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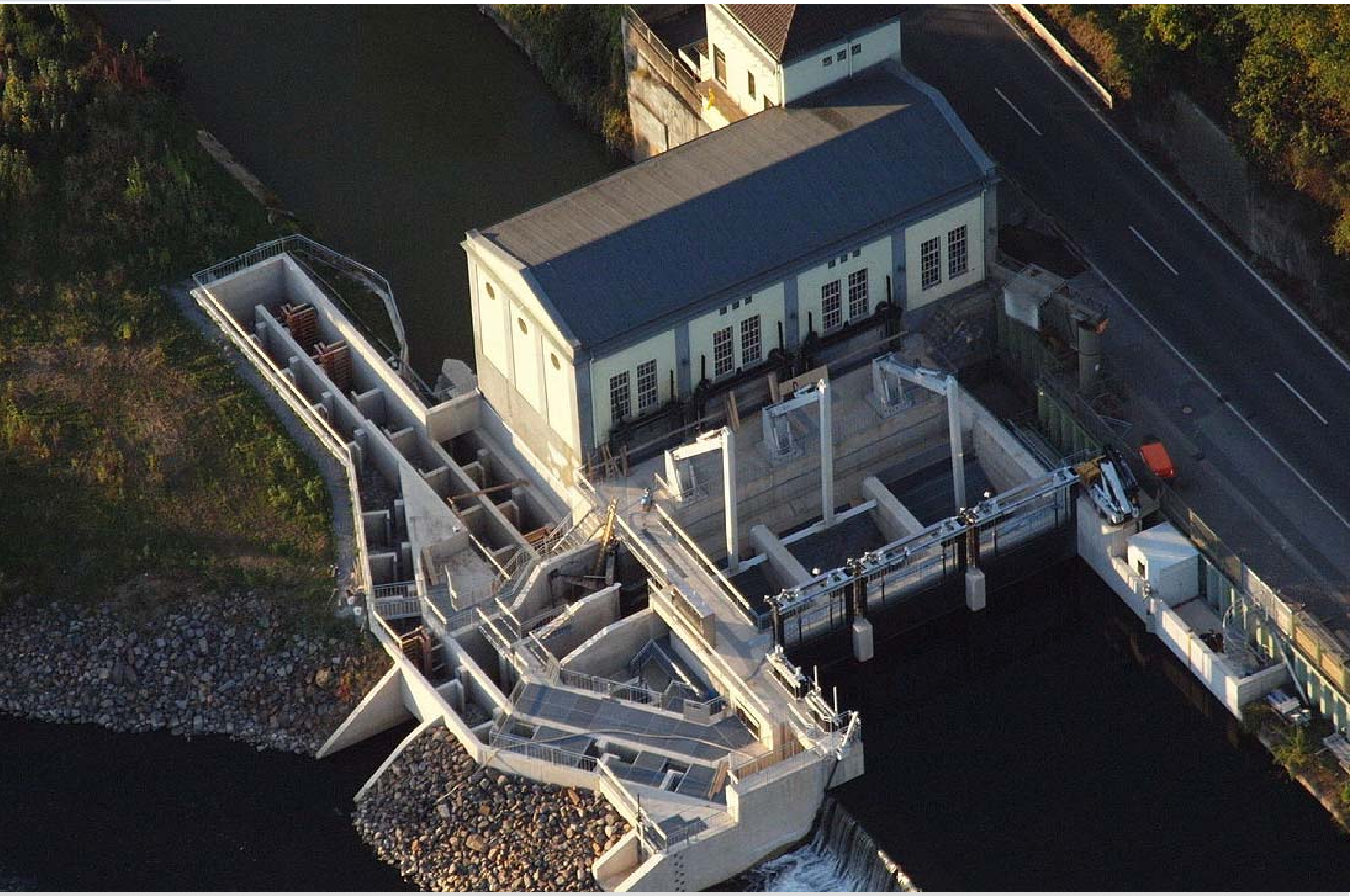

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Downstream migration of Atlantic salmon smolt at three German hydropower stations

Finn Økland[1]
Maxim A.K. Teichert[2]
Eva B. Thorstad[1]
Torgeir B. Havn[1]
Lisa Heermann[2]
Stein Are Sæther[1]
Ola H. Diserud[1]
Meelis Tambets[3]
Richard D. Hedger[1]
Jost Borcherding[2]

[1]Norwegian Institute for Nature Research
[2]University of Cologne
[3]Wildlife Estonia

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CONTACT DETAILS

NINA head office
Phone +47 73 80 14 00
Postboks 5685
Sluppen
NO-7485 Trondheim
Norway

www.nina.no

Universität zu Köln/University of Cologne
Biozentrum, Institute of Zoology
Allgemeine Ökologie und Limnologie
Zülpicher Straße 47b
D-50674 Köln
Germany

www.uni-koeln.de

Short summary

Økland, F., Teichert, M.A.K., Thorstad, E.B., Havn, T.B., Heermann, L., Sæther, S.A., Diserud, O.H., Tambets, M., Hedger, R.D. & Borcherding, J. 2016. Downstream migration of Atlantic salmon smolt at three German hydropower stations. NINA Report 1203: 1-47.

The aim of this study was to examine migration routes and losses of Atlantic salmon smolt past three hydropower stations, which were the Unkelmühle (River Sieg), Gengenbach (River Kinzig), and Kuhlemühle (River Diemel) power stations. These three power stations represent the use of different technologies to reduce negative impact on downstream migrating fish. The study was performed by tagging 525 Atlantic salmon smolt with radio transmitters and recording their migration when passing the power stations.

In 2015, the loss of downstream migrating smolt due to the power station was 12.8% at Unkelmühle and 3.1-6.3% at the power station in Gengenbach. This represents the percentage of smolt entering the power station area that were lost due to this being a power station instead of a free-flowing river. Immediate mortality for smolt that passed through the Archimedes screw turbine at Kuhlemühle was estimated at 0-8%.

Results showed that also reservoirs upstream of power stations can be areas of high mortality. Of smolt entering the reservoir upstream of Unkelmühle, 7.2% and 17.1% (two study years) were lost due to this being a reservoir instead of a free-flowing river. The main reason was likely presence of more fish predators (*i.e.*, larger fishes eating smolt) in the slow-flowing reservoir compared to the free-flowing river stretches.

Summary

Økland, F., Teichert, M.A.K., Thorstad, E.B., Havn, T.B., Heermann, L., Sæther, S.A., Diserud, O.H., Tambets, M., Hedger, R.D. & Borcherding, J. 2016. Downstream migration of Atlantic salmon smolt at three German power stations. NINA Report 1203: 1-47.

Background and study aim

The aim of this study was to examine migration routes and losses of Atlantic salmon smolt past three run-of-the river hydropower stations in Germany. These were the Unkelmühle power station in the Sieg, the power station in Gengenbach in the Kinzig (both tributaries to the Rhine), and Kuhlemühle power station in the Diemel (tributary to the Weser).

The Unkelmühle power station is designed with several bypass routes where fish can pass outside the turbines. Narrowly spaced bar racks have been installed in front of the turbine intakes to prevent fish from entering the turbines. At the power station in Gengenbach, the position of a movable turbine can be adjusted to let downstream migrating fish pass above or under the turbine. At the Kuhlemühle power station, an Archimedes screw turbine is installed. Archimedes screws are regarded as relatively fish-friendly turbines, but few studies have tested this assumption.

Methods

The study was performed by tagging 525 Atlantic salmon smolt with radio transmitters and recording their migration in the river and past the power stations. Their movements were recorded 1) on free-flowing reference stretches upstream of the power stations, 2) on impounded stretches upstream of the power stations, 3) when they passed the power stations, and 4) on downstream river stretches. Migration routes used by tagged fish when they passed the power stations were mapped in detail by using a network of automatic, stationary receivers. Results from a pilot study in 2014 (Unkelmühle) and studies in 2015 (Unkelmühle, Gengenbach and Kuhlemühle) are presented in this report.

The loss of downstream migrating smolt due to impoundments and past power stations 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 is representative for the developed stretch if it had been a free-flowing river instead of being impounded by a dam and having a power station.

Results and conclusions

The loss of downstream migrating smolt due to the power station was minimum 12.8% at Unkelmühle and 3.1-6.3% at the power station in Gengenbach during the study in 2015. This represents the percentage of smolt entering the power station area that were lost due to this being a power station area instead of a free-flowing river. The loss estimates represent direct loss at the power station, but may also include delayed mortality due to the power station on the stretches downstream (8 km). For Kuhlemühle, a probability estimate indicated that immediate mortality for smolt that passed through the Archimedes screw turbine was 0-8%.

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

The causes for mortality at the power stations seemed to be physical injuries when passing and increased predation rates, but exact causes could not be determined in all cases.

At Unkelmühle, there was no turbine mortality, because none of the smolt 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 smolt passing Unkelmühle power station was likely related to physical injuries in bypass routes aimed at guiding smolt outside the turbines, and increased predation. For the smolt lost at the movable turbine in Gengenbach, we do not know if they passed through, above or under the turbine.

Mortality rates at power stations may vary among years. This was demonstrated by results from Unkelmühle, where a pilot study was conducted in 2014. The results indicated that the mortality in the bypass route that leads smolt outside the turbines was higher in 2014 than in 2015, likely because smolt became trapped in an area of the bypass route where debris and branches piled up in 2014, but not in 2015.

Results showed that reservoirs upstream of power stations can be areas of high mortality for downstream migrating smolt. At Unkelmühle in 2015, the loss due to the reservoir was even larger than the loss caused by the power station.

Of smolt entering the reservoir upstream of Unkelmühle, 7.2% in 2014 and 17.1% in 2015 were lost due to this being a reservoir instead of a free-flowing river. This was a much higher loss than on the impounded river stretches upstream of the power stations in Gengenbach (1.5% extra loss) and Kuhlemühle (no extra loss), probably because these are not reservoirs, but only short stretches with slightly slowed down water velocity. 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 extra loss in the reservoir is likely presence of more fish predators in the slow-flowing reservoir compared to the free-flowing river stretches. Results from Unkelmühle showed that reservoir mortality may vary among years, probably due to variation in the predator community.

Finn Økland (finn.okland@nina.no), Maxim A.K. Teichert (mteicher@uni-koeln.de),
Eva B. Thorstad (eva.thorstad@nina.no), Torgeir B. Havn (torgeir.havn@nina.no),
Lisa Heermann (lisa.heermann@uni-koeln.de), Stein Are Sæther (stein.sather@nina.no),
Ola H. Diserud (ola.diserud@nina.no), Meelis Tambets (meelis.tambets@gmail.com),
Richard D. Hedger (richard.hedger@nina.no), Jost Borcherding (jost.borcherding@uni-koeln.de)

Contents

Foreword

The necessity to decrease carbon dioxide emissions in order to reduce effects of anthropogenic induced climate change requires an increasing production of green energy. This is also an important objective for the government of North-Rhine-Westphalia and was laid down in the coalition contract for the current governmental period. In contrast to for instance solar energy, for which limited impact on the environment is usually expected, green 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. Thus, 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 green energy with as little impact on fish migration as possible, the government of North-Rhine-Westphalia is cooperating with the RWE hydroelectric power company. Together, they have improved the technical facilities of the Unkelmühle power station in the Sieg to allow a safe downstream migration. To assess the efficiency of these measures, the Ministry for Climate Protection, Environment, Agriculture, Conservation and Consumer Protection of the State of North Rhine-Westphalia (MKULNV) commissioned the University of Cologne, 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) to monitor fish migration at this site by using radio telemetry methods. Here, the telemetry results are summarised for Atlantic salmon smolt. This study additionally includes telemetry studies at two other power stations, which are Kuhlemühle at the Diemel (Archimedes screw turbine) and Gengenbach at the Kinzig (movable turbine) to evaluate their potential for safe passage of downstream migrating fish.

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August 2016

Finn Økland	Jost Borcherding
Project leader NINA	Project leader University of Cologne

1 Introduction

Turbines and other installations at power stations may cause physical injury and mortality in downstream migrating fish (Ruggles 1980, Doherty & McCarthy 1997, Hvidsten & Johnsen 1997, Larinier & Travade 2002). For fish passing through turbines, the mortality rate depends on fish size, head and turbine type, and size and speed of the turbine (Larinier & Travade 2002). Fish may also be injured when passing via bypass routes such as over dams or through different types of gates and sluices. There are few published studies of detailed migration patterns of fish at power stations during downstream migration.

In reservoirs upstream of power station dams, there are usually no physical installations that may harm fish, but reservoirs and slack water above dams may create favourable habitats for predatory fish species and thereby increase mortality (Jepsen et al. 1998, 2000, Aarestrup et al. 1999, Serrano et al. 2009). Migration may also be delayed in reservoirs, which may further increase predation risk. In a Danish reservoir, 90% mortality of Atlantic salmon smolt was recorded, largely due to predation by northern pike (56% mortality) and avian predators (31% mortality) such as red-necked grebe and grey heron (Jepsen et al. 1998, Aarestrup et al. 1999).

The aim of this study was to examine migration routes and losses of Atlantic salmon smolt past three run-of-the river hydropower stations in Germany. These were the Unkelmühle power station at the Sieg, the power station in Gengenbach at the Kinzig (both tributaries to the Rhine), and the Kuhlemühle power station at the Diemel (tributary to the Weser).

The Unkelmühle power station was especially designed with several possible bypass routes for fish to pass outside the turbines. Narrowly spaced bar racks (opening 10 mm) are installed at the turbine intakes to prevent fish from entering the turbines. At the power station in Gengenbach, the position of a movable turbine can be adjusted to let downstream migrating fish pass, but the efficiency of this measure is unknown. At the Kuhlemühle power station, a new Archimedes screw turbine is installed. Archimedes screws are regarded as relatively fish-friendly turbines, but few investigations of this have been done. The performance and success of downstream migrating Atlantic salmon related to the specific measures at these power stations were recorded in this study.

The study was performed by tagging 525 Atlantic salmon smolt with radio transmitters and recording their downstream migration when passing these three power stations by automatic receivers and manual tracking. Their movements were recorded 1) on free-flowing reference stretches upstream of the power stations, 2) on impounded stretches upstream of the power stations, 3) when they passed the power stations, and 4) on downstream river stretches. Migration routes used by tagged fish when they passed the power stations were mapped by using a network of automatic, stationary receivers.

Results from a pilot study in 2014 (Unkelmühle) and from studies in 2015 (Unkelmühle, Gengenbach and Kuhlemühle) are presented here. The study continues at Unkelmühle in 2016. This report aims at informing the interested public on main results, and details are not included. Scientific publications with more detailed results will follow later.

Atlantic salmon

Atlantic salmon is a fish species of large cultural and economic importance. They spawn and grow up as juveniles in freshwater and perform long-distance marine feeding migrations in the Atlantic Ocean.

After the juvenile phase in freshwater (usually 1-4 years), they migrate downstream in rivers to reach the ocean, mainly in the spring. During this life stage, when they migrate downriver, they are about 10-20 cm long and are termed smolt.

After the ocean feeding migration, which usually lasts 1-4 years, they return to their home river for spawning. They may have reached body sizes of 1-20 kg when they return for spawning. Some individuals may even be larger than 30 kg.

Atlantic salmon populations have declined in most of the distribution area, and were lost from all German watersheds due to pollution, migration barriers and habitat degradation.

Wild adult Atlantic salmon (left) and hatchery-reared smolt (right). Photos Eva B. Thorstad.

The Rhine and the tributaries Sieg and Kinzig

The Rhine (catchment area 185 000 km^2) origins in Switzerland, forms part of the French-German border, flows through Germany and empties into the North Sea in the Netherlands. It is 1233 km long, of which 870 km runs through Germany, and has a mean discharge of 2280 m^3s^{-1} at the German-Dutch border.

The Rhine used to be among the main Atlantic salmon rivers in Central Europe (Monnerjahn 2011). A decline of Atlantic salmon in German rivers began with the industrial revolution, caused by pollution, habitat degradation and fragmentation by weirs and dams. By the end of the 1950s, salmon populations were extinct (Molls & Nemitz 2008, Monnerjahn 2011). In the Rhine, re-introduction programs have been initiated, and salmon have reproduced naturally in several German tributaries, including the Sieg, but self-sustaining populations are not yet re-established (Molls & Nemitz 2008, Monnerjahn 2011).


The Sieg.


The Kinzig. Photos Eva B. Thorstad.

The Sieg, where the Unkelmühle power station is situated, is a 153 km long tributary to the Rhine, with a catchment area of 2862 km^2. The average water discharge at the confluence with the Rhine, close to the city of Bonn and about 725 river kilometers from the sea, is 53 m^3s^{-1}.

The Kinzig, where the power station in Gengenbach is situated, is a 93 km long tributary to the Rhine in southern Germany, with a catchment area of 1406 km^2. The average water discharge at Gengenbach is 23 m^3s^{-1}. In the middle and lower part, the Kinzig is heavily channelized.

The last salmon was captured in the River Kinzig in 1952, according to a newspaper article (Mittelbadische Presse 13 September 2014). A re-introduction program for Atlantic salmon was initiated in 2002, and some salmon have returned from the sea (Mittelbadische Presse 13 September 2014). Spawning and successful production of Atlantic salmon juveniles have occurred, but there are no official reports on monitoring of Atlantic salmon in the river.

The Weser and the tributary Diemel

The Weser is a 452 km long river in northwestern Germany, emptying into the North Sea at Bremerhaven, with a catchment area of 46 306 km^2 and average water discharge of 327 m^3s^{-1}. It used to be among the main Atlantic salmon rivers in Germany (Monnerjahn 2011). Re-introduction programs have been initiated, but dams and weirs within the river system still block migrations (Monnerjahn 2011).

The Diemel is a 110 km long tributary to the Weser, with a catchment area of 1762 km^2 and an average discharge of 16 m^3s^{-1} at Helmarshausen.

The Diemel. Photo Eva B. Thorstad.

2 Methods

Methods used in this study are described in **figures 2.1-2.11** and **table 2.1**.

Figure 2.1. The fish studied were hatchery-reared Atlantic salmon smolt (Albaum hatchery or Lachszucht Wolftal hatchery), or smolt captured from the Sieg at Unkelmühle (most likely originating from stocking of fry or parr by hatcheries, but could also be the result of natural spawning in the river). Photos Eva B. Thorstad and Torgeir B. Havn.

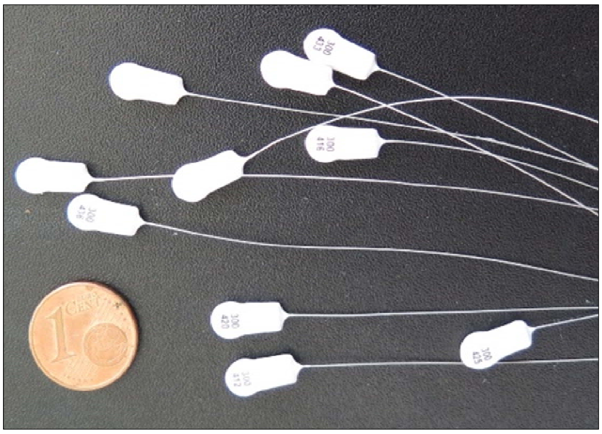


Figure 2.2. The Atlantic salmon smolt were tagged with small radio transmitters (shown together with a one Euro cent). Photo Eva B. Thorstad.

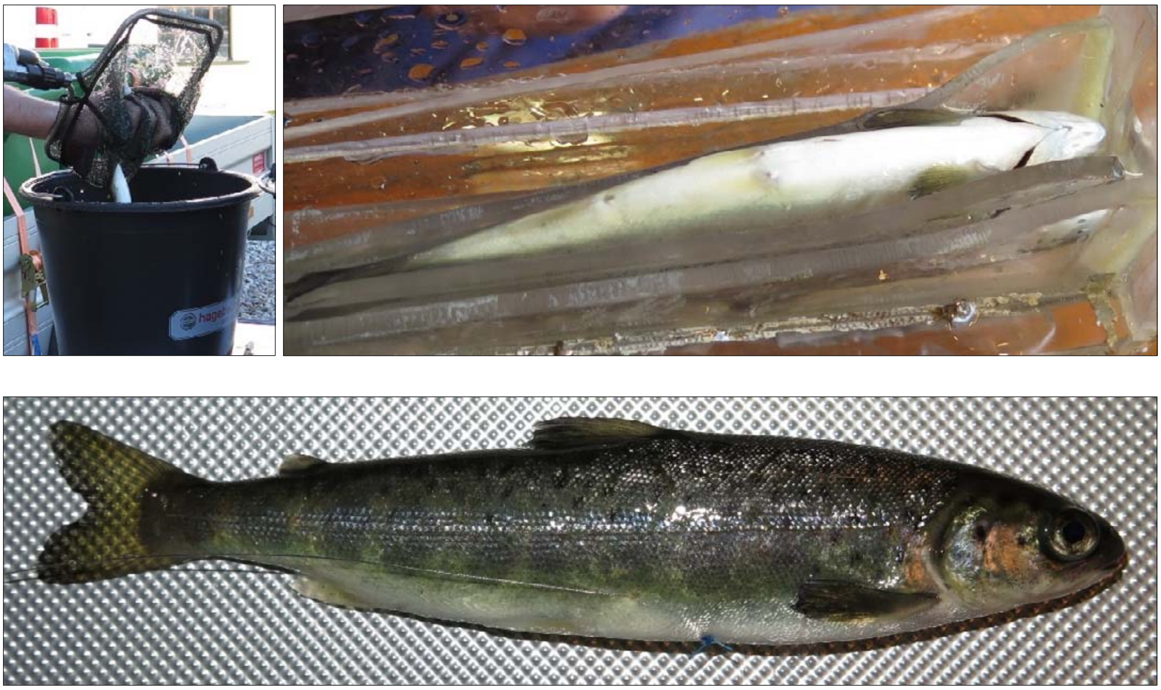


Figure 2.3. The fish were anaesthetised before tagging (3-5 min in a bath with benzocaine and water). The tag was inserted into the fish body cavity during a surgical procedure lasting a few minutes. The incision was closed with sutures. Photos Eva B. Thorstad and Torgeir B. Havn.

Figure 2.4. After tagging, the fish were kept in a bin with water, where they recovered and could swim normally after a few minutes. The radio antenna wire can be seen in the photo, exiting through the body wall of the fish. Photo Torgeir B. Havn.

Figure 2.5. Radio tagged fish were released in the rivers 4.6-10.1 km upstream of the studied power stations.

In each river, downstream migration and loss of tagged fish were recorded 1) on a free-flowing reference stretch, 2) on the impounded stretch upstream of the dam, 3) past the power station, and 4) on a river stretch below the power station. Photo Torgeir B. Havn.

Figure 2.6. Downstream migration of tagged fish was studied by using stationary receivers, which automatically stored information on time and id of tagged fish when they were within the detection range of receiver antennas. Photos from the Kinzig (left) and the Sieg (right) by Eva B. Thorstad.

Figure 2.7. Detailed recording of the movements of tagged fish at the power stations was done by using a network of stationary receivers with antennas covering all possible migration routes. Lotek model SRX 600 data loggers were used with 3-, 4-, 6- and 9-element Yagi-antennas or co-axial antennas used underwater or in air. When a tagged fish was within the detection range of an antenna, date, time, individual fish code, signal strength from the transmitter and individual antenna number were automatically recorded and stored by the receiver and later downloaded to a computer.
Photos from Unkelmühle, by Eva B. Thorstad and Stein Are Sæther.

Figure 2.8. Tagged fish were also positioned by manual tracking, by walking along the river or using a bike or boat searching for tagged fish with a portable antenna and receiver. Searches for tags from fish were also done in cormorant colonies. Photo from the Sieg, by Eva B. Thorstad.

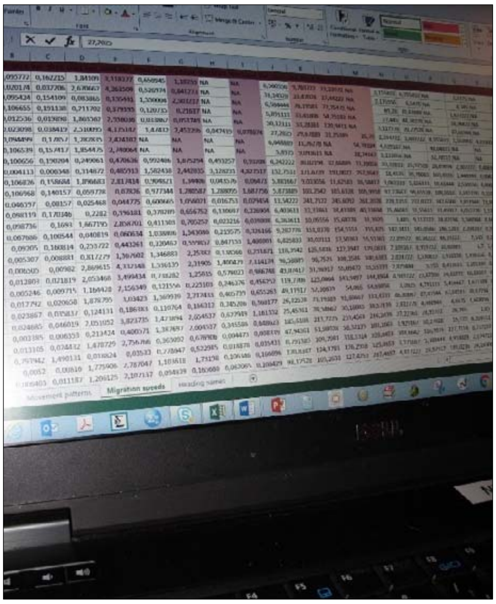


Figure 2.9. Determination of smolt loss is based on fish (*i.e.*, transmitters) that stopped moving or disappeared from the river. The reasons for loss can be predation by mammals, fish or birds, other mortality reasons and transmitter failure. The transmitters used are usually reliable, so significant 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 that move the fish out of range, the transmitter signal will disappear from the river.

Some smolt showed clear signs of being taken by bird predators based on bird-like signal recordings, such as for instance fast upstream movements past power stations. Photo by Eva B. Thorstad

Figure 2.10. To help distinguishing between live downstream migrating fish and dead drifting fish, some already dead salmon smolt were released in or immediately downstream of the turbines in all study rivers. The distance dead fish drifted was up to 2.4 km downstream from the power station.
Photo from Kuhlemühle, by Torgeir B. Havn.

Figure 2.11. The loss of smolt due to hydropower development was calculated by comparing loss on free-flowing reference stretches with loss on the impounded river stretch above the dam and past the power station in each river. This is based on the assumption that the loss per km recorded on the reference stretch is representative for the developed stretch if it had been a free-flowing river instead of being impounded and having the power station. Photo from the reference stretch in the Sieg by Eva B. Thorstad.

Table 2.1. Overview of tagged and released Atlantic salmon smolt.

River	Year	Tagging and release dates	Number of fish tagged	Fish size (minimum-maximum total length)	Fish origin
Sieg	2014	25-30 March	78	14-21 cm	Captured from the Sieg at Unkelmühle
Sieg	2015	9-28 April	178	11-20 cm	Captured from the Sieg at Unkelmühle and Albaum hatchery
Kinzig	2015	13-21 April	157	10-21 cm	Lachszucht Wolftal hatchery
Diemel	2015	10-15 April	112	10-18 cm	Albaum hatchery

3 Description of the power stations

3.1 Unkelmühle power station in the Sieg

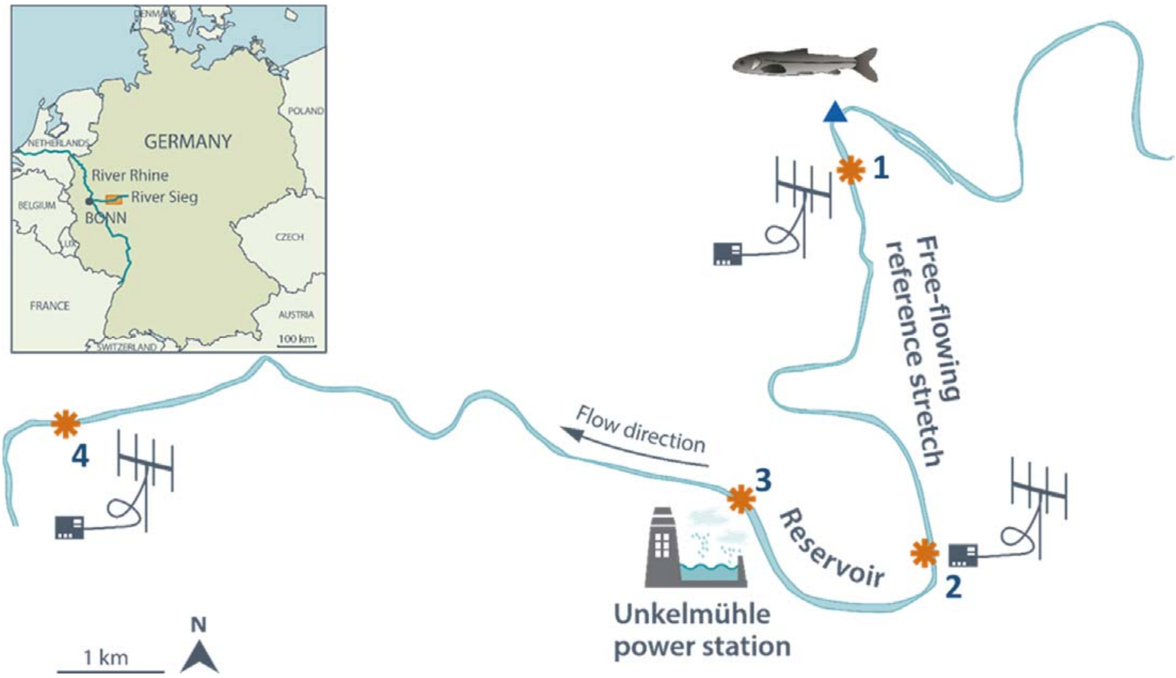


Figure 3.1. Study area in the Sieg showing release sites for radio tagged Atlantic salmon smolt (blue triangle), receiver sites where they were recorded when passing (orange stars, denoted with site numbers 1-4) and the Unkelmühle power station. Site 4 was operating in 2015, but not in 2014.

Unkelmühle is a run-of-the river power station on the Sieg, 44 km upstream from the confluence with the Rhine (**figure 3.1, 3.2**). 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.

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 are covered by a horizontally sloped rack (27° relative to the ground) with 10 mm bar spacing.

Ten migration routes can be used by downstream migrating fish past the power station (**figures 3.2-3.4**). Bottom and side passes specially designed for eel were not in operation during this study. Due to low water discharge in the spring 2014, water was not released over the ice gate, spillway gate or dam, so radio tagged smolt could not use these alternatives for passage, and could therefore use five different routes. In 2015, the situation was the same, except that the spillway gate was open on five occasions (median time open 22 min, range 16 min – 5 hours). Water discharge in the vertical slot fish passage is 0.3 m^3s^{-1}. Water discharge in the nature-like fishway and canoe pass is 0.2 m^3s^{-1} in each.

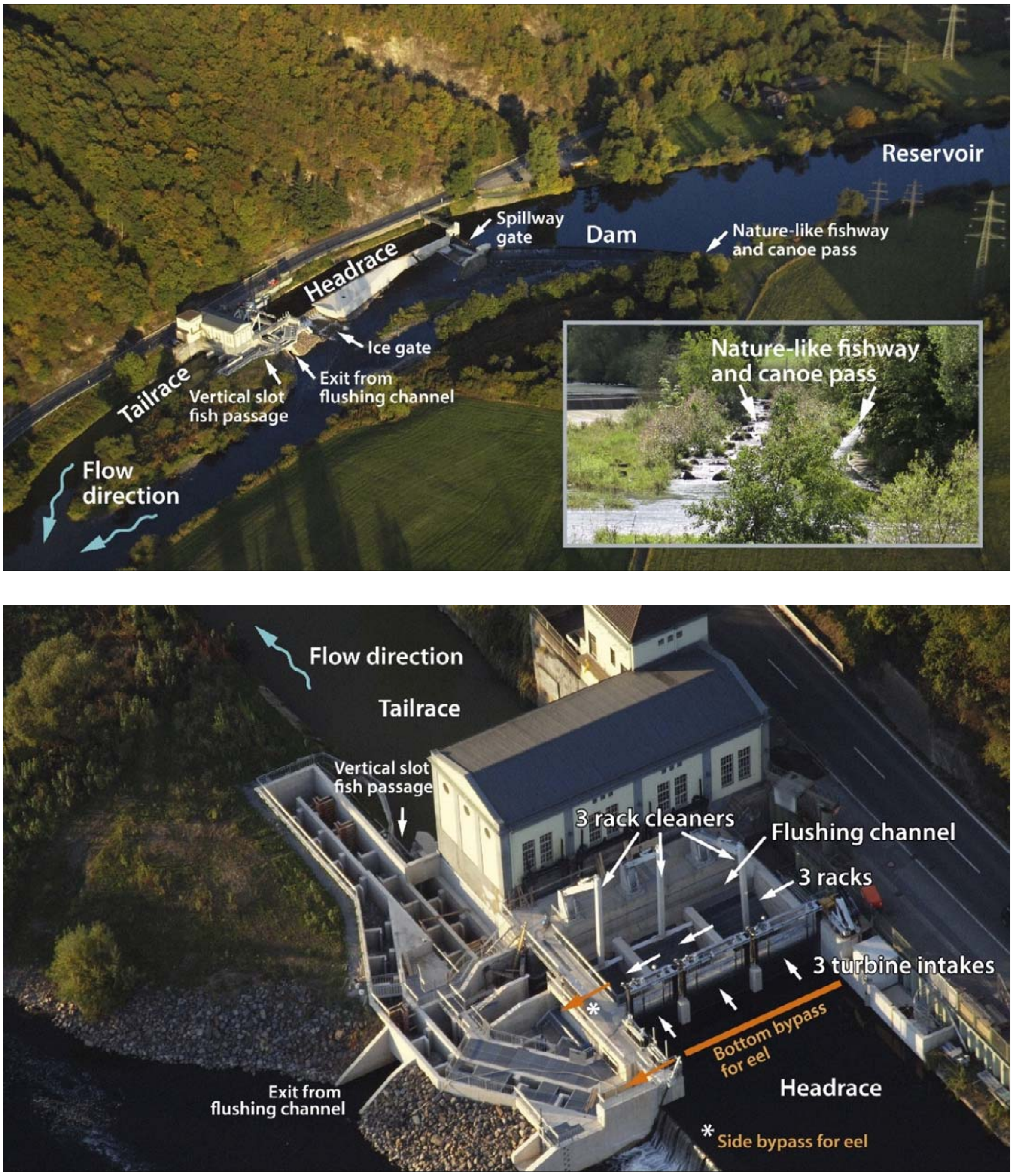


Figure 3.2. Unkelmühle power station with the different passages where downstream migrating fish can pass. The upper panel shows an overview of the power station area, and the lower panel shows the power station in more detail. The different migration routes past the power station are further described in **figure 3.3**. Photos: Wikimedia Commons and Eva B. Thorstad.

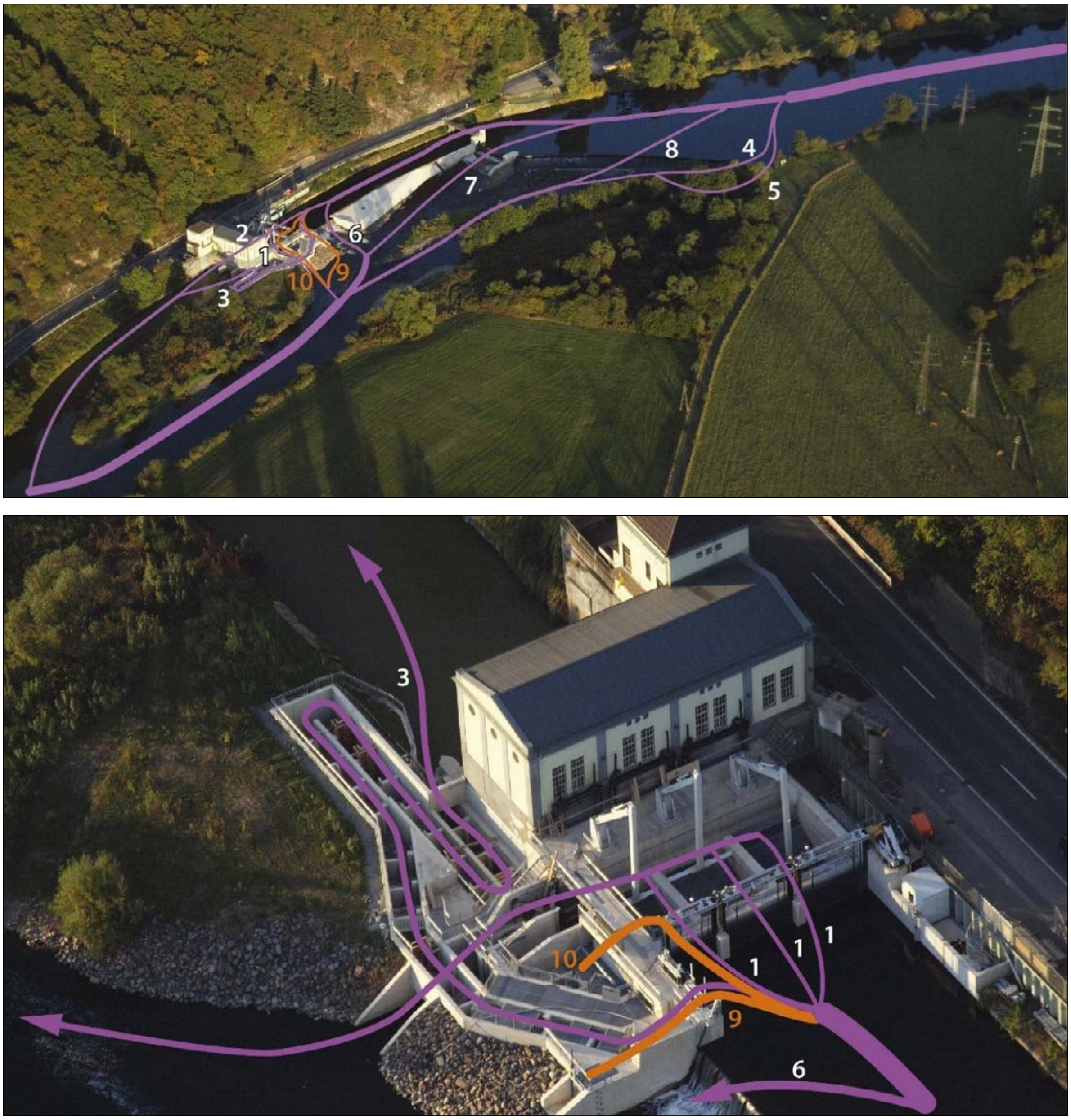


Figure 3.3. The different routes downstream migrating fish can use to pass the Unkelmühle power station: 1) via custom-made openings in the racks that leads fish to a route outside the turbines via the flushing channel, 2) through turbines if they slip through the bar spacing of the racks, 3) through the vertical slot fish passage 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.

One of the possible migration routes for downstream migrating fish is through custom-made openings in the racks in front of the turbines, which enable them to bypass the turbines via the flushing channel (**figure 3.3, 3.4**). During this study, fish could move freely from the flushing channel at all times and 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 the same channel as debris from the racks were flushed out 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 depend on amount of debris. During periods of high water and increased debris transport, they are continuously operated.

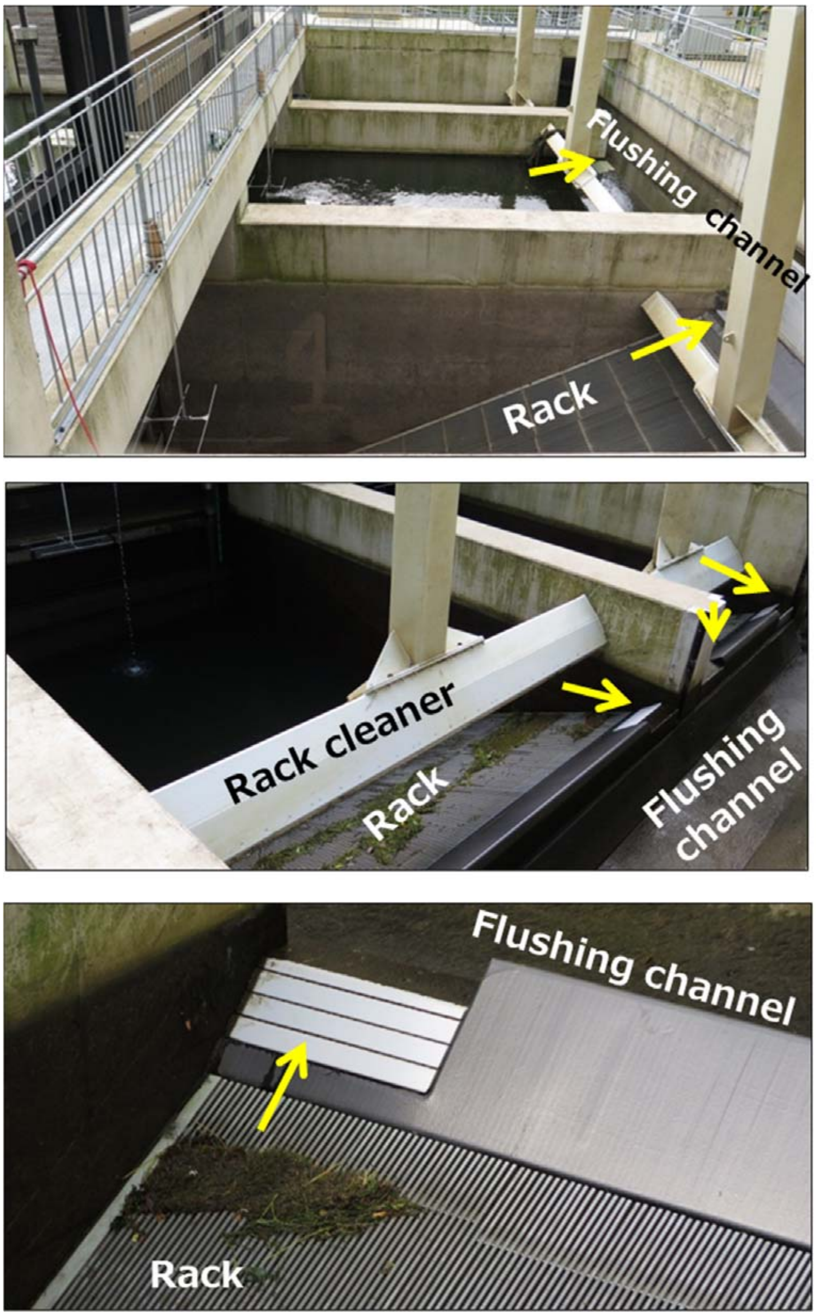


Figure 3.4. Details from the turbine intake at the Unkelmühle power station.

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 enters the flushing channel can follow a migration route past the power station outside the turbines (shown in figure 3.3).
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 is 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: Close-up of one of the rack openings, where fish can pass (turbine not operating).

Photos: Eva B. Thorstad

Detailed behaviour of radio tagged fish at the power station was recorded by using multiple antenna data loggers (total of 5 data loggers and 15 antennas in 2014 and 17 antennas in 2015, **figure 3.5**). Antennas had reception ranges covering different areas, enabling identification of the migration routes and speeds of individual fish.

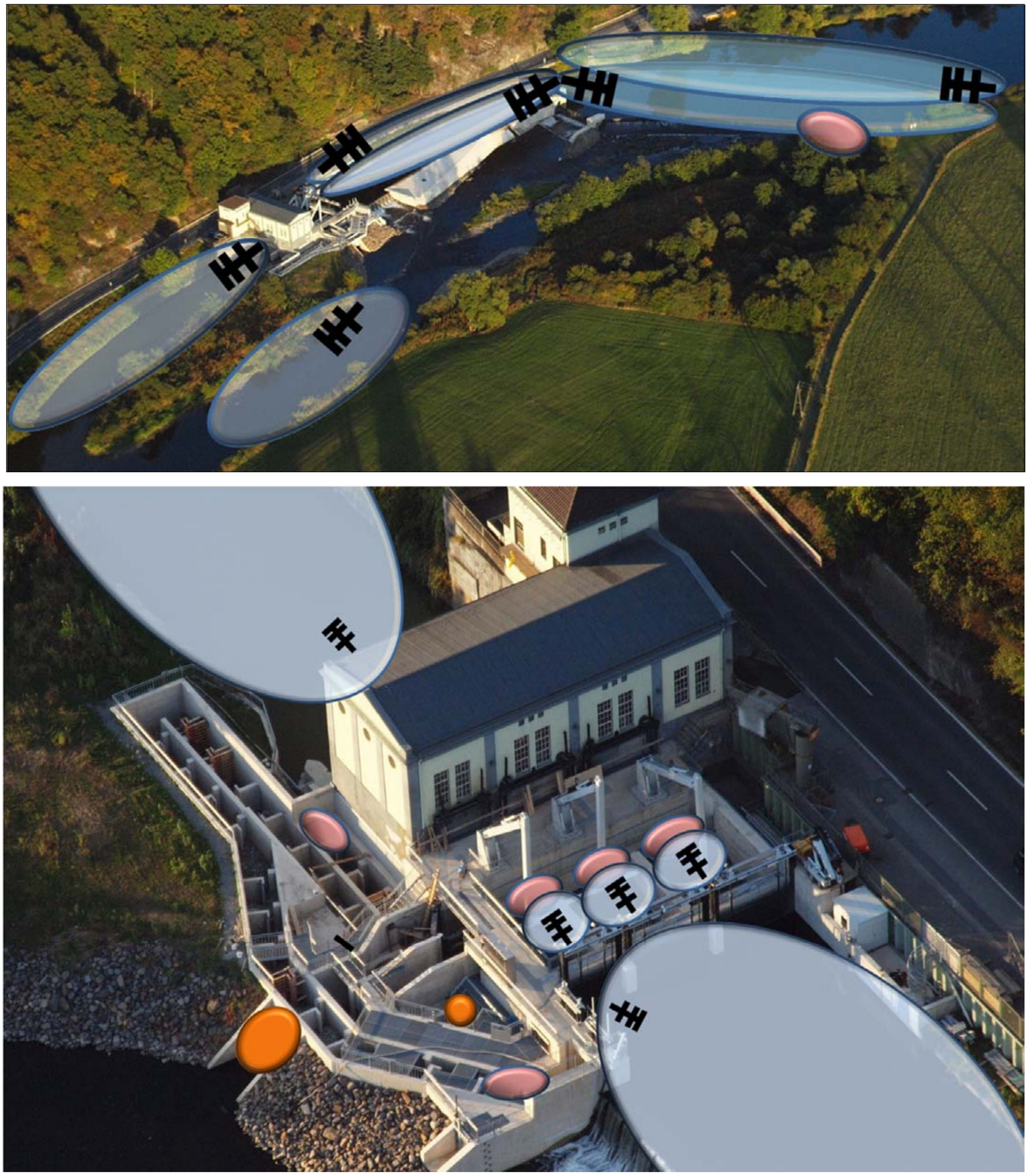


Figure 3.5. Overview of radio antennas and their approximate detection ranges used to record signals from radio tagged smolt at Unkelmühle power station in 2014 and 2015. **Upper panel:** Overview of the power station area. **Lower panel:** Power station area in more detail. Detection ranges for aerial Yagi antennas are shown with blue bubbles and co-axial underwater antennas with pink or orange bubbles. Orange bubbles indicate antennas used in 2015, but not in 2014.
Photos: Wikimedia Commons.

3.2 Gengenbach power station in the Kinzig

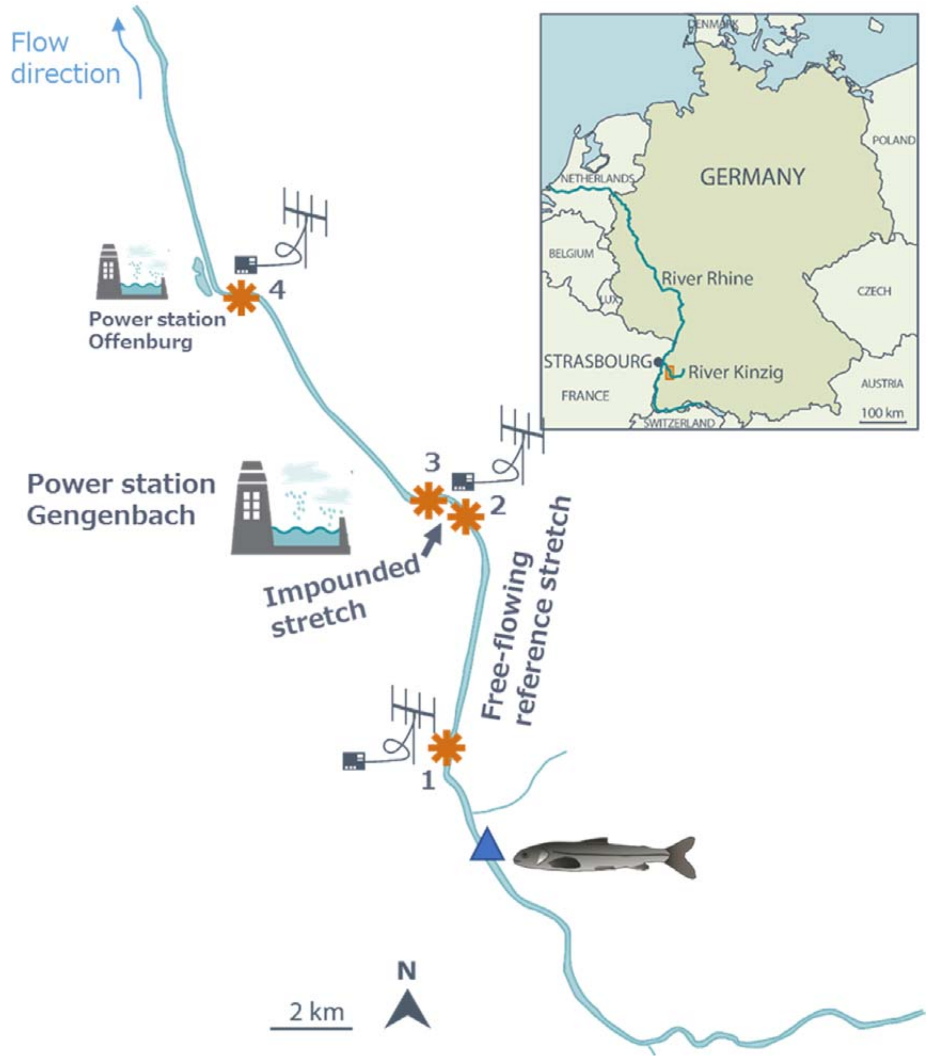


Figure 3.6. Study area in the Kinzig showing the release site of Atlantic salmon smolt tagged with radio transmitters (blue triangle), receiver sites where they were recorded when passing (orange stars, denoted with site numbers 1-4) and the power station in Gengenbach. The lowermost receiver was installed immediately upstream of the power station at Offenburg.

The power station in Gengenbach is a run-of-the river power station in the Kinzig, 30 km upstream from the confluence with the Rhine (**figure 3.6, 3.7**). A movable Kaplan bulb turbine (maximum capacity of 20 m^3s^{-1}, **figure 3.8**) is installed in the dam, which exploits a drop of 3.2 m.

Downstream migrating fish can use six different routes when they pass the power station (**figure 3.9**). There is no lake-like reservoir upstream of the dam, but the dam is affecting the river by slowing down water velocity for approximately 1.2 km upstream (termed impounded river stretch).

Figure 3.7. Photo of the dam and power station in Gengenbach, Kinzig, during low water discharge and the turbine in a lowered position. Photo: Eva B. Thorstad, taken 19 April 2015, at water discharge 17 m^3s^{-1}.

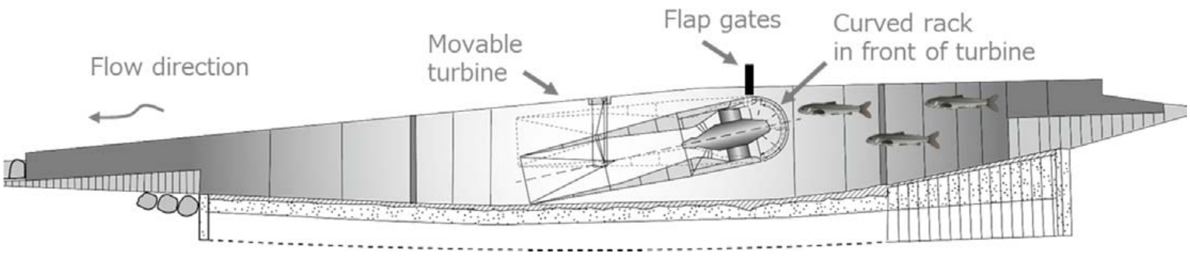


Figure 3.8. The movable bulb turbine installed in the dam at Gengenbach, in the Kinzig.

The turbine intake is covered by a curved rack with 15 mm bar spacing (**figure 3.10**). If a fish slips through the bar racks, it will pass through the turbine. Fish can also pass above or under the turbine. Depending on discharge, the turbine can be moved up and down (**figure 3.10**). It is usually lowered at low flow and elevated at higher flows (when the discharge exceeds the turbine capacity of about 20 m^3s^{-1}). During the present study, the turbine was lowered, except 1-5 May, when it was elevated. Independent of position, some water spills over the turbine, and downstream migrating fish can pass through an opening between two flap gates (**figure 3.9, 3.10**). Fish (and sediments) can also pass under the turbine tube when it is elevated during high water discharge, but not when it is lowered.

When water discharge is low and the turbine is lowered (usually in the spring and summer), an automatic bar rack cleaner operates every 10th hour. During each cleaning operation, which lasts for about 2 minutes, the flap gates are lowered. When the water discharge increases, the turbine is elevated between 0.2 m to 2.5 m above the bottom, dependent on discharge, and the flap gates are constantly lowered. During high water discharge, frequent cleaning operations are usually not needed.

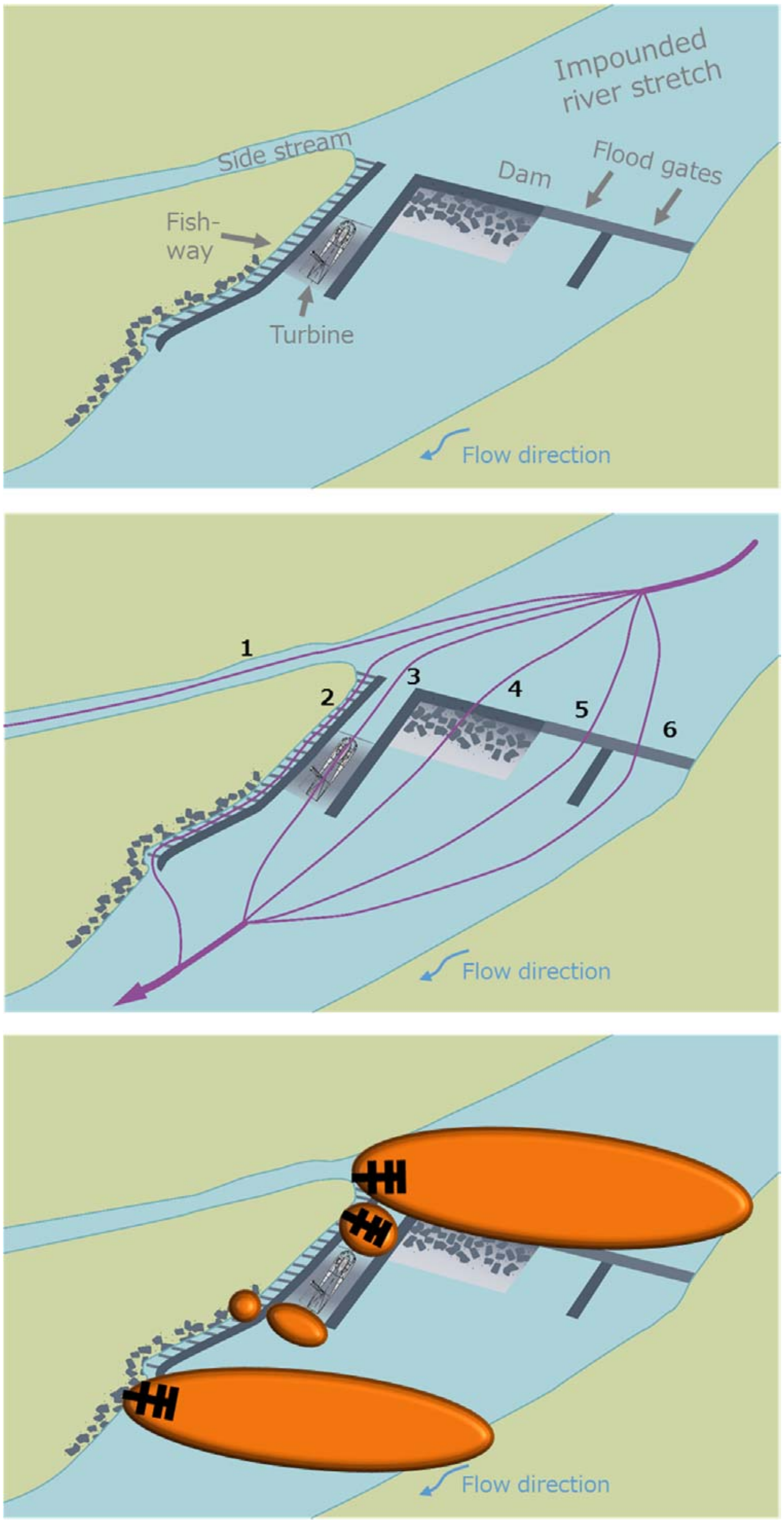


Figure 3.9.

Upper panel: Dam and power station at Gengenbach in the Kinzig.

Middle panel: The different routes downstream migrating fish can use to pass the power station: 1) via the millrace, 2) through the rock-ramp fishway constructed for upstream migrants, 3) through the section where the turbine is installed, 4) over the dam, 5) and 6) through the two floodgates.
The millrace enters the main river again 0.7 km downstream from the dam. The dam (route 4) can be passed only when the water discharge is large enough for excess water to flow over the dam crest. The floodgates can be passed only when they are open. Flooding over the dam or opening of the floodgates did not occur during this study, so route 4, 5 and 6 were not available.
Water discharge in the millrace is 0.5 m^3s^{-1} and in the fishway 0.6 m^3s^{-1}.

Lower panel: Overview of radio antennas and their detection ranges (in orange) used to record signals from radio tagged fish at the power station.
Ranges with black antenna symbols indicate the use of Yagi antennas, whereas ranges without antenna symbols indicate the use of coaxial antennas (in the fishways and tailrace of the turbine).

3.3 Kuhlemühle power station in the Diemel

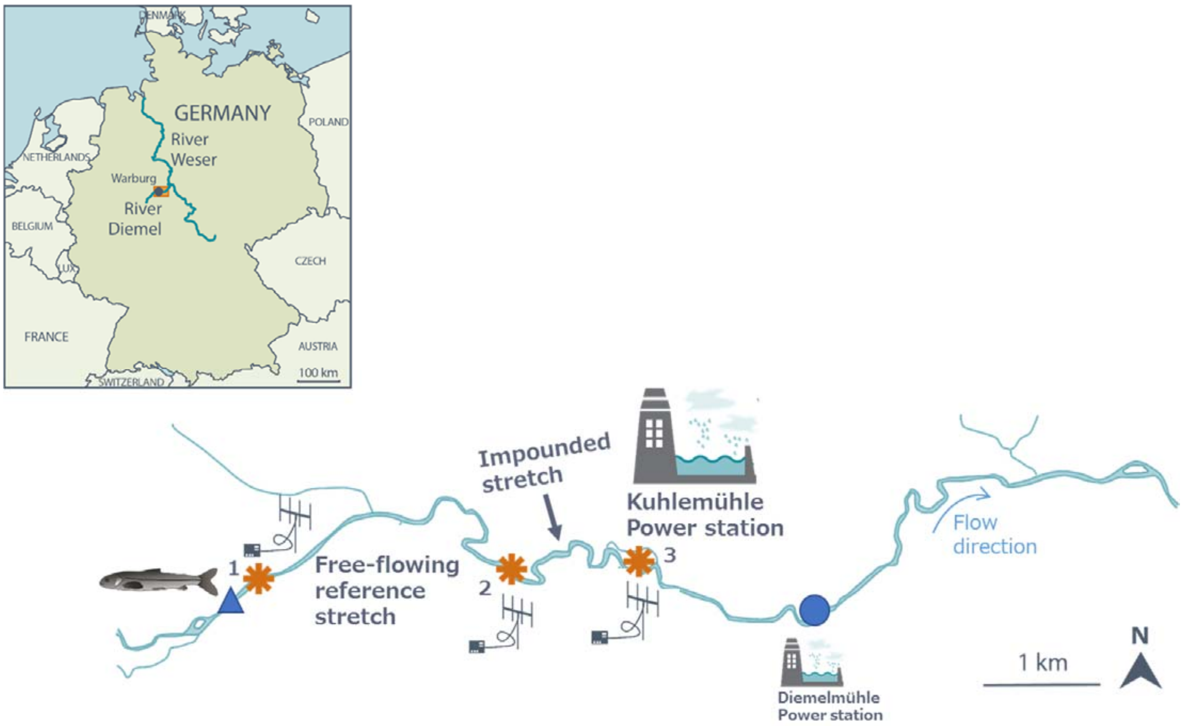


Figure 3.10. Study area in the Diemel showing the release site of Atlantic salmon smolt tagged with radio transmitters (blue triangle), receiver sites where they were recorded when passing (orange stars, denoted with site numbers 1-4) and the Kuhlemühle power station. Diemelmühle power station is also shown on the map, but no receivers were installed to monitor smolt at this site.

Kuhlemühle is a run-of-the river power station on the Diemel, 4 km downstream from the town Warburg (**figure 3.10, 3.11**). A 4-bladed Archimedes screw turbine is installed (3.4 m diameter and 7 m long, **figure 3.12**), which is run on either slow (12 revolutions per minute) or fast speed (24 revolutions per minute), corresponding to a water discharge through the turbine of 3 m^3s^{-1} and 5 m^3s^{-1}, respectively. There is no rack in front of the Archimedes screw to prevent fish from entering the turbine.

There is also a power station with two Francis turbines at the site (capacity of 4.5 and 2.0 m^3s^{-1}, respectively), which optimally exploits a drop of 2.6 m. The turbine intake is covered by a horizontal rack with 20 mm bar spacing (**figure 3.13**).

Downstream migrating fish can use six different routes when they pass the Kuhlemühle power station (**figure 3.11, 3.14**). There is no true reservoir upstream of Kuhlemühle, but the dam affects the river by slowing down water velocity for approximately 1.3 km upstream (termed impounded river stretch).

There is another power station at the Diemel, Diemelmühle, 2.1 km downstream from Kuhlemühle (**figure 3.10**). Fish can potentially be damaged or killed also at this site, but monitoring at this site was not part of the study.

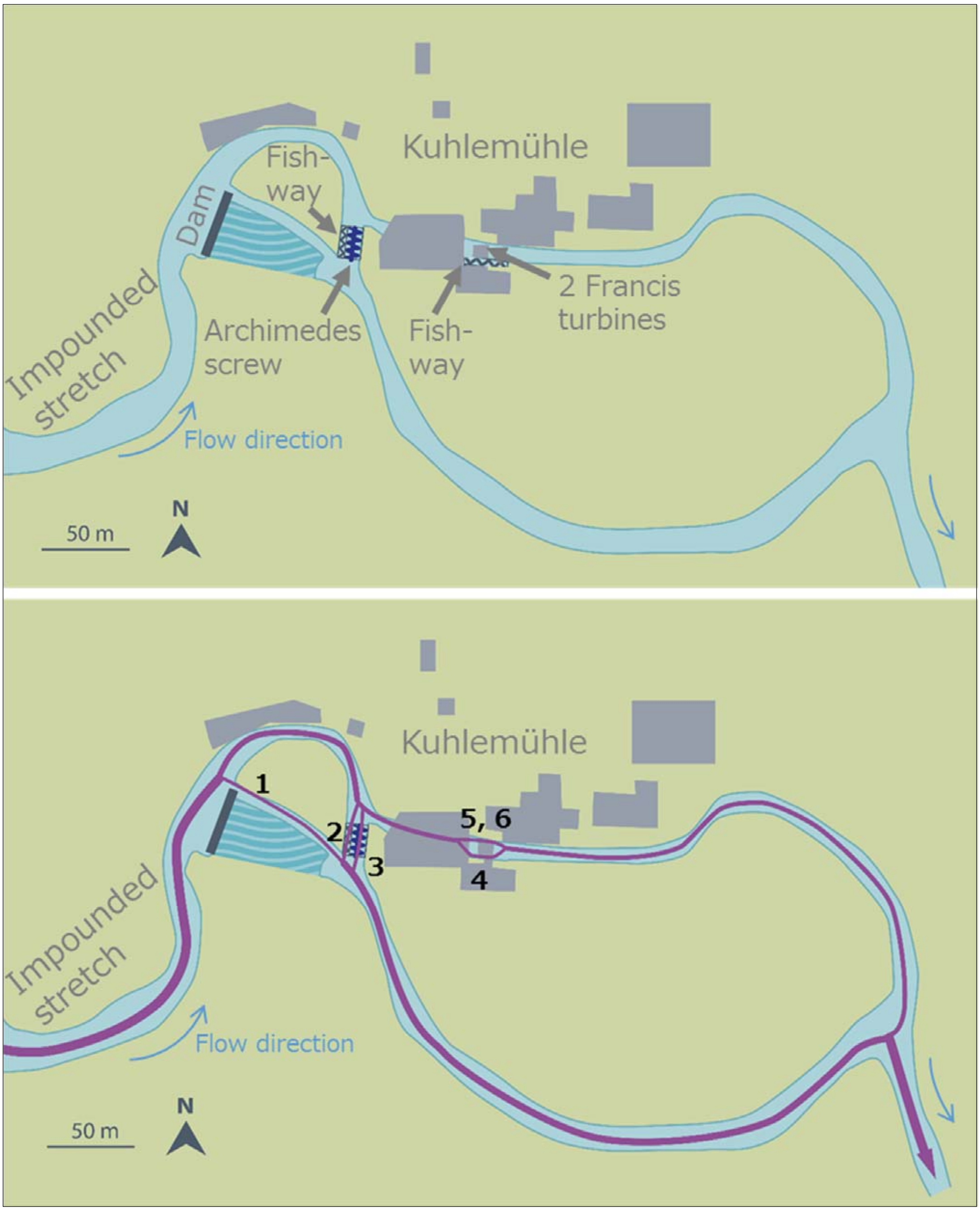


Figure 3.11. Kuhlemühle power station. **Upper panel:** Turbines and fishways. **Lower panel:** The different routes downstream migrating fish can use to pass: 1) over the dam and outside the area with hydropower installations, but only when the water discharge is large enough for excess water to flow over the dam crest (> 12 m^3s^{-1}), or when a gate is opened to get debris past (which occurred 7 times during the study), 2) through the weir fishway constructed for upstream migrants at the Archimedes screw turbine (water discharge 0.4 m^3s^{-1}), and 3) through the Archimedes screw. Fish can also enter the water intake of the Francis turbines and can either 4) use a fishway constructed for upstream migrants (water discharge 0.1 m^3s^{-1}), which leads them outside the Francis turbines, 5) pass through the turbines if they slip through the bar spacing of the racks in front of the turbines, or 6) be flushed through an opening for debris, which is automatically opened for 15 seconds each time the rack cleaners are operating (water discharge 1.3 m^3s^{-1}). The rack cleaners were operating ca. every 2 hours during most of the study, but ca. every 3 hours from 18 May.

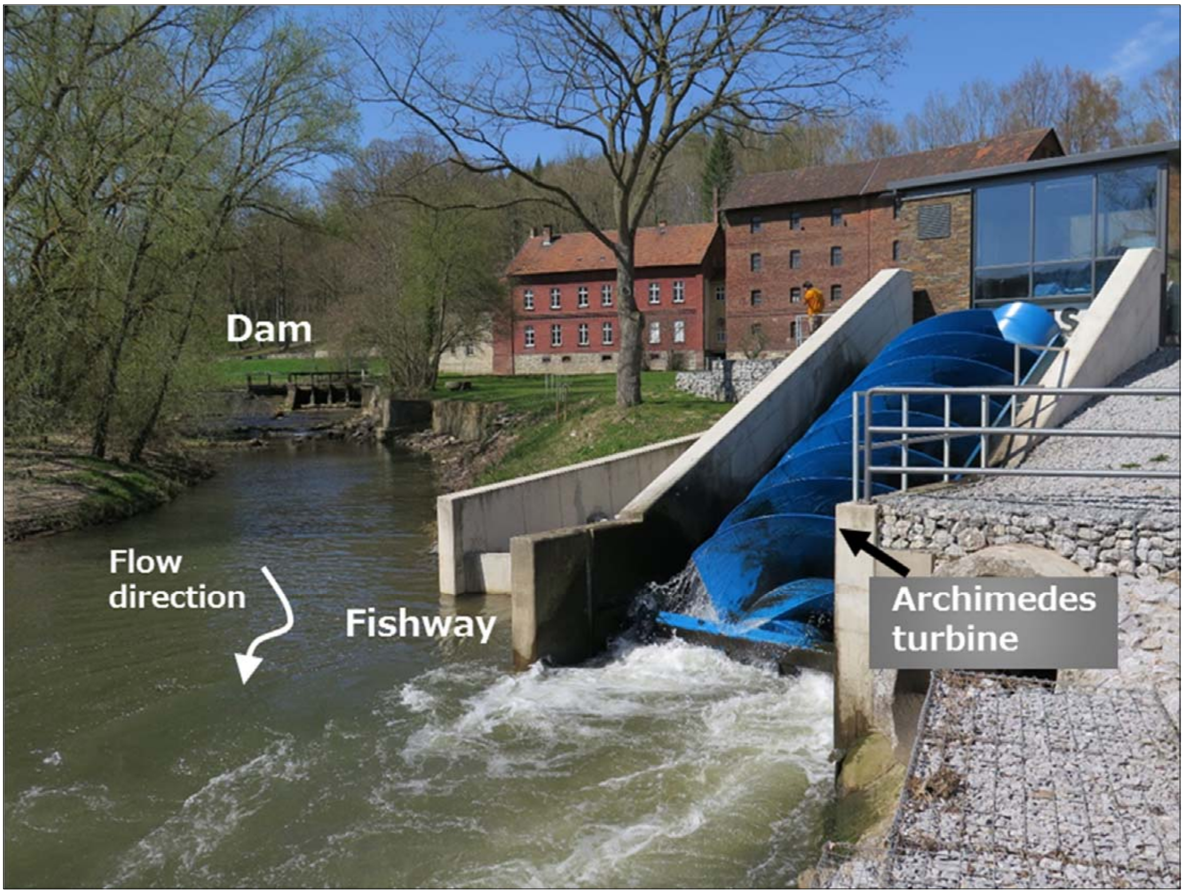


Figure 3.12. Archimedes screw turbine at Kuhlemühle. Photo Torgeir B. Havn.

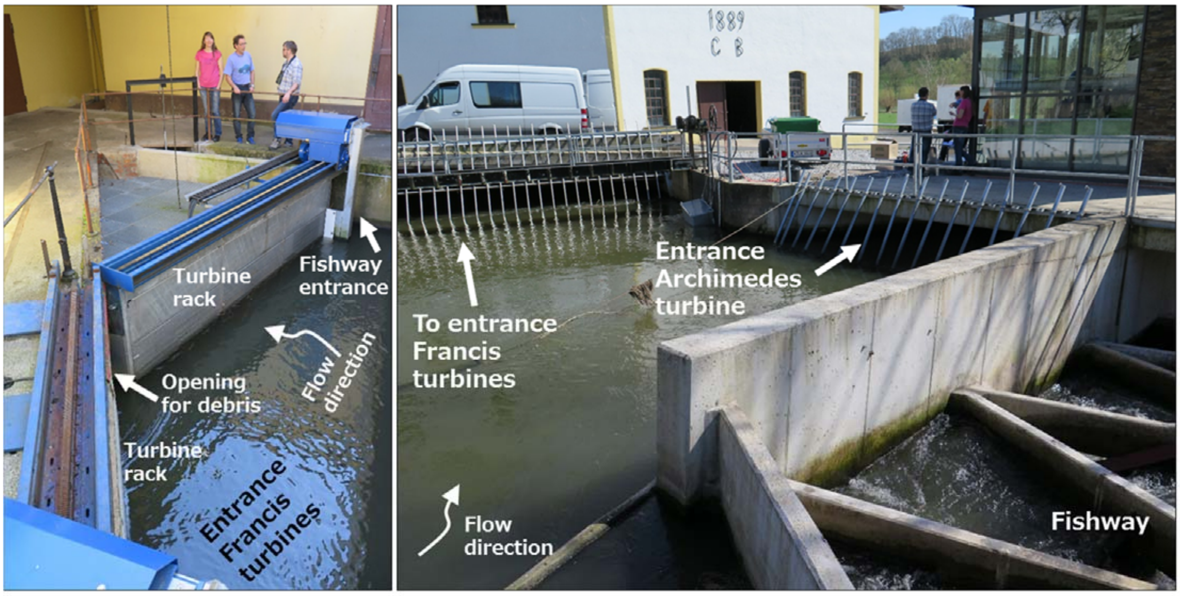


Figure 3.13. Entrance to Francis turbines and Archimedes screw turbine at Kuhlemühle. Photos Torgeir B. Havn.

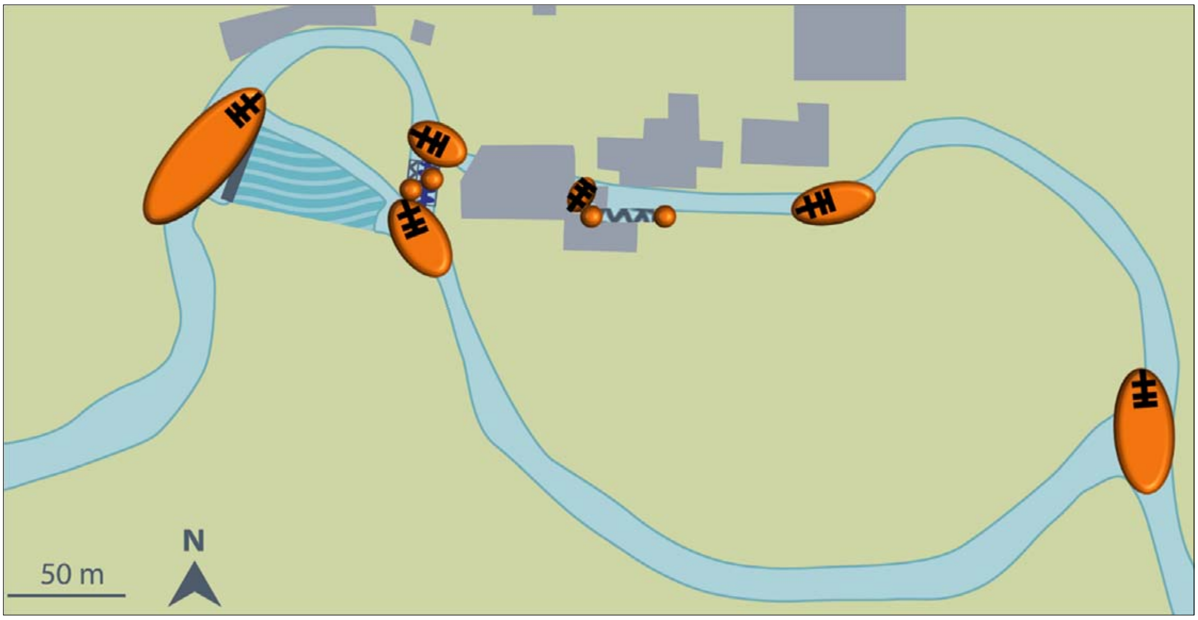


Figure 3.16. Overview of radio antennas and their approximate detection ranges (in orange) used to record signals from radio tagged fish at Kuhlemühle. Ranges with black antenna symbols indicate the use of Yagi antennas, whereas ranges without antenna symbols indicate the use of coaxial antennas (in the fishways and Archimedes screw turbine).

4 Results

4.1 Unkelmühle power station in the Sieg

Summary

Downstream migration was studied by tagging 256 Atlantic salmon smolt with radio transmitters in 2014 and 2015. Migration was recorded on a free-flowing reference stretch (5.8 km), in the reservoir (2.3 km), past the power station (0.2 km) and below the power station (7.5 km, only in 2015).

Loss of smolt on the reference stretch was 1.5 and 1.6% per km in the two years, and in the reservoir 4.8 and 9.6% per km (**figure 4.1**). There was 7.2% loss in the reservoir due to the river regulation in 2014 and 17.1% in 2015 (*i.e.*, 7.2 and 17.1% of smolt entering the reservoir were lost due to this being a reservoir instead of a free-flowing river).

At the power station, most smolt followed the migration route towards the bar racks in front of the turbines (83% in 2014, 95% in 2015). Few smolt used the spillway gate (0% in 2014, 1% in 2015), vertical slot fish passage (5% in 2014, 1% in 2015) and nature-like fishway or canoe pass (12% in 2014, 3% in 2015). No smolt passed through the bar spacing of the racks and through the turbines.

Minimum loss due to the power station was 9.9% in 2014 and 12.8% in 2015 (*i.e.*, 9.9% and 12.8% of smolt entering the power station area were lost due to this being a power station instead of a free-flowing river). Combined loss due to hydropower at Unkelmühle, *i.e.*, in the reservoir and at the power station, was minimum 16.0% in 2014 and 25.1% in 2015 (of fish entering the reservoir).

The loss estimates for 2014 are underestimates compared to 2015, because fish were not followed downstream of the power station in 2014, and for instance fish that possibly died at the power station but floated dead downstream, and increased predation below the power station, were not included. The loss estimates from 2015 are more complete because the fish were followed also downstream of the power station, and the loss estimate is therefore not only based on recordings at the power station, but also on the 7.5 km stretch below.

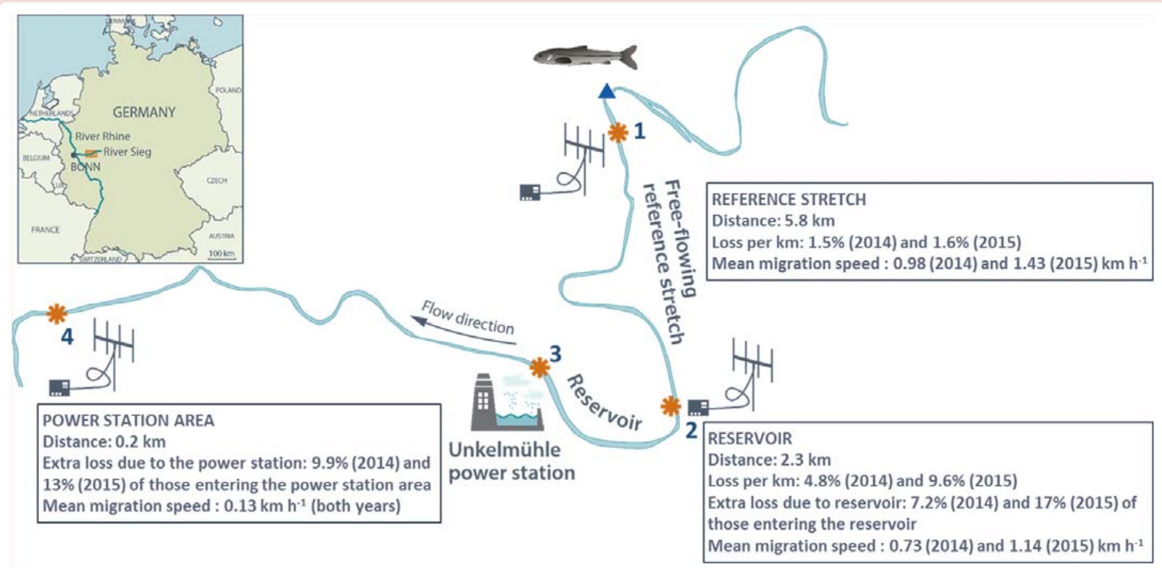


Figure 4.1. Main results for radio tagged smolt on different river stretches summarised in boxes. Blue triangle shows the release site of tagged smolt and orange stars receiver sites where passing fish were recorded (site 4 were only operated in 2015).

4.1.1 Loss of smolt on the reference stretch and in the reservoir

In 2014, 6 of 78 smolt (8%) did not migrate from the release area, and in 2015 19 of 178 smolt (11%). Further, 6 (2014) and 14 (2015) smolt were lost on the 5.8 km long reference stretch, which corresponds to a loss of 8.3% and 8.8% in the two years (1.5% and 1.6% per km).

In the 2.3 km long reservoir, 7 (2014) and 30 (2015) smolt were lost. This corresponds to a loss of 10.6% and 20.7% (4.8% and 9.6% per km). The remaining 59 (2014) and 115 (2015) smolt reached the Unkelmühle power station.

4.1.2 Migration routes in the power station area

Most of the smolt that passed the power station followed the migration route towards the bar racks in front of the turbines (83% in 2014, 95% in 2015, **figure 4.2**), which leads the fish to a route outside the turbines via the flushing channel. Few smolt used the spillway gate (0% in 2014, 1% in 2015), vertical slot fish passage (5% in 2014, 1% in 2015) and nature-like fishway or canoe pass (12% in 2014, 3% in 2015). For the smolt that used the nature-like fishway or canoe pass, we cannot determine which of these two routes they used. 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).

Figure 4.2. Numbers of smolt in 2014/2015 that used the different migration routes past the power station. Total number of smolt passing was 59 in 2014 and 115 in 2015. Water was not flowing over the dam or through the ice gate during the study, so these migration routes were not available (indicated with an X). Similarly, the bottom and side passes designed for eel were not in operation (orange lines, also indicated with an X). Water was flowing over the spillway gate only for short periods during the study in 2015, *i.e.*, 16 min - 5 hours on five occasions.

4.1.3 Loss of smolt in the power station area and downstream

2014

The loss of downstream migrating smolt in the power station area was 6 of 59 smolt (10.2%), or 41.5% loss per km (0.2 km stretch at power station). This must be regarded as a minimum loss, because tagged fish were not monitored downstream of the power station in 2014. Hence, fish that possibly died in the power station area but floated dead downstream, delayed mortality from injuries caused when passing the power station, and increased predation risk below the power station were not included in the loss estimate.

Smolt lost in the power station area were all among those following the migration route towards the bar racks in front of the turbines. The loss seemed to be related to mortality due to physical injury in bypass routes aimed at guiding smolt outside the turbines. Two smolt probably died in the bar rack area, which could be due to physical injury at the bar racks, but was not related to operation of the rack cleaners. Three smolt were lost in the bypass immediately before exit to the river, in an area where smolt could become trapped and die because debris and branches flowing with the river were piling up (**figure 4.3**). One more smolt was likely injured or died in the same area, because the tag became stationary immediately after exit to the river via the same route.

The loss of smolt on the 0.2 km long stretch constituting the power station area was much higher than on the reference stretch. If the loss on the power station stretch had been similar to the reference stretch, no smolt (estimated at 0.18 smolt) would have been expected lost, instead of the 6 smolt that were documented as lost.

Figure 4.3. Area of the bypass route outside the turbines at the Unkelmühle power station where debris and branches were piling up in 2014 and likely caused mortality in Atlantic salmon smolt that were trapped (left). There was no debris piling up and no recorded mortality at this particular site during the study in 2015 (right). Photo: Finn Økland and automatic monitoring camera.

2015

Of the 103 smolt that passed the power station without being captured for monitoring, 78 (76%) passed the receiver 7.5 km downstream of the power station (site 4, see **figure 4.1**), hence 25 smolt were lost. One of these became stationary in the power station area, and three were likely taken by bird predators after exit from the bypass route (based on bird-like movements of the transmitter). Signals from 13 smolt disappeared from the river after they had passed the power station, of which 9 later had bird-like recordings. These 13 smolt could potentially have died immediately in the power station area and drifted downstream, or they could have been lost on the river stretches downstream of the power station. The remaining four smolt became stationary in the lower part of the 7.5 km stretch below the power station.

4.1.4 Estimates of loss related to the reservoir and power station

2014
Based on results given above, there was 7.2% loss in the reservoir compared to if this stretch had been a free-flowing river (i.e. 7.2% of smolt entering the reservoir were lost due to this being a reservoir instead of a free-flowing river). Further, minimum extra loss in the power station area was 9.9% (i.e. 9.9% of smolt entering the power station area were lost due to this being a power station instead of a free-flowing river). If we combine loss in the reservoir and in the power station area into a total loss due to hydropower, this would be a minimum total loss of 16.0% of the fish entering the reservoir.

2015
There was 17.1% extra loss in the reservoir, compared to if this stretch had been a free-flowing river (*i.e.*, 17.1%, of smolt entering the reservoir, were lost due to this being a reservoir instead of a free-flowing river).

Minimum extra loss of smolt due to the Unkelmühle power station was 12.8% (of smolt entering the power station area). This was based on the recorded loss in the power station area and 7.5 km stretch below compared to the loss on the unimpounded river stretch.

If we combine loss in the reservoir, in the power station area and 7.5 km below the power station compared to if this stretch had the same loss as the reference stretch, this corresponds to a minimum total extra smolt loss of 25.1% due to hydropower, including the reservoir (*i.e.*, of smolt entering the reservoir).

Estimates of loss related to the power station: results from 2014 and 2015 compared

The loss estimate of 9.9% due to the power station based on the results from 2014 was probably particularly underestimated and cannot be regarded as a complete loss estimate for the Unkelmühle power station in 2014, nor be directly compared with the more complete loss estimate of 12.8% based on the results from 2015. If we calculate the loss estimate we would had achieved for 2015 if we had not recorded the fish downstream of the power station (i.e., if we had used the same study design as in 2014), we would have recorded a loss of only 4 of 103 smolt due to the power station in 2015. This corresponds to an extra loss due to the power station of 3.6%, which is the comparable number to the 9.9% estimate in 2014 (**table 4.1**). Hence, the loss due to the power station in 2015 (12.8%) was 3.6 times higher than would have been estimated if we had used a study design similar to 2014 (3.6%). These results indicate that the loss estimate of 9.9% in 2014 was particularly underestimated, but we do not know if it was underestimated to the same degree as the 2015-analysis points to. However, the results from the two years particularly indicate that the mortality recorded in the bypass route that leads smolt outside the turbines was higher in 2014 than in 2015. The higher mortality in 2014 was likely because some smolt became trapped and died in the bypass route where debris and branches were sometimes piling up in 2014, but not in 2015 (**figure 4.3**). In both years, no smolt passed through the bar spacing of the racks and through the turbines.

Table 4.1. Proportion of smolt becoming stationary or taken by predators at the Unkelmühle power station (adjusted for mortality per km in the reference stretch) in 2014 and 2015. These estimates cannot be regarded as complete loss estimates for the power station, because the estimates does not include smolt that died and drifted out of detection range of the antennas installed in the power station area, or smolt that were taken by predators further downstream. Hence, the proportions given in the table only represent part of the total loss due to hydropower development at the power station. The complete loss estimate for 2014 is unknown, and for 2015 it was 12.8%.

River	Power station	Year	Proportion of smolt stationary or taken by predators at power station
Sieg	Unkelmühle	2014	9.9%
Sieg	Unkelmühle	2015	3.6%

4.1.5 Migration speeds

In 2014, migration speeds did not differ between the reference stretch (mean 0.98 km h^{-1}) and reservoir (mean 0.73 km h^{-1}), but was slower during passage of the power station (mean 0.13 km h^{-1}). The smolt spent on average 25 hours in passing the power station area (range 0.3-161 hours).

In 2015, migration speeds also did not differ among the reference stretch (mean 1.43 km h^{-1}), reservoir (mean 1.14 km h^{-1}) and the 7.5 km stretch downstream of the power station (mean 1.23 km h^{-1}). Similar to 2014, the migration speed was slower when passing the power station area (mean 0.13 km h^{-1}). The smolt spent on average 14 hours in passing the power station area (range 0.4-115 hours).

4.2 Gengenbach power station in the Kinzig

Summary

Downstream migration was studied by tagging 157 Atlantic salmon smolt with radio transmitters. Migration was recorded on a free-flowing reference stretch (7.2 km), on an impounded stretch above the dam (1.2 km), past the power station (0.08 km) and on a river stretch below the power station (7.5 km) (**figure 4.4**).

Loss of smolt on the reference stretch was 0.7% per km, and on the impounded stretch 2.3% per km. There was 1.5% loss on the impounded stretch due to the river regulation (*i.e.*, 1.5% of smolt entering the stretch were lost due to this being impounded by a dam instead of a free-flowing river).

In the power station area, most smolt passed through the section where the turbine is installed (119 smolt, 94%), 5 smolt (4%) passed through the fishway and 2 smolt (2%) passed via the mill race. The loss of smolt in the power station area was 4-8 of 126 smolt (all lost smolt had passed through the turbine section). The reason for the range in the estimate is that for four smolt likely taken by predators downstream of the power station, we do not know if they were dead or injured due to passing the power station and therefore taken by predators, or if they were uninjured from passing the power station but taken by predators further downstream.

Minimum loss in the power station area due to hydropower was 3.1-6.3% (i.e. 3.1-6.3% of smolt entering the power station area were lost due to this being a power station instead of a free-flowing river). Combined loss due to hydropower at Gengenbach, *i.e.*, on the impounded stretch and in the power station area, was minimum 4.5-7.6% (of fish entering the impounded stretch).

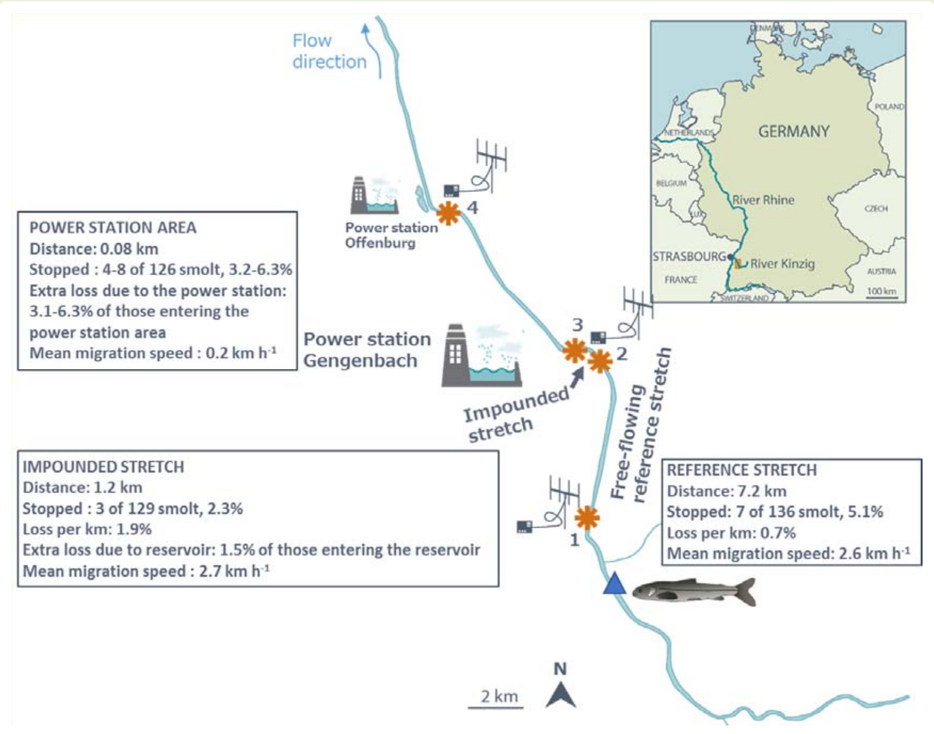


Figure 4.4. Main results for radio tagged smolt on different river stretches summarised in boxes. Blue triangle shows the release site of tagged smolt and orange stars receiver sites where passing fish were recorded.

4.2.1 Loss of smolt on the reference stretch and impounded stretch

Of 157 radio tagged smolt, 21 individuals (13%) did not migrate from the release area, 7 were lost on the 7.2 km long reference stretch, and 3 were lost in the 1.2 km long impounded stretch above the dam. This corresponds to a loss of 5.1% on the reference stretch (7 of 136 smolt, 0.7% per km) and 2.3% on the impounded stretch (3 of 129 smolt, 1.9% per km). The remaining 126 smolt reached Gengenbach power station.

4.2.2 Migration routes in the power station area

Of 126 smolt that passed the power station area, the majority passed through the dam section where the turbine is installed (119 smolt, 94%), whereas 5 smolt (4%) moved through the fishway and 2 smolt (2%) used the mill race (**figure 4.5**). Smolt that passed through the turbine section could theoretically have passed above the turbine between the flap gates, above the turbine when the rack cleaner was operating, under the turbine, or through the turbine if slipping through the bar spacing. We cannot separate between these options. No smolt passed the power station during the period when the turbine was constantly elevated (1-5 May).

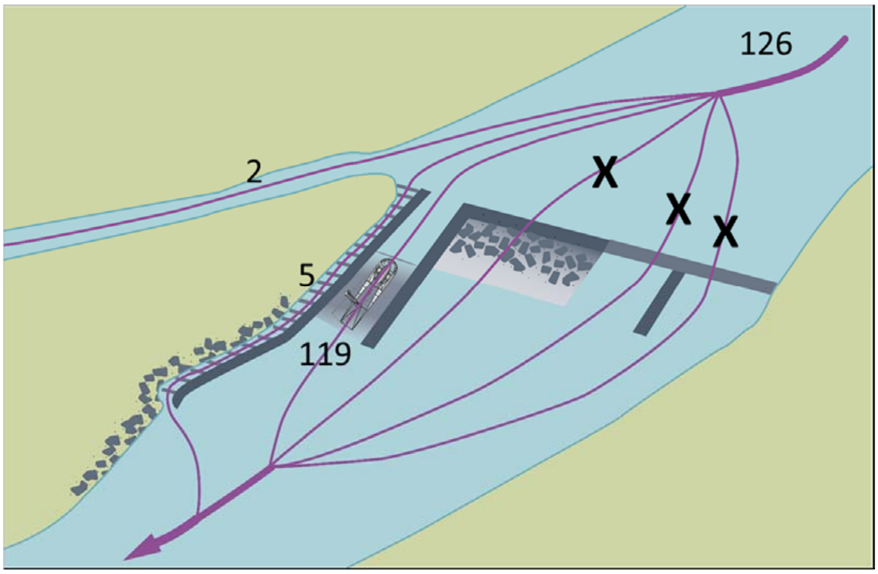


Figure 4.5. Numbers of smolt that used the different migration routes past the power station. Total number of smolt passing was 126 smolt. Water was not flowing over the dam or through the floodgates during the study, so these routes were unavailable (indicated with an X).

4.2.3 Loss of smolt in the power station area and downstream

Of the 126 smolt that passed the power station, at least 9 smolt were lost (of which all had passed the dam through the turbine section):

- Four likely died during or immediately after passing the power station, because they became stationary within the detection range of the antenna below the dam (**figure 3.9**) until the end of the study.
- Four were likely taken by predators at or downstream of the power station (based on the movement pattern, which became bird-like), but we do not know exactly where they were lost.

- One stopped 3.5 km downstream of the power station and became stationary during the rest of the study. Most likely it died sometime after passing the power station, because it is not likely that a smolt dying at the power station would drift this far. To be able to distinguish between live smolt and dead drifting smolt, 20 already dead smolt were radio tagged and released at the turbine. The longest drift recorded by any dead smolt was 200 m downstream from the power station.

Except the 9 smolt referred to above, all the remaining smolt that passed the power station reached receiver site 4 at Offenburg and probably survived passing Gengenbach power station.

Based on these results, the immediate loss of downstream migrating smolt at Gengenbach power station was between 4 and 8 of 126 smolt (3.2-6.3%). The reason for this range in estimate is that for the four smolt likely taken by predators, we do not know if they were dead or injured due to passing the power station and therefore taken by predators, or if they were uninjured from passing the power station but taken by predators on the downstream stretches.

4.2.4 Estimates of loss related to the reservoir and power station

Based on results given above, there was 1.5% extra loss on the impounded stretch, compared to if this stretch had been a free-flowing river (*i.e.*, 1.5% of smolt entering the impounded stretch were lost due to this being impounded by the dam instead of a free-flowing river). Minimum extra loss at the power station was 3.1-6.3% (*i.e.*, 3.1-6.3% of smolt entering the power station area were lost due to this being a power station instead of a free-flowing river). Combined extra loss due to hydropower, *i.e.*, in the reservoir and at the power station, was minimum 4.5-7.6% (of fish entering the impounded stretch).

Smolt injured from passing the power station may suffer delayed mortality. The low loss on the river stretch between Gengenbach and Offenburg indicates that significant delayed mortality of injured smolt did not occur on this stretch. However, loss estimates presented here must be regarded as minimum estimates, because injured fish may experience delayed mortality over a longer period than we followed them.

4.2.5 Migration speeds

There was no difference in migration speeds among the reference stretch (mean 2.6 km h^{-1}), impounded stretch (mean 2.7 km h^{-1}) and the stretch between the power stations in Gengenbach and Offenburg (mean 2.5 km h^{-1}). However, smolt moved slower during passage of the power station area (mean 0.2 km h^{-1}). They spent on average 8.6 hours in passing the power station area (range 0.02-92 hours).

4.3 Kuhlemühle power station in the Diemel

Summary

Downstream migration was studied by tagging 112 Atlantic salmon smolt with radio transmitters. Migration was recorded on a free-flowing reference stretch (3.0 km), on an impounded stretch above the dam (1.3 km), past the power station (0.6 km) and below the power station (7.7 km) (**figure 4.6**).

Loss of smolt on the reference stretch was 2.5% per km, and on the impounded stretch 1.5% per km. Hence, loss on the impounded stretch was not elevated compared to the reference stretch.

At the power station, the largest proportion of smolt passed through the Archimedes screw turbine (43 smolt, 43%), or moved through the Francis turbines or were flushed through the nearby opening for debris (33 smolt, 33%). Further, 14 smolt (14%) used the fishway at the Archimedes screw, 8 smolt (8%) used the fishway at the Francis turbines, and 3 smolt (3%) migrated over the dam.

No immediate loss was recorded at Kuhlemühle. However, the loss of fish passing the power station area is uncertain, because of unknown fate for a proportion of the smolt after passing. A probability estimate indicated that 0-8% of the smolt that passed through the Archimedes screw suffered immediate mortality in the screw.

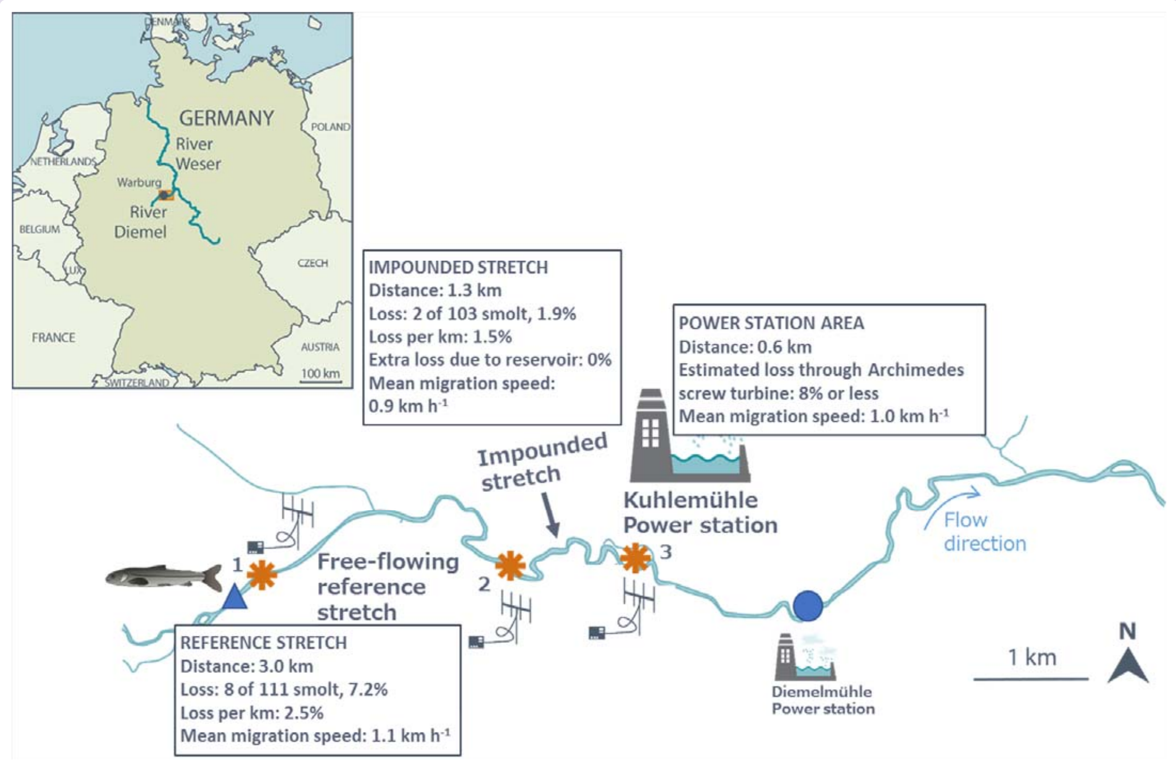


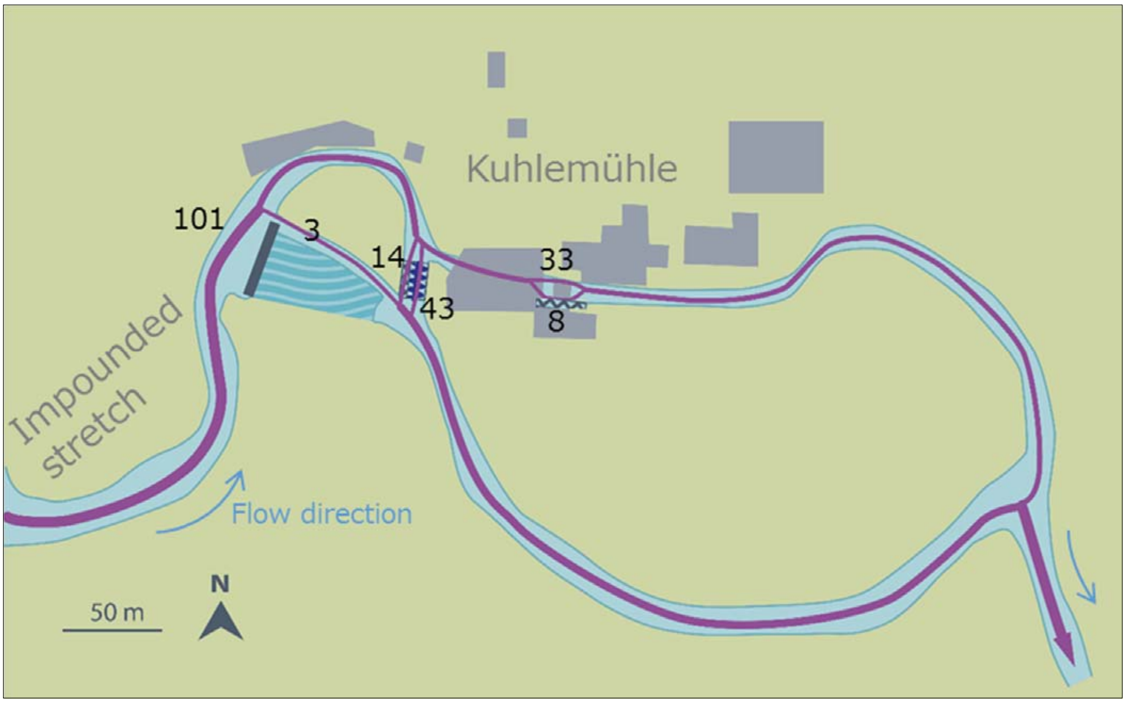
Figure 4.6. Main results for radio tagged smolt on different river stretches summarised in boxes. Blue triangle shows the release site of tagged smolt and orange stars receiver sites where passing fish were recorded. Diemelmühle power station is also shown on the map, but smolt behaviour was not monitored at this site.

4.3.1 Loss of smolt on the reference stretch and impounded stretch

Of 112 radio tagged smolt, 1 individual (0.9%) did not migrate from the release area, 8 were lost on the 3.0 km long reference stretch, and 2 were lost on the 1.3 km long impounded stretch above the dam. This corresponds to a loss of 7.2% on the reference stretch (8 of 111 smolt, 2.5% per km) and 1.9% on the impounded stretch (2 of 103 smolt, 1.5% per km). Hence, loss on the impounded stretch was not elevated compared to the reference stretch. The remaining 101 smolt passed the power station.

4.3.2 Migration routes in the power station area

Of 101 smolt that passed the power station, the largest proportion passed through the Archimedes screw turbine (43 smolt, 43%), or moved through the Francis turbines or were flushed through the nearby opening for debris (33 smolt, 33%, we cannot separate between passage through the turbines and opening for debris) (**figure 4.7**). Further, 14 smolt (14%) used the fishway at the Archimedes screw, 8 smolt (8%) used the fishway at the Francis turbines and 3 smolt (3%) migrated over the dam.



Figur 4.7. Numbers of smolt that used the different migration routes past the power station. Total number of smolt passing was 101 smolt.

4.3.3 Loss of smolt in the power station area and downstream

No immediate loss was recorded in the power station area by recording of fish signals becoming stationary in the area. Mortality was documented for eight smolt downstream of Kuhlemühle, because they became stationary in the river and remained there for the rest of the study period. Most likely, they died sometime after passing the power station, because it is not likely that a smolt dying at the power station drifted as far as these smolt moved before they settled (based on drift of 20 already dead smolt radio tagged and released in the Archimedes screw). All eight smolt became stationary downstream of

Diemelmühle, which is a power station 2.1 km downstream of Kuhlemühle. Hence, it is possible that they died due to injuries at Diemelmühle, or by a combination of injuries and stress by passing two power stations (Kuhlemühle and Diemelmühle).

For the remaining smolt passing the power station *(i.e.*, except those eight described above), no loss was documented, because they all disappeared from the manually tracked stretch (up to 8 km downstream from the power station), either without being recorded by manual tracking (58 smolt, 57%), or after they were recorded one or several times by manual tracking (35 smolt, 35%) (none were recorded with bird-like behaviour on upstream automatic receivers). Hence, all these smolt could potentially have passed the entire tracked stretch and moved further downstream. However, it is uncertain if some of them were moved out of the river by predators. Predators can potentially take both alive and dead smolt out of the river. Signals from 7 of the 20 (35%) dead smolt that were released in the Archimedes screw disappeared from the river relatively fast, indicating that there were predators in the system that moved dead fish out of the river. Four of the smolt that disappeared also showed signs of being taken by predators before they disappeared, by signal recordings indicating a bird-like behaviour. The uncertainty of what happened to the 58 smolt never recorded after passing the power station makes it difficult to provide a total loss estimate for the power station.

A probability estimate indicated that 0-8% of the smolt that passed through the Archimedes screw suffered immediate mortality in the screw. This was based on patterns of recordings of already dead smolt released in the Archimedes screw, which were used to calculate the probability of detecting mortality of smolt potentially killed when passing the screw.

4.3.4 Migration speeds

There was no difference in migration speeds among the reference stretch (mean 1.07 km h^{-1}), impounded stretch above the dam (mean 0.93 km h^{-1}) and power station area (mean 1.03 km h^{-1}). The smolt spent on average 20 hours in passing the power station area (range 0.17-293 hours), but many fish migrated faster (half of the fish spent less than half an hour in passing). The speed past the power station area differed among migration routes. The fish that passed the Archimedes screw and nearby fishway had the fastest migration speeds.

5 Archimedes screw turbines and effects on fish – a summary of international studies

The Archimedes screw turbine is often regarded as less harmful to fish than other hydropower turbines, and reported damage and loss rates are usually low (Spah 2001, VisAdvies 2007, Kibel 2007, 2008, Kibel et al. 2009a,b, Kibel & Coe 2011, Potter et al. 2012, Bracken & Lucas 2013). The reasons for being regarded as less damaging to fish are the slow rotation speed of the turbine and the absence of extreme pressures and shear forces (Potter et al. 2012). The water travels in blocks at a slow speed down the screw, with enough space to hold fish.

Mechanical impacts on fish travelling through the Archimedes screw turbine may be direct strikes from the leading edge of the blades, grinding effects if fish are caught between moving and stationary parts of the turbine, and abrasions against the sides or other parts of the turbine, resulting in scale and mucous loss (Kibel 2007, 2008, Kibel et al. 2009a,b, Kibel & Coe 2011, Potter et al. 2012, Bracken & Lucas 2013). There is low risk of immediate mortality for fish travelling through the turbine according to the few studies done, but injuries like described above can lead to delayed mortality (Potter et al. 2012). The probability of the turbine blade striking the fish increases with increasing number of turbine blades, rotational speed and fish size (Kibel & Coe 2011, Potter et al. 2012). If fish decrease the entry speed into the turbine, for instance due to trying to swim against the current, this may also increase the probability of turbine blade striking (Potter et al. 2011).

Figure 6.1. The Archimedes screw turbine at Kuhlemühle in the Diemel.

Archimedes screw turbines may differ in characteristics such as length, number of blades, speed, size of openings between different parts of the turbine and shape of the front of the blades. Such differences may affect the extent of injuries to fish. Impact of Archimedes screw turbine on fish will therefore to a certain extent be site specific.
Photo by Eva B. Thorstad.

There is generally little knowledge on the effects of Archimedes screw turbines on fish, and there is particularly an absence of scientifically evaluated knowledge. We are aware of only one publication on effects of Archimedes screw turbines in an international scientific journal, which is on lamprey larvae (Bracken & Lucas 2013). Except for this publication, the existing knowledge is based on a few reports from studies by a consultancy company in England (Kibel 2007, 2008, Kibel et al. 2009a,b, Kibel & Coe 2011), and two reports from German and Dutch studies (Spah 2001, VisAdvies 2007). Only one of these reports is on smolt (Kibel 2007). These reports belong to the so-called “grey literature”. Grey literature usually does not have an independent peer review quality control, unlike publications in scientific journals, which are evaluated by independent scientists and editors.

Scientists from Centre for Environment, Fisheries and Aquaculture (CEFAS) in England have made an evaluation of known and possible effects by Archimedes screw turbines on Atlantic salmon and sea trout smolts based on the existing reports and general scientific knowledge on salmonids (Potter et al. 2012). They concluded that the most likely damage to fish from passage through Archimedes screw turbines are mechanical injuries, in particular blade striking and grinding. They refer to the one study on smolts, which indicated that 1-3% of the smolts suffered from mechanical injury, with individual fish showing up to 10% scale loss (Kibel 2007). Damage to fish mucous after passing the turbines have not been studied (Potter et al. 2012).

The scientists from CEFAS particularly pointed out that the potential for damage of Atlantic salmon smolts at some sites may be higher than previously reported, and that more work is required to evaluate effects by Archimedes screw turbines on Atlantic salmon smolt and other fishes (Potter et al. 2012). They particularly pointed out the risk of scale and mucous loss and longer term effects. There is also concern about the effects of multiple power stations within the same catchment. The effects can be estimated by adding or multiplying impacts from individual hydropower facilities, but this does not take into account possible cumulative effects of damage or delays (Potter et al. 2012).

Our results, estimating that less than 8% of the tagged smolt passing the Archimedes screw turbine in Kuhlemühle suffered direct mortality, comply with the low mortality recorded in other studies. The extent of scale loss and other injuries possibly causing delayed mortality for smolt passing this turbine, is not known.

Figure 6.2. The upper part of the Archimedes screw turbine at Kuhlemühle in the Diemel. Photo by Eva B. Thorstad.

6 Overall results and conclusions

6.1 Loss of smolt at the power stations

The loss of downstream migrating smolt due to the hydropower station was minimum 12.8% at Unkelmühle (Sieg) and 3.1-6.3% at the power station in Gengenbach (Kinzig) during our study in 2015 (**table 6.1**). For both sites (**figure 6.1, 6.2**), this represents the percentage of smolt entering the power station area that were lost due to this being a hydropower station instead of a free-flowing river. For Kuhlemühle (Diemel), a probability estimate indicated that 0-8% of the smolt that passed through the Archimedes screw suffered immediate mortality in the screw (**table 6.1**).

These loss estimates must be regarded as minimum estimates, because injured fish can experience delayed mortality at later stages than recorded in this study. Hence, total smolt loss due to the power station may have been higher than recorded. Another reason for a possible underestimation of the loss in Unkelmühle and Gengenbach is that we compared loss on the regulated river stretches with the loss on upstream reference stretches, assuming that the loss recorded per km on the reference stretches is representative for the developed stretches if it had been a free-flowing river. However, there might have been selective mortality in the reference stretches and impounded stretches above the dams, with the weakest individuals already been lost and the fittest individuals remaining. Therefore, the mortality on the stretch at the power station and on stretches further downstream, if unaffected by hydropower regulation, might have been lower than the loss recorded on the reference stretch that we used for comparison.

Table 6.1. Overview of results. Loss of downstream migrating smolt due to hydropower development is calculated by comparing loss on the reference stretch with loss on the impounded stretch above the dam and past the power station area, except for the Diemel, where a probability estimate only for instantaneous loss in the Archimedes screw is given. Loss due to hydropower development on the impounded stretch is given as percentage of those entering the impounded stretch. Loss due to the power station area is given as percentage of those entering the power station area. All losses are minimum estimates, because it is possible that injured fish can survive the monitored stretches, but experience delayed mortality at later stages.

River	**Power station**	**Year**	**Loss on reference stretch** (per km)	**Loss on impounded stretch** (per km)	**Loss due to hydropower development on impounded stretch**	**Loss due to hydropower development related to power station area**
Sieg	Unkelmühle	2014	1.5%	4.8%	7.2%	Not known[1]
Sieg	Unkelmühle	2015	1.6%	9.6%	17.1%	12.8%
Kinzig	Gengenbach	2015	0.7%	1.9%	1.5%	3.1-6.3%
Diemel	Kuhlemühle	2015	2.5%	1.5%	0%	8% or less (for the Archimedes screw turbine)

[1]No recording downstream possible for technical reasons. An incomplete estimate, based on loss of smolt recorded within the detection range of antennas installed at the power station only is given in chapter 4.1.4.

Figure 6.1. Unkelmühle power station in the Sieg. Photo: Eva B. Thorstad.

Figure 6.2. Dam and power station in Gengenbach, Kinzig. Photo: Eva B. Thorstad.

The causes for mortality at the power stations seemed to be physical injuries when passing and increased predation rates, but exact causes could not be determined in all cases. Results showed that fish mortality at a power station may not necessarily result in the transmitter becoming stationary at the power station, because dead smolt released at the power stations moved up to 2.4 km downstream before the radio transmitter settled and became stationary in the river. Results from releases of dead smolt also showed that dead fish to a large extent were taken out of the river by predators. This means that for a smolt released alive, but that showed bird-like behaviour after passing the power station, it is difficult to know whether it was already dead from injuries at the power station when taken by the bird predator, or if it was injured and weakened and therefore taken by the predator. Predation rates might be increased below power stations, also for non-injured fish, because these may be areas attracting predators because of the occurrence of injured and dead fish below the power station (Koed et al. 2002).

At Unkelmühle, there was no turbine mortality, because none of the smolt passed through the bar racks in front of the turbines, likely due to the narrow bar spacing of the racks. Hence, the extra loss of smolt passing Unkelmühle power station was likely related to physical injuries in bypass routes aimed at guiding smolt outside the turbines causing mortality, and increased predation. For the smolt lost at the movable turbine in Gengenbach, we do not know if they passed through, under or above the turbine.

Mortality rates in power station areas may vary among years, which was demonstrated by results from Unkelmühle, where a pilot study was conducted in 2014. The mortality in the bypass route was larger in 2014 than in 2015. This bypass route leads the smolt outside the turbines via custom-made openings in the racks in front of the turbines. The higher mortality in 2014 was likely because some smolt became trapped and died in the bypass route where debris and branches were piling up in 2014, but not in 2015. It should be noted that the overall loss recorded at Unkelmühle in 2014 was lower than in 2015 (**table 6.1**), but estimates for 2014 are underestimates compared to 2015, because fish were not followed downstream of the power station in 2014 (see chapter 4.1.4).

It should be noted that effects of the three different types of hydropower stations were studied in three different rivers, and a direct comparison of the results between the different types of power stations should be done with caution. River specific effects caused by for instance different water flows, water quality, presence of predators and other environmental conditions may affect mortality differently at technically similar hydropower stations.

6.2 Loss of smolt on impounded stretches above dams

Results in this study have shown that reservoirs upstream of power stations can be areas of high mortality for downstream migrating smolt (**table 6.1**). In Unkelmühle in 2015, the loss due to the reservoir was even larger than the loss caused by the power station.

Of smolt entering the reservoir upstream of Unkelmühle (**figure 6.3**), 7.2% (2014) and 17.1% (2015) were lost due to this being a reservoir instead of a free-flowing river. This was a much higher loss than upstream of the power station in Gengenbach (1.5% extra loss, **figure 6.4**) and Kuhlemühle (no extra loss), probably because these are not true reservoirs, but only short stretches with slightly slowed down water velocity. The reason for the larger loss in the reservoir at Unkelmühle is likely that this is the largest reservoir of the three sites, being 2.3 km long, with slow-flowing water and more resembling a lake than a river.

The main reason for extra loss in reservoirs compared to the reference stretches is likely predation due to presence of more fish predators in the slow-flowing reservoirs. Results from Unkelmühle indicated that there was more predation by fish than birds in the reservoir, and more predation by birds at the power station and on the stretches downstream of the power station.

Results in this study showed that reservoir mortality may vary among years, since the extra smolt loss in the reservoir upstream of Unkelmühle was considerably larger in 2015 than in 2014. Smolt migrated faster through the reservoir in 2015 than in 2014, so a longer time spent in the reservoir cannot be the explanation for a larger loss in 2015. Further, a difference in smolt size or quality did not seem to explain the different loss rates between the two years. It is possible that the predator community in the reservoir during the smolt migration varies among years, and that variation in for instance number, size and species composition of predators among years affected the proportion of smolt lost.

Figure 6.3. Lower part of reservoir upstream of Unkelmühle in the Sieg. Photo: Eva B. Thorstad.

Figure 6.4. Lower part of the impounded river stretch above the dam at the power station in Gengenbach in the Kinzig. Photo: Eva B. Thorstad.

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Norwegian Institute for Nature Research
NINA head office
Postal address: P.O. Box 5685 Sluppen, NO-7485 Trondheim, NORWAY
Visiting address: Høgskoleringen 9, 7034 Trondheim
Phone: +47 73 80 14 00
E-mail: firmapost@nina.no
Organization Number: 9500 37 687
http://www.nina.no

University of Cologne
Biozentrum, Institute of Zoology
Allgemeine Ökologie und Limnologie
Zülpicher Straße 47b
D-50674 Köln
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