passive displace-

* Corresponding author.
E-mail addresses: Torgeir.Havn@nina.no (T.B Havn), Stein.Saether@nina.no (S.A Sæther), Eva.Thorstad@nina.no (E.B Thorstad), mteicher@uni-koeln.de (M.A.K. Teichert), Lisa.Heermann@uni-koeln.de (L. Heermann), Ola.Diserud@nina.no (O.H. Diserud), Jost.Borcherding@uni-koeln.de (J. Borcherding), meelis.tambets@gmail.com (M. Tambets), Finn.Okland@nina.no (F. Økland).

http://dx.doi.org/10.1016/j.ecoleng.2017.04.043
0925-8574/

ment by river currents, but several studies have documented that active migration occurs, with smolts swimming faster than the current (Davidsen et al., 2005; Svendsen et al., 2007). Little is still known of the movement patterns and swimming speeds of smolts in rivers (McCormick et al., 1998; Thorstad et al., 2012).

The smolt stage can be a challenging phase with high mortality (McCormick et al., 1998; Thorstad et al., 2012). Hydropower stations, dams, weirs and other barriers may lead to elevated mortality and major passage problems for downstream migrating smolts (*e.g.*, Hvidsten and Johnsen, 1997; Larinier and Travade 2002; Scruton et al., 2008; Stich et al., 2014; Nyqvist et al., 2016). Increased mortality rate at power stations is not only due to fish being killed by turbines, but depends on factors such as predation in the reservoir or impounded river stretch above the power station dam, the proportion of smolts passing through the turbines, the immediate and delayed mortality of smolts passing through the turbines, and the mortality of smolts using alternative passages around power stations (Thorstad et al., 2012). Alternative passages may for instance be spillways, purpose-built bypasses and old river beds. The proportion of smolts passing through the turbines or other passages may be related to the proportion of water diverted through each of the routes (Hvidsten and Johnsen 1997; Serrano et al., 2009), but there are few published studies of detailed smolt behaviour at power stations and other river barriers (but see *e.g.*, Scruton et al., 2002, 2008; Gardner et al., 2016).

Mortality for smolts passing through turbines depends on turbine type, other characteristics of the turbines, height of water heads, fish size and a number of other factors (Ruggles 1980; Eicher 1987; Thorstad et al., 2012). Efforts have been made to construct more fish-friendly turbines (Čada, 2001; Castro-Santos and Haro 2015; Thorstad et al., 2017), including the Archimedes screw turbine. This turbine design is often regarded as less harmful to fish than other turbines (Bracken and Lucas 2013) due to the slow rotation speed, the absence of extreme pressures and shear forces, and because the water travels in blocks at a slow speed down the screw, with enough space to hold fish (Potter et al., 2012). However, negative effects may not only be related to direct injuries when passing the turbine, but also to migration delays above or below the turbine. There is generally little knowledge of the effects of Archimedes screw turbines on behaviour and mortality of downstream migrating fish. We know of only one scientific publication on the effects on fish, by Bracken and Lucas (2013), who found minor impacts on larvae and juvenile lamprey *Lampetra* sp. Some technical reports exist (summarized by Potter et al., 2012), but there is an absence of scientifically evaluated knowledge of the effects of Archimedes screw turbines.

In German rivers, a decline of Atlantic salmon began with the industrial revolution, caused by pollution, habitat degradation and fragmentation by weirs and dams. By the end of the 1950s, German salmon populations were extinct (Molls and Nemitz 2008; Monnerjahn 2011). Re-introduction programs have been initiated in several rivers, including the Weser (Molls and Nemitz 2008; Monnerjahn 2011). The aim of this study was to examine downstream migration of Atlantic salmon smolts on free-flowing river stretches and at the Kuhlemühle power station in the Diemel, which is a tributary to the Weser. Specific objectives were to examine 1) mortality and migration speeds during riverine migrations and at the power station, 2) choice of migration routes at the power station related to water discharge, and 3) migration behaviour and mortality for smolts passing through Archimedes screw and Francis turbines. Smolts were tagged with radio transmitters, released 4.6 km above the power station, and their movements followed by using stationary receivers and manual tracking. Detailed monitoring of the behaviour of the smolts at the power station was done by using a network of stationary receivers.

2. Study area

The Weser is a 452 km long river in northwestern Germany, emptying into the North Sea at Bremerhaven (Fig. 1), with a catchment area of 46 306 km^2 and average water discharge of 327 $m^3 s^{-1}$. It used to be among the main Atlantic salmon rivers in Germany (Monnerjahn 2011). Re-introduction programs have been initiated, but dams and weirs within the river system still block migrations (Monnerjahn 2011). Hence, there is no self-sustained Atlantic salmon population or re-introduction programme in the Diemel, where this study was performed. The Diemel is a 110 km long tributary to the Weser, with a catchment area of 1762 km^2 and an average discharge of 16 $m^3 s^{-1}$ at Helmarshausen near the confluence to the River Weser.

Kuhlemühle is a run-of-the-river power station (Figs. 1 and 2). A 4-bladed Archimedes screw turbine is installed (3.4 m diameter and 7 m long), which is run on either slow (12 revolutions per minute) or fast speed (24 revolutions per minute), corresponding to a water discharge through the turbine of 3 $m^3 s^{-1}$ and 5 $m^3 s^{-1}$, respectively. The turbine does not have rubber buffer strips on the blades, but the lowermost end of the blades are cut in a slight angle compared to a straight angle to the stem – to reduce the risk that they will strike and damage fish. The gap between the blade and the housing is ~1.5 cm. There is no rack in front of the Archimedes screw to prevent fish from entering the turbine. There are also two Francis turbines at the site (capacity of 4.5 and 2.2 $m^3 s^{-1}$, respectively, 90 rotations per minute), which optimally exploit a drop of 2.6 m. The entire intake to the Francis turbines is covered by a horizontal rack with 20 mm bar spacing. The efficiency of the Francis turbines is 5–8% higher than the Archimedes screw turbine, but according to the owner, the maintenance costs of the screen, screen cleaner, electronics etc. for operating the Francis turbines ultimately negates their higher efficiency (Michael Kohlschein, personal communication).

The dam at the power station affects the river by slowing down water velocity for approximately 1.3 km upstream, referred to as the impounded river stretch. Downstream migrating fish can use six different routes when they pass the power station (Fig. 2). The fish can move over the dam and outside the area with hydropower installations only when the water discharge is large enough for excess water to flow over the dam crest (>12 $m^3 s^{-1}$, occurred 10–15 April, and for 10 h on 27 April), or when a gate is opened to flush debris through (opened 7 times during the study for ca. 5 min each time). The passage for debris at the Francis turbine was automatically opened for 15 s when the rack cleaners were operating (approximately every 2 h during most of the study, but approximately every 3 h from 18 May). Another power station, Diemelmühle, is located 2.1 km downstream from Kuhlemühle (Fig. 1). Monitoring at this site was not part of the study.

3. Methods

3.1. Tagging of Atlantic salmon smolts

In total, 112 two-year old hatchery-reared Atlantic salmon smolts from the Albaum hatchery were tagged and released (69 smolts on 10 April and 43 smolts on 15 April 2015). Mean total length was 155 mm (range 101–180 mm, SD 11.4) and mean mass 41 g (range 27–61 g, SD 8.1). The smolts were transported by car in 600 l tanks with oxygen supply from the hatchery to Kuhlemühle the same day as they were tagged (transport time 2–3 h), and the tagging was performed at Kuhlemühle. Transmitters were surgically implanted into the body cavity using methods described by Finstad et al. (2005). Prior to tagging, the fish were anaesthetized in 75 $mg\,l^{-1}$ benzocaine, and during surgery