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Downstream migration of Atlantic salmon smolts at Unkelmühle power station and Buisdorf dam in 2016

Torgeir B. Havn, Finn Økland, Lisa Heermann, Eva B. Thorstad, Maxim A.K. Teichert, Stein Are Sæther, Meelis Tambets and Jost Borcherding

University of Cologne
Norwegian Institute for Nature Research

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Summary

Havn, T.B., Økland, F., Heermann, L., Thorstad, E.B., Teichert, M.A.K., Sæther, S.A., Tambets, M. & Borcherding, J. 2018. Downstream migration of Atlantic salmon smolts at Unkelmühle power station and Buisdorf dam in 2016. NINA Report 1412. Norwegian institute for nature research.

Background and study aim
The aim of this study was to examine migration routes and losses of Atlantic salmon smolts past the Unkelmühle hydropower station in the Sieg. Results from the study in 2016 are the main focus of this report. The results from 2016 are also compared with results from similar studies at Unkelmühle in 2014 and 2015. Technical facilities at Unkelmühle are designed to facilitate safe passage of downstream migrating fish, including ten different bypass routes where fish can pass outside the turbines, and narrowly spaced racks installed in front of the turbine intakes to prevent fish from entering the turbines. The efficiency of these measures are evaluated.

Downstream migration past Buisdorf dam was also examined in 2016. This enabled comparison of loss and migration speeds of smolts between the Unkelmühle hydropower station and a weir without a hydropower station at Buisdorf.

Methods
The study was performed by tagging 227 Atlantic salmon smolts with radio transmitters and recording their migration in the river and past Unkelmühle power station and Buisdorf dam. Their movements were recorded 1) on free-flowing reference stretches upstream of the power station and dam, 2) on impounded stretches upstream of the power station and dam, 3) when they passed the power station and dam, and 4) on downstream river stretches. Migration routes used by tagged fish when they passed the power station and dam were mapped in detail by using networks of automatic, stationary receivers.

The loss of downstream migrating smolts due to impoundments and past the power station and dam was calculated by comparing losses in these areas with losses on the reference stretches. This is based on the assumption that the loss per km recorded on the reference stretches (termed “reference loss” in this report) is representative for the developed stretch (stretch affected by hydropower development) if it had been a free-flowing river instead of being impounded by a reservoir and having a power station or dam. To examine if the location of the reference stretches affected the estimated loss caused by hydropower development, we compared two estimates of loss due to Unkelmühle power station based on reference loss on two different reference stretches.

Results and conclusions
The loss of downstream migrating smolts due to Unkelmühle power station was minimum 2.9% during the study in 2016. This represents the percentage of smolts arriving at the power station area that were lost due to this being a power station area instead of a free-flowing river. The loss estimate represents direct loss at the power station and delayed mortality due to the power station on the stretches downstream (7.5 km). There was no difference in loss between fish using the headrace to pass the power station and those passing over the weir. Loss due to the Buisdorf dam was minimum 3.4 and 5.7% (two different estimates) and not significantly different from the loss at Unkelmühle.

The loss estimates are minimum estimates, because fish injured when passing the power station or dam can experience delayed mortality at later stages than recorded in this study, and the total mortality might therefore have been higher.

There was no turbine mortality at the power station, because none of the smolts passed through the bar racks in front of the turbines, as expected due to the narrow bar spacing (10 mm) of the racks. Hence, the extra loss of smolts passing the power station was likely related to physical injuries in bypass routes aimed at guiding smolts outside the turbines, and increased predation.

Loss due to the hydropower station was lower in 2016 compared to the two previous study years (minimum 9.9% in 2014 and 12.8% in 2015). Although total loss due to the power station was highest in 2015, loss in the bypass route that leads smolts outside the turbines was higher in 2014 than in 2015 and 2016. This was likely caused by smolts becoming trapped in an area of the bypass route where debris and branches piled up in 2014, but not in 2015 and 2016. Water discharge was higher in 2016 compared to the previous study years, and the high water discharge was probably an important factor for reducing loss of smolts passing the power station in 2016.

Results showed that the reservoir upstream of the power station can be an area of high mortality for downstream migrating smolts. Of all smolts entering the reservoir upstream of Unkelmühle, 7.2% in 2014, 17.1% in 2015 and 4.4% in 2016 were lost due to this being a reservoir instead of a free-flowing river. The reservoir upstream of Unkelmühle is 2.3 km long, with slow-flowing water, and more resembling a lake than a river. The main reason for the extra loss in the reservoir is likely presence of more fish predators in the slow-flowing reservoir compared to the free-flowing river stretches. These results show that reservoir mortality may vary among years, probably due to variation in the predator community.

In contrast to at Unkelmühle, where fish were delayed at the power station, fish moved at the same speed past Buisdorf dam as on unimpounded stretches. This difference in migration speed was also found when comparing only fish that migrated through the spillway gate at Unkelmühle with fish that used the weir at Buisdorf. No fish spent time in the turbine intakes before swimming back upstream and using the spillway gate to pass the power station, so behaviour upstream of the power station did not seem to explain why fish moved slower past the power station compared to the dam. However, smolts seem to follow the main water flow when navigating past power stations, and the observed differences may be caused by a higher proportion of the total water discharge running over the weir at Buisdorf compared to the proportion running through the spillway gate at Unkelmühle, making navigation over the weir and exit of the tailrace faster at Buisdorf compared to Unkelmühle.

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Foreword

The necessity to decrease carbon dioxide emissions in order to reduce effects of anthropogenic induced climate change requires energy saving and an increasing production of renewable (“green”) energy. In contrast to for instance solar energy, for which limited impact on the environment is usually expected, energy generated by wind or water has been shown to have adverse effects on nature. A negative impact on migrating fishes that have to pass barriers at hydropower stations during their life cycle is likely, and has been recorded in several previous studies.

Hydropower production constitutes a political trade-off between sustainable energy generation and the impact on the connectivity, and thus on the integrity of natural rivers. To achieve a good ecological status of rivers according to the EU water framework directive, and to reduce the impact of barriers, many fish ladders were built in recent decades improving upstream migration of fish at man-made migration barriers. These fishways are, however, not always suitable for downstream migration. Therefore, it is necessary to improve mitigation measures for downstream migration as well and to save fish from injury and mortality by the turbines and other installations at hydropower stations.

To be able to generate energy with as little impact on fish migration as possible, the government of North-Rhine-Westphalia cooperates with the hydropower company innogy SE. Together, they have improved the technical facilities of the Unkelmühle power station in the Sieg, aiming to allow for a safe downstream migration. To assess the efficiency of these measures, the Ministry for Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia (MULNV) commissioned the University of Cologne to monitor fish migration at this site by using radio telemetry methods, in close cooperation with the Norwegian Institute for Nature Research (NINA) and the North Rhine-Westphalian State Agency for Nature, Environment and Consumer Protection (LANUV).

In Germany, many dams and weirs used for hydropower production were established hundreds of years ago. These historical dams and weirs associated with hydropower production might have negative impacts on fish populations, and it has been decided that they should be evaluated, especially if they have recently been equipped with fish protection and bypass systems. The question is if there are any negative consequences involved for fish bypassing the hydropower turbines and passing directly over a weir. To answer this question, we compared behavior and mortality of Atlantic salmon smolts passing a protected turbine intake with several bypass options with smolts passing a spillway gate or natural fishway at the Unkelmühle power station in the Sieg. In addition, we examined how a dam without a hydropower station in Buisdorf affected downstream migration of smolts.

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February 2018

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1 Introduction

Atlantic salmon (*Salmo salar*) is a fish species of large cultural and economic importance. Many populations have declined within the entire distribution area of the species (ICES, 2016). Atlantic salmon was lost from all German watersheds due to pollution, migration barriers and habitat destruction (Monnerjahn 2011). By the end of the 1950s, salmon was extinct in many rivers, including the River Rhine, which once was among the main Atlantic salmon rivers in Central Europe (Molls & Nemitz 2008). Re-introduction programs have been initiated in the Rhine. Atlantic salmon have reproduced naturally in several tributaries including the River Sieg, where this study was performed, but self-sustaining populations are not yet re-established (Molls & Nemitz 2008; Monnerjahn 2011; Schneider 2011).

Concurrent with attempts to re-introduce Atlantic salmon, there is a desire to produce renewable hydroelectric energy. Hydropower installations and other man-made installations such as dams and weirs, may reduce river connectivity and can cause injuries, delays and mortality in migrating fish (*e.g.*, Rivinoja et al. 2001; Larinier 2008; Stich et al. 2015a, b). Atlantic salmon migrate downstream in rivers towards the sea in the spring, and after a year or more of feeding in the sea they return to their home river to spawn. To re-establish Atlantic salmon, migrating fish need to pass hydropower installations and other man-made installations with little mortality. Increased mortality in regulated rivers may be due to fish being killed by turbines, predation in the reservoir above the power station, and increased mortality in alternative passages that lead fish outside the turbines (Thorstad et al. 2012). In addition, the timing of the smolt run may be adapted through natural selection to meet the most optimal environmental conditions in the sea (McCormick et al. 1998; Thorstad et al. 2012), and delays due to hydropower installations may therefore reduce the sea survival.

The Unkelmühle power station was especially designed with several possible bypass routes for fish outside the turbines. Narrowly spaced racks (opening 10 mm) are installed at the turbine intakes to prevent fish from entering the turbines. The performance and success of downstream migrating Atlantic salmon related to these measures were recorded in this study.

The aim of this study was to examine migration routes and losses of Atlantic salmon smolts past the Unkelmühle power station in the Sieg in 2016. Results from such studies may vary considerably between years due to for instance variation in predator communities and environmental variables. We therefore performed studies at Unkelmühle in three consecutive years (2014-2016) to account for potential variation in losses. Results from 2016 are compared with previously reported results from 2014 and 2015 (Økland et al. 2016, Havn et al. 2017).

Few smolts passed the Unkelmühle power station over the spillway gate in 2014 and 2015, mainly because it was closed most of the time due to low water discharge in the river. Therefore, a downstream dam and its reservoir in Buisdorf were included in the study in 2016 to ensure that more data from fish passing over weirs were collected. In addition, the study design at Unkelmühle and Buisdorf was nearly identical, allowing for an approximate comparison of loss and migration speed between the Buisdorf dam and power station.

The study was performed by tagging 227 Atlantic salmon smolts with radio transmitters and recording their downstream migration when passing the Unkelmühle power station and Buisdorf dam by automatic receivers and manual tracking. Their movements were recorded 1) on free-flowing reference stretches upstream of the power station and dam, 2) on impounded stretches upstream of the power station and dam, 3) when they passed the power station and dam, and 4) on downstream river stretches. Migration routes used by tagged fish when they passed the power station and Buisdorf dam were mapped by using a network of automatic, stationary receivers.

2 Description of Unkelmühle power station and Buisdorf dam

2.1 Unkelmühle power station

Unkelmühle is a run-of-the river power station on the Sieg, 44 km upstream from the confluence with the Rhine (**figure 2.1, 3.1**). The reservoir upstream of the power station is 2.3 km long and narrow (99 m at the widest). The reservoir has no water storage capacity and the water level is kept at 90.069 m.a.s.l., but can be higher during floods.

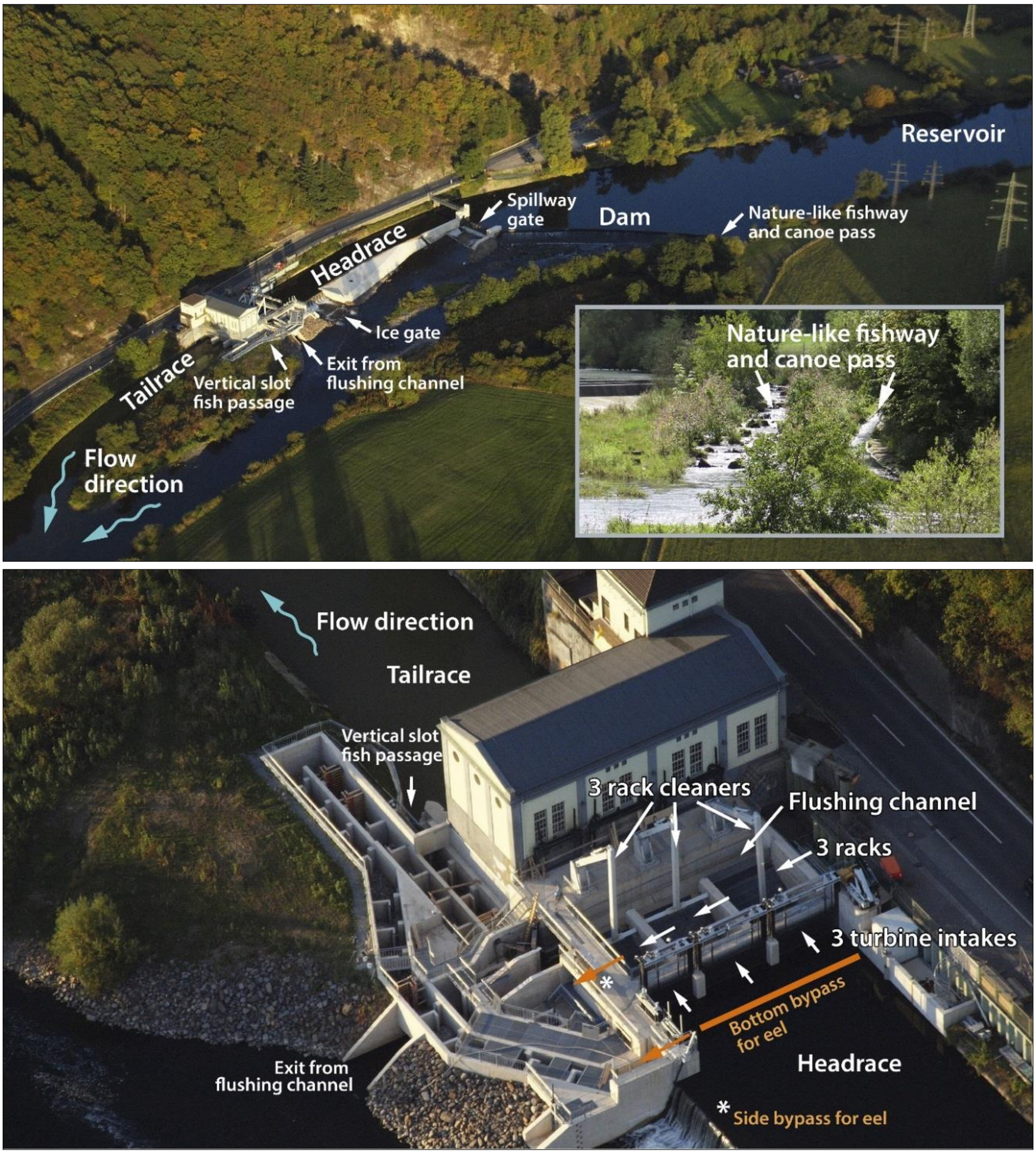


Figure 2.1. Unkelmühle power station with the different passages where downstream migrating fish can pass. The upper panel shows an overview of the power station area, and the lower panel shows the power station in more detail. The different migration routes past the power station are further described in **figure 2.2**. Photos: Wikimedia Commons and Eva B. Thorstad.

Figure 2.2. The different routes downstream migrating fish can use to pass the Unkelmühle power station: 1) via the surface bypass; custom-made openings in the racks that leads fish to a route outside the turbines via the flushing channel, 2) through turbines if they slip through the bar spacing of the racks, 3) through the vertical slot fishway constructed for upstream migrants, 4) through the nature-like fishway, 5) through the canoe pass, 6) via the ice gate, 7) over the spillway gate, 8) over the dam, 9) via the bottom bypass for eel, and 10) via side bypasses for eel (the two latter, indicated in orange, are only in operation during the eel run in the autumn). Numbers in both panels refer to the different migration routes. Photos: Wikimedia Commons.

The power station has three Francis turbines with a total capacity of 27 m^3s^{-1} and exploits a drop of 2.7 m. Each of the three turbine intakes is covered by a horizontally sloped rack (27° relative to the ground, drop-shaped profile or y-shaped profile in combination with flat steel bars) with 10 mm bar spacing.

Ten migration routes can be used by downstream migrating fish past the power station (**figures 2.1-2.3**). Bottom and side passes designed for eel were not in operation during this study. The spillway gate was open for 6.2 days in the beginning of the study period (study period lasted from 31 March to 16 May), and thereafter opened on nine occasions (median time open 0.9 hours, range 0.5-9.8 hours). Discharge in the vertical slot fishway was 0.3 m^3s^{-1}. Water discharge in the nature-like fishway and canoe pass was 0.2 m^3s^{-1} in each.

One of the possible migration routes for downstream migrating fish is through custom-made openings in the racks (14 or 24 cm deep and 70 cm wide) in front of the turbines, which enable them to bypass the turbines via the flushing channel (termed surface bypass, water discharge 0.6 m^3s^{-1}, **figure 2.2, 2.3**). During this study, fish could move freely to and from the flushing channel at all times. From the flushing channel, they were either guided to holding pools where they were collected for monitoring purposes, or they were guided back to the river outside the turbines via a channel. Debris from the racks were flushed out in the same channel when the rack cleaners were in operation. Which of these two routes fish are guided to is determined by the position of a movable valve. The operation of the rack cleaners depends on amount of debris. During periods of high water and increased debris transport, they are continuously operated.

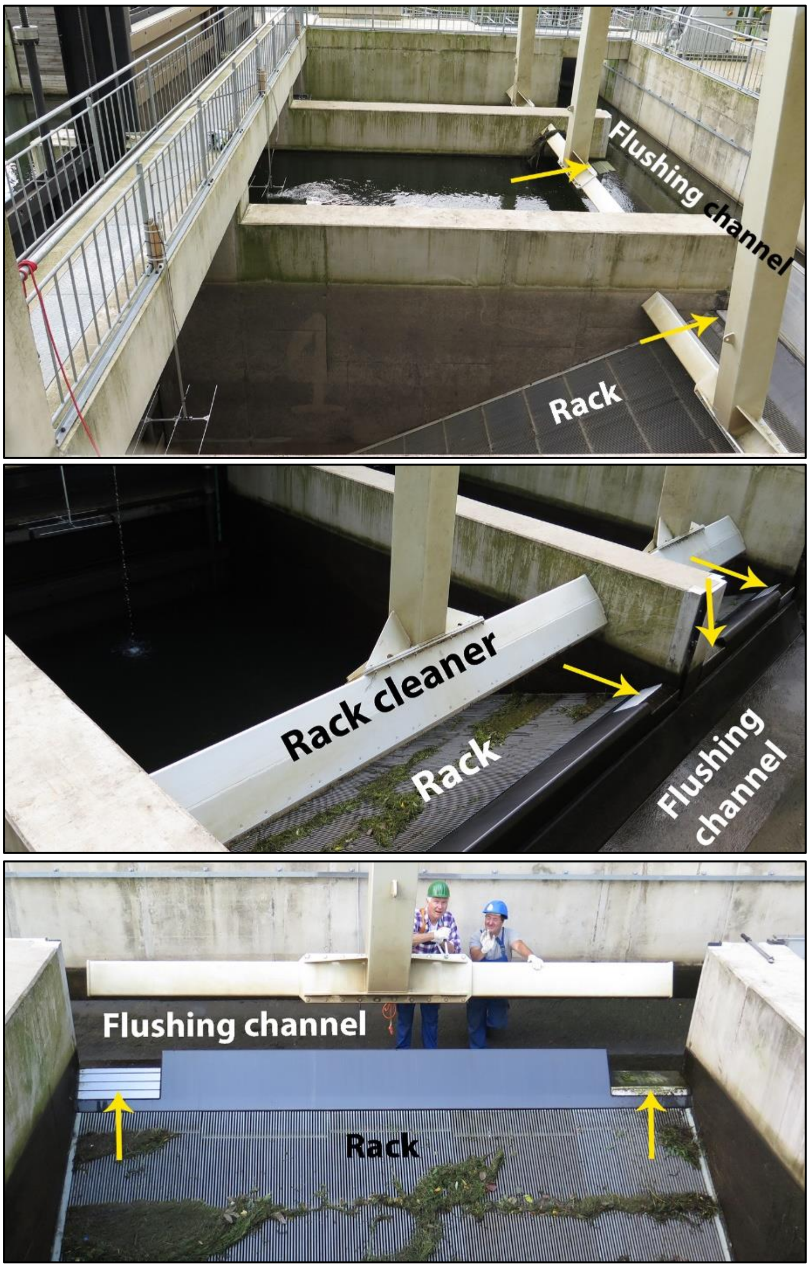


Figure 2.3. Details from the turbine intake at the Unkelmühle power station.

Upper panel: The three turbine intakes with racks and rack cleaners. Yellow arrows show custom-made openings near the surface where fish approaching the rack can pass through and move into the flushing channel. There are two openings in each rack, one on each side, in total six openings. Fish that enter the flushing channel can follow a migration route past the power station outside the turbines (shown in figure 2.2). When turbines were operating during this study, the water level covered the racks, openings and flushing channel. When the photo was taken, only two turbines were operating and one of the racks was therefore not water covered. Yagi antennas detecting signals from tagged fish in each of the turbine intakes can also be seen.

Middle panel: Two of the three turbine intakes.

Lower panel: Two rack openings of different depth, where fish can pass (turbine not operating).

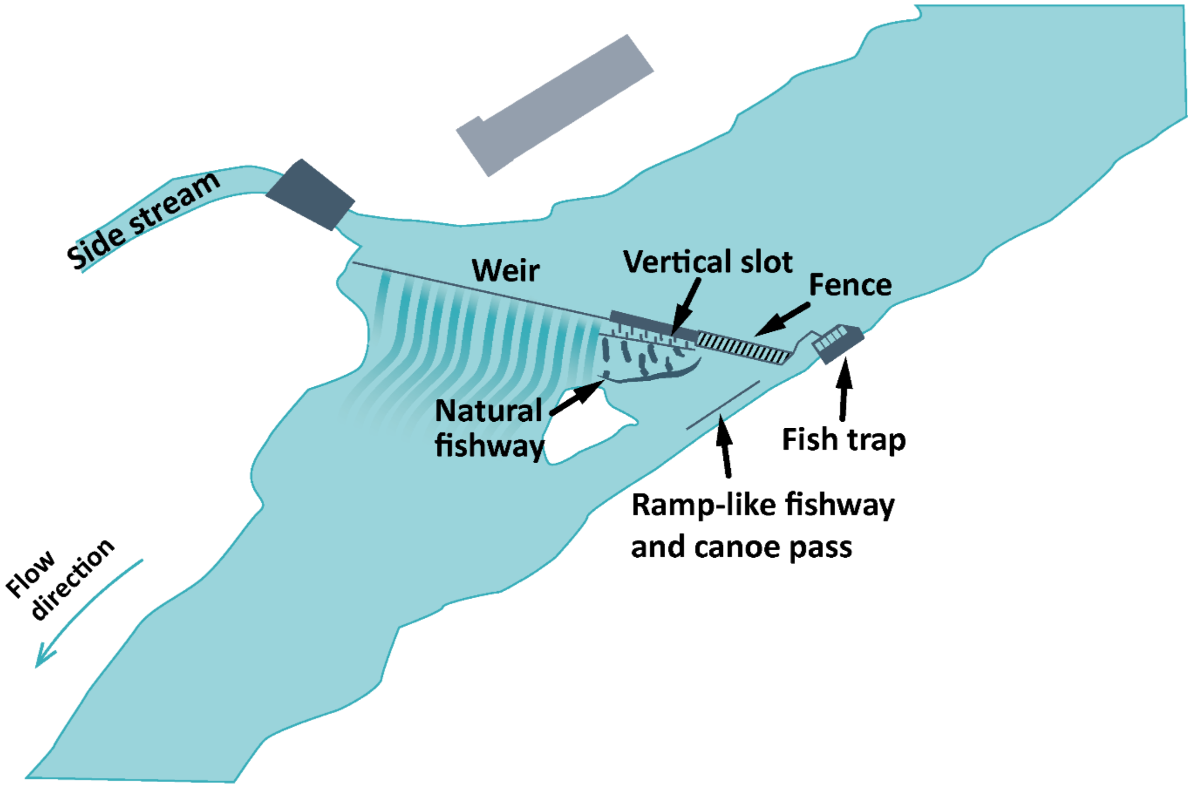
Photos: Eva B. Thorstad

2.2 Buisdorf dam

Buisdorf dam in the River Sieg is located 29 km downstream of Unkelmühle power station and 15 km upstream of the confluence with the River Rhine. When it was constructed more than 500 years ago, its main purpose was to serve water for the gardens of the monastery Saint Michael. Later, water mills were installed in the dam, which supplied power for industrial purposes. The reservoir upstream the dam (1.9 km long, **figure 2.4**, **3.1**) is used as a rowing area for a local rowing club.

Downstream migrating fish can choose between eight different migration routes past the dam (**figure 2.5**). Fish can pass the dam over the weir, or via a side stream (water discharge 0.5 m^3s^{-1} during flooding, otherwise it depends on the discharge in the Sieg) and thereafter re-enter the river 5.1 km below the dam (**figure 2.5**). In 1999, a monitoring station was constructed at the south bank of the dam, enabling counting (the station is periodically equipped with a VAKI fish counter) and catching of upstream migrating fish. Downstream migrating fish can also pass the dam through the monitoring station, and fish using this route or fish passing the dam via a fence (bar spacing adjustable 40-60 mm) can thereafter migrate through a vertical slot fishway (7 pools, maximum water current at 1.9 ms^{-1}), a nature-like fishway (length: 65 m, width: 15 m, water current: 0.5 to 2.0 ms^{-1}) or via a ramp-like fishway or canoe pass (**figure 2.5**). The head of the dam is 2.6 m.

Figure 2.4. Buisdorf dam. Photo: Torgeir B. Havn



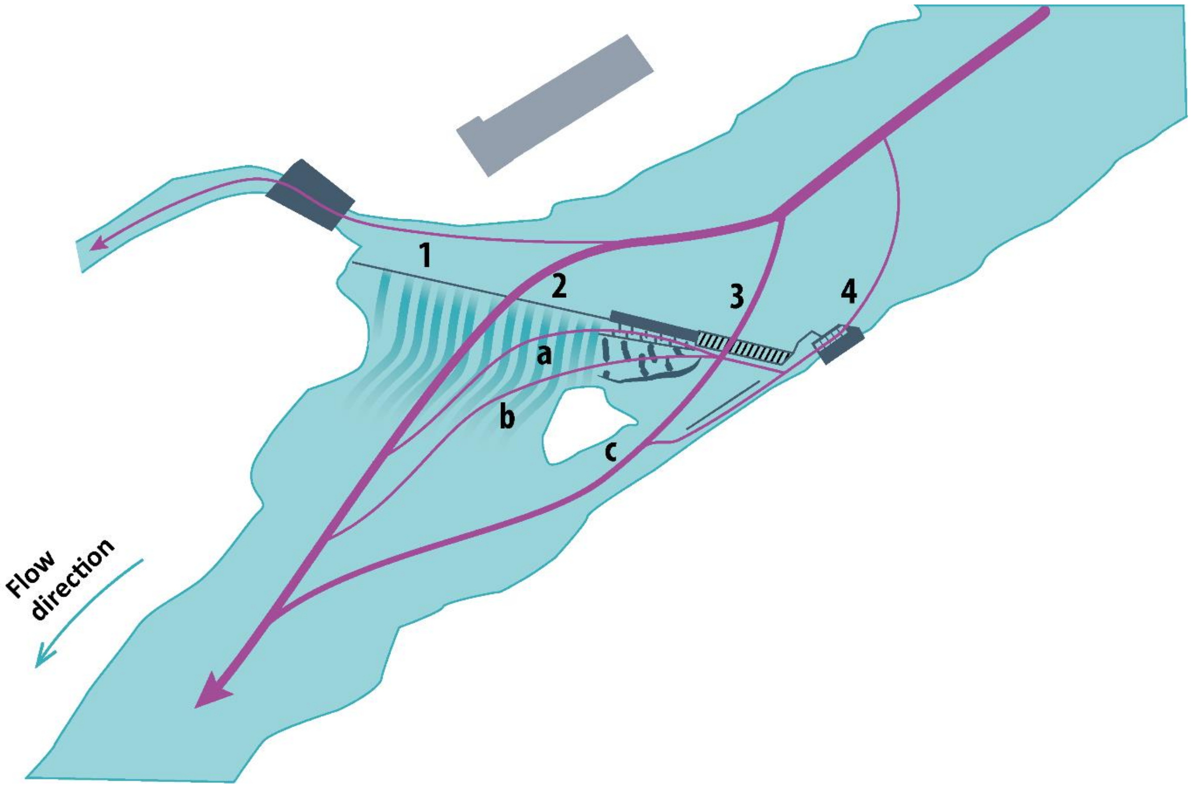


Figure 2.5. The upper panel shows an overview of the dam, and the lower panel shows the different migration routes past the dam. The lower panel shows the routes: 1) via the side stream, 2) over the weir, 3) through the fence or 4) through the fish trap, and then via a) the vertical slot fishway, b) natural fishway, or c) ramp-like fishway or canoe pass.

Figure 2.6. Details from the Buisdorf dam.

Upper panel: The fish trap at the dam. Upstream migrating fish move through the entrance and are trapped in a 10 m^2 chamber. A 900 l tank, capable of holding up to 50 adult Atlantic salmon, is lifted from the floor of the trap to collect the fish.

Middle panel: Fish passing the dam through the fish trap or fence can migrate further downstream via the vertical slot fishway, natural fishway or ramp-like fishway or canoe pass. The weir can be seen in the background.

Lower panel: The side stream which re-enters the main river 5.1 km downstream of the dam.

Photos: Torgeir B. Havn

3 Methods

3.1 Capture and tagging of Atlantic salmon smolts

A total of 227 smolts were radio tagged and released, of which 120 were released upstream of Unkelmühle power station, 60 just downstream of the power station and 47 upstream of Buisdorf dam (**figure 3.1**, **table 3.1**). In addition, 20 already dead smolts were tagged and released immediately downstream of the power station and the dam to distinguish between live downstream migrating fish and dead drifting fish (**table 3.1**). All smolts were captured for tagging by guiding them from the flushing channel to holding pools during their downstream migration at the power station, except for 5 smolts taken from the Agger hatchery (**table 3.1**). Groups of smolts were released at different points in time to increase variation in environmental variables during their downstream migration (**table 3.1**). Neither body length or body mass differed between live smolts released upstream of Unkelmühle (mean length: 159 mm, mean body mass: 34.8 g), downstream of Unkelmühle (mean length: 158 mm, mean body mass: 35.9 g) or at Buisdorf (mean length: 156 mm, mean body mass: 33.2 g, One-Way ANOVA of body length: $F_{2,224} = 0.33$, $P = 0.72$, One-Way ANOVA of mass: $F_{2,224} = 0.69$, $P = 0.50$). Water discharge and water temperature at release are shown in **table 3.1** and **figure 4.2**.

Table 3.1. Capture and release information for radio tagged smolts in the Sieg 2016. Letters denoting stretches refer to **figure 3.1**. Water discharge and temperature were measured at Unkelmühle power station.

Group	N	Capture method	Capture date	Release date and time	Release site	Water discharge at release (m^3 s^{-1})	Water temperature at release (°C)
Unkelmühle 1	60	Monitoring at Unkelmühle	31 March-1 April	1 April 22:14	Above site 1 (a)	68.4	8.8
Unkelmühle 2	60	Monitoring at Unkelmühle	5-6 April	7 April 18:12	Above site 1 (a)	27.0	11.2
Downstream Unkelmühle 1	30	Monitoring at Unkelmühle	1-2 April	2 April 13:36	Below power station (e)	62.5	8.1
Downstream Unkelmühle 2	30	Monitoring at Unkelmühle	6-7 April	7 April 18:56	Below power station (e)	26.7	11.2
Dead Unkelmühle 1	5	Agger hatchery	28 March	2 April 16:09	Flood gate (d)	61.5	8.8
Dead Unkelmühle 2	5	Monitoring at Unkelmühle	5-6 April	7 April 17:25	Turbines tailrace (d)	27.1	11.0
Buisdorf 1	24	Monitoring at Unkelmühle	1-2 April	2 April 19:42	Between site 4 and 5 (g)	60.1	9.2
Buisdorf 2	23	Monitoring at Unkelmühle	5-6 April	8 April 13:25	Between site 4 and 5 (g)	22.2	9.4
Dead Buisdorf 1	5	Monitoring at Unkelmühle	1-2 April	2 April 20:05	Dam Buisdorf (j)	60.0	9.2
Dead Buisdorf 2	5	Monitoring at Unkelmühle	5-6 April	8 April 13:55	Dam Buisdorf (j)	22.0	9.4

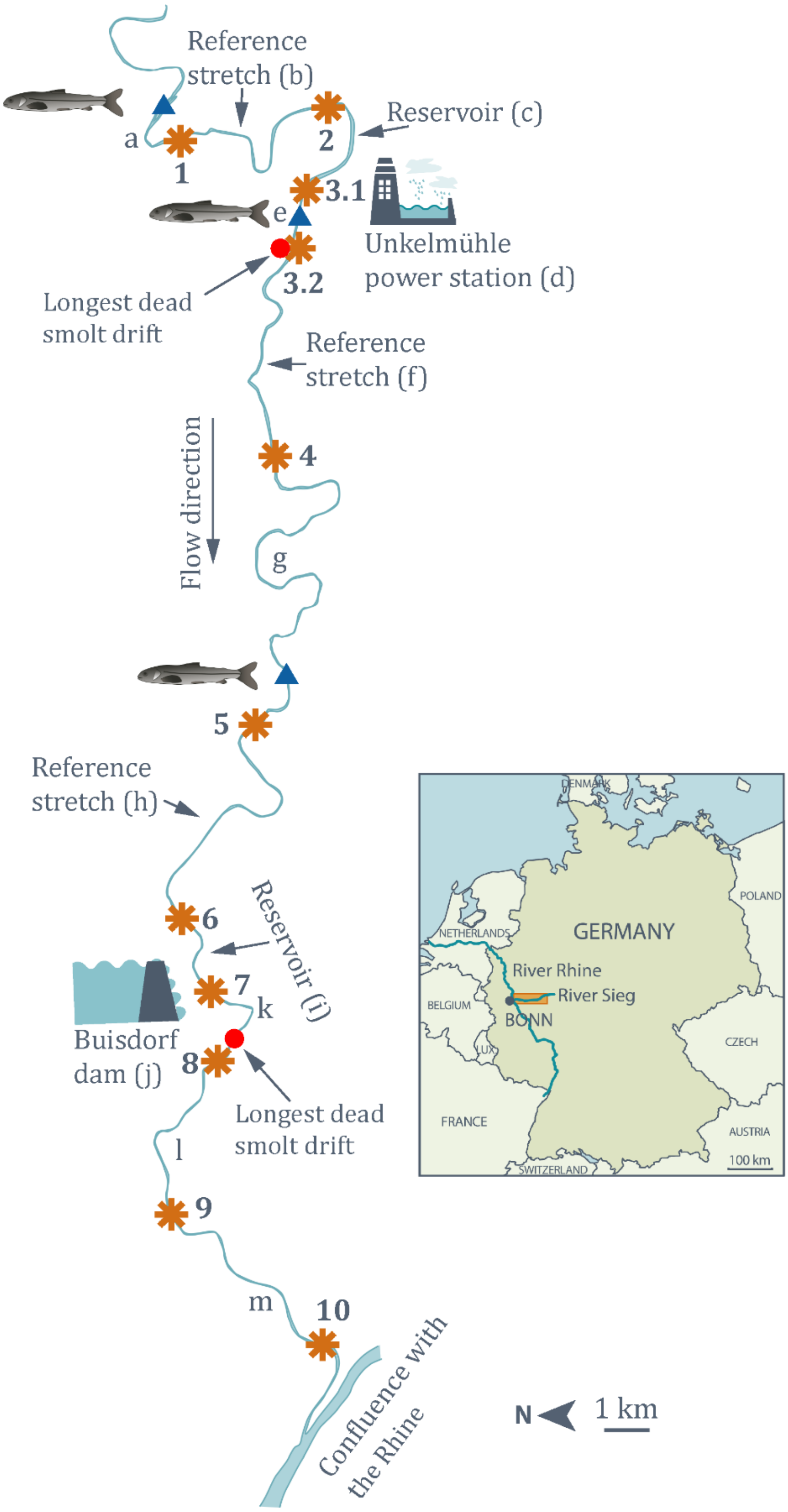


Figure 3.1. Map of the River Sieg showing the three different release sites of smolts tagged with radio transmitters (blue triangles) and receiver sites (orange stars) where they were recorded. The different stretches are denoted with letters a-m. Lengths of the stretches are given in **table 3.2**. The longest drift of already dead smolts released at Unkelmühle power station and Buisdorf dam are shown.

Table 3.2. Description of the different river stretches at Unkelmühle and Buisdorf, their lengths and distances from the most upstream release site. Stretches are denoted with letters referring to **figure 3.1**.

Stretch	Stretch description	Position	Site distances from release site (km)	Stretch length (km)
a	Above most upstream receiver site	Release site to site 1	0-1.5	1.5
b	Reference stretch	Site 1 to 2	1.5-7.3	5.8
c	Reservoir at Unkelmühle power station	Site 2 to 3.1	7.3-9.6	2.3
d	Unkelmühle power station area	Within site 3.1	9.6-9.8	0.2
e	Downstream power station (stretch 1)	Site 3.1 to 3.2	9.8-11.7	1.9
f	Downstream power station (stretch 2) / reference stretch	Site 3.2 to 4	11.7-17.3	5.6
g	Between site 4 and 5	Site 4 to 5	17.3-29.5	12.2
h	Reference stretch	Site 5 to 6	29.5-36.8	7.3
i	Reservoir at Buisdorf dam	Site 6 to 7	36.8-38.7	1.9
j	Buisdorf dam area	Within site 7	38.7-38.9	0.2
k	Downstream dam (stretch 1)	Site 7 to 8	38.9-41.4	2.5
l	Downstream dam (stretch 2)	Site 8 to 9	41.4-45.9	4.5
m	Between site 9 and 10	Site 9 to 10	45.9-51.2	5.3

Transmitters were surgically implanted into the body cavity according to methods described by Finstad et al. (2005). Prior to tagging, fish were anaesthetized in 50 mg l^{-1} benzocaine (Aethylium p-aminobenzoicum, Caesar & Loretz GmbH, Hilden, Germany), whereas during surgery a 25 mg l^{-1} solution of benzocaine was circulated on the surgical table. Radio transmitters used were individually coded Nano tags produced by Lotek Wireless Inc., Canada, model NTQ-2, frequency 150.300 MHz (dimensions 5 × 3 x 10 mm; mass in air 0.31 g, pulse rates between 2.0 and 7.2 s, expected life time 16 to 31 days dependent on pulse repetition rates).

3.2 Recording of tagged smolts after release

Downstream migration was recorded at 11 different sites by 17 receiver stations that automatically recorded id of the fish and time when it passed a station. The study area was divided into several stretches (**figure 3.1, table 3.2**), where each stretch was defined by a receiver site at the start and end of the stretch.

Detailed behaviour and choice of migration route at Unkelmühle power station and Buisdorf dam were recorded by using multiple antenna receivers at both sites (total of 5 receivers and 17 antennas at the power station and 3 receivers and 8 antennas at the dam, **figure 3.2 and 3.3**). Lotek model SRX 600 receivers were used with 3-, 4- and 6-element Yagi-antennas and underwater antennas. Antennas had reception ranges covering different areas, enabling identification of all possible migration routes past the power station and dam.

Tagged fish were also positioned during 20 manual tracking surveys from 3 April to 11 May 2016. Tracking surveys were done by boat, and alternated between covering the study area upstream of Buisdorf and the stretch from Buisdorf to the confluence with the Rhine.

Determination of smolt loss

Determination of smolt loss is based on fish (*i.e.*, transmitters) that stopped moving or disappeared from the river within the area we investigated (stretches a-m). The reasons for loss can be predation by mammals, fish or birds, other mortality reasons and transmitter failure.

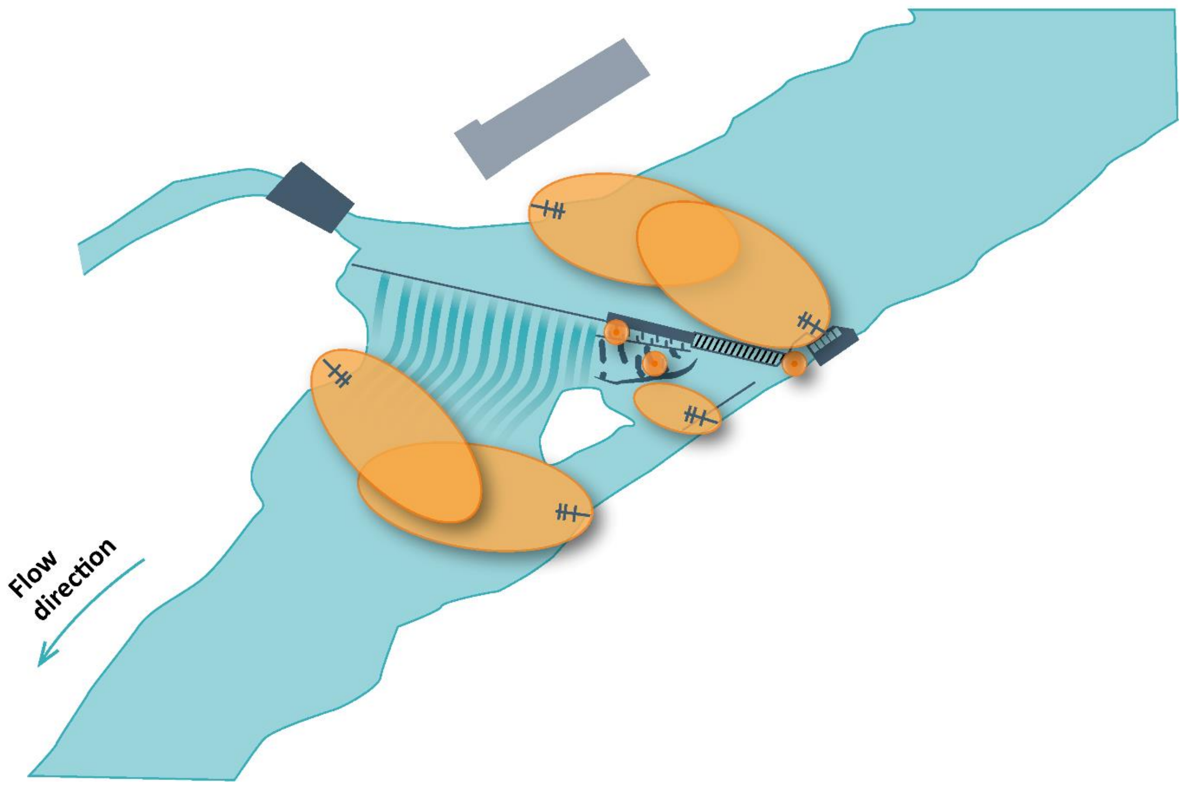


Figure 3.2. Overview of radio antennas and their approximate detection ranges (in orange) used to record signals from radio tagged smolts at Buisdorf dam. Detection ranges with antenna symbols indicate the use of aerial Yagi antennas, whereas ranges without antenna symbols indicate the use of underwater coaxial antennas.

The transmitters used are usually reliable, so significant loss due to transmitter failure was not expected. For fish eaten by fish predators or that died for other reasons, the transmitter will remain in the river. For transmitters failing, or for fish being taken by bird or mammal predators or scavengers that move the fish out of range, the transmitter signal will disappear from the river. Some smolts showed clear signs of being taken by bird predators or scavengers based on bird-like recordings, such as for instance fast upstream movements past the power station.

3.3 Estimation of smolt loss due to hydropower development at Unkelmühle and dam at Buisdorf

To determine effects of hydropower at Unkelmühle and effects of the dam at Buisdorf, downstream migration and loss of tagged fish were recorded 1) on a free-flowing reference stretch (stretch b and h), 2) in the reservoir upstream of the power station or dam (stretch c and i), 3) at the power station area or dam area (stretch d and j), and 4) on a river stretch below the power station or dam (stretches e-f and k-l, **table 3.2**). Loss on a stretch downstream the power station and dam were included in the estimates, because release of 20 dead smolts at the power station and dam indicated that smolts that die during passage can potentially drift at least 1.9 km downstream of the power station or 1.8 km downstream of the dam before settling and becoming stationary. Loss at the power station and dam includes loss of smolts that used any of the available migration routes past the power station or dam (shown in **figure 2.2** and **2.5**) and became stationary or were predated within 200 m downstream of the power station or dam.

Figure 3.3. Overview of radio antennas and their approximate detection ranges used to record signals from radio tagged smolts at Unkelmühle power station. **Upper panel:** Overview of the power station area. **Lower panel:** Power station area in more detail. Detection ranges with antenna symbols indicate the use of aerial Yagi antennas, whereas ranges without antenna symbols indicate the use of underwater coaxial antennas Photos: Wikimedia Commons.

The loss of smolts due to hydropower development at Unkelmühle and loss of smolts due to the dam at Buisdorf, termed “extra loss” in this report, was calculated by comparing loss on the corresponding free-flowing reference stretches (stretch b for Unkelmühle and stretch h for Buisdorf, **figure 3.1**) with loss in the reservoir, at the power station or dam and past the power station or dam.

Loss on the reference stretches were used to calculate expected loss for smolts entering the stretches affected by hydropower production, and the loss exceeding this baseline mortality was defined as loss caused by hydropower production.

The loss estimates are based on the assumption that loss per km recorded on the reference stretches is representative for the developed stretches if they had been free-flowing river stretches instead of being impounded and having the power station or dam. If expected loss on a developed stretch exceeded the observed loss, resulting in negative extra loss, extra loss on that stretch was set to zero.

In all study years, we compared the loss on the impacted stretches at Unkelmühle to loss on a free-flowing reference stretch upstream of the reservoir (reference stretch b, **figure 3.1, table 3.2**) to calculate extra loss. As mentioned above, the assumption for these estimates is that the reference mortality on the free-flowing stretch was representative for the impacted stretches. This however may not necessarily be true, since there might have been a selective mortality in the reference stretch, reservoir and power station, with the weakest individuals being lost and the strongest individuals remaining. If so, extra loss was underestimated due to overestimating baseline loss on impounded stretches. Alternatively, smolts may have been weakened by passing developed stretches resulting in increased mortality with time and distance moved. Therefore, loss on impacted stretches was also compared to the loss on a stretch downstream of the power station in 2016 (reference stretch f, **figure 3.1, table 3.2**). This was done by releasing smolts just below the power station (groups downstream Unkelmühle 1 and 2, **table 3.1**) and recording loss on a reference stretch between site 3.2 and 4 (stretch f). This enabled us to test if using a reference value derived from the stretch where some of the loss caused by hydropower development was recorded (reference stretch f) gave different extra loss estimates compared to when using the reference stretch upstream of Unkelmühle (stretch b). A hypothesis could be that using a reference stretch (reference stretch f) located closer to the impacted stretches would give more correct reference values than when using a reference stretch far upstream (reference stretch b).

4 Results

4.1 Loss of smolts at and upstream of Unkelmühle power station

Loss of smolts upstream of Unkelmühle power station
Of the 120 smolts that were released upstream of Unkelmühle power station (group Unkelmühle 1 and 2, **table 3.1**), six did not migrate from the release area, three were lost on the free-flowing reference stretch (stretch b) and six were lost in the reservoir (stretch c, **appendix 1**). The remaining 105 smolts entered the power station area. This corresponds to a loss of 2.6% and 5.4% of the fish entering the reference stretch and reservoir, respectively (0.5% and 2.4% per km).

Migration routes at the power station area
Of the 105 smolts that passed the power station, 63 smolts (60%) followed migration route 1 towards the trash racks in front of the turbines, 38 smolts (36%) passed through the flood gate (route 7), two smolts (2%) used the vertical slot fishway (route 3) and two smolts (2%) used the nature-like fishway or the canoe pass (route 4 or 5) (**figure 4.1**, **table 4.1**). No smolt slipped through the bar spacing of the racks and passed through the turbines, as expected due to the narrow spacing between the bars (10 mm). Six of the 63 smolts that used migration route 1 were captured for monitoring purposes before being released back into the river downstream of the power station. Smolts that were captured for monitoring purposes could possibly have a reduced chance of surviving passage of the power station due to extra handling from being captured and are therefore removed from further analyses.

Loss of smolts at and downstream of the power station
Of the 99 smolts that passed the power station (excluding those captured for monitoring purposes), five smolts were lost at the power station or on the stretch between the power station and site 4 (stretch d, e and f, **table 4.1, appendix 1**). One of the five lost smolts passed through the surface bypass and became stationary immediately downstream of the power station. One smolt was predated or scavenged after using the spillway gate to pass the power station, and was moved upstream to the entrance of the natural fishway where the transmitter became stationary. One smolt passed the power station via the surface bypass and was then recorded to move up and downstream in the tailrace before it moved at a speed of more than 50 km h^{-1} between two receiver sites, indicating that it was predated or scavenged by a bird at the power station. The transmitter of this smolt was later recorded at a cormorant colony 34 km downstream of the power station. Two smolts disappeared from the tracked stretches between site 3.2 and site 4 (one passed the power station using the surface bypass and one used the spillway gate). In summary, three smolts were lost in the power station area and two on the stretch from station 3.1 to site 4. This corresponds to a loss of 3.0% (14.3% per km) at the power station area and 2.1% (0.3% per km) on the stretch downstream of the power station to station 4. The proportion of fish classified as likely survived after passing the power station did not differ between those passing via the headrace (56 of 59) and those passing over the weir (38 of 40, Fisher's exact test, P = 1, **table 4.1**).

Estimates of loss related to the reservoir and power station
Based on the results given above, there was 4.4% extra loss in the reservoir compared to what would be expected if the loss was the same as on the free-flowing reference stretch b upstream of the reservoir (*i.e.*, 4.4% of the smolts entering the reservoir were lost due to this being a reservoir instead of a free-flowing river, **table 4.2**). Extra loss due to the Unkelmühle power station was 2.9% (extra loss at the power station area and 7.5 km downstream combined, **table 4.2**). If the losses in the reservoir, power station area and 7.5 km downstream are combined, total minimum extra loss due to hydropower was 7.2% (*i.e.*, of smolts entering the reservoir, **table 4.2**).

Figure 4.1. Number and proportion of smolts using the different migration routes past the power station

Table 4.1. Number of smolts that passed the power station and fates in relation to migration route.

	Migration route				
Fate	**Surface bypass** (route 1)	**Vertical slot fishway** (route 3)	**Canoe pass or natural fishway** (route 4)	**Spillway gate** (route 7)	**Total**
Survived	54	2	2	36	**94**
Lost	3	0	0	2	**5**
Total	**57**	**2**	**2**	**38**	**99**

Table 4.2. Overview of results in the three study years.

Year	**Loss on reference stretch** (per km)	**Extra loss in reservoir**	**Extra loss if including recording at antennas only at power station area**	**Extra loss due to the power station (based on recordings until site 4)**	**Total extra loss due to hydropower at Unkelmühle**
2014	1.5%	7.2%	9.9%	Not known[1]	16.0%[2]
2015	1.6%	17.1%	3.6%	12.8%	25.1%
2016	0.5%	4.4%	2.9%	2.9%	7.2%

[1]Fish were not monitored downstream of the power station, and the loss estimates for the power station are incomplete and underestimated in 2014.
[2]For instance fish dying at the power station and floating dead downstream are not included in this estimate.

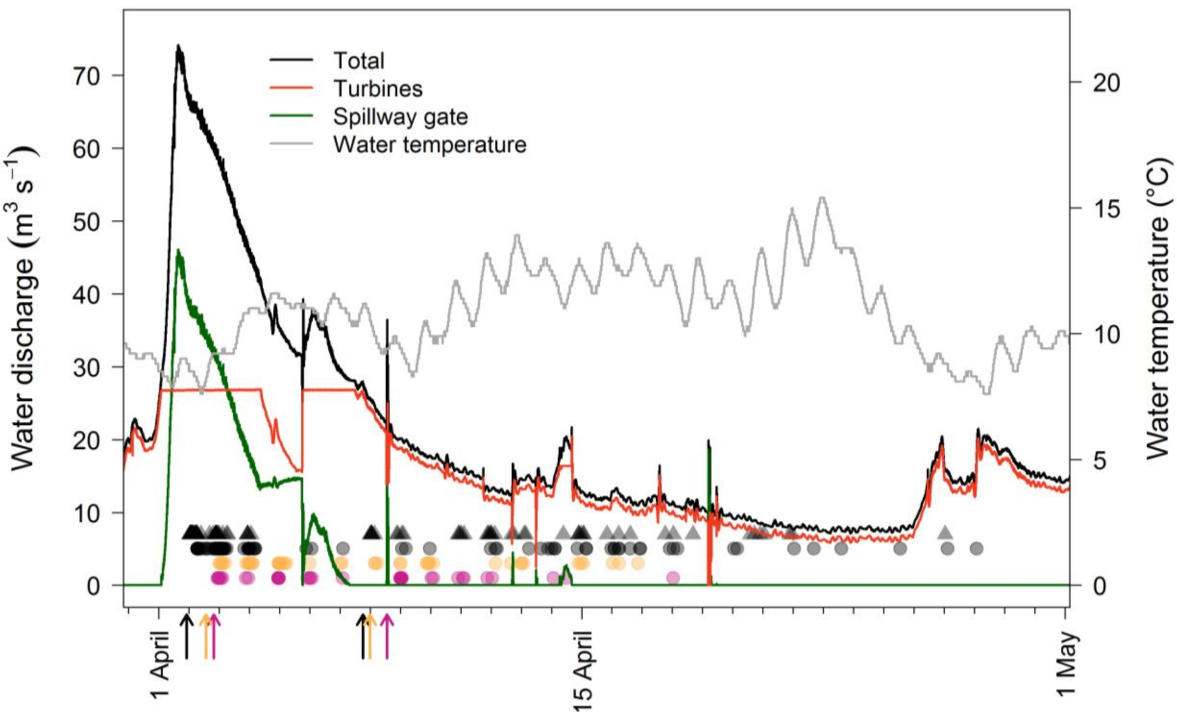


Figure 4.2. Total water discharge (black line), turbine discharge (red line), spillway gate discharge (green line) and water temperature (grey line) recorded at Unkelmühle power station during the study period. Time of release of tagged smolts is shown for the groups (see **table 3.1)** released upstream of Unkelmühle power station (black arrows, Unkelmühle 1 and 2), just downstream of the power station (orange arrows, Downstream Unkelmühle 1 and 2) and at Buisdorf (pink arrows, Buisdorf 1 and 2). Black triangles indicate when individual smolts passed Unkelmühle power station and colored circles when they passed Buisdorf dam (different colours represent different release groups, corresponding to the arrow colours). The symbols are transparent, so the darker colour, the more fish have passed at that point in time.

Estimates of loss related to the power station based on different reference values

Loss on the reference stretch below the power station (stretch f, **figure 3.1**) for fish released downstream of the power station (groups downstream Unkelmühle 1 and 2, **table 3.1**) was slightly higher (1.0% per km) than loss of fish released upstream of the power station (groups Unkelmühle 1 and 2) on the reference stretch upstream of the power station (stretch b, 0.5% per km, **figure 3.1**). However, the proportion expected lost fish due to the power station at Unkelmühle was not significantly different when using stretch b as a reference value (3.4 out of 99 fish were expected lost) than when using stretch f as a reference value (7.4 out of 99 fish were expected lost, Fisher's exact test = 0.21). Since a Fisher`s test requires integers, and to make the test conservative, number of expected fish lost were rounded up or down for largest difference between the two estimates in the test. Since there was no significant difference in calculated expected loss based on the two different reference values (and consequently no difference in extra loss), we present extra loss calculated based on the reference value from stretch b as in previous study years (2014 and 2015).

Migration speeds

Median time spent from release to passing site 4 for individual smolts was 25.1 hours (mean 79.4, range 3.7-465.5, SD 99.5). Migration speed on reference stretch b (median 4.2 km h^{-1}) was faster than in the reservoir (median 2.5 km h^{-1}) and past the power station (median 0.4 km h^{-1}, pairwise Wilcoxon test with Bonferroni correction: both P-values < 0.01 **table 4.4, figure 4.4**), but did not differ from the speed on the stretch from the power station to site 4 (4.5 km h^{-1}, pairwise Wilcoxon test with Bonferroni correction: P = 1). The fish migrated slower past the power station than on all other stretches (pairwise Wilcoxon test with Bonferroni correction: all P-values < 0.01). Only smolts that were recorded on all receiver sites from release to site 4 were included in these analyses (n = 93). At the power station, those passing via the headrace (surface bypass or vertical slot fishway) were slower in passing the power station (median 0.1 km h^{-1}, range 0.001-2.4, SD 0.5, n = 56) than those passing via the spillway gate, natural fishway or canoe pass (median 1.6 km h^{-1}, range 0.3-4.2, SD 0.7, n = 38, Mann-Whitney U test: W = 103.5, P < 0.001, **table 4.5**). All smolts that successfully passed the power station and reached site 4 were included in this analysis (n = 94).

Migration speeds in 2016 were faster compared to previous study years on the reference stretch (Kruskal-Wallis H test, H = 79.2, P < 0.001, Dunn`s test, all P < 0.001), reservoir (Kruskal-Wallis H test, H = 60.0, P < 0.001, Dunn`s test, all P < 0.001), power station (Kruskal-Wallis H test, H = 42.9, P < 0.001, Dunn`s test, all P < 0.001) and downstream stretch (Mann-Whitney U test, W = 1520, P < 0.001, **table 4.6**). Note that, within previous study years, migration speeds were not significantly different between the reference stretch, reservoir and downstream stretch, but migration speed past the power station was slower than at other stretches in both 2014 and 2015 (Økland et al. 2016).

Table 4.4. Migration speeds, given as km h^{-1}, on the reference stretch b, in the reservoir, past the power station and from the power station to site 4. Only smolts recorded on all receiver sites from release to site 4, excluding those captured for monitoring puropses, are included (n = 93).

River stretch	**Median** (km h^{-1}/hours)	**Average** (km h^{-1}/hours)	**Minimum-maximum** (km h^{-1})	**Minimum-maximum** (hours)	**Standard deviation** (km h^{-1}/hours)
Reference stretch b	4.2/1.4	3.4/7.3	0.04-7.9	0.7-140.5	1.8/18.1
Reservoir	2.5/0.9	2.3/3.9	0.03-4.6	0.5-66.9	1.3/9.3
Power station	0.4/0.5	0.8/6.2	0.001-4.2	0.05-137.3	0.8/17.7
Power station to site 4	4.5/1.7	3.5/13.5	0.05-6.1	1.2-142.0	2.1/29.6

Table 4.5. Migration speeds, given as km h^{-1}, past the power station for fish using different migration routes. All smolts that successfully passed the power station and reached site 4 are included (n = 94).

Migration route past the power station	**Median** (km h^{-1})	**Average** (km h^{-1})	**Minimum-maximum** (km h^{-1})	**Standard deviation** (km h^{-1})
Surface bypass (route 1, n = 54)	0.1	0.29	0.001-2.4	0.5
Vertical slot fishway (route 3, n = 2)	0.05	0.05	0.01-0.08	0.05
Canoe pass or natural fishway (route 4, n = 2)	0.9	0.9	0.3-1.6	0.9
Spillway gate (route 7, n = 36)	1.6	1.6	0.4-4.2	0.7

Table 4.6. Migration speeds, given as median ± standard deviation km h^{-1}, on the reference stretch b, in the reservoir, past the power station and from the power station to site 4 for all study years (the other stretches included in the study in 2016 were not studied in previous years). Only smolts recorded on all receiver sites from release to site 4, excluding those captured for monitoring purposes, are included.

	Study year		
River stretch	**2014 (n = 51)** (km h^{-1})	**2015 (n = 78)** (km h^{-1})	**2016 (n = 93)** (km h^{-1})
Reference stretch b	0.3 ± 1.0	0.6 ± 1.5	4.2 ± 1.8
Reservoir	0.7 ± 0.5	1.3 ± 0.6	2.5 ± 1.3
Power station	0.03 ± 0.2	0.05 ± 0.2	0.4 ± 0.8
Power station to site 4	-[1]	0.6 ± 1.2	4.5 ± 2.1

[1] Fish were not monitored downstream of the power station in 2014.

4.2 Loss at Buisdorf dam

Loss of smolts upstream of Buisdorf dam

Of the 47 smolts that were released at Buisdorf (group Buisdorf 1 and 2, **table 3.1**), seven did not migrate from the release area, one was lost on the reference stretch (stretch h) and two were lost in the reservoir (stretch i, **appendix 1**). The remaining 37 smolts passed the dam. This corresponds to a loss of 2.5% on the reference stretch, and a loss of 5.1% in the reservoir for those fish entering the reservoir (0.4% per km on the reference stretch and 2.7% per km in the reservoir).

Migration routes at Buisdorf dam

Of the 37 smolts that passed the dam, 35 smolts (95%) migrated over the weir (route 2) while two (5%) passed through the fence and then moved down the ramp-like fishway or canoe pass (route 3-c, **figure 4.3**, see **figure 2.5** for route numbers).

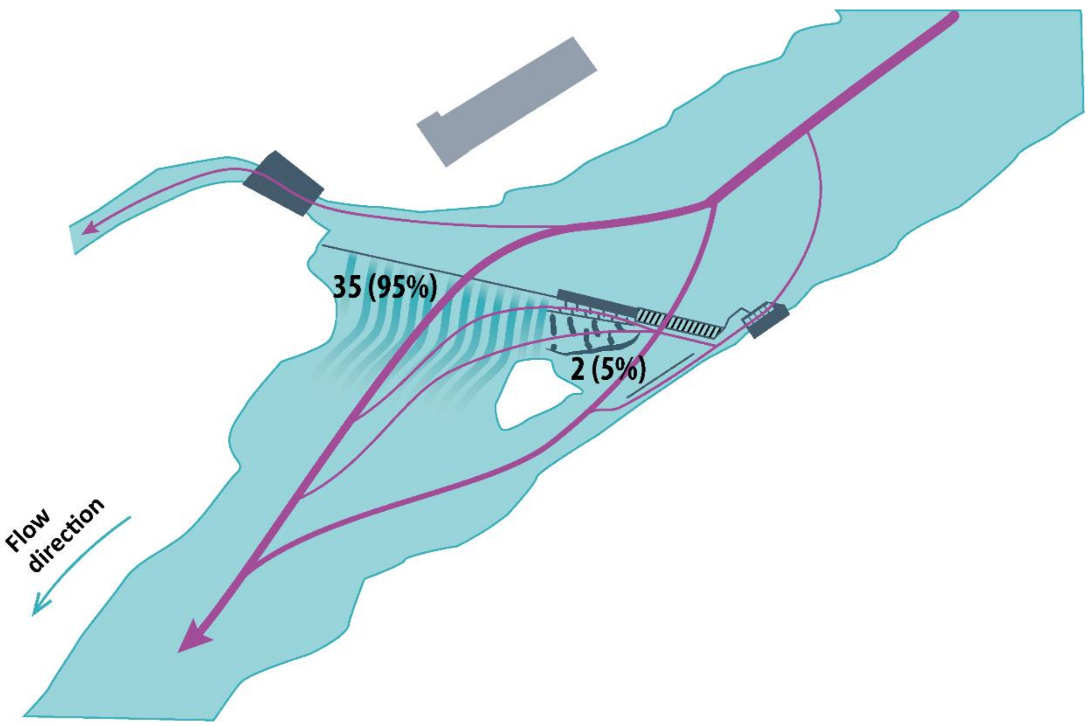


Figure 4.3. Number and proportion of smolts using the different migration routes past the dam at Buisdorf.

Losses of smolts at and downstream of Buisdorf dam

Of the 37 smolts that passed the dam, none were lost in the dam area (0.2 km). However, two smolts were predated or scavenged somewhere between the dam and receiver site 8, and one became stationary between site 8 and 9. All of the lost smolts passed over the weir. This corresponds to a loss of 8.1% (1.2% per km) on the 7.0 km long stretch from the dam to site 9.

Estimates of loss related to the reservoir and Buisdorf dam

Based on the results given above, there was 4.5% extra loss in the reservoir compared to the free-flowing reference stretch h (*i.e.*, 4.5% of the smolts entering the reservoir were lost due to this being a reservoir instead of a free-flowing river, **table 4.7**). Extra loss due to the dam was 5.7% (extra loss at the dam area and 7.0 km stretch downstream combined, **table 4.7**). If the loss in the reservoir, dam area and on the downstream stretch is combined, total minimum extra loss due to the dam and its reservoir was 9.9% (*i.e.*, of smolts entering the reservoir, **table 4.7**).

Migration speeds

Median time used from release to passing receiver site 9 for individual smolts was 53.1 hours (mean 59.2, range 4.4-229.9, SD 50.6). Migration speed did not differ between the reference stretch, dam and the stretch from the dam to site 9 (median 4.3 km h^{-1}, 4.4 km h^{-1} and 4.1 km h^{-1}, respectively, pairwise Wilcoxon test with Bonferroni correction: all P-values > 0.95, **table 4.6**, **figure 4.4**). Migration speed in the reservoir was slower than on all other stretches (pairwise Wilcoxon test with Bonferroni correction: all P-values < 0.03, **table 4.6**, **figure 4.4**). Only smolts that successfully passed the dam and were recorded on all receiver sites were included in the analyses (n = 34).

Table 4.6. Migration speeds, given as km h^{-1} and number of hours used, on the reference stretch (stretch h), in the reservoir upstream of Buisdorf dam, past the Buisdorf dam and from the dam to site 9. Only smolts recorded on all receiver sites from release to site 9 were included in the table (n = 34).

River stretch	**Median** (km h^{-1}/hours)	**Average** (km h^{-1}/hours)	**Minimum-maximum** (km h^{-1})	**Minimum-maximum** (hours)	**Standard deviation** (km h^{-1}/hours)
Reference stretch h	4.3/1.7	3.9/4.1	0.3-5.9	1.2-25.0	1.8/6.4
Reservoir	2.6/0.7	2.5/1.7	0.1-3.9	0.5-15.0	0.9/3.2
Dam	4.4/0.5	4.5/2.6	0.003-12.0	0.02-68.6	3.2/11.8
Dam to site 9	4.1/1.7	3.7/7.4	0.2-5.9	1.2-47.1	1.8/13.5

4.3 Comparison of loss and migration speed at Unkelmühle power station and Buisdorf dam

Loss at Unkelmühle and Buisdorf

The proportion extra loss due to the dam at Buisdorf (extra loss at the dam and on the downstream stretch) for release groups Buisdorf 1 and 2 (5.7%) was not significantly different from extra loss due to the power station at Unkelmühle (extra loss at the power station and downstream stretch) for release groups Unkelmühle 1 and 2 (2.9%, Fisher's exact test with Bonferroni correction: P = 0.81, **table 4.7**). Similarly, there was no significant difference in the proportion total extra loss at developed stretches in Buisdorf (9.9%) compared to Unkelmühle (7.2%, Fisher's exact test with Bonferroni correction: P = 0.76, **table 4.7**). Number of extra lost fish are estimated with decimals, but since a Fisher`s test requires integers, and to make the test conservative, number of extra fish were rounded up or down for largest difference between Unkelmühle and Buisdorf.

We did not find indications of selective mortality of weaker fish after release, or of increased mortality over time, because there was no difference in the proportion of lost fish between groups on any of the stretches where loss for all groups were recorded (stretch h-l, Fisher's exact tests: all P-values > 0.60, **appendix 2**). Since we did not find an indication of selective mortality, we compared the extra loss caused by Buisdorf dam and Unkelmühle power station by including all fish entering reference stretch h, irrespective of release site, in the analysis as a basis for the loss estimate at Buisdorf (n = 175, test shown in paragraph below). Hence, the sample size was increased compared to if only fish that were released at Buisdorf (groups Buisdorf 1 and 2) were included in the test (n = 40, test shown in the paragraph above).

The proportion extra loss due to Buisdorf dam (extra loss at the dam and on the downstream stretch) for all fish entering reference stretch h (3.4%) was not different from the extra loss due to Unkelmühle power station (extra loss at the power station and downstream stretch) for release groups Unkelmühle 1 and 2 (2.9%, Fisher's exact test with Bonferroni correction: P = 0.81, **table 4.7**). Similarly, there was no difference in total extra loss on developed stretches (5.2% and 7.2% at Buisdorf and Unkelmühle, respectively, Fisher's exact test with Bonferroni correction: P = 0.76, **table 4.7**). Number of extra lost fish were rounded up or down for largest difference between Unkelmühle and Buisdorf. An extended comparison of extra loss at Unkelmühle and Buisdorf given for more and different combinations of groups of fish can be found in **appendix 3**, showing similar results as the analyses above.

Table 4.7. A comparison of extra loss of smolts between Unkelmühle power station and Buisdorf dam for the different groups of fish. Information about the groups can be found in **table 3.1**.

Site	Released in stretch	Reference stretch	N entering reference stretch	Loss on reference stretch (per km)	Extra loss in reservoir	Extra loss at power station or dam	Extra loss at power station or dam and downstream stretch	Total extra loss from reservoir to downstream stretch
Unkelmühle	a	b	114	0.5%	4.4%	2.9%	2.9%	7.2%
Buisdorf	g	h	40	0.4%	4.5%	0.0%	5.7%	9.9%
Buisdorf	a,e,g[1]	h	175	0.6%	1.9%	1.2%	3.4%	5.2%

[1]Results for all smolts entering stretch h irrespective of release site (released on either site a, e or g).

Migration speed

Migration speed for fish released at Buisdorf (groups Buisdorf 1 and 2, n = 34) when passing Buisdorf dam was significantly higher than migration speed for fish released upstream of Unkelmühle when passing the Unkelmühle power station (n = 94, Mann-Whitney U test: W = 430, P < 0.001, see **table 4.4** and **table 4.6** for speeds), even though water discharge was higher and water temperature lower when fish passed the power station (median 59 $m^3 s^{-1}$ and 9.2 °C) than the dam (median 35 $m^3 s^{-1}$ and 11.0 °C , **figure 4.2**, Mann-Whitney U tests: both P-values < 0.02). Similarly, when considering only fish that passed both the Unkelmühle power station and Buisdorf dam (n = 62), fish moved faster when passing the dam (median 5.6 km h^{-1}, range 0.01-12.0, SD 3.7) than the power station (median 0.4 km h^{-1}, range 0.001-4.2, SD 0.9, Wilcoxon signed-rank test: V = 11, P < 0.001). Water discharge was higher and water temperature lower at passage of the power station (median 59 $m^3 s^{-1}$ and 9.2 °C) compared to passage of the dam (median 46 $m^3 s^{-1}$ and 10.8 °C) also for these fish (Wilcoxon signed-rank tests: both P-values < 0.001). Migration speed for fish using the spillway when passing the power station (median 1.6 km h^{-1}, range 0.4-4.2, SD 0.7, n = 36) was slower than migration speed over the weir at Buisdorf dam for fish released at Buisdorf (4.2 km h^{-1}, range 0.03-12, SD 3.1, n = 32, Mann-Whitney U-test: W = 945, P < 0.001). Only smolts that successfully passed the power station or dam and were recorded on all receiver sites were included in the analyses.

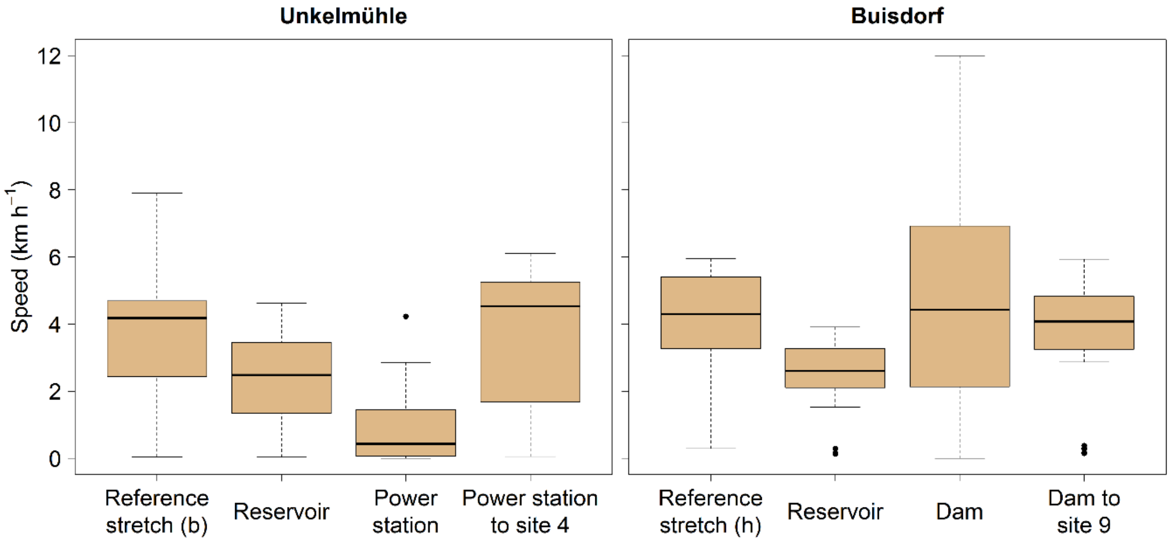


Figure 4.4. Migration speed past the reference stretch, reservoir, power station and downstream stretch for fish released upstream of Unkelmühle (left panel, groups Unkelmühle 1 and 2, n = 93) and migration speed past the reference stretch, reservoir, dam at Buisdorf and downstream stretch for fish released at Buisdorf (right panel, groups Buisdorf 1 and 2, n = 34). Boxes show the median (middle line within the box) and upper and lower quartile of data (*i.e.*, 50% of the data values are within the box). Whiskers show the range of data (within the upper / lower quartile + / - 1.5 IQ) and dots show outlier values.

5 Discussion

Loss of downstream migrating smolts passing the hydropower station at Unkelmühle was low in 2016. Only 2.9% of the smolts that entered the power station area were lost due to this being a hydropower station instead of a free-flowing river stretch. However, smolts passing the power station may be injured and experience delayed mortality downstream of the monitored stretches or when entering saltwater (McCormick et al. 2009; Zydlewski et al. 2010; Stich et al. 2015a, b). Therefore, loss estimates at Unkelmühle should be regarded as conservative estimates. The estimate for loss due to the power station in 2014 (9.9%) was likely particularly underestimated, because smolts were not recorded downstream of the power station that year, and only those becoming stationary at the power station were included in the loss estimate.

Loss due to the hydropower station was lower in 2016 compared to the two previous study years (9.9% in 2014 and 12.8% in 2015). Both 2014 and 2015 were years with low water discharge during the smolt run. Therefore, few radio tagged smolts passed over the spillway gate at Unkelmühle. In 2016, the water discharge was higher than in previous years, with more smolts successfully passing the power station via the spillway gate. However, loss of smolts passing the power station via the headrace was also low, and the high water discharge was probably an important factor for reducing loss of smolts using all migration routes in 2016. High flow resulted in smolts spending less time passing the power station compared to previous study years, thus reducing the exposure time for predators in the tailrace and on the downstream stretch. Furthermore, high flow also increased the turbidity and thus the visibility of the smolts to potential predators. At Buisdorf dam there are no turbines, and almost all smolts passed over the weir. The loss of smolts was low (two estimates, 3.4 and 5.7%) and not significantly different from loss at the Unkelmühle power station.

The exact causes of mortality at Unkelmühle power station are unknown, but might be related to injuries inflicted in the bypass routes and increased predation. No fish entered the turbines and there was consequently no turbine mortality, as expected due to the narrow bar rack spacing (10 mm). Mortality of smolts using the surface bypass route at the power station was lower in 2016 and 2015 compared to 2014, probably because smolts were more prone to entrapment in debris in 2014 than in the two other study years. Debris was piling up in the exit channel of the surface bypass in 2014, but video monitoring (own unpublished data) showed that debris was not piling up to the same extent in 2015 and 2016.

In all three study years, smolt loss caused by hydropower development was estimated as the extra loss on impacted stretches compared to what the loss would have been if this was unimpounded stretches (based on loss on a free-flowing reference stretch upstream of the reservoir). An assumption for these estimates is that the reference mortality on the free-flowing stretch was representative for the impacted stretches, which may not necessarily be true. In particular, there might have been a selective mortality in the reference stretch, reservoir and power station, with the weakest individuals being lost and the strongest individuals remaining. If so, extra loss was underestimated due to overestimating baseline loss on impounded stretches. Alternatively, smolts may have been weakened by passing developed stretches resulting in increased mortality with time and distance moved. There was, however, no differences in mortality when comparing groups of tagged smolts that had migrated long stretches before entering a river stretch to those being released immediately above.

An alternative to using the loss on a stretch upstream of the reservoir as reference mortality could be to release fish below the power station and record losses on the downstream stretch. Although this does not solve the potential selection problem discussed in the paragraph above, estimates of baseline loss would be based on reference loss on the same stretch as some of the loss caused by the power station was recorded, instead of using an upstream stretch as a proxy. On the other hand, predators may be attracted to areas downstream of power stations due to occurrence of dead and injured fish (Koed et al. 2002). Uninjured smolts released in this area might therefore experience an increased predation risk as an indirect effect of the power station, which makes such stretches less suitable as reference stretches. Nonetheless, although the loss of smolts was slightly higher on the reference stretch downstream of the power station compared to on the reference stretch upstream, the total extra loss did not differ when comparing estimates based on the two different reference stretches.

Results from Unkelmühle in previous study years show that mortality could be relatively high in the reservoir upstream of the power station, but that the mortality varied between years (7.2% in 2014 and 17.1% in 2015). The main reason for the extra loss in the reservoir is likely presence of more fish predators in the slow-flowing reservoir compared to the free-flowing river stretches. Loss in the reservoir in 2016 was the lowest of the three study years, with 4.4% of the fish entering the reservoir lost due to this being a reservoir instead of a free-flowing river stretch. Water discharge was higher and fish migrated faster through the reservoir in 2016 compared to the two previous study years, possibly reducing exposure time to predators and thus reducing loss. In addition, the turbidity is higher during periods with rain and high flow, reducing the visibility of tagged smolts to potential predators. However, fish migrated faster through the reservoir in 2015 than 2014, so time spent in the reservoir may not always explain variation in loss. The observed variation in loss in the reservoir between study years may be caused by variation in the predator community in terms of number, size and species composition. Jepsen et al. (2000) found that the temporal overlap between the smolt run and predator-spawning may be an important factor affecting smolt survival, which may also vary among years.

Also at Buisdorf, smolts moved relatively fast on the reference stretch and downstream of the dam, but slower in the reservoir. In contrast to at Unkelmühle, where fish were delayed at the power station, fish moved at the same speed past Buisdorf dam as on the reference stretch and below the dam. This difference in migration speed was also found when only fish that migrated through the spillway gate at Unkelmühle and fish that used the weir at Buisdorf were compared. No fish spent time in the turbine intakes before swimming back upstream and using the spillway gate to pass the power station, so behaviour upstream of the power station did not seem to explain why fish moved slower past the power station compared to the dam. However, smolts seem to follow the main water flow when navigating past power stations (Økland et al. 2016), and the observed differences may be caused by a higher proportion of the total water discharge running over the weir at Buisdorf compared to the proportion running through the spillway gate at Unkelmühle, making navigation over the weir and exit of the tailrace faster at Buisdorf compared to Unkelmühle.

In conclusion, the results of our studies on downstream migrating smolts at the power station at Unkelmühle and Buisdorf dam show:

1. Mortality caused by the Unkelmühle power station was lower in 2016 than in previous years. At the same time, migration speeds were higher in all parts of the river in 2016 than in previous years. Both lower mortality and faster migration might be related to the higher discharge of the Sieg in 2016 during the main migration period.

2. Losses of smolt did not differ between the power station at Unkelmühle and Buisdorf dam, neither in the reservoirs, nor when passing the power station and dam. However, the migration speed of salmon smolts was significantly reduced at the Unkelmühle power station, but not at Buisdorf dam.

6 Appendix

Appendix 1. Fate of radio tagged smolts (n = 227) in the Sieg in 2016, with an overview for each stretch and group of number of smolts that entered the stretch (In), were predated or scavenged (P), stopped (S) and left the stretch (Out). U refers to fish with an uncertain fate. Letters denoting stretches and site numbers refer to **figure 3.1** and **table 3.2**. Cells with smolts that were lost at Unkelmühle power station or Buisdorf dam are in red. Cells with smolts that survived passing Unkelmühle, but were lost when passing Buisdorf, are in orange. Green cells show smolts that survived passing either Unkelmühle or Buisdorf, or both.

		Group																			
Stretch	**Description**	**Unkelmühle 1 and 2 (n = 120)**					**Downstream Unkelmühle 1 and 2 (n = 60)**					**Buisdorf 1 and 2 (n = 47)**					**All smolts entering reference stretch h (n = 175)**				
		In	**P**	**S**	**U**	**Out**	**In**	**P**	**S**	**U**	**Out**	**In**	**P**	**S**	**U**	**Out**	**In**	**P**	**S**	**U**	**Out**
a	Above most upstream receiver site	120	6	0	0	114															
b	Reference stretch (5.8 km)	114	3	0	0	111															
c	Reservoir at Unkelmühle (2.3 km)	111	2	4	0	105															
d	Unkelmühle power station area (0.2 km)	99[1]	2[4]	1	0	96															
e	Downstream power station (stretch 1) (1.9 km)	96	0	0	0	96	60	7	0	0	53										
f	Downstream power station (stretch 2) / reference stretch (5.6 km)	96	2	0	0	94	53	3	0	0	50										
g	Between site 4 and 5 (12.2 km)	94	4	2	0	88	50	1[4]	2	0	47	47	6[4]	1	0	40					
h	Reference stretch (7.3 km)	88	5	0	0	83	47	0	1	0	46	40	1	0	0	39	175	6	1	0	168
i	Reservoir at Buisdorf (1.9 km)	83	2	0	0	81	46	1[4]	0	0	45	39	2	0	0	37	168	5	0	0	163
j	Buisdorf dam area (0.2 km)	68[2]	0	1	0	67	45	0	1	0	44	37	0	0	0	37	150[2]	0	2	0	148
k	Downstream dam (stretch 1) (2.5 km)	67	2	0	0	65	44	0	0	0	44	37	2	0	0	35	148	4	0	0	144
l	Downstream dam (stretch 2) (4.5 km)	65	2[4]	1	0	62	44	1	0	0	43	35	0	1	0	34	144	3	2	0	139
m	Between site 9 and 10 (5.3 km)	62	0	0	6[3]	56	43	0	0	3[3]	40	34	0	0	1[3]	33	139	0	0	10[3]	129

[1]Number “in” is reduced because 6 smolts that were captured for monitoring purposes are excluded.
[2]Number “in” is reduced because 13 smolts passed Buisdorf dam before all receiver sites were operating.
[3]Disappeared between site 9 and 10, but are treated as uncertain since site 10 were not functioning optimally. They could have left the river undetected or be predated.
[4]The transmitter of one of the smolts in this group was later found in a cormorant colony 34 km downstream of the power station

Appendix 2. Loss per km on stretches at Buisdorf for fish released at different sites in the river. The number of released smolts in each group is given in brackets. Letters denoting stretches refer to **figure 3.1** and group names to **table 3.1**.

			Stretch				
Group	**Released in stretch**	**Distance from release site to reference stretch in Buisdorf**	**% lost before entering reference stretch in Buisdorf (n in brackets)**	**Reference stretch Buisdorf (h, 7.3km)**	**Reservoir Buisdorf (I, 1.9 km)**	**Buisdorf dam and stretch downstream to site 9 (j-l , 7.3 km)**	**Reservoir to site 9 combined (h-l ,9.2 km)**
Unkelmühle 1 and 2 (n = 120)	a	29.5 km	22.8% (26)	0.8%	1.3%	1.3%	0.8%
Downstream Unkelmühle 1 and 2 (n = 60)	e	19.5 km	21.7% (13)	0.3%	1.2%	0.6%	0.7%
Buisdorf 1 and 2 (n = 47)	g	2.0 km	14.9% (7)	0.4%	2.7%	1.2%	1.5%
All groups combined (n = 227)	a,e,g	-	-	0.6%	1.6%	1.0%	1.2%

Appendix 3. Detailed comparison of smolt loss at Unkelmühle and Buisdorf. Extra loss at Buisdorf are given for the different release groups and their corresponding reference values, and combined for all smolts that entered the reference stretch at Buisdorf (stretch h, n = 175). Letters denoting stretches refer to **figure 3.1.**

Location of loss	**Released in stretch**	**Reference stretch**	**Number entering reference stretch**	**Loss on reference stretch (per km)**	**Extra loss in reservoir**	**Extra loss at power station or dam**	**Extra loss at power station or dam and downstream stretch**	**Total extra loss from reservoir to downstream stretch**
Unkelmühle	a	b	114	0.5% (5.8 km)	4.4% (2.3 km)	2.9% (0.2 km)	2.9% (7.7 km)	7.2% (10.0 km)
Buisdorf	e	h	47	0.3% (7.3 km)	1.6% (1.9 km)	2.2% (0.2 km)	2.4% (7.3 km)	3.9% (9.2 km)
Buisdorf	g	h	40	0.4% (7.3 km)	4.5% (1.9 km)	0.0% (0.2 km)	5.7% (7.3 km)	9.9% (9.2 km)
Buisdorf	e,g	h	87	0.3% (7.3 km)	2.9% (1.9 km)	1.2% (0.2 km)	3.8% (7.3 km)	6.6% (9.2 km)
Buisdorf	a,e,g[1]	h	175	0.6% (7.3 km)	1.9% (1.9 km)	1.2% (0.2 km)	3.4% (7.3 km)	5.2% (9.2 km)

[1]All smolts released in either stretch a, e or g that entered the reference stretch “h” above Buisdorf.

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