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Upstream and downstream passage of migrating adult Atlantic salmon: Remedial measures improve passage performance at a hydropower dam

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ABSTRACT

Habitat connectivity is central for life-cycle progression for migrating organisms. Passage of hydropower dams is associated with mortality, delay, and migratory failure for migrating fish, and the need for remedial measures to facilitate passage is widely recognized. Lately, nature-like fishways have been promoted for upstream migrating fish, and low-sloping turbine intake racks for downstream migrating fish, but evaluations of these remedial measures are largely lacking. At Herting hydropower dam in southern Sweden, a technical fishway for upstream migrating salmonids, and a simple bypass entrance/trash gate for downstream migrating fish have been replaced by a large nature-like fishway for up and downstream migrating fish, and a low-sloping rack, guiding downstream migrating fish to the bypass entrance, has been installed. In this study, we evaluated these remedial measures for adult Atlantic salmon, spawners and kelts, in a before/after improved remedial measures radio telemetry study. Passage performance was improved for both up- and downstream migrating adult Atlantic salmon after remedial measures. Passage rate increased for fish migrating in both directions, and overall delay decreased while overall passage efficiency increased for upstream migrating fish. After the improved passage solutions almost all tagged fish passed the dam with very little delay. Before modifications, upstream passage performance through the technical fishway was higher at higher temperatures, at day compared to night, and for males compared to females. No such effects were observed for the after-measures nature-like fishway, indicating good passage performance for both sexes under a wide range of environmental conditions. Similarly, for downstream migrating kelts, discharge positively affected passage rate before but not after the fishway modifications. Altogether, our work demonstrates the possibility of coexistence between hydropower and Atlantic salmon in a regulated river.

1. Introduction

Habitat connectivity is central for life-cycle progression for migrating organisms. In rivers, fish may migrate to feed, reproduce or to seek refuge (Lucas et al., 2001). River longitudinal connectivity may be disrupted by man-made dams that constitute barriers for migrating fish (Jonsson et al., 1999), and the need to safeguard longitudinal river connectivity by enabling two-way passage for fish at such migration obstacles has been acknowledged since hundreds of years (Montgomery, 2004; Waldman, 2013). Despite this, during the last century, fish passage solutions have focused mainly on the upstream passage of strong swimmers such as large salmonids, resulting in construction of many technical solutions such as Denil, vertical slot, and pool and weir fishways (Katopodis and Williams, 2012), with variable functionality even for salmonids (Bunt et al., 2012; Noonan et al., 2012). During the last decades, however, nature-like fishways, for upstream- and downstream migrating fish, as well as more technical downstream passage solutions have been widely promoted (Calles et al., 2013a; Castro-Santos et al., 2009; Katopodis et al., 2001).

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The Atlantic salmon (*Salmo salar*) life cycle typically consists of a juvenile stage in freshwater followed by smoltification and downstream migration to marine feeding areas. After months or years of growth at sea, the salmon return to their rivers of origin to spawn. Atlantic salmon that survive spawning (called kelts) migrate back to feeding areas at sea and return to spawn also in subsequent years (Jonsson and Jonsson, 2011), are viewed as of genetic (Saunders and Schom, 1985), stabilizing (portfolio effect; Moore et al., 2014; Schindler et al., 2010) and productive (Halttunen, 2011) importance for salmon populations. Downstream migration of both smolts and adult post-spawners, as well as upstream migration of adult spawners, are pivotal for continuation of the Atlantic salmon life cycle. In regulated rivers, the Atlantic salmon therefore need to pass dams in both up- and downstream directions, potentially on several occasions (Calles and Greenberg, 2009).

Even with fish passage solutions present, both up- and downstream passage is often associated with delays and migration failure. Upstream migrating salmonids can fail to pass (Gowans et al., 2003; Karppinen et al., 2002; Thorstad et al., 2008), whereas downstream migrating fish in addition might suffer direct or delayed mortality as an effect of spill, bypass or turbine passage (Muir et al., 2001; Ferguson, 2005; Ferguson et al., 2006). Both upstream and downstream migrating fish may also experience costly delays (Marschall et al., 2011; Thorstad et al., 2008; Venditti et al., 2000), related to increased susceptibility to disease, predation and sport fishery mortality (de Leaniz 2008; Gowans et al., 1999; Gowans et al., 2003). Delays and dam passage have also been associated with post-passage mortality for both upstream and downstream migrating salmonids (Caudill et al., 2007; Roscoe et al., 2011; Stich et al., 2015).

Where remedial measures for downstream migrating fish exist, the fish pass via bypasses, fishways or spill water (Calles et al., 2013a; Colotelo et al., 2012). As many downstream migrating fish follow the bulk flow of water (Coutant and Whitney, 2000; Jansen et al., 2007; Williams et al., 2011), structural guidance is often needed to guide the downstream migrating fish, away from turbines, to a safe route past hydropower plants to increase passage efficiency and reduce delays (Larinier, 1998). Low-sloping intake racks, use the natural water current to guide the downstream migrating fish towards a bypass entrance, and have been applied for several species with variable success (Gosset et al., 2005; Nettles and Gloss, 1985; EPRI, 2001).

Nature-like fishways simulate natural streams, offer a diversity of substrates and hydraulic conditions, and are supposed to provide suitable passage conditions and habitat for a wide variety of fish species, including Atlantic salmon (Castro-Santos et al., 2009; Katopodis et al., 2001). Many species have been observed to use nature-like fishways (Calles and Greenberg, 2005; Makrakis et al., 2007; Schmutz et al., 1998), but both attraction and passage efficiency seem to be variable (Aarestrup et al., 2003; Bunt et al., 2012; Steffensen et al., 2013). Although often intended to facilitate upstream passage, nature-like fishways may, if correctly placed, pass fish in both up- and downstream directions.

Evaluation of existing fish passage solutions and increased understanding of fish behavior are important aspects of fish-passage science (Castro-Santos et al., 2009; Roscoe and Hinch, 2010). Low-sloping racks and nature-like fishways hold great potential for allowing migrating fish to pass hydropower dams, but thorough evaluations are largely lacking for both remedial solutions. In River Ätran, Sweden, the Herting hydropower dam has recently undergone substantial remediation reconstruction, where a former technical fishway for upstream migrating salmonids and a simple bypass for downstream migrating fish have been replaced with a nature-like fishway for up and downstream migrating fish, as well as a low-sloping rack guiding downstream migrating fish to the bypass entrance. Here we compare upstream- and downstream passage performance (passage rate, passage efficiencies and delay) for adult Atlantic salmon at the dam, before and after these remedial measures, considering effects of both environmental conditions (water temperature, discharge, daylight) and fish characteristics (sex, fish length).

2. Material and methods

2.1. Study river

The River Ätran (56°52′55″N, 12°28′46″E) is located in southwestern Sweden and enters the North Sea (Kattegatt) in the city of Falkenberg. The river is 243 km long with a mean annual discharge of 57 $m^3 s^{-1}$ (range 20–319 $m^3 s^{-1}$; 1990–2011; Olofsson, 2013). The catchment contains a large number of barriers to migrating fish, with eight hydropower dams in the lowermost 58 km of the main stem. The study site, Herting, is the first hydropower dam in the river, situated about 3 km upstream from the sea, and the only dam in the main stem equipped with fish passage solutions. Fish that pass Herting have access to 24 km of River Ätran, up to the second hydropower dam (Ätrafors), and 34 km of the tributary River Högvadsån (Fig. 1; Calles et al., 2010, 2012, 2013a).

2.2. Herting hydropower dam

Two hydropower plants are located by the Herting dam (Fig. 2), Herting 1 (H1) and Herting 2 (H2). H1 is a diversion hydropower plant built in 1903 and equipped with two Kaplan turbines with a combined intake capacity of 40 $m^3 s^{-1}$ (nr 1: 250 rpm, 15.0 $m^3 s^{-1}$; nr 2: 187 rpm, 25.0 $m^3 s^{-1}$). H2 is a run-of-river hydropower plant, constructed in 1945, and equipped with one Kaplan turbine (187 rpm, 25.0 $m^3 s^{-1}$). The total intake capacity of the two power plants is 65.0 $m^3 s^{-1}$. The dam was modified in 2013, when new fish passage facilities were built to improve two-way connectivity (Fig. 2).

2.3. Fish passage conditions at Herting 1945–2012

The main stem of the river was kept open, albeit with a reduced discharge as compared to natural conditions, and allowed fish passage until a 90 m wide dam and the second hydropower plant were built in 1945. At the same time, a Denil fishway (1.4 $m^3 s^{-1}$) was built in the tail-race of H2 to provide upstream passage, primarily for salmonids. To increase the attraction flow to the fishway, an additional 1.6 $m^3 s^{-1}$ was released in the proximity of the fishway entrance.

Until 2006, when the first downstream passage solution was implemented at the dam, downstream migrating fish had to pass via the turbines, or via the spill gates when water was spilled. A rack with 40 mm spacing, located at the entrance to the intake channel leading to H1, 150 m upstream of the turbine intake, prevented some fish from entering the intake channel. The turbine intake itself was protected by a rack with 90 mm spacing, angled about 60° from the horizontal. The H2 turbine intake was preceded by a 40 mm rack, angled about 77° from the horizontal, complemented by a 22 mm overlay installed during spring to prevent smolt passage. In 2006, 1.0 m wide panels were removed from each side of the 40 mm rack at the beginning of the intake channel to allow large fish to proceed downstream to the H1 turbine intake where fish could pass via a surface spill bypass. The bypass was 3.3 m wide and positioned on the side of the intake channel, i.e. the water entered the bypass at a 90° angle. Approximately 2.0 $m^3 s^{-1}$ was released into the bypass in spring (1 March–31 May) and 0.3 $m^3 s^{-1}$ in summer and autumn (1 June–15 November).