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Master's Thesis

Evaluation of innovative rehabilitation measures targeting downstream migrating Atlantic salmon smolt (*Salmo salar*) at a hydroelectric power plant in southern Sweden

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Date of submission: January 05th 2015

Master's thesis statement of originality

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Zusammenfassung

Der ökologische Zustand von Fließgewässern hat sich aufgrund verschiedener anthropogener Einflüsse weltweit stark verschlechtert. Die Bestände von diadromen Fischarten leiden maßgeblich unter der Veränderung ihrer Wanderkorridore durch Querbauwerke. Um die Durchgängigkeit für wandernde Fische an Wasserkraftanlagen zu erhöhen, werden häufig Fischpässe verschiedener Bauart errichtet. Diese Maßnahme kann die Durchgängigkeit für die stromaufwärts gerichtete Migration an Wasserkraftanlagen verbessern. Die Effizienz ist jedoch meist deutlich geringer für stromabwärts wandernde Fische. Des Weiteren existieren nur wenige technische Lösungen, die explizit die Durchgängigkeit für die stromabwärts gerichtete Migration erhöhen und die bestehenden Lösungen wurden häufig nicht vollständig evaluiert. Daraus resultiert, dass eine große Anzahl von stromabwärts wandernden Fischen, wie z.B. Smolts des Atlantischen Lachses (*Salmo salar*), gezwungen sind, die Turbinen von Wasserkraftwerken zu passieren, um den Ozean zu erreichen.

Diese Radiotelemetrie-Studie bewertet moderne Maßnahmen zur Durchgängigkeitssteigerung für abwandernde Smolts des Atlantischen Lachses an einer Wasserkraftanlage in Südschweden, im Vergleich zur dort bisher verwendeten Lösung. Am Versuchskraftwerk wurde, im Zuge einer extensiven Modernisierung, der konventionelle Turbinenrechen mit anschließendem Oberflächen-Bypass durch ein innovatives Leitrechen-Bypass-System ersetzt. Zudem wurde ein naturnahes Umgehungsgewässer angelegt.

Die Ergebnisse der Arbeit zeigen, dass diese Modernisierung die Bedingungen für die stromabwärts gerichtete Smolt-Migration gegenüber der ursprünglichen Lösung deutlich verbessert. Die Effizienz der Bypass-Anlage konnte um 68 % gesteigert werden, wohingegen die Anzahl an Turbinen-Passagen um 63 % reduziert wurde. Auch wenn es Komplikationen mit dem Betrieb der Bypass-Monitoring-Station gab, sind die Ergebnisse vielversprechend und es sollte möglich sein, die Bedingungen für die stromabwärts gerichtete Fisch-Migration an weiteren kleinen- bis mittleren Wasserkraftanlagen durch die Installation des bewerteten Systems zu verbessern.

Abstract

The ecological state of streams and rivers has aggravated on a global scale due to a wide range of anthropogenic influences. The disruption of migratory routes for diadromous fishes by hydroelectric power plants have led to major stock declines over the last century. As a result fishways have been built at many hydroelectric power plants in Europe to improve migration conditions at such obstacles. This measure may improve upstream migration, but typically does not solve corresponding passage problems for downstream migrating fish. Consequently large numbers of downstream migrants, e.g. Atlantic salmon smolt (*Salmo salar*), are forced to pass turbines on their way to the ocean. There are few rehabilitation measures specifically targeting downstream passage conditions and most of them lack scientific evaluation.

This thesis reports on a radio-telemetric-study to evaluate innovative rehabilitation measures targeting downstream migrating Atlantic salmon smolt, at a hydropower plant in southern Sweden. There had been extensive renovation works at the study site to improve passage conditions for migrating fishes. The conventional turbine rack and a modified conventional trash gate were replaced by a low sloping β-rack adjacent to a full depth bypass channel. Moreover, a nature-like fishway was built at the site.

The results show that the evaluated rehabilitation measures were able to significantly improve downstream passage conditions for Atlantic salmon smolts. Total passage success was high (94%) and bypass efficiency has increased by 68%, whereas the number of smolts passing through the turbines was reduced by 63%. Although there were some issues associated with the monitoring station in the new bypass, the results are promising and so prospective constructions of low-sloping β-racks with full-depth bypasses should lead to improved downstream passage conditions at additional hydroelectric power plants.

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1 Introduction

Various human activities are affecting and shifting the ecological state of streams and rivers worldwide (Rosenberg et al., 1997; Dudgeon et al., 2006). Habitat changes, high nutrition input and altered water regimes are just a few examples of anthropogenic changes in river systems (Rahel, 2002; Bunn and Arthington, 2002; Smith, 2003). Diadromous fish species, i.e. species that migrate between marine and freshwater, are especially affected by the disruption of their migratory routes by structures such as weirs, dams or hydroelectric power plants (HEP's) (Larinier, 2001). Hydroelectric power plants present a severe problem for migrating fish and are known to be responsible for 50% of all threatened fishes in Europe (Northcote, 1998). The longitudinal connectivity between spawning grounds and other relevant habitats, which is needed to ensure successful reproduction of diadromous species, has been significantly modified in most European rivers (Behrmann-Godel and Eckman, 2003; Lucas and Baras, 2001). Fishways have been built at many HEP's in Europe to allow upstream migrating fish to pass obstacles (Bratrich et al., 2004; Saltveit, 1993). This measure can be an effective tool for restoring upstream connectivity, but the efficiency is typically considerably lower for downstream migrating fish (Larinier, 1998). To ensure survival and recovery of severely decreased stocks of diadromous fish, both up- and downstream connectivity must be restored (Arnekleiv, Kraabol and Museth, 2007; Calles and Greenberg, 2009). Consequently a separate passage for downstream migrating fish is needed. Yet there are few technical solutions to improve downstream connectivity at HEP's and most of them lack scientific evaluations (Larinier, 1998; Calles and Greenberg, 2005; Rivinoja, 2005). It is crucial to evaluate existing innovative fish passage solutions in order to assess their respective efficiency and generate knowledge that may facilitate the development of new and highly efficient measures that rehabilitates migratory pathways in regulated rivers.

The Atlantic salmon *(Salmo salar)* is of high commercial value and thus among the most well-studied species of European anadromous fishes (Jonsson and Jonsson, 2011). Stocks of Atlantic salmon in Europe decreased drastically during the last century and it is know that HEP's are one of the main factors behind this negative trend (Parrish et al., 1998; Hindar, Gallaugher and Wood, 2003). Salmon migration has been thoroughly studied resulting in a variety of solutions to improve upstream connectivity for them at man-made obstacles (McCormick et al., 1998; Noonan, Grant and Jackson, 2012). Lesser attention has been paid to downstream migrating kelt and smolt (Noonan, Grant and Jackson, 2012). Still, many populations of Atlantic salmon are on an alarmingly low level, thus indicating the need of a holistic approach for rehabilitation measure targeting up- and downstream migrating fish (Calles and Greenberg, 2009). While some studies have been carried out on downstream migrating salmonids, there is still a severe deficit in scientific approaches and evaluations in order to improve downstream passage success at hydropower plants (Ferguson, 2005 a; Scruton et al., 2007; Calles et al., 2012).

In the life cycle of the Atlantic salmon, smolt stage is especially vulnerable to negative effects of HEP's (Fjeldstad et al., 2012). The characteristic behavior of following the main current during downstream migration, tend to guide smolts into the turbine intakes (Ferguson, 2005 a; Rivinoja, 2005). Due to their relatively small body size, conventional trash racks do not prevent them from passing. As a consequence, vast numbers of smolts are forced to pass through turbines on their way to the sea, sometimes even on more than one occasion. Even though direct turbine-induced mortality through blade strikes (Monten, 1985) or shear injuries (Mathur et al., 2000) might be low for commonly used Kaplan turbines (Larinier and Dartiguelongue, 1989), possible long term damages caused by passing a turbine are known to induce delayed mortality for salmonid smolts (Ferguson et al., 2006). The long-term effects of turbine passage are difficult to study and quantify, yet most likely it has a negative effect on a large proportion of the smolts that survive passing through turbines (Ebel, 2013). Studies have shown that HEP's can cause a delay on downstream migrating smolt (Beames-Derfer et al., 1990). The increased duration of time spent in the headwater of HEP's is known to increase the amount of predation on salmonid smolts (Ferguson et al., 2005 b) and should hence be minimized.

The aim of this radio-telemetric study was to evaluate newly built rehabilitation measures at a HEP targeting downstream migrating Atlantic salmon smolts in southern Sweden. The studied HEP was extensively modernized in 2013 to improve passage success for diadromous fishes. Key features of the modernizations are the replacement of the former downstream passage solution, consisting of a conventional turbine rack and a surface trash gate, with a horizontal composite β-rack followed by a full-depth bypass channel (Ebel, 2013).

With this study presenting the first quantitative evaluation of a composite β-rack targeting downstream migrating Atlantic salmon smolt, the general research approach was to compare the performance of the new passage solution to the old in regards of: 1. Overall passage success; 2. Fish guidance efficiency of the new bypass system; 3. Route selection i.e. passage through turbines in relation to other routes; 4. Mortality caused by the HEP; 5. Delay on smolt migration. To achieve this, data generated in this study were compared to the results of a pre-study which took place at the same site in 2007 (Calles et al., 2012).

2 Materials and methods

2.1 Study area and study site

The studied HEP is situated at river Ätran in the city of Falkenberg in south-western Sweden (N56° 54' 3.348" E12° 31' 19.567", Figure 1). River Ätran, with a total length of 243 km, a drainage area of 3342 km² and the mean annual discharge of 48.0 m^3s^{-1} (1961–1993) and 59.6 m^3s^{-1} during the last decades (1990–2011) (Olofsson, 2013), origins from a wetland area near the city of Gullered. The river flows through the Swedish provinces of Västergötland and Halland and enters the North Sea (Kattegatt subbasin) in the city of Falkenberg. There are eight HEP's in the main stem of the river. Six out of those eight HEP's are located in the lower catchment area of the river system (about 58 km from the river mouth) and in addition, there are several HEP's inside tributaries of which two are located in the biggest tributary river Högvadsån(Figure 1).

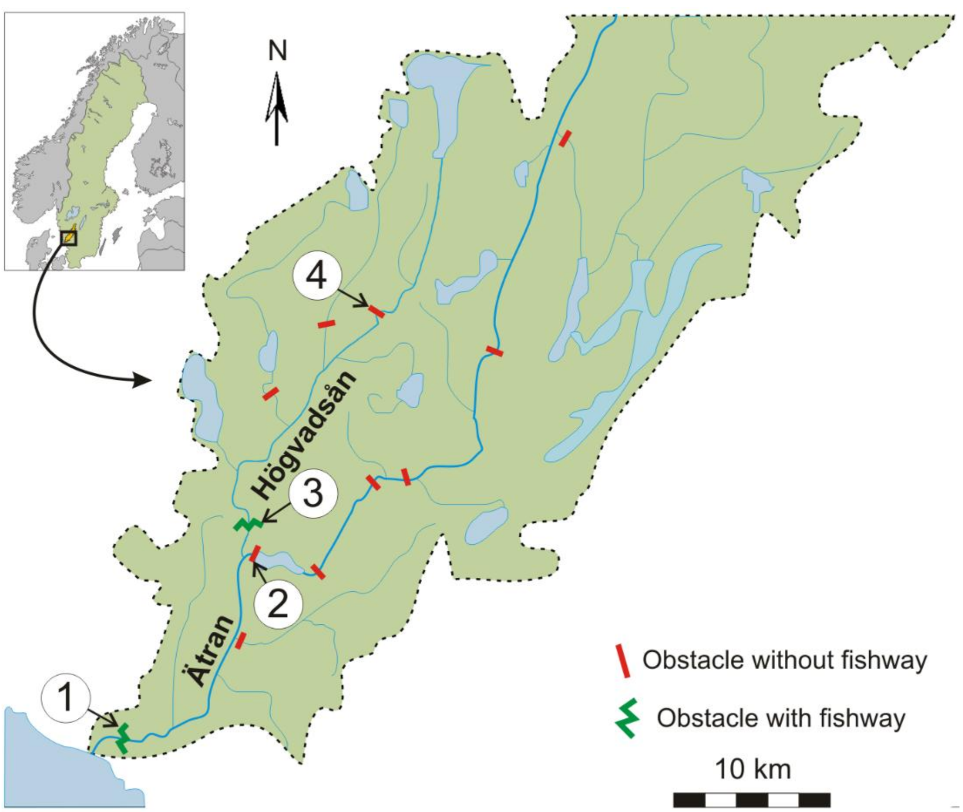

Figure 1: Lower catchment area of river Ätran with obstacles in the main stem of the river: the studied HEP Herting (1) and the next impassable obstacle Ätrafors HEP (2), and in tributary Högvadsån: the Nydala HEP (3) and the next impassable HEP (4). Major rearing areas for salmon are located in river Ätran and Högvadsån between sites 1 and 4 (Modified from Calles et al., (2012)).

Available spawning and rearing habitats for Atlantic salmon are limited in the river system due to these obstacles, as compared to pristine conditions (technical data about the studied HEP, as well as general data about river Ätran, was provided by the company owning the Herting hydroelectric power plant, Falkenberg Energi). Nowadays most spawning and rearing of Atlantic salmon takes place in two river stretches: An about 24 km long stretch in river Ätran, from the river mouth to the impassable Ätrafors hydropower plant (Figure 1) and an approximately 34 km long stretch in tributary river Högvadsån, from the river outfall to the next impassable HEP (Figure 1). The Nydala HEP, an old mill in the rearing stretch of river Högvadsån, is located about 5 km from the river mouth. This obstacle is equipped with monitoring stations for up- and downstream migrating fish. Salmon can pass this obstacle by either passage over a weir or by entering one of the fish traps. Fish caught are subsequently, depending on their migration direction, put back either upstream or downstream of the HEP.

The study object, the Herting HEP, consists of two powerhouses (Figure 2). It is the last hydroelectric power plant encountered by downstream migrating fish, and hence the first to be encountered by upstream moving fish, situated approximately 2 km upstream the estuary. Longitudinal connectivity at the Herting HEP is of high ecological importance for the entire river system, as successful reproduction of all indigenous diadromous fishes is limited by the amount of migrants successfully passing this HEP.

The first powerhouse (H1), a diversion plant, was built in 1903. It is equipped with two Kaplan turbines (turbine 1: 250 rpm, 15.0 m^3s^{-1}; turbine 2: 187 rpm, 25.0 m^3s^{-1}). In 1945 a second powerhouse was added to the site. The second powerhouse, the run-of-river plant (H2), is located inside the old riverbed and equipped with one Kaplan turbine (187 rpm, 25.0 m^3s^{-1}). There have been extensive renovation works at Herting hydropower plant throughout 2013 in order to improve up- and downstream migration success of diadromous fishes (Figure 2).

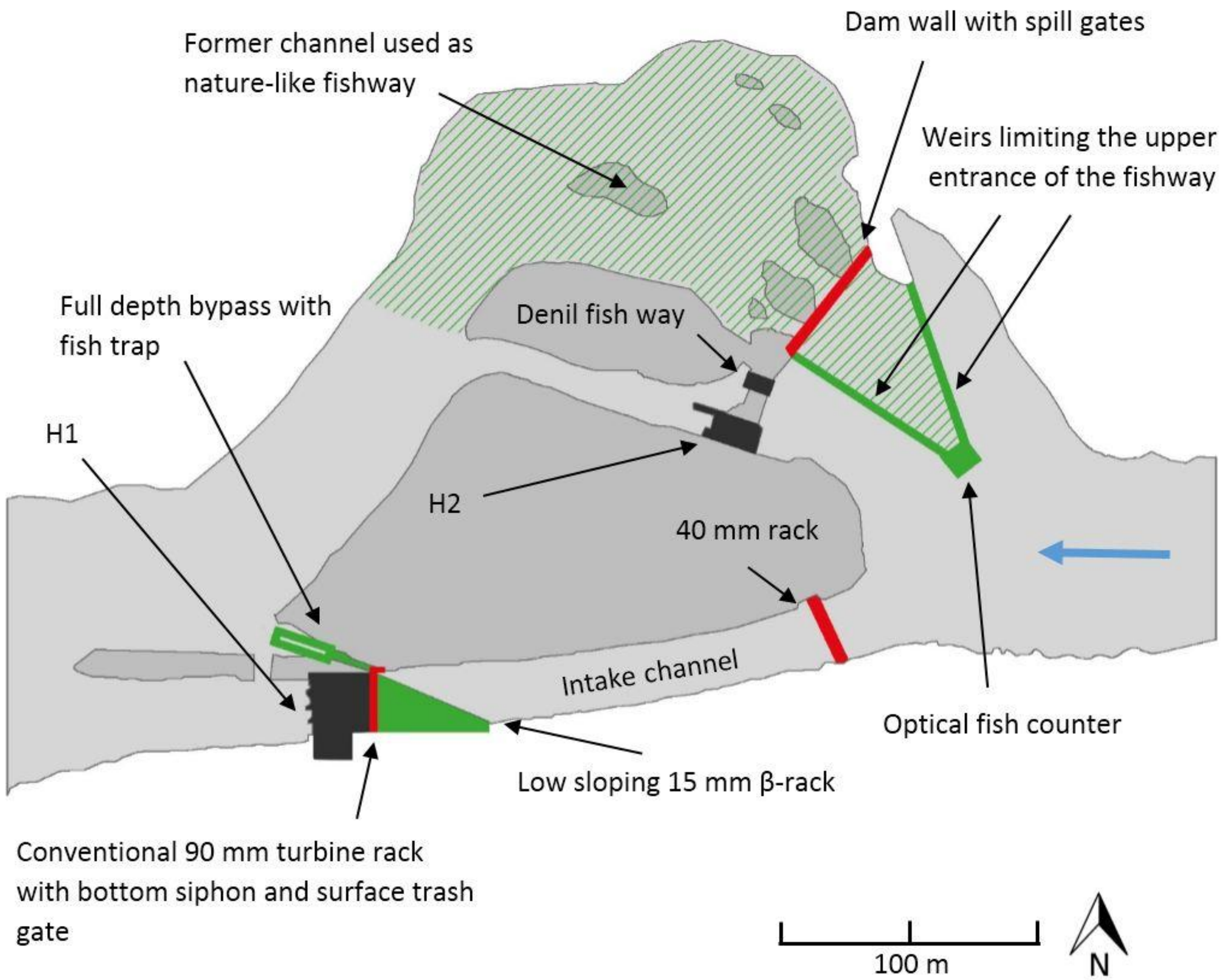

Figure 2: Herting hydroelectric power plant before and after the rehabilitation works in 2013. Facilities that were removed during the modernization are colored red, whereas the new implemented facilities are shown in green. Facilities remaining unchanged are displayed in black (Old powerhouse (H1), New powerhouse (H2)). The blue arrow indicates the direction of the current.

2.1.1 Downstream passage conditions before the rehabilitation works

In the original state (pre - 2006) there were no fish migration facilities at the old powerhouse (H1). Hence, it situated an impassable obstacle for upstream migrating fish. The only way to pass this obstacle for downstream swimming fish was to pass via the turbines. The old powerhouse was equipped with two trash racks to prevent flotsam from entering the turbines: a 40 mm trash rack at the beginning of the intake channel (located under a bridge), and a vertical 90 mm turbine rack, angled about 60° to the vertical (Figure 2). Fish that were too large to pass these racks were not able to pass the old powerhouse on their downstream migration. In 2006 a temporary surface bypass was introduced to the old powerhouse (Calles et al., 2012). This surface bypass was positioned on the side of the intake channel immediately before the turbine rack discharging 2 m^3s^{-1} maximum. The 3.3 m wide bypass discharged water in a 90° angle, in relation to the intake channel, past the old powerhouse into the former channel. To allow large fish to enter the intake channel and to continue their migration to and through this bypass, two one meter wide panels were removed from the 40 mm rack at the beginning of the turbine intake. In addition to the surface bypass, a pipe (200 mm diameter) located at the base of the original 90 mm rack siphoned water (0.25 m^3s^{-1}) to improve passage success for European eel (*Anguilla anguilla*). The pipe proved unsuccessful for the intended purpose, and is not further described here (Calles et al., 2012).

The second powerhouse, the run-of-river plant, was located at the end of the dam that crossed the old riverbed. The dam wall was equipped with spill gates releasing water into the former channel if the intake capacity of the Herting HEP was exceeded. The new powerhouse was connected to a Denil-fishway (1.4 m^3s^{-1}) and a separate spill gate for increased attraction to the fishway (1.6 m^3s^{-1}) since its construction and was supposedly passable for upstream swimming fish. There were no passage facilities targeting downstream swimming fish at H2. Downstream migrating fish that didn't pass through the turbine had to find the entrance to the Denil-fishway or pass via the spill gates of the dam wall. Powerhouse H2 was equipped with a 40 mm turbine rack angled about 77° from the vertical. During the annual smolt migration in spring, a rack with smaller bar spacing's (22 mm) was placed in front of the original turbine rack, to prevent salmonid smolts from entering the turbine at H2. There was no bypass available for smolts stopped by the replaced rack, they hence had to locate the other available routes for downstream passage.

2.1.2 Study site after the rehabilitation works

In order to improve downstream passage conditions at the old powerhouse, the original 90 mm turbine rack was replaced by a 40 m long composite β-guiding-rack, with a horizontal 15 mm gap spacing, and a 30°-angle in relation to the sides of the intake channel (Figure 3). The former downstream passage facilities at the old powerhouse were removed and a full depth bypass (Ebel, 2013) with an average discharge of 0.3 m^3s^{-1} was implemented. In consequence, the 40 mm rack situated under the bridge at the entrance of the intake channel was removed in order to enable downstream migrating fish to enter the bypass.

Apart from the novel material of the rack and the hydrodynamic shape of the bars (CompRack®, Halmstad, Sweden) the downstream passage facility followed the original design by Ebel, Gluch and Kehl (Ebel, 2013) Another difference between the original design and the facility installed at the Herting HEP is, that no weir was installed inside the full depth bypass (Figure 3 A). The new turbine β-rack is equipped with an automated cleaning device, starting when the pressure gradient exceeds a certain level, i.e. at a certain head-loss over the β-rack, typically caused by trash impingement. The entrance profile of the bypass, and hence the discharge, is regulated by an electrically controlled hydraulic hatch, which automatically opens when the rack cleaner starts its cycle, resulting in a temporary increase of flow (to total 2 m^3s^{-1}) released through the bypass. The bypass channel is connected to a fish trap, (Wolf, 1951) with a 6 meter long and 1.2 m wide low-sloping bottom rack (8 mm bar-spacing) for dewatering, leading to a holding container with impermeable walls at the base and an 8 mm dewatering rack-wall at the top (Figure 3 B). The low sloping bottom rack adjacent to the fish trap removes most water from the bypass, which is spilled into the new fishway. The amount of water left is gathered inside a chute located in the middle of the bottom rack-screen. In consequence fish passing via the bypass channel are guided into the chute. The discharge in the chute spills into the holding container, were fish are kept until the trap is emptied.

A second migration corridor was introduced to the site by removing the dam across the former channel. The former channel now serves as nature-like fishway (minimum discharge 11 m^3s^{-1}) primary targeting upstream migrating fish. Two weirs were build inside the forebay of the new powerhouse, guiding upstream migrating fish through an optical fish counter station (model Riverwatcher, VAKI, Iceland) situated at the downstream end of the limiting weirs (Figure 2). The fish counter station, consist of a passable video-tunnel and two guiding-rack-screens with 35 mm gap spacing. Downstream passage via the nature-like fishway is yet possible, since fish that are too large to pass through the guiding-screens do not necessarily have to locate the camera tunnel in order to descend, as the weirs are designed to be overflowed at all times, which was also the case during the entire study period. The new powerhouse, three large adjacent spill gates (capacity 15; 26; 26 m^3s^{-1}) and the Denil fishway remain unchanged and will be kept operational. Since no rehabilitation measures were implemented at the new powerhouse, power production of H2 is limited to periods of minimum fish migration ever since the modernization works, which is expected to occur during winter months. The new powerhouse was not running during the study.

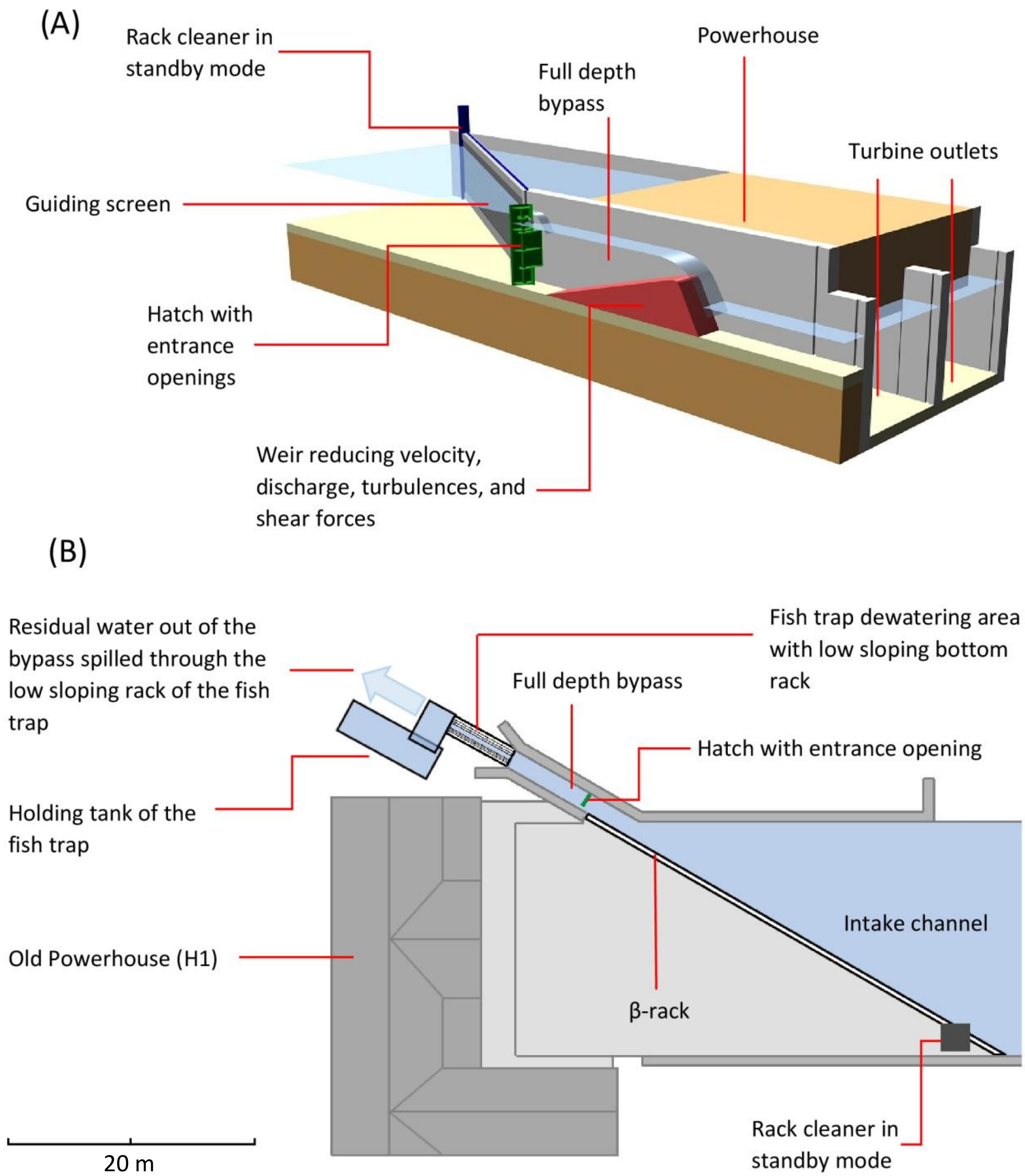

Figure 3: (A) General sketch of a guiding-screen-bypass-system as published by Ebel, Gluch and Kehl (Ebel, 2013). (B) Aerial view on the old powerhouse of the Herting HEP including 30°-angled β-rack, full depth bypass, and, adjacent fish trap.

2.2 Discharge distribution

The discharge situation changed due to the implementation of the new passage facilities, mainly as a result of the removal of the dam wall, the lowered upstream water levels (average 40 cm lower) and the fact that the new powerhouse was not in operation during the study. Even though the new powerhouse was not running, a small percentage of the total discharge flowed through the run-of-river plant and the remaining spill gates (Table 1). The distribution of relative discharge between intake channel and fishway is mainly influenced by the minimum discharge of the fishway (11 m^3s^{-1}) and the maximum capacity of the old powerhouse (40 m^3s^{-1}). If the total discharge of the river is lower than 11 m^3s^{-1}, all water flows through the fishway. The old powerhouse is operating at discharges greater than 12 m^3s^{-1} and receives all inflow until full capacity is reached at a total discharge of 52 m^3s^{-1}. All additional discharge exceeding 53 m^3s^{-1} is spilled through the fishway. Average discharge was distributed equally between the two main routes (fishway 49%, intake channel 47%) during the study period and average of 0.3 m^3s^{-1} flowed through the new bypass. The discharge distribution during the study is shown in Table 1.

Table 1: Mean discharge (m^3s^{-1}) distribution and recorded min. and max. values (m^3s^{-1}) for all contributing discharge paths at the study site during the study period, April-15th to May-07th.

Discharge paths:	H1	H2	Spill	Fishway	Bypass	Total
Mean discharge	21.5	1.3	0.5	22.6	0.3	45.9
Minimum discharge	0.2	1.1	0.4	7.0	0.3	58.9
Maximum discharge	40.1	1.5	0.6	37.7	2.0	33.3

2.3 Tagging and tracking of Atlantic salmon smolt

2.3.1 Fish tagging and release procedure

To evaluate the efficiency of the new passage facilities for downstream migrating wild Atlantic salmon smolt, fish (N = 44) were radio-tagged, released, and tracked at the Herting HEP. The tagged individuals were divided into a treatment group and a control group. Smolts of the treatment group (N = 35) were released in 5 batches, ranging from 4 to 8 individuals (Table 2), approximately 390 m upstream of H1 (Figure 4), which was the same release site as during the pre-study (Calles et al., 2012). The control group (N = 9) were released in two batches at a pedestrian bridge approximately 160 m downstream of H1 (Figure 4, Table 2).

The treatment group did not differ from the control group in regards of length, height, weight, or degree of smoltification (individual Mann–Whitney U tests, all $p >> 0.05$). All tagged fish were caught in one of the fish traps at the Nydala HEP in tributary river Högvadsån (Figure 1). Before tagging, smolts were checked for injuries and their general condition was assessed. Only healthy fish were tagged. Smolt tagging followed the procedure for surgical implants of trailing-whip antenna radio transmitter (Jepsen et al., 2002). One type of transmitter were used during the study (Model ATS F1525, weight 0.65 g, life 21 days; Advanced Telemetry Systems, Isanti, USA). Fish were anesthetized in an immersion of a solution of Benzocaine with the time for sedation ranging from 1.65 min to 4.14 min (mean 2.63 min). After the initial incision, a needle was used to penetrate through the skin into the body cavity. The antenna was extracted with the needle and the transmitter was inserted into the body cavity. The incisions were closed by one suture (Vicryl, V391h, 5/0; Ethicon Inc., USA). Total procedure, including anesthesia and surgery, lasted from 3.53 min to 7.13 min (mean 4.96 min). Body measures were taken for: total length (mm), height (at the posterior end of the dorsal fin, mm), weight (+/- 0.1 g), and degree of smoltification (1 - 3) (Tanguy et al., 1994). All tagged fish were kept for post-surgery observation 4.25 h (mean) in a 70l holding tank with constant freshwater supply from the river to ensure recovery after the tagging procedure. Five fish died during this period, and have therefore been excluded from the study.

Table 2: Release dates, batch sizes, purpose (control group (CT), treatment (TR)), average body measures (length, height, weight) with standard deviation and median degree of smoltification of all released smolt batches.

Date and time of release	N	Purpose (CT/TR)	Length (mm)	Height (mm)	Weight (g)	Degree of smoltification (1-3)
April-14th 20:30	6	TR	144 ± 5	23 ± 3	24.2 ± 3.3	2
April-16th 20:31	8	TR	147 ± 9	24 ± 2	26.0 ± 2.6	2
April-16th 20:24	5	CR	151 ± 8	25 ± 1	26.2 ± 3.3	2
April-18th 21:20	6	TR	147 ± 5	25 ± 2	27.3 ± 3.0	2
April-18th 21:10	4	CR	146 ± 3	25 ± 2	27.8 ± 6.6	2
April-21st 20:40	8	TR	146 ± 5	24 ± 1	27.2 ± 2.0	2
April-23rd 19:50	7	TR	149 ± 5	25 ± 1	26.4 ± 2.2	2
Total	**44**	**TR + CR**	**147 ± 6**	**24 ± 2**	**26.3 ± 3.2**	**2**

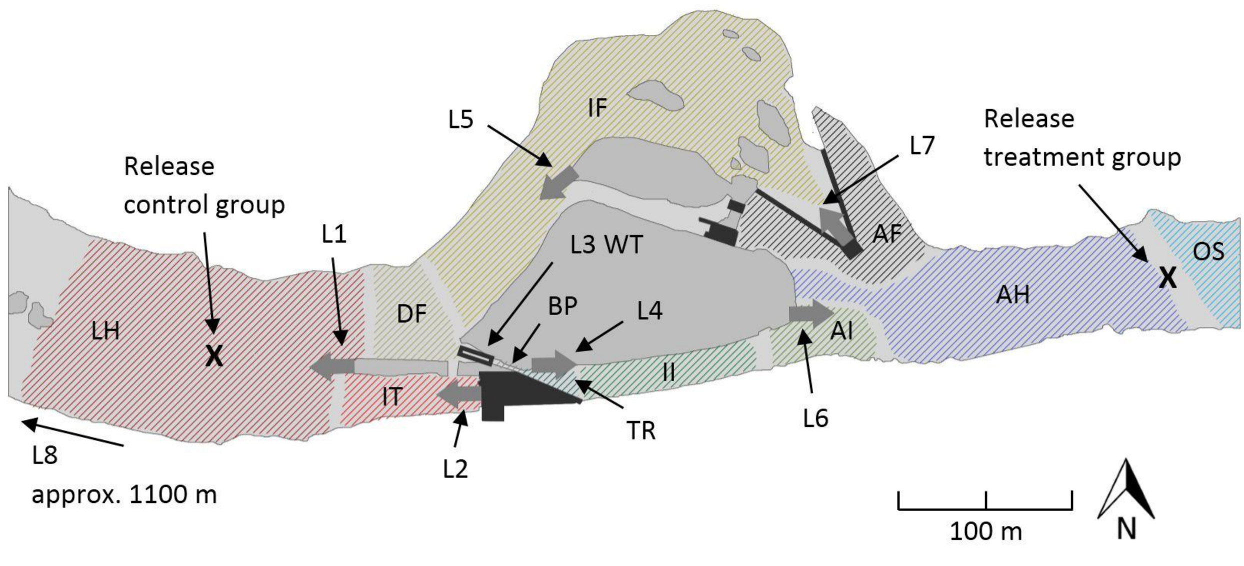

Figure 4: Placement of logger stations in the study area (L1 – L8) indicated by gray arrows, pointing in the direction the antennas were directed. Release locations for treatment and control fish are marked by "X". Areas used for reconstructing the migration paths of tagged smolts are shown by shaded areas (outside study site (OS), approaching HEP (AH), approaching turbine intake (AI), inside turbine intake (II), at turbine rack (TR), approaching fishway (AF), inside fishway (IF), downstream fishway (DF), inside bypass channel (BP), inside fish trap (WT), inside tailrace (IT), leaving study site (LH).

2.3.2 Fish tracking procedure

Fish tracking was performed by placing automatic loggers (L1 – L8) (model R4500s, ATS, USA) connected to 3-element Yagi antennas in eight locations in the area around the HEP (Figure 4). Logger station L1 was placed at the western end of the small island about 75 m downstream of the old powerhouse. The main purpose of L1 was to record data of tagged fish leaving the study site. L2 was installed on a handrail directly above the turbine outlets of the old powerhouse to indicate turbine passages. Logger station L3 was connected to a stripped antenna cable (John, Grant and Haner, 2004) positioned at about one meter water depth inside the Wolf-trap to indicate when tagged smolts entered the trap. The bypass channel and the β-rack were monitored mainly by L4 located on the opposite river bank of the turbine rack, approximately 10 m upstream of the bypass entrance. L5 was placed at the end of the new power plant tailrace to register fish present inside the fishway. Logger L7 was installed on the platform housing the electric fish counter to record smolts that approached and/or entered the fishway. Logger L6 was placed at the entrance of the intake channel, about 180 m upstream of the old powerhouse, to cover the area upstream of the study site. L8, the logger positioned furthest downstream, was installed approximately 1100 m downstream of H1 to indicate if tagged smolts successfully continued their migration to the sea after passing the Herting HEP. Logger stations L4, L5, and L7, consisted of two automatic loggers connected to one antenna in order to increase detection rate.

To verify automatic generated logger data, all fish were manually tracked and positioned daily, using a manual receiver (R2000, ATS, USA) and a 3-element Yagi-antenna. The positions found during manual tracking were inserted in a tablet computer (iPad, Apple, USA) using a GIS-software (GIS Pro, Garafa, LLC, USA).

2.4 Maintenance of the fish trap

The fish trap was emptied every morning at approximately 9:00 hrs during the entire study period. All caught fish were identified to species level and total length was measured to the closest millimeter. Due to high abundance of salmonid smolts only sub-samples (median count 10, range 8 – 45 individuals) of randomly picked individuals were measured. Fish were checked for injuries and other abnormalities. If irregularities were found the fish were photographed. All fish, except tagged smolts, caught in the fish trap were released downstream of the bypass channel.

When tagged fish were recaptured, the transmitter was removed (i.e. fish were de-tagged) before they were released. For this reason, individual transmitters were used for up to three different individuals.

2.5 Data analysis

A pilot-test was carried out to gather knowledge about the strength of the recorded signal during a typical passage. For this purpose three transmitters were held into the water at a depth of 0.5 m for 120 sec at 46 strategic sites within the detection areas of logger stations L1– L7. The results of this test were used to create a signal-strength-map indicating the average signal strength for all actively recording logger stations per site (Appendix I). The river at the study site was divided into 12 specific areas to set time marks for important events during a passage e.g. entering the bypass channel or leaving the study site Figure 4. Distinct signal strength signatures/combinations, based on the results of the pilot test, were used to set rules in order to identify if tagged smolts entered or left these specific areas.

The term “areas upstream of the HEP” will hereafter refer to the grouped areas: outside study site (OS), approaching HEP (AH), approaching turbine intake (AI), inside turbine intake (II), at turbine rack (TR), approaching fishway (AF), inside bypass channel (BP) whereas “areas downstream of the HEP” will refer to: inside fishway (IF), downstream fishway (DF), inside fish trap (WT), inside tailrace (IT), leaving study site (LH).

The passage pattern acquired through this method was used to reconstruct the path of tagged smolts as well as the timing of chosen parts of the passage. The following requirements were set to define, if fish passed the old powerhouse and successfully continued their migration after passing the HEP. Total passage success (TPS) was declared if tagged fish continued their migration after passing the obstacle and passed the logger positioned at the furthest downstream point (L8), or if fish were caught in the bypass trap. The control group were released downstream of H1. Hence, they did not have to pass the HEP in order to reach the sea. Instead of total passage success, migration success was analyzed, which was declared if tagged smolts of the control group reached the last logger station (L8). The new bypass was evaluated by calculating the corresponding fish guidance efficiency (FGE). FGE refers to tagged fish and was determined as the percentage of fish entering the bypass out of the total number of smolts, which visited the turbine rack at least once

(Scruton et al., 2003). Three different time periods were analyzed to quantify how much the radio-tagged fish were delayed when passing the HEP: (1) Time spent from release to passage, i.e. time from release until either entering the fishway or, if fish passed via the intake channel, time from release until entering fish trap or turbines; (2) Time spent from passing the HEP until reaching the last logger (L8); (3) Total passage duration, i.e. time from release until reaching the most downstream located logger (L8)).

Further, migration rate was analyzed in order to compensate for, that fish following different routes had to swim different distances (Table 3), which hence was expected to affect passage duration. Migration rate was analyzed for the same stretches used in the recording of passage time and was calculated by dividing the length of a certain stretch by the corresponding duration of time spent in that stretch.

Table 3: Length of all measured stretches, used to calculate migration rate and their corresponding relevance for either treatment or control fish.

Measured stretch	Relevant for (Treatment/Control : route)	Distance (m)
Release point of treatment fish – bypass channel	Treatment: intake channel	400
Tailrace – last logger (L8)	Treatment: possible turbine passage	1090
Total migration path intake channel	Treatment: possible turbine passage	1490
Release point of treatment fish –fishway entrance	Treatment: fishway	200
Fishway entrance – last logger (L8)	Treatment: fishway	1390
Total migration path fishway	Treatment: fishway	1590
Release point of control fish – last logger (L8)	Control	930

2.6 Statistical analysis and acquisition of abiotic data

Acquired data was analyzed through univariate analyses. Normality of all data sets was tested using the Shapiro-Wilk test. Data sets of two grouping factors were tested using the Man-Whitney U-test. Data sets with more than two grouping factors were analyzed with the Kruskal-Wallis test and if significances were found, post-hoc pairwise Mann-Whitney U-tests were conducted. Correlations between migration rate and abiotic- or biotic parameters were verified by individual Spearman’s rank correlations. In addition, a linear regression model was performed to assess the overall effect of abiotic- and biotic parameters on migration rate, whereas a binary logistic model was used to verify the impact of those parameters on route choice. Significances in regression models were tested with a Wald test. In all statistical analyses carried out, significance was accepted when p-values of ≤ 0.05 were acquired. Significance will be written as "$p < 0.05$" significant, "$p > 0.5$" for $p > 0.05 \leq 0.10$ and "$p >> 0.05$" for $p > 0.10$. The statistics programs Sigma Plot 12 (Systat Software Inc, USA) and SPSS 21 (IBM, USA) were used for statistical analysis and plots. Discharge data was provided by the owner of the Herting hydroelectric plants, Falkenberg Energi, and Fiskevårdsteknik AB. Water temperature was measured daily using a digital thermometer, installed inside the bypass trap. Geographical measurements were realized on satellite pictures provided by Google Maps (Google, USA). Plans, Maps, and sketches, were created in Adobe Photoshop CC 2014 (Adobe, USA) and Corel Draw 5 (Corel Corporation, Canada).

3 Results

3.1 Fish trap catches

A total of 5167 individuals comprising of 13 fish species were caught in the bypass trap during the study (Table 4). The total salmonid smolt catch was 5073, of which 4435 were Atlantic salmon (87%) and 638 were brown trout (*Salmo trutta*) (13%, Figure 5). The median length of caught non-tagged Atlantic salmon smolts was 140 mm (range 122 mm – 184 mm, N = 346) and 145 mm (range 110 mm – 201 mm, N = 21) for brown trout. Daily catches of salmonid smolts decreased gradually during the study period (Figure 5) ranging from 28 to 411 individuals per day for Atlantic salmon and one to 68 for brown trout. A total of 12 radio-tagged smolts were caught in the bypass trap over the study period. In addition, nine salmon kelt and 25 brown trout kelt were caught in the bypass trap. A total of 82 individuals of different species were found dead on the bypass rack or inside the holding container of the fish trap, resulting in a mortality of 2% caused by the monitoring facility for non-tagged fish.

Table 4: Species and number of fish caught in the bypass trap over the study period (April-14th – May-07th).

Species		Number of fish caught (N)
Atlantic salmon (smolt)	*Salmo salar*	4435
Atlantic salmon (kelt)	*Salmo salar*	9
Brown trout (smolt)	*Salmo trutta*	638
Brown trout (kelt)	*Salmo trutta*	25
Burbot	*Lota lota*	1
European eel	*Anguilla anguilla*	7
European perch	*Perca fluviatilis*	2
Northern pike	*Esox lucius*	2
Rainbow trout	*Oncorhynchus mykiss*	10
Roach	*Rutilus rutilus*	28
Rud	*Scardinius erythrophthalmus*	2
Ruffe	*Gymnocephalus cernua*	1
Silver bream	*Blicca bjoerkna*	1
Zander	*Sander lucioperca*	6

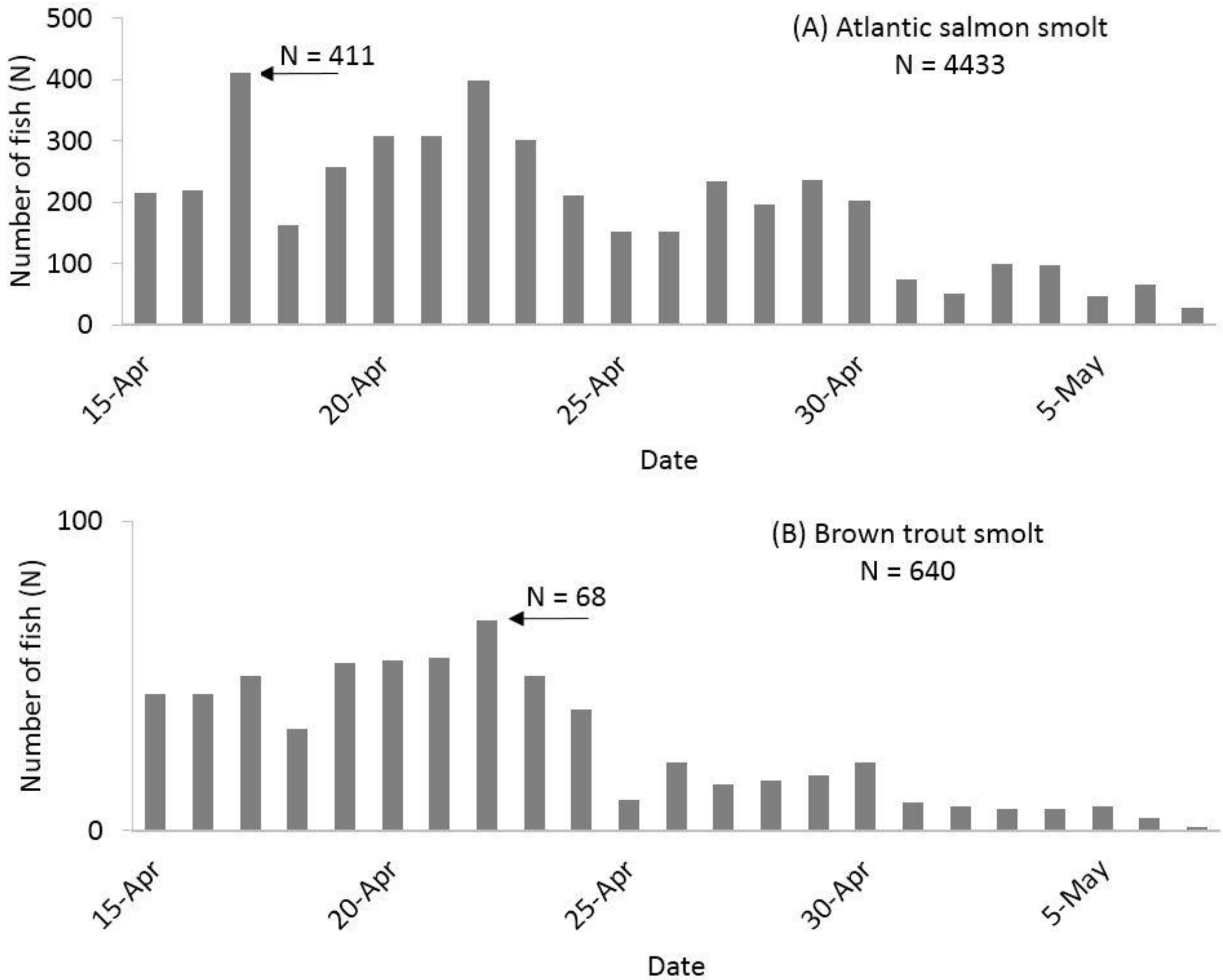

Figure 5: Daily catches of (A) Atlantic salmon smolts and (B) brown trout smolts in the fish trap over the study duration. Arrows indicate the day of maximum catch.

3.2 Route selection

All but one tagged fish of the treatment group (N = 35) passed the Herting HEP. The single smolt that did not pass the HEP stayed upstream of the power plant for the entire study period. This individual stayed in areas with overall low velocity, swimming back and forth between the areas “outside study area” (OH), “approaching HEP” (AH), “approach fishway”(AF) and paid one visit to the turbine rack (TR, Figure 4). The individual was actively moving for about 13 days after release. A change in movement pattern, i.e. decreased movement speed, could be identified 6.40 h after release indicating a possible predation event. Out of the 34 (= 100%) tagged smolts that passed the HEP, 15 individuals (44%) choose the new fishway as the passage route whereas 19 individuals (56%) passed through the intake channel (Figure 6). One individual did not continue its migration after passing the obstacle via the new fishway, but stayed inside the fishway until the end of the study. The position of this tagged smolt did not indicate predation, i.e. it was holding in lotic positions, and the individual showed movement inside the fishway until the battery of the transmitter ran out. None of the tagged smolts passed via the non-operating new powerhouse or the adjacent, non-operating, Denil-fishway.

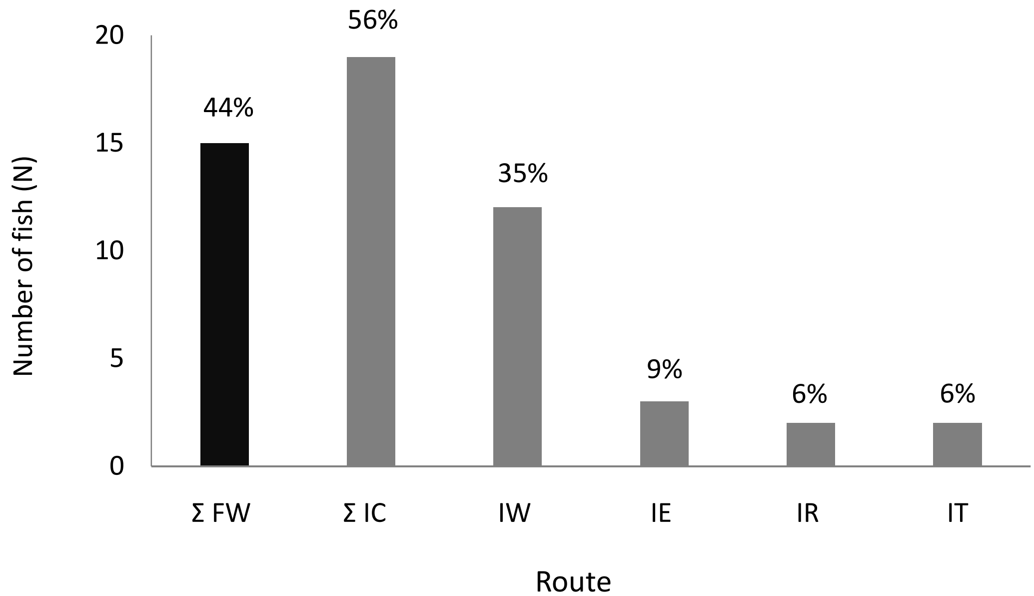

Figure 6: Distribution of tagged fish that successfully passed the Herting HEP (N = 34) on all used routes. (Routes: fishway (FW), intake channel (IC), intake channel fish trap (IW), intake channel escaped via bypass rack (IE), intake channel washed up on bypass rack (IR), intake channel turbine (IT))

3.2.1 Sub routes at the old powerhouse and bypass efficiency

Four sub-routes were identified for smolts passing via the turbine intake (Figure 6): 12 of 19 smolts were caught in the bypass trap (IW); 3 of 19 escaped through the low sloping bottom rack adjacent to the fish trap and continued their migration (IE); 2 of 19 got washed up on the low sloping bottom rack of the fish trap and died (IR); 2 of 19 passed through the β-rack and consequently through the turbines (IT) without observed direct turbine-induced mortality, since both individuals proceeded swiftly to the last logger (L8). In total 17 of 19 tagged smolts migrating via the intake channel entered the new bypass, resulting in the fish guidance efficiency (FGE) of 85 % (17 of 20) for the new bypass. The FGE was based on the individuals that passed the Herting HEP via the intake channel plus the individual that paid one visit to the turbine rack, but never passed the HEP. The complete opening of the hatch at the entrance of the bypass and the resulting temporary increase of flow in the bypass channel, did not influence the passage behavior of smolts migrating via the intake channel, since none of the passages through the bypass occurred within 4 h before or after the hatch opened.

3.2.2 Total passage success and total mortality

After removing the 14 de-tagged smolts from the study (12 caught in the fish trap and two washed up on the bottom rack), 21 tagged migrating fish remained. Of those 21 smolts the total passage success was declared for 19 smolts. As stated above, one fish did not pass the Herting hydropower plant at all and one fish stayed inside the fishway during the entire study period. The total passage success (TPS) for the treatment group was 94% (33 of 35) based on the originally declared definition for TPS or 89% (31 of 35), if mortality caused by the low sloping bottom rack of the monitoring facility was taken into account. All fish of the control group reached logger station L8. Migration success for the control group was therefore 100% (9 of 9). Total mortality was 9% (3 of 35) as two fish died due to the monitoring facility and one tagged smolt was declared as possible predation.

Table 5: Number of turbine passages, total mortality, fish guidance efficiency of the new bypass, and total passage success for radio-tagged Atlantic salmon smolts in river Ätran, 2014.

Investigated factor	Result
Number of turbine passages	2 of 35 = 6%
Total Mortality	3 of 35 = 9%
Fish guidance efficiency of the new bypass	17 of 20 = 85%
Total Passage Success	33 of 35 = 94% 31 of 35 = 89%a

[a] alternative definition of total passage success including mortalities caused by the monitoring facility

3.2.3 Influence of abiotic and biotic parameters on route selection

There was no indication that body measures influenced the route choice of tagged fish (Appendix II), since no differences were found between fish migrating through the intake channel and smolts passing via the fishway in regards of length, height, weight and degree of smoltification (individual Mann–Whitney U tests, all $p >> 0.05$; Appendix III). Furthermore, no differences were found in length, height, weight or degree of smoltification for tagged smolts regularly passing via the new bypass (N = 12) as compared to the other alternative routes at the old powerhouse (N = 7; Mann–Whitney U test, $p >> 0.05$). The route selection of tagged smolts was not significantly impacted by changes in total discharge, since the mean of total discharge from release to passage for each individual did not differ between fish passing via the fishway and fish passing through the intake channel (Mann–Whitney U test, $p >> 0.05$). Additionally there was no difference between the ratio: intake channel mean discharge / fishway mean discharge, from release to passage and route choice (Mann–Whitney U test, $p >> 0.05$, Table 6). Consequentially, 59% (20 of 34) of all individuals that passed the HEP, did so via the route carrying less discharge at the moment of passage (Appendix IV). Route selection of smolts seemed to be distributed equally between release dates, and during an average day of release 40% of tagged smolts passed via the fishway, whereas 60% passed through the intake channel (Fisher's exact test, $p >> 0.05$, Appendix IV). Analog to the individual comparisons, no correlations were found between abiotic- and biotic parameters and route selection in a binary logistic regression model (Appendix V).

Table 6: Medians of mean discharges (m^3s^-1) from release to passage for fish migrating via intake channel and fishway. Values in brackets state min. and max. values.

Selected route	Discharge path			
	Median total discharge	**Median discharge fishway (MQF)**	**Median discharge intake channel (MQI)**	**Ratio MQI/MQF**
Intake channel N = 19	54.7 (50.4 – 58.9)	27.04 (24.1 – 33.4)	24.5 (21.3 – 24.5)	0.9 (0.5 – 1.0)
Fishway N = 15	52.9 (47.0 – 58.0)	25.9 (22.3 – 31.5)	24.5 (19.6 – 25.1)	0.9 (0.6 – 1.0)

3.3 Passage delay and corresponding migration rates

The median smolt passed the obstacle 9.8 h after release. There was no significant difference in time from release to passage between smolts migrating through the fishway (median 9.9 h) and smolts passing via the intake channel (median 10.1 h; Mann-Whitney U-test, $p >> 0.05$). A comparison of correspondent migration rates showed higher swim speeds for tagged fish that chose the intake channel (median 39.8 mh^{-1}, N = 19) compared to fish passing through the fishway (median 20.6 mh^{-1}; Figure 7). This comparison was, however, not significant (Kruskal-Wallis test, $K_2 = 5.277$, $p > 0.05$; Figure 7).

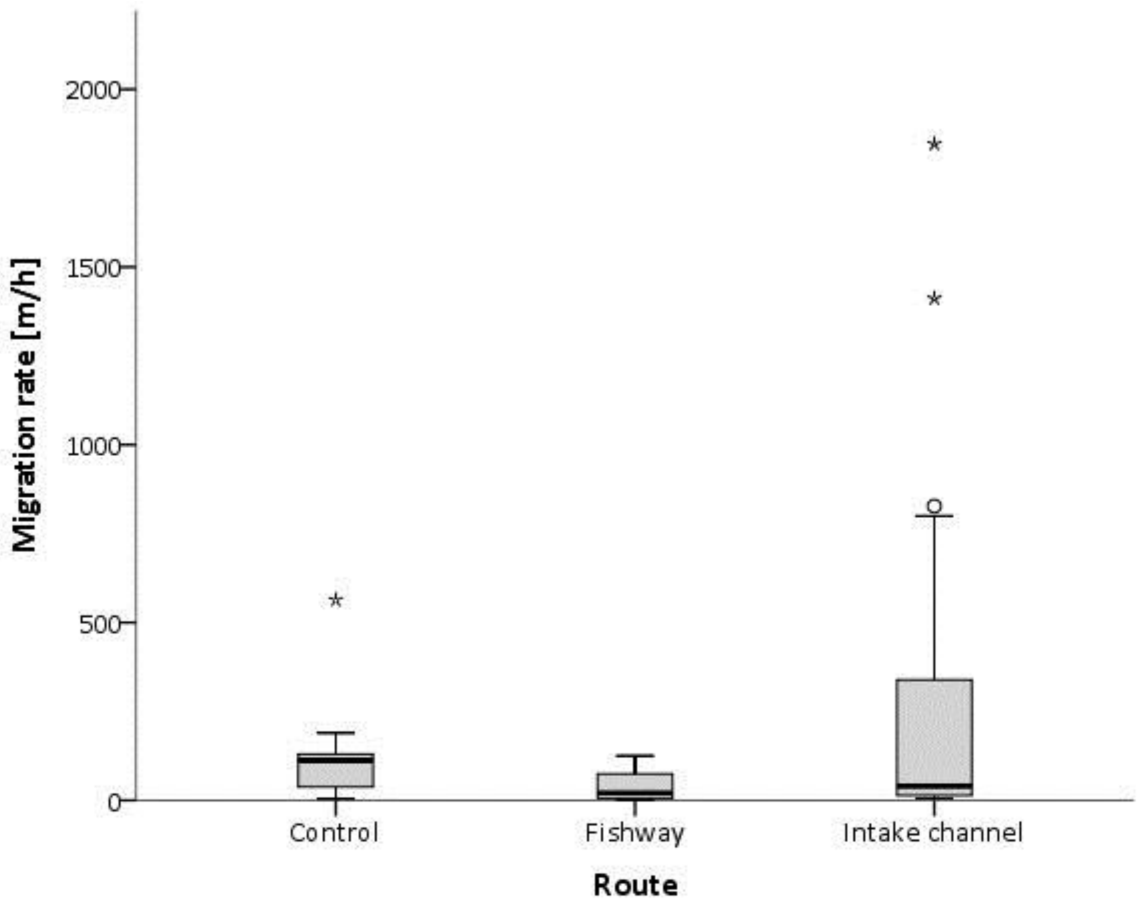

Figure 7: Migration rates of tagged smolts per route from release to HEP-passage by either entering bypass and turbines (intake channel) or the fishway and the total migration rate of the control group. Box: 25% quantile, median, 75% quantile; whisker: ≤ 1.5 IQR, outliners: >1.5 IQR are true values. Groups shown in this figure were not significantly different.

After passing, smolts proceeded swiftly towards the sea and 90% (N = 17) of all remaining smolts passed the last logger (L8) in less than 24 h after passage. Migration rate after passage, to the last logger L8 differed significantly between the selected routes (Kruskal-Wallis, $K_3 = 9.313$, $p < 0.05$; Table 7). Fish that chose the fishway, or passed via the turbines continued their migration faster than smolts that escaped the fish trap or fish of the control group. Post hoc pairwise comparison, however, was insignificant for all routes (all post hoc pairwise Mann-Whitney U comparisons, $p > 0.05$; Figure 8).

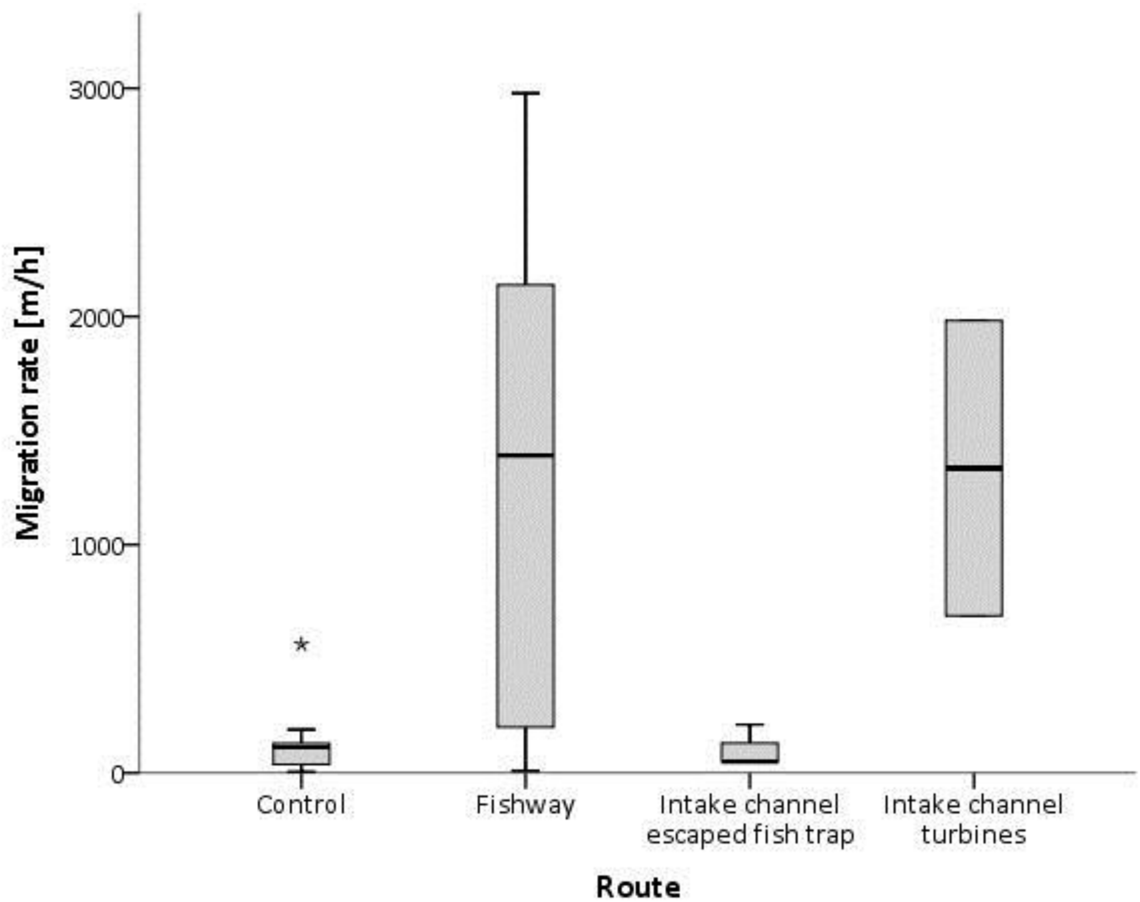

Figure 8: Distribution of migration rates for the stretch downstream of the hydropower plant to the last logger (L8) for all different routes and the control group. Box: 25% quantile, median, 75% quantile; whisker: ≤ 1.5 IQR, outliners: >1.5 IQR are true values. Post hoc comparison was insignificant for all shown routes.

The comparison of migration rates for both stretches (up- and downstream of the HEP) and the control group indicated that the swimming behavior of tagged smolts changed after passing the obstacle (Kruskal-Wallis test $K_2 = 14.698$, $p < 0.05$; Figure 9). Migration rate of tagged fish was significantly lower for the stretches upstream of the Herting HEP (median 23.91 mh^{-1}, N = 34) compared to migration rates calculated for the stretches downstream of the obstacle (median 689 mh^{-1}, N = 19; post hoc pairwise Mann-Whitney U comparisons, before passage ~ after passage: $p < 0.05$; other: $p >> 0.05$).

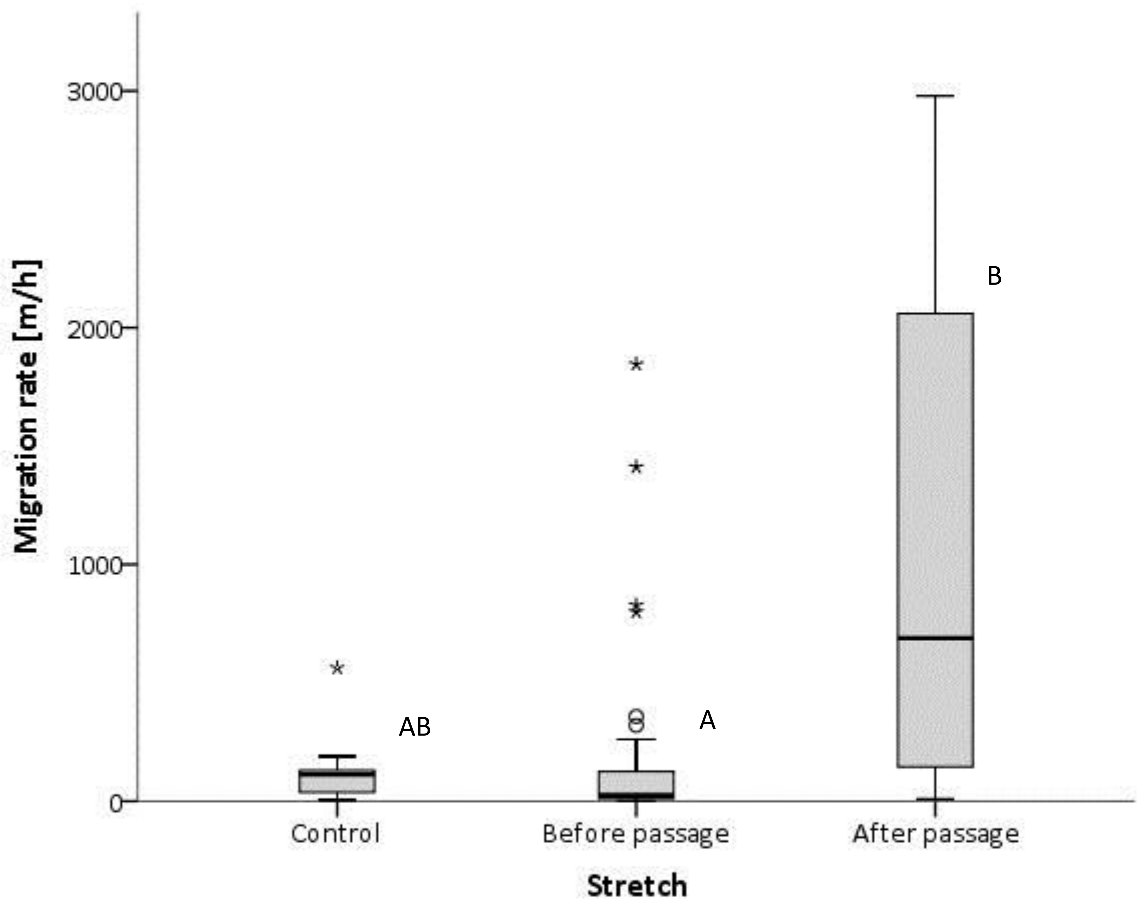

Figure 9: Calculated migration rates for all passed smolts in the areas upstream of the Herting HEP (Before passage) and after passing the obstacle, until reaching the last logger station (After passage). Box: 25% quantile, median, 75% quantile; whisker: ≤ 1.5 IQR, outliners: >1.5 IQR are true values. Significances are shown by the use of different letters (A) and (B). Groups labeled with different letters are significantly different.

Table 7: Time durations and migration rates of tagged fish migrating via the intake channel and sub routes, smolts passing the fishway and, the control group for all three analyzed stretches.

Stretch	Number of fish (N)	Duration (h)		Migration rate (mh^{-1})	
Route		Median	Range	Median	Range
Release – passage	**34**	**9.8**	**0.2 – 171.3**	**23.9**	**1.1 – 1846,1**
Fishway	15	9.9	1.1 – 171.8	20.6	1.16 – 125.0
Intake channel	19	10.1	0. 2 – 73.0	39.8	5.4 – 1846.1
Passage – last logger (L8)	**19**	**1.1**	**0.4 – 159.3**	**689.0**	**8.7 - 2978.5**
Fishway	14	1.0	0.4 – 159.3	1391.1	8.7 – 2978.5
Intake channel turbines	2	1.07	0.5 – 1.5	1335.1	688.4 – 1981.8
Intake channel esc. trap	3	21.8	5.13 – 22.0	49.8	49.3 – 212.3
Release – last logger (L8)	**19**	**18.6**	**1.6 – 195.6**	**65.3**	**4.7 – 769.3**
Fishway	14	17.9	2.07 – 194.8	107.9	8.1 – 769.3
Intake channel turbines	2	28.94	26.6 – 31.2	63.8	47.7 – 55.8
Intake channel esc. trap	3	23.33	7.6 – 53.4	63.8	27.8 – 194.7
Control	9	8.2	1.6 – 195.6	112.5	4.7 – 563.3

3.3.1 Influence of abiotic and biotic parameters on migration rate from release to passage

Time from release to passage was shortest for the last group released (April-23rd, Appendix IV), but there was no statistical correlation between migration rate and date of release (Kruskal-Wallis test, $K_4 = 4.89$, $p >> 0.05$). Discharge, expressed as total discharge from release to passage and ratio of: intake channel mean discharge / fishway mean discharge from release to passage, water temperature from release to passage and body measures (length, height, weight, degree of smoltification) did not seem to influence migration rate, as individual comparisons (Individual Spearman’s rank correlation, all $p >> 0.05$; Appendix III) did not show any significances. Analog to the individual correlations, no significant correlations between these parameters and migration rate were found by a linear regression model (Appendix VI). A linear regression model, using logarithmic migration rate values, implied a significant impact of smolt weight and date of release on migration rate from release to passage (Appendix VII). The found significances, however, proved to be highly dependent on the selection of variables and were therefore not further analyzed.

3.4 Search behavior of smolts upstream of the obstacle

Tagged individuals showed different patterns of movements before passing the HEP (Figure 10). The median smolt paid five visits (range 2 – 25) to seven existing areas upstream of the Herting HEP: 1) outside study site (OS); 2) approaching HEP (AH); 3) approaching fishway (AF); 4) approaching intake channel (AI); 5) inside intake channel (II); 6) at turbine rack (AR); 7) inside bypass (BP) (Figure 4), before finding a migration route past the obstacle. This search behavior did not seem to differ between individuals eventually choosing one of the two different main routes, since fish migrating via the intake channel paid a similar number of additional visits (i.e. all visits except the ones obligatory for the shortest possible area sequence before passage) to areas upstream of the hydro power plant (median 2 visits) as fish passing through the fishway (median 2 visits; Mann-Whitney U-test $p >> 0.05$). Most tagged fish did not tend to explore the alternative routes before passing. Only five out of 15 smolts migrating through the fishway first visited the start of the intake channel first (Figure 10) and none of them entered the intake channel. There was not a single visit made to the area just upstream of the fishway (AF) by smolts migrating into the intake channel. The median time spent in these seven areas upstream of the HEP varied significantly (Kruskal-Wallis test, $K_6 = 34.304$, $p < 0.05$; Figure 11). Post hoc comparison of the durations for all visits ($N = 219$) to the seven different areas upstream of the Herting HEP showed that tagged smolts spent less time at the turbine rack, compared to the areas further upstream (post hoc pairwise Mann-Whitney U comparison: AF ~ TR, AH ~ TR, AI ~ TR, II ~ TR, OS ~ TR, $p < 0.05$; other $p >> 0.05$; Figure 11, Table 8).

Table 8: Median time spent in the individual areas upstream of the HEP based on all visits of fish that successfully passed.

Area	Visits (N)	Time spent per area (h)	
		Median	Range
Outside study site (OH)	27	0.48	0.17 – 7.68
Approaching HEP (AH)	81	0.80	0.01 – 26.05
Approaching fishway (AF)	20	1.33	0.06 – 171.62
Approaching intake channel (AI)	44	0.77	0.01 – 14.30
Inside intake channel (II)	22	0.36	0.01 – 15.83
At turbine rack (AR)	15	0.01	0.01 – 3.90
Inside bypass (BP)	10	0.01	0.01 – 0.02

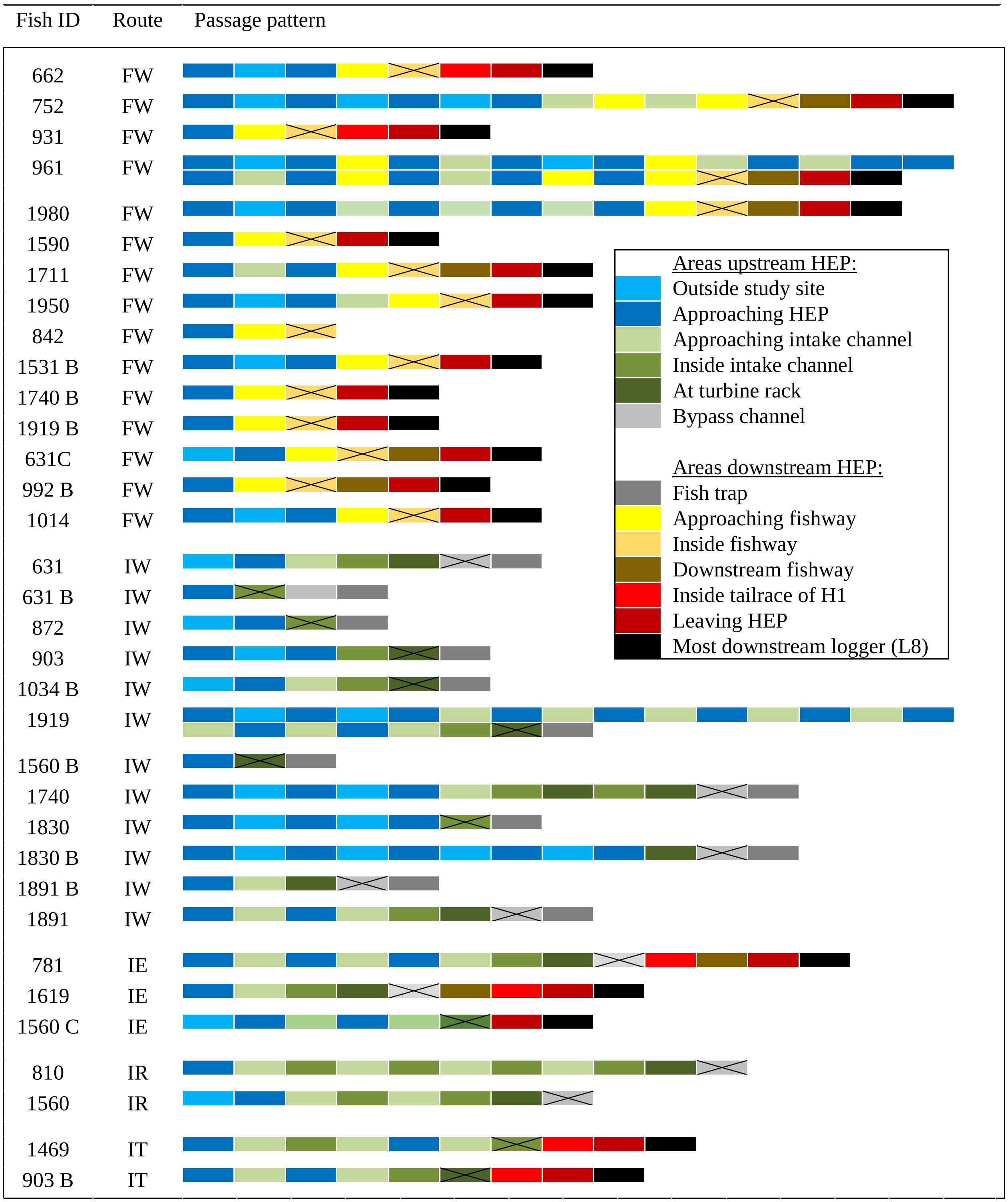

Figure 10: Passage patterns for all tagged fish that passed the Herting HEP. Each bracket represents a visit to a pre-defined area. Areas are color coded. Bracket size does not represent the duration of a visit. The first registered visit to an area after passing the HEP is marked by "X". Routes: fishway (FW), N = 14; intake channel escaped through bottom rack (IE), N = 3; intake channel washed up on bottom rack (IR), N = 2; intake channel turbines (IT), N = 2; intake channel fish trap (IW), N = 12.

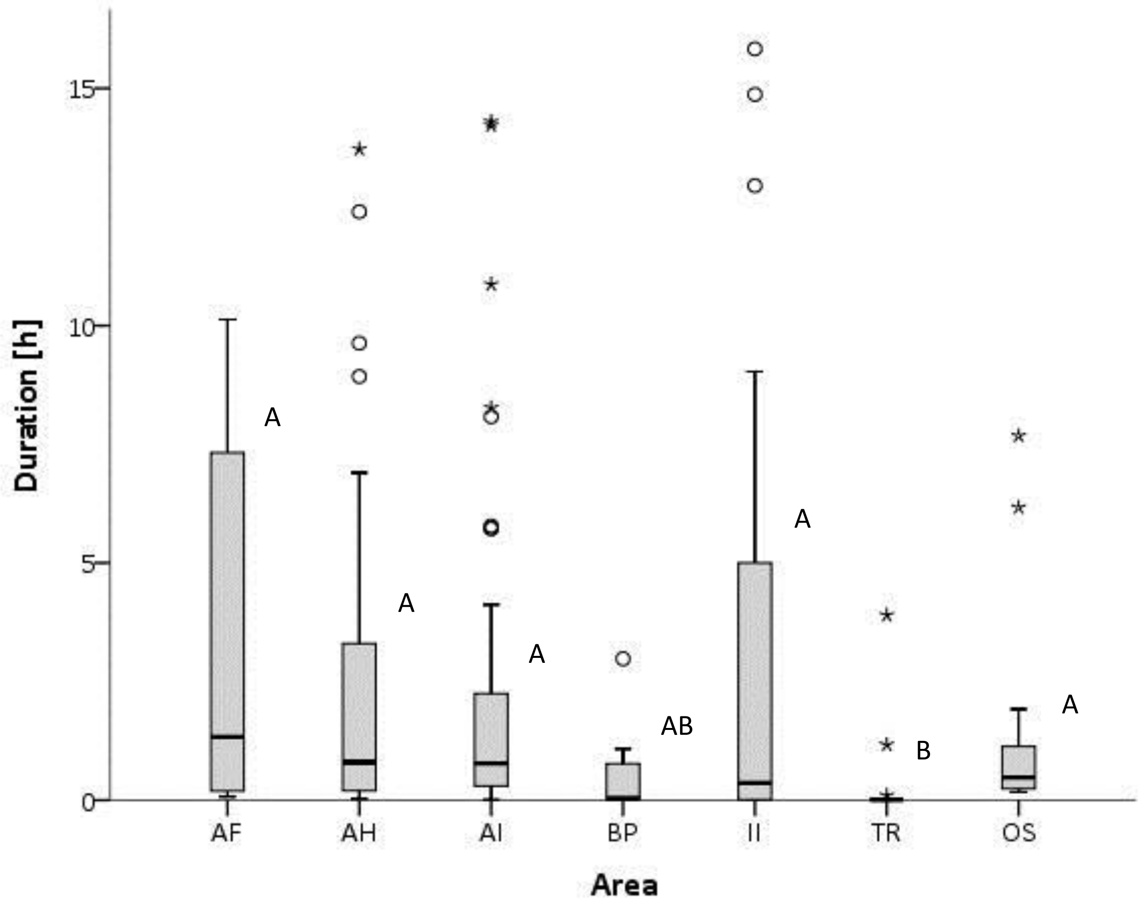

Figure 11: Distribution of time spent in the individual areas upstream of the Herting HEP for all passed smolts. Box: 25% quantile, median, 75% quantile; whisker: ≤ 1.5 IQR, outliners: >1.5 IQR are true values. Significances are shown by the use of different letters (A), (B). Groups labeled with different letters are significantly different. Outliners exceeding 15 h were excluded from this graph. Areas: approaching fishway (AF), approaching HEP (AH), approaching intake (AI), bypass (BP), inside intake channel (II), at turbine rack (AR), outside study site (OS).

Smolts that passed the HEP and continued their migration did not pay any additional visits to the five areas downstream of the Herting HEP i.e. 1) inside fishway (FW); 2) downstream fishway (DF); 3) bypass channel (BP); 4) turbine tailrace (TR); and 5) downstream HEP (DH). All of the 19 fish followed the shortest possible route until they reached the furthest downstream positioned logger (L8) (Figure 10).

4 Discussion

The replacement of the conventional 90 mm rack and attached surface trash gate by a 30°-sloped β-rack and adjacent full-depth bypass at the Herting hydroelectric plant significantly improved downstream passage conditions for Atlantic salmon smolts in river Ätran. During the pre-study most salmonid smolts (69%) passed through the turbines, and relatively few non-tagged individuals (about 1000) were caught in the bypass trap (Calles et al., 2012).With the new solution in place, however, a very small proportion of tagged smolts passed through the turbines (6%) and as a result more than 5000 non-tagged salmonid smolts were caught in the bypass trap during the smolt migration in spring 2014. Taking into account that a considerable number of tagged smolts passed the HEP via the nature-like fishway, the results are even more encouraging. Although some problems associated with the new bypass were experienced during the first year of operation, the solution is very promising and should improve downstream passage conditions at additional small- to medium-sized hydroelectric power plants in prospective constructions.

4.1 Overall passage success

This study showed that the new measures at the study site are potentially able to create conditions with total passage success exceeding 94% for downstream migrating salmon smolts. Total passage success for downstream migrating salmon smolt has increased from 90% in 2007 (Calles et al., 2012) to 94% in 2014. The observed total passage success is high when compared to similar studies. Calles and Greenberg (2009) studied the effects of two successive HEP's on migratory brown trout. Total passage success for brown trout smolts was 66% for the first and 76% for the second encountered HEP. The main reason for the overall lower TPS during this study were a high amount of predation and high numbers of turbine induced mortality (Calles and Greenberg, 2009). This was not the case at Herting. The initial calculated total passage success (TPS) of 94%, based on the original definition for TPS, can even be corrected to 97% since one smolt successfully passed the obstacle but seized to continue migrating to the sea. One reason that this individual did not continue its migration could be that the necessary biological adaptions for a life in saline water were not yet fully developed and this smolt thus, was not ready to enter the ocean (McCormick et al., 1998). The difference in total passage success between the pre-study compared to the study conducted in 2014 was overall negligible, yet the significant decrease in number of turbine passages marks a fundamental improvement.

4.2 Passage through turbines in relation to other routes and turbine induced mortality

Three key aspects guide attempts to successfully rehabilitate downstream passage measures: (1) stop fish from entering turbines, (2) concentrate them to a certain point, and (3) force or attract the same fish into a bypass (Calles et al., 2012). The cause of the large numbers of turbine passages in 2007 can be traced back to the failure of the turbine racks at both power plants to stop the approaching smolts (failure of aspect (1)). The number of turbine passages for tagged salmon smolts has decreased by 63% from 69% in 2007 (Calles et al., 2012), to 6% in 2014 and total turbine induced mortality was reduced from 8% in 2007 (Calles et al., 2012) to zero in 2014. This developments indicates that the new β-rack was able to address the major issue (that smolts were not stopped by the old turbine rack and consequently passed the turbines) for migrating smolts encountering the Herting HEP. The bar spacing of 15 mm in the β-rack seems appropriate for the evaluated rack type since the goal was to prevent the majority of migrating smolts (> 90%) from entering the turbines (Ebel, 2013). The significant decrease in turbine passages is a major improvement compared to the former solution since turbine passages can lead to substantial delayed mortality (Ferguson et al., 2006) and it is therefore likely that a high percentage of smolts that passed the turbines in 2007 did not survive long enough to successfully reproduce.

The number of turbine passages in similar studies varies correspondent to the type of rack, bar spacing's, and available bypass (Scruton et al., 2007; Calles and Greenberg, 2009). Narrow bar spacing's may stop approaching smolts but those require access to an alternative route to proceed their migration (Fjeldstad et al., 2012; Ebel, 2013).

4.3 Fish guidance efficiency of the new bypass

The evaluated full depth bypass proved to be highly efficient for downstream migrating Atlantic salmon smolt. The fish guidance efficiency of the bypass at the old powerhouse has increased from 17% for the surface trash gate evaluated in 2007 (Calles et al., 2012) to 85% for the new full depth bypass used in 2014. Even if there are few scientific evaluations for bypass systems targeting downstream migrating salmon smolts, it is stated that FGE's ranging from 60-85% can be achieved under optimal conditions (Larinier and Travade, 1999).There are no comparative studies targeting an identical design combination of full depth bypass and a low sloped β-guiding screen targeting downstream migrating salmonid smolts, but a similar solution in Germany showed a FGE of 83.3% for downstream migrating European silver eel (Ebel, 2013). In the study conducted by Ebel (2013), however, fyke-nets attached to turbine outlets and bypass exit were used to quantify the amount of eel passing through the bypass. There is no information about the number of eel that possibly visited the rack without passing, whereas additional visits of tagged smolts made to the turbine rack at the Herting HEP affected the observed FGE during the smolt study in 2014. A direct comparison of both recorded FGE's is unsuitable due to such methodical differences, but the general high performance of the evaluated system, expressed in a small number of turbine passages, can be verified by this thesis. Ebel (2013) summarized, that the relative discharge in a bypass system plays a minor role for its efficiency if other core features, e.g. geometrical metrics, hydraulics or entrance design, are implemented in a beneficial way. This can be reinforced by this study as the relative discharge used in the bypass was reduced from 25% in 2007 (Calles et al., 2012) to 1.4% in 2014 (with 100% being the average discharge in the intake channel during the correspondent study). The combination of high observed FGE and low relative discharge is an essential feature of the evaluated bypass system, since the efficiency of alternative bypass solutions often relies on diverting large parts of the river discharge into the bypass at the cost of power production (Johnson and Dauble, 2006; Fjeldstad et al., 2012).

Other studies have shown that salmonid smolts can be reluctant to enter a bypass (Larinier, 1998; Scruton et al., 2003). This was not the case for the evaluated bypass as smolts that found their way to the β-rack proceeded swiftly into the bypass channel without significant delay. This indicates an optimal guiding effect of the evaluated β-rack and an ideal positioning and entrance design of the subsequent full depth bypass (Ebel, 2013). One major issue during this study was, however, that the monitoring facility of the rehabilitated bypass caused mortality.

4.4 Total mortality

Even if turbine induced mortality was significantly reduced, total mortality for tagged Atlantic salmon smolt passing the Herting HEP did not change between 2007 (10%) (Calles et al., 2012) and 2014 (9%). This stagnation can be traced back to the mortality caused by the monitoring facility. Total mortality in similar studies may vary depending on the circumstances of the study in question, but is usually related to predation and/or turbine induced mortality (Larinier, 1998; Ferguson et al., 2005 b; Fjeldstad et al., 2012). A research conducted by Aarestrup, Jepsen and Rasmussen (1999) showed a total mortality of 90% for tagged hatchery-reared Atlantic salmon smolts navigating through an about 8 km long reservoir on their way to a HEP located at the end of this reservoir. The high losses for tagged smolts were mainly caused by predation during the long time spent passing through the lotic river stretch. Another similar study carried out by Scruton et al. (2007) evaluated the efficiency of a retrofitted bypass system for Atlantic salmon smolt in 2003 and 2004 respective. In this study tagged smolts were released directly inside the forebay of a HEP and a total mortality of 16% was observed in 2004 (total mortality was not assessed for 2003). The mortality observed by Scruton (2003) was mainly attributed to turbine passage. Turbine passage (0%) and predation (3%) caused limited mortality to downstream migrating smolt at the Herting HEP in 2014. The fact, that the monitoring station at the new bypass was responsible for the majority of mortality, presents a notable challenge to the evaluated downstrem passage system. The mortality caused by the fish trap installed at the Herting HEP was not limited to tagged smolts as several non-tagged dead Atlantic salmon smolt and dead fish of other species were found on the bypass rack or inside the holding container of the trap. It seems, as adverse hydraulic conditions at the bypass rack and inside the holding tank resulted in fish getting stuck between bars and other gaps of both dewatering areas of the rack and holding tank. Addressing this challenge should be of the highest priority in prospective constructions, as the trapping facility seems to be one of few sources of mortality at the Herting HEP. Mortality caused by the monitoring facility, based on the individuals that entered the bypass, was higher for tagged smolts compared to non-tagged fish. Earlier studies have shown that the transmitters used in this study typically do not significantly impact on the swimming behavior of tagged salmonid smolts (Murchie, Cooke and Schreer, 2004). The antennas of the used transmitters may still have resulted in fish getting stuck on the bottom rack thus leading to a higher mortality for tagged smolt at the monitoring facility.

The single observed possible predation during this study could not been verified. In similar studies, piscivore predation on tagged fish is often proved by the capture of the predator through electrofishing or by retrieval of the non-digestible receiver shortly after the observed predation (Aarestrup et al., 1999; Dieperink, Pedersen and Pedersen, 2001). Neither was possible in the context of this study. It is likely that the fish was not taken by a predator since the signal of the tagged individual displayed movements for another 13 days. The low predation rate on tagged smolts can probably be explained by the relatively short migration delay caused by the Herting HEP, as the risk of predation is typically positively correlated to delayed migration (Ferguson et al., 2005 b).

4.5 Migration delay and searching behavior of tagged smolts

Time from release to passage has been decreased by 31% from median 14.4 h in 2007 (Calles et al., 2012) to median 9.9 h in 2014. The most time consuming route during the pre-study used to be the bypass (median 35.4 h (Calles et al., 2012)), which is no longer the case as the median smolt migrating via the new bypass took 70% less time to find the entrance of the bypass than in the study of 2007 (Calles et al., 2012). The behavior of tagged smolts in the areas upstream of the Herting HEP indicates, however, that some tagged individuals were reluctant to enter, or were not able to find the available routes as seen in the significantly higher overall migration rates after passing the obstacle. This shows that the evaluated rehabilitation measures, although generally convincing, were not able to entirely prevent a migration delay caused by the Herting HEP. Still, the total delay of less than 15 h for both years is relatively low when comparing the results to similar studies (Aarestrup and Koed, 2003; Scruton et al., 2007; Calles and Greenberg, 2009) thus indicating a minor effect on smolt migration. This can be affirmed by the fact that tagged smolts that approached the HEP were not exposed to elevated predation rates which is often observed in similar studies (Ruggles and Murray, 1983; Ferguson et al., 2005 b). We suggest, that the cause for the observed delay is a combination of reduced velocity inside the forebay of the Herting HEP, compared to riverine stretches further upstream, as suggested by Tiffan et al, (2009), and the observed searching behavior for a migration corridor. We can’t rule out, that the observed delay at the Herting facility is any different from what would be observed at e.g. a rapid or some other kind of natural obstacle that may require time for a smolt to overcome.

The similar distribution of tagged smolts between the two main migration routes corresponds with the average discharge distribution (which was close to equal between fishway and intake channel during the study period), as salmonid smolts generally follow the main current during their migration to the sea (Hansen and Jonsson, 1985; Rivinoja, 2005). Both available main migration routes proved to be important corridors for tagged smolts on their way to the sea. The equal importance of both routes is especially noteworthy because the new fishway is primarily designed for upstream migrating fish (Fiskevårdsteknik AB, unpublished). The nature-like fishway was expected to be of limited importance for downstream migrating fish, since the water intake was partially blocked by the guiding-screens of the optical fish counter. Both, rack screens of the fish counter, and the weirs limiting the upstream entrance of the fishway were expected to constitute behavioral migration barriers thus preventing tagged smolts from entering the fishway (Taft and Bazarian, 1983; DWA, 2005). The median smolt, however, was not reluctant to enter the fishway, since 40% of all tagged smolts passed via the new fishway and about 55% through the turbine intake channel. There are no published evaluations targeting downstream passage efficiency of a similar fishway entrance design, but Aarestrup and Koed (2003) recorded delays of more than seven days at two small water overflowed weirs for tagged brown trout smolts. The observed delay was shorter at the Herting fishway, and it did not seem like the typical smolt was reluctant to enter the fishway by passing over the weirs or by swimming through the screens and/or fish counter. There were no recordings of smolts passing the fish counter and given that the resolution of the used telemetry system was not high enough to differ where tagged smolts entered the fishway in particular, we can only speculate if smolts migrating through the fishway did drop over the weirs or swam through the guiding screens of the fish counter.

4.6 Total number of smolts produced in 2014 and 2007

During the period of the study, 50% of all tagged treatment fish that passed the Herting HEP entered the new bypass whereas only 10% of tagged Atlantic salmon smolts used the surface trash gate in 2007 (Calles et al., 2012). The corresponding calculated number of total smolts migrating, by using the total number of non-tagged salmonid smolts caught in the fish trap and the percentage of tagged smolts that migrated through this route, was 10,510 smolts in 2007 and 10,146 in 2014. The similarity of these numbers supports the initial observation that the new bypass is working more efficiently than the old temporary solution. Hence, the possibility that an increased number of smolts produced in the rivers system in 2014 is responsible for a higher count of smolts caught in the bypass trap is lowered. High daily catches of salmonid smolts during the first days of the study show that smolt migration was already occurring at that time, thus indicating that the study period did not cover the entire migration period. An unknown number of smolts passed the Herting HEP before April-14th, but we argue that the main migration run was covered by the study since daily catches for both trout and salmon smolt peaked during the study period (April-17th and April-22nd, respectively). Furthermore only about 10% of the total smolt catch was recorded in the bypass trap before April-14th during the pre-study in 2007 (Calles et al., 2012). For trout smolt, however, the corresponding catch before April 14th was 41% in 2007 (Calles et al., 2012), and so the study in 2014 may have missed a significant part of the trout smolt-run.

4.7 Conclusion and management implications

The evaluated measures improved the passage conditions for downstream migrating salmon smolts in river Ätran. The installation of a β-rack and adjacent full depth bypass resulted in a highly improved FGE of the bypass and a significantly reduced amount of turbine passages at the Herting hydroelectric power plant. Total passage success and total morality, both of which were already above average during the pre-study compared to similar studies, could not be considerably improved, due to mortalities induced by the monitoring facility. The mortality caused by the bottom rack of the fish trap must be taken into account in prospective constructions (e.g. through increase of slope of the bottom rack). If the monitoring facility at Herting is to be used in prospective smolt migration researches, we suggest to run the fish trap in a sub-sample style, e.g. one day per week, to reduce the negative effect and to combine trap catches with respective telemetry-studies.

In spite of the concerns related to the maintenance of the monitoring facility, the overall results of the evaluation are very convincing. We therefore recommend to install the tested measures on additional small to medium sized hydro power plants, not only to increase local passage conditions, but also to set the basis for further evaluations of the full depth bypass and β-rack with varying factors such as discharge and velocity. The installation of such measures is associated with substantial construction costs and, in the case of the Herting HEP, an increased head loss. Yet in some cases the head-loss can be reduced instead of increased as a result of the increased surface area of low sloping turbine racks (Calles et al., 2013). Hence, under certain circumstances low-sloping racks can both improve the longitudinal connectivity and increase production of electricity (Calles et al., 2013). Furthermore, the Herting HEP has an overall low production of electricity and is situated in the lowermost part of one of the most important rivers for diadromous fish species in Sweden (Calles, Rivinoja and Greenberg, 2013). We thus argue, that the value of improving passage conditions for migrating fishes by far exceeds the loss of electricity production.

Although we proved that the implemented measures successfully increased passage conditions for Atlantic salmon smolt at Herting HEP, further investigations to evaluate the passage efficiency for additional diadromous species and life stages are imperative. Of particular concern are salmonid kelt, since the fish trap catches of kelt were considerably smaller in 2014 compared to the pre-study in 2007 (Calles et al., 2012). The explanation for the limited bypass catches of kelt could be due to a poor performance of the bypass for larger salmonids, or a preference to pass downstream using the nature-like fishway. Additional telemetry studies conducted at the Herting HEP throughout summer and fall 2014 included an evaluation of the new measures targeting downstream migrating silver eel and upstream migrating Atlantic salmon spawners. The insight gained in these observations in combination with the results presented here, will provide a detailed evaluation about the overall performance of the new β-rack and full-depth bypass system for up– and downstream migrating diadromous fishes. This combined evaluation will help to improve sparse overall knowledge on how to successfully improve downstream passage conditions at hydroelectric power plants (Fjeldstad et al., 2012; Noonan, Grant and Jackson, 2012).

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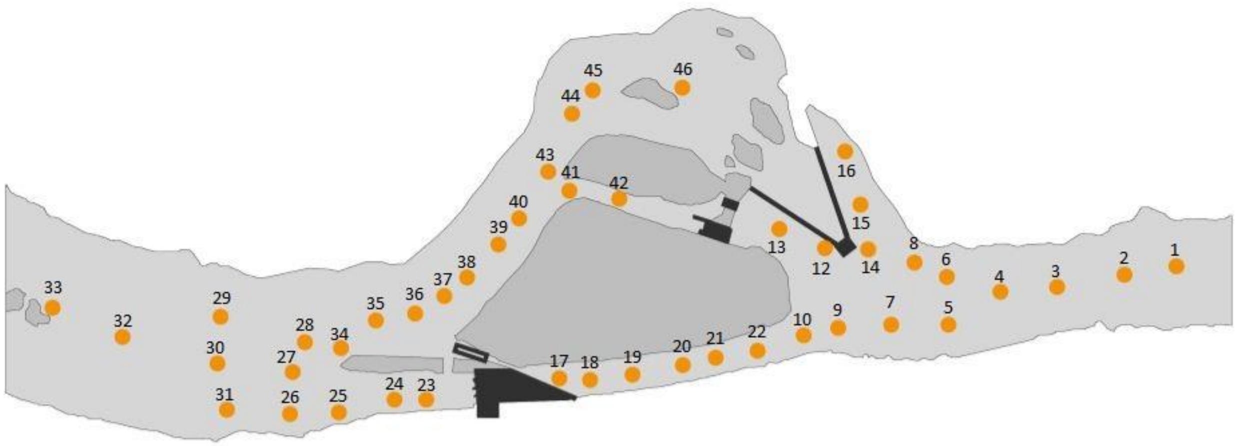
HEP	Hydroelectric power plant
TPS	Total passage success
FGE	Fish guidance efficiency
FW	Fishway
IC	Intake channel
IW	Intake channel caught in fish trap
IE	Intake channel escaped through fish trap
IT	Intake channel passed turbines
H1	Old Powerhouse
H2	New Powerhouse
OS	Outside study site
AH	Approaching hydroelectric power plant
AI	Approaching intake channel
II	Inside intake channel
AR	At turbine rack
BP	Inside bypass channel
WT	Inside fish trap
TR	Inside tailrace of H1
AF	Approaching fishway
IF	Inside fishway
DF	Downstream fishway
LS	Left study site

Acknowledgments

Firstly I would like to thank Prof. Dr. Herwig Stibor and Prof Dr. Jürgen Geist for their excellent supervision and assistance on several issues during the writing and preparation of this thesis. I really appreciate the great support during the last two years, including the extraordinary help while applying for a scholarship, and the opportunity for being a part of Prof. Jürgen Geist's Chair for Aquatic Systems Biology and Prof. Dr. Herwig Stibor's workgroup on aquatic ecology. Further, I would like to thank Dr. Olle Calles. I am truly grateful that you enabled me to spend the last months of my masters course in Sweden and that you sacrificed countless hours on assisting me during my master's thesis regardless of date and time. Additionally I would like to thank the entire staff from the Chair for Aquatic Systems Biology for two great years and especially Dr. Joachim Pander and Dr. Melanie Müller who's know how contributed to this study in a very positive way. Special thanks to Dr. Sabine Schultes who helped me out on countless occasions during my master's course and to Almond Stöcker for assisting in various statistical issues. Last but not least I would like to thank Jonas Christiansson and Peter Olsson for sharing their time and home with me for several months. It has been a pleasure working with you guys!

Appendix

Appendix I: Locations of all strategic points used during the pilot test, conducted to create a signal-strength-map, and the results in form of the average signal strength of the corresponding loggers per point (table below).



Location number	Recoredet signal strenght (mean) per logger		Location number	Recoredet signal strenght (mean) per logger	
1	L6: 0	L7: 0	**24**	L1: 88 L2: 133	L4: 90 L5: 91
2	L6: 88.5		**25**	L1: 95 L2: 129 L4: 87	L5: 102 L6: 90
3	L6: 94		**26**	L1: 108 L2: 113	L5: 96
4	L6: 95		**27**	L1: 111 L2: 101	L5: 84
5	L6: 105	L7: 110.5	**28**	L1: 109 L2: 92	L5: 91
6	L6: 107	L7: 106	**29**	L1: 96	L2: 93
7	L6: 109	L7: 106.5	**30**	L1: 93 L2: 95	L5: 87
8	L6: 121.5	L7: 119	**31**	L1: 101 L2: 95	L5: 94.5
9	L4: 80.5 L6: 125	L7: 104.5	**32**	L1: 83.5	L2: 96
10	L4: 87.5 L6: 129.5	L7: 98	**33**	L1: 79	L2: 88

11	L6: 119	L7: 118	**34**	L1: 108 L2: 107	L5:112.5 L6: 97
12	L6: 114	L7: 106.5	**35**	L1: 99 L2: 117 L4: 84	L5: 109 L6: 95.5
13	L6: 94	L7: 103	**36**	L1: 76 L2: 122	L4: 91 L5: 102
14	L6: 110	L7: 147	**37**	L1:86.5 L2: 119.5	L4: 78.5 L5: 115
15	L6: 106	L7: 137.5	**38**	L1: 84 L2: 107.5	L5: 120
16	L6: 107	L7: 115.5	**39**	L1: 79 L2: 112.5	L4: 83 L5: 127
17	L4: 125	L6: 103	**40**	L1: 73.5 L2: 99	L5: 130
18	L2: 79	L4: 112 L6: 111	**41**	L5: 111	
19	L2: 91 L4: 107.5	L6: 109	**42**	L5: 93.5	L6: 92.5
20	L4: 105 L5: 79.5	L6: 119.5	**43**	L2: 93 L5: 137	L6: 93.5
21	L4: 122.5	L6: 96	**44**	L5: 111	L7: 102.5
22	L6: 119		**45**	L5: 107	L7: 105.5
23	L1: 76 L2: 132	L5: 87	**46**	L5: 92	L7: 111

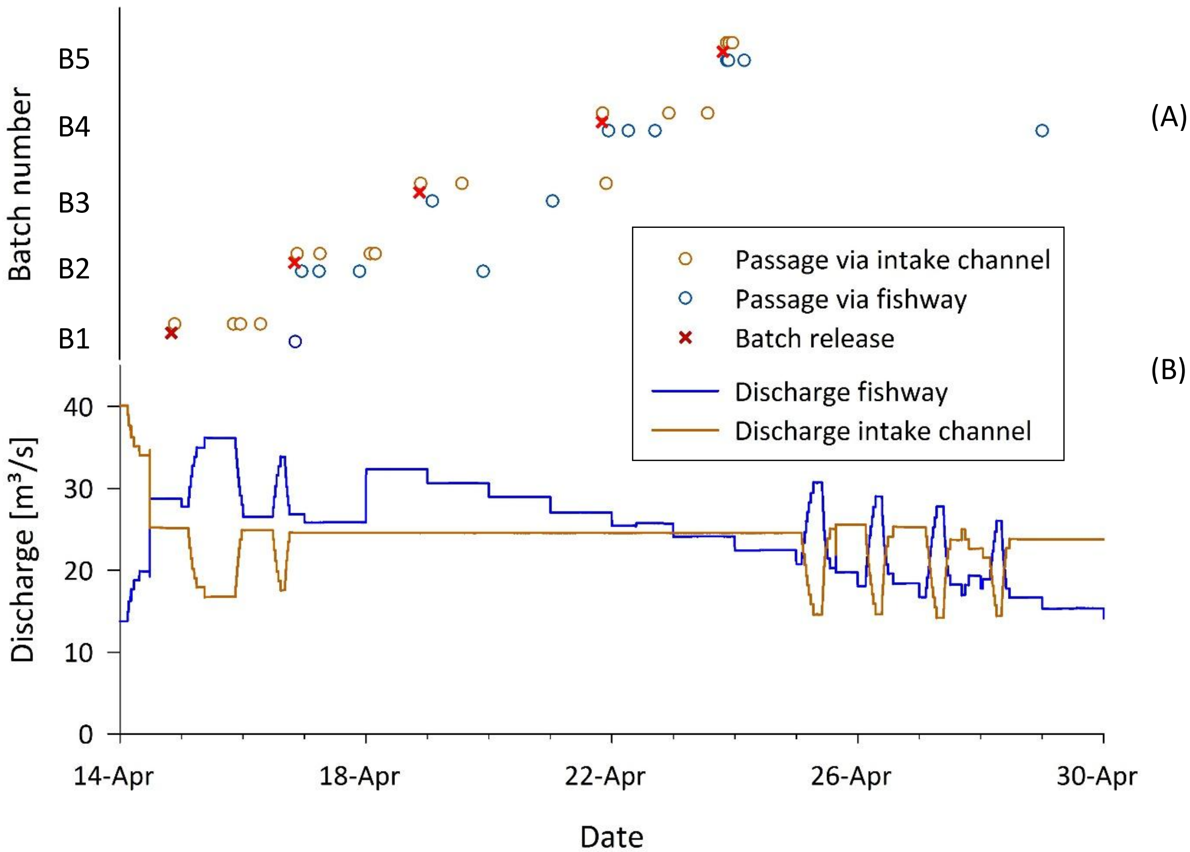
Appendix II: Median body measures in relation to route- and sub route selection of all tagged smolts that successfully passed the Herting HEP. Values in brackets display min. and max values

Route	Number of fish (N)	Length (mm)	Height (mm)	Weight (g)	Degree of smoltification (1-3)
Total Fishway	15	148 (136 – 156)	24 (23 – 27)	26.5 (24.2 – 31.5)	2 (1 – 3)
Total Intake channel	19	145 (137 – 160)	24 (18 – 29)	26.0 (21.2 – 33.7)	2 (1 – 3)
Turbines	2	156 (143 – 164)	24 (23 – 25)	25.5 (22.0 – 29.0)	2 (1 – 2)
Escaped through fish trap	3	146 (145 – 153)	25 (25 – 27)	30.0 (24.0 – 31.0)	2 (1 – 2)
Washed up on bottom rack	2	148 (145 – 150)	26 (23 – 28)	28.0 (22.0 – 34.0)	2 (2 – 3)
Regular bypass passage	12	147 (138 – 160)	24 (23 – 27)	26.5 (24.0 – 31.0)	2 (1 – 2)

Appendix III: Results of all individual comparisons conducted to verify if abiotic- and biotic parameters affected route choice and migration rate from release to passage.

Purpose	Test	Result
Influence of smolt length on route choice	Mann Whitney U Test	p = 0.157 U = 183.50
Influence of smolt height on route choice	Mann Whitney U Test	p = 0.607 U = 157.50
Influence of smolt weight on route choice	Mann Whitney U Test	p = 0.111 U = 188.50
Influence of degree of smoltification on route choice	Mann Whitney U Test	P = 0.811 U = 135.00
Test if fish passing the turbines differed from other fish passing via the bypass in length	Mann Whitney U Test	p = 0.659 U = 7.00
Test if fish passing the turbines differed from other fish passing via the bypass in height	Mann Whitney U Test	p = 0.659 U = 14.50
Test if fish passing the turbines differed from other fish passing via the bypass in weight	Mann Whitney U Test	p = 0.659 U = 9.00
Test if fish passing the turbines differed from other fish passing via the bypass in degree of smoltification	Mann Whitney U Test	p = 0.659 U = 9.00
Test if fish escaping the fish trap differed from other fish passing via the bypass in length	Mann Whitney U Test	p = 1.000 U = 18.50
Test if fish escaping the fish trap differed from other fish passing via the bypass in height	Mann Whitney U Test	p = 0.233 U = 26.50
Test if fish escaping the fish trap differed from other fish passing via the bypass in weight	Mann Whitney U Test	p = 0.180 U = 27.50
Test if fish escaping the fish trap differed from other fish passing via the bypass in degree of smoltification	Mann Whitney U Test	p = 0.840 U = 19.50
Test if fish washed up on the bottom rack of the fish trap differed from other fish passing via the bypass in length	Mann Whitney U Test	p = 1.000 U = 12.50
Test if fish washed up on the bottom rack of the fish trap differed from other fish passing via the bypass height	Mann Whitney U Test	p = 1.000 U = 13.00
Test if fish washed up on the bottom rack of the fish trap differed from other fish passing via the bypass in weight	Mann Whitney U Test	p = 1.000 U = 12.00
Test if fish washed up on the bottom rack of the fish trap differed from other fish passing via the bypass in degree of smoltification	Mann Whitney U Test	p = 0.264 U = 18.50

Correlation of migration rate before passage and total length	Spearman’s rank correlation	$p = 0.080$ $\rho = 0.305$
Correlation of migration rate before passage and height	Spearman’s rank correlation	$p = 0.168$ $\rho = 0.342$
Correlation of migration rate before passage and weight	Spearman’s rank correlation	$p = 0.070$ $\rho = 0.314$
Correlation of migration rate before passage and degree of smoltification	Spearman’s rank correlation	$p = 0.794$ $\rho = - 0.047$
Correlation between migration rate and total discharge from release to passage	Spearman’s rank correlation	$p = 0.827$ $\rho = - 0.039$
Impact of total discharge on route choice	Mann Whitney U Test	$p = 0.096$ $U = 190.50$
Impact of average discharge in the fishway on route choice	Mann Whitney U Test	$p = 0.128$ $U = 187.00$
Impact of average discharge in the intake channel on route choice	Mann Whitney U Test	$p = 0.945$ $U = 140.00$
Correlation of average water temperature and migration rate from release to passage	Spearman’s rank correlation	$p = 0.621$ $\rho = 0.088$
Influence of average water temperature on route choice	Mann Whitney U Test	$p = 0.214$ $U = 106.50$



Appendix IV: Passage events for all released batches (A) (B1: 14-Apr., B2: 16-Apr., B3: 18-Apr., B4: 21-Apr., B5: 23-Apr.) and corresponding discharge distribution between fishway and intake channel (B). Both parts of the graph, (A) and (B) share the same x-Axis.

Appendix V: Results of the binary regression model used to predict route choice of tagged smolts using abiotic- and biotic parameters (Wald test).

Parameter	Coefficient	p value
Release date	-0.03	0.97
Total mean discharge	0.27	0.34
Ratio: intake channel mean discharge / fishway mean discharge	-6.33	0.37
Length	0.10	0.48
Height	-0.21	0.45
Weight	0.32	0.12
Degree of smoltification	-0.53	0.80
Water temperature	0.69	0.59

Appendix VI: Results of the linear model used to predict migration rate from release to passage using abiotic and biotic parameters (Wald test).

Parameter	Coefficient	p value
Release date	68.45	0.71
Total mean discharge	72.41	0.17
Ratio: intake channel mean discharge / fishway mean discharge	- 175.50	0.88
Length	-2.52	0.92
Height	-26.71	0.63
Weight	29.56	0.43
Degree of smoltification	-124.129	0.76
Water temperature	113.727	0.62

Appendix VII: Results of the log-linear model used to predict migration rate from release to passage from abiotic and biotic parameters (Wald test).

Parameter	Coefficient	p value
Release date	0.71	0.02
Total mean discharge	0.64	0.45
ratio of intake channel mean discharge / fishway mean discharge	- 1.42	0.47
Length	-0.13	0.74
Height	-0.09	0.28
Weight	0.13	0.03
Degree of smoltification	-0.53	0.41
Water temperature	-0.42	0.26