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Downstream migration of European eel at three German hydropower stations

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

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Norwegian Institute for Nature Research

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Downstream migration of European eel at three German hydropower stations

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European silver eel. Photo by Eva B. Thorstad.

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Summary

Økland, F., Teichert, M.A.K., Havn, T.B., Thorstad, E.B., Heermann, L., Sæther, S.A., Tambets, M. & Borcherding, J. 2017. Downstream migration of European eel at three German power stations. NINA Report 1355: 53 pages, including appendix.

Background and methods
The aim of this study was to examine migration behaviour and losses of European silver eel when passing 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. 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. Narrowly spaced bar racks have been installed in front of the turbine intakes at both Unkelmühle, River Sieg (10 mm), and Gengenbach, River Kinzig (15 mm), to prevent fish from entering the turbines. At the Kuhlemühle power station, River Diemel, an Archimedes screw turbine is installed without a bar rack in front of its entrance. Archimedes screws are regarded as being fish-friendly turbines, but few studies have tested this assumption.

The study was performed during 2014 to 2016 by tagging 542 European silver eels with radio transmitters. Their migration in the river and past the power stations was recorded.

Results and conclusions
Overall, we recorded low mortality for downstream migrating silver eels at these power stations. However, there are uncertainties linked to the survival estimates, particularly at Gengenbach and Kuhlemühle.

The mortality of eels when they passed the Unkelmühle power station was 0-4% and 0-8% in the two consecutive study years. This shows that it is possible to obtain low mortalities for downstream migrating eels at run-of-the-river power stations with special protection measures to facilitate migration and reduce mortality. No direct turbine mortality occurred, as no eel slipped through the bar racks in front of the turbines, as expected due to the narrow bar spacing.

The reason that we give mortality estimates as a range (0-4% and 0-8%), is that the fate of some tagged eels after passing the Unkelmühle power station is unknown, which makes it difficult to determine if they were alive or dead after passing. Further, three individuals showed movements indicating that they were taken by birds, but it is not known whether they were dead at the power station and taken by bird predators, injured by passing the power station and therefore taken by predators, or whether they were uninjured but taken by predators anyway. The estimates given as ranges take this uncertainty into account, and imply that the mortality at the Unkelmühle power station could have been zero in both study years, but the mortality could also have been up to 4% in the first study year and up to 8% in the second year.

If there was some mortality linked to passing Unkelmühle power station, this must have been due to injuries occurring in the bypass routes, or increased predation at the power station area. Increased predation may occur if fish are injured and thereby easier prey. It is also possible that presence of injured fish of different species at power stations attracts

predators, such that the likelihood of being taken by a predator increases also for uninjured fish.

None of the tagged eels became stationary at the power station, indicative of being dead, neither at Gengenbach or Kuhlemühle. However, there are uncertainties for the survival estimates at these power stations, because eels may drift downstream after they are dead. Release of tagged dead eels showed that eels that potentially died when passing Gengenbach or Kuhlemühle could have drifted several kilometers and out of the monitored area below the power stations. Hence, mortality at the power station is in such cases not necessarily detected. The survival estimates at Unkelmühle were more certain, because the fish were tracked over a longer distance below the power station, and implicitly there were fewer individuals with an uncertain fate. Some eels became stationary on river stretches below Gengenbach and Kuhlemühle power stations, and might be dead (14% and 23% of the eels that passed the Gengenbach and Kuhlemühle, respectively). However, eels may cease migration and migrate downstream another year, so an eel becoming stationary may not necessarily be dead.

Eels mainly used migration routes with a large proportion of the water flow when passing the power stations. At Unkelmühle, most of the downstream migrating eels used the spillway gate, or the bypass route leading fish from the bar racks in front of the turbines into the flushing channel and back to the river via a route outside the turbines. Only two eels used the custom-made side bypasses for eels, and only a small proportion of the eels (<10%) used the custom-made bottom bypass at Unkelmühle.

At Gengenbach, the largest proportion of eels passed through the section where the moveable turbine was installed, and at Kuhlemühle, the largest proportion passed through the Archimedes screw turbine. A potential negative effect by Archimedes screw turbines may be migration delays. However, most eels migrated fast through the Archimedes screw turbine, and did not hesitate or stop the migration either upstream or downstream of the turbine. In fact, eels migrating through the Archimedes screw turbine or over the dam passed the power station area faster than eels using the other routes. Hence, eels were not markedly delayed in their downstream migration by using the Archimedes screw. However, there was large individual variation, and some individuals spent a long time in passing the power station.

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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 governmental period 2012 to 2017. In contrast to for instance solar energy, for which limited impact on the environment is usually expected during operation, 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 innogy SE 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 European silver eel. 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. A previous report summarised studies of downstream migrating Atlantic salmon smolts at the same three sites (Økland et al. 2016).

We would like to thank Leon Barthel, Matthias Fleckhammer, Michael Kohlschein, Toni Kröber, Laura Mehner, Nico Menge, Andreas Pilgram, Stefan Scheffels, Stefan Staas, Anna Stiller and Stephan Wagner and for help during the fieldwork. Further, we thank Innogy SE, E-Werke Mittelbaden and Hydroenergie Roth and Warburger Brauerei Kohlschein for the possibility to perform the studies at their power stations (Unkelmühle, Gengenbach and Kuhlemühle power stations, respectively). We would also like to thank Freiburg regional council, Herbrand Pharma Chemicals GmbH, Dirk Krumpiepe, Warburg city council, Rolf Stommel and Heiko Weiser for providing safe locations for receiver stations. Thanks to Richard D. Hedger (NINA) for help with data analyses and Kari Siversten (NINA) for help with graphic design of figures in the report.

October 2017

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1 Introduction

The abundance of European eel has seriously declined throughout the distribution area during recent decades (ICES 2016). A number of causes have been suggested, including migration barriers, habitat loss, hydropower mortality, parasites, virus infections, contaminants, changes in ocean currents, climate change and overfishing. Several of these factors have likely contributed to the decline. The annual recruitment of glass eel from the Sargasso Sea to European waters in 2016 remained low, at 3-11% of the 1960-1979 level in the monitoring data series (ICES 2016). Due to this population decline, European eel has been included as critically endangered in the IUCN Red List of threatened species (International Union for the Conservation of Nature and Natural Resources).

In 2007, European Union legislation was imposed to address the decline in the European eel (Council Regulation EC No 1100/2007). Member states had to prepare and implement Eel Management Plans for individual river basin districts. The objective of each management plan is to reduce anthropogenic mortalities to enable the escapement of at least 40% of the silver eel biomass that would have existed in the absence of anthropogenic impacts. According to the regulation, management plans should include measures to attain this objective, which could include reducing fishing mortality and mortality caused by factors such as hydroelectric turbines, pumps and predators.

Hydropower stations, dams, weirs and other barriers can cause migration delays and elevated mortality for downstream migrating eels (*e.g.*, Doherty & McCarthy 1997, Larinier & Travade 2002, Calles et al. 2010). 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, Calles et al. 2010). Increased mortality rate at power stations is not only determined by immediate and delayed mortality of fish passing through the turbines, but depends also on factors such as predation, the proportion of fish passing through the turbines, and the mortality of fish using alternative passages around power stations. Alternative passages may for instance be spillways, purpose-built bypasses and old river beds. There are few published studies of detailed migration patterns of European eel at power stations during downstream migration.

The aim of this study was to examine migration routes, behaviour and mortality of European eel 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 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, complying with the North Rhine-Westphalian design criterions for power stations in salmon (maximum opening 10 mm) and eel (maximum opening 15 mm) target waters. 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. The Kinzig is a target water for eel and salmon, and according to the local legislation in Baden-Württemberg, bar rack spacing in front of the turbine is slightly wider at Gengenbach (15 mm) compared to Unkelmühle. 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 conducted (Potter et al. 2012, Økland et al. 2016). The behaviour of downstream migrating silver eel related to the specific measures at these power stations were recorded.

The study was performed by tagging 542 European silver eels with radio transmitters and recording their downstream migration when passing these three power stations by automatic receivers and manual tracking. This report aims at informing the interested public on the main results, and therefore details are not included. Scientific publications with more detailed results will follow later.

European eel

European eel *Anguilla anguilla* are believed to spawn in the Sargasso Sea, but undertake long migrations and spend most of their life in fresh, brackish and coastal waters in Europe and North Africa, including the Mediterranean and Black Sea coasts of Africa and Asia (**figure 1.1**).

After hatching in the Sargasso Sea, the pelagic willow-leaf shaped leptocephali larvae drift and move actively towards the European coasts. They metamorphose into few centimeters long unpigmented glass eel when they reach the continental shelf waters. Those entering rivers enter as glass eels, or they may have developed further into pigmented yellow eel when they enter the rivers.

The yellow eel stage is the growth stage, which may last for up to 20 years or longer. The largest individuals reach body lengths of more than one meter. The European eel is a facultative catadromous species, which means that some individuals enter freshwater during the yellow eel stage, whereas some individuals remain in the marine environment along the coasts and never enter freshwater. Females grow larger and older than males.

Individuals metamorphose from yellow eel to silver eel prior to the return migration to the ocean spawning areas. Silvering is a gradual process involving morphological and physiological changes such as increased eye size and pectoral fin length, silvery body colour, increased fat content, regression of the alimentary tract as they cease feeding and some proliferation of the gonads. Little is known on the ocean spawning migration and spawning, and adult eels have never been recorded in the Sargasso Sea - only early larvae stages. Adults are believed to die after spawning.

Figure 1.1. Life cycle of European eel and photos of a silver eel (upper right) and young yellow eels (lower 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 Swiss-German and French-German borders, flows through Germany and empties into the North Sea in the Netherlands. It is 1233 km long – most of which runs through Germany – and has a mean discharge of 2280 m^{3}s^{-1} at the German-Dutch border.

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 approximately 360 river kilometers from the sea, is 53 m^{3}s^{-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^{3}s^{-1}. In the middle and lower part, the Kinzig is heavily channelized.

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 an average water discharge of 327 m^3s^{-1}.

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 eels captured by local fishers in the Rhine and the Mosel. Photos from the Mosel by Eva B. Thorstad.

Figure 2.2. The eels were tagged with small radio transmitters (dimensions 9 x 30 mm; mass in air 4.3 g). Photos by Eva B. Thorstad.

Figure 2.3. The eels were anaesthetised before tagging (approximately 5 min in a bath with metomidate and water). The tag was inserted into the body cavity during a surgical procedure lasting a few minutes (further described by Økland & Thorstad 2013, Thorstad et al. 2013). The incision was closed with sutures. Photos by Eva B. Thorstad.

Figure 2.4. After tagging, the eels were transferred to a bin with water, where they recovered and could swim normally after a few minutes. Photo by Eva B. Thorstad.

Figure 2.5. Radio tagged eels were transported in 600 L tanks to the release sites. They were released in the rivers 4.6-10.1 km upstream of the studied power stations.

In each river, downstream migration of tagged fish was recorded 1) on an free-flowing reference stretch upstream of the power station, 2) on the impounded stretch upstream of the power station dam, 3) past the power station, and 4) on a river stretch below the power station. Photos by Eva B. Thorstad.

Figure 2.6. Downstream migration of tagged fish was studied by using stationary receivers, which automatically stored information on time and identity of tagged fish when they were within the detection range of receiver antennas. Photos from the Sieg 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 Stein Are Sæther and Eva B. Thorstad.

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. For fish eaten by fish predators or that died for other reasons, the transmitter will remain in the river. In these cases, the transmitter may become stationary on the bottom, or it may remain for some time within the fish predator, which move around in the river. 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 eels showed clear signs of being taken by bird predators based on bird-like movements, such as for instance fast upstream movements past power stations and receiver stations. Photo from the Sieg by Eva B. Thorstad.

Figure 2.10. Eels may cease migration and become stationary in the river for one or several years after tagging, even though they were regarded as being at the migrating silver eel stage when they were tagged. Hence, an eel becoming stationary is not necessarily dead, but can be alive and migrate downstream towards the ocean in a later year. For this reason, we did not estimate mortality rates of eels on the impounded stretch or on other stretches above the power station. Photo by Eva B. Thorstad.

Figure 2.11. To help distinguishing between live downstream moving fish and dead drifting fish, some dead eels were radio tagged and released in or immediately downstream of the turbines in all study rivers. The maximum distance dead eels drifted downstream was 21 km in the Sieg and 5 km in the Diemel, whereas dead eels in the Kinzig drifted more than 30 km downstream. The results also showed that dead fish can be moved upstream or be taken out of the river by scavengers. Photo by Eva B. Thorstad.

Table 2.1. Overview of tagged and released eels.

River	**Year**	**Release dates**	**Number of fish**	**Fish size** (min-max length)	**Fish origin**
Sieg	2014	8 Oct. - 14 Nov.	136	60-108 cm	Captured in the Mosel and the Rhine
Sieg	2015	10-13 Oct.	134	66-101 cm	Captured in the Rhine
Kinzig	2015	8-12 Oct.	136	65-101 cm	Captured in the Rhine
Diemel	2014	5-22 Oct.	136	60-114 cm	Captured in the Mosel and the Rhine

3 Description of the power stations

3.1 Unkelmühle power station in the Sieg

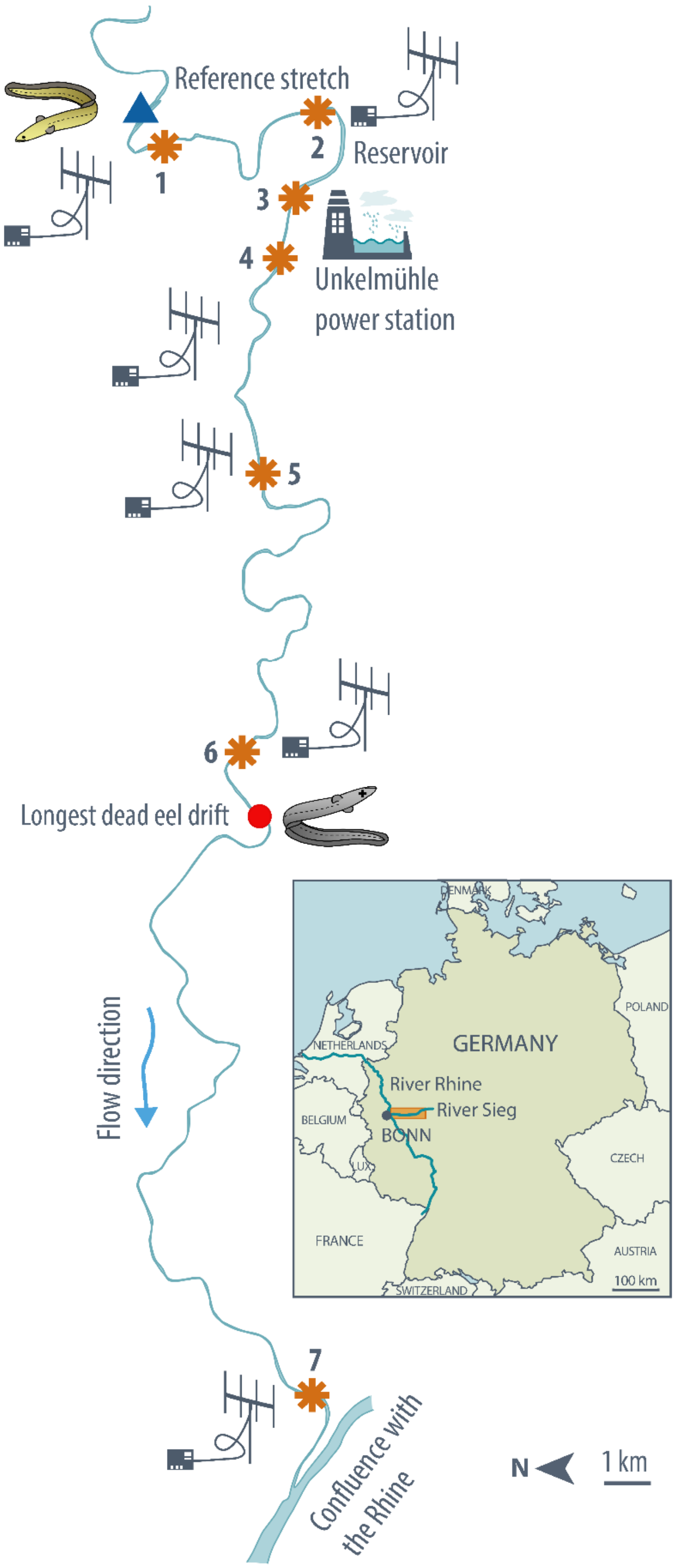

Figure 3.1. Study area in the Sieg showing the release site for radio tagged European eels (blue triangle) and receiver sites where they were recorded when passing (orange stars, denoted with site numbers 1-7). The Unkelmühle power station is situated at site 3. The receivers at site 6 and 7 were installed before the fish were tagged in 2015, so fish tagged in 2014 were not recorded at these sites. The longest drift of radio tagged dead eels released at the power station is also shown. Distance downstream from the release site was 1.6 km for site 1, 7.3 km for site 2, 9.7 km for site 3, 11.7 km for site 4, 17.3 km for site 5, 38.8 km for site 6 and 51.3 km for site 7.

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 meters above sea level, 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.

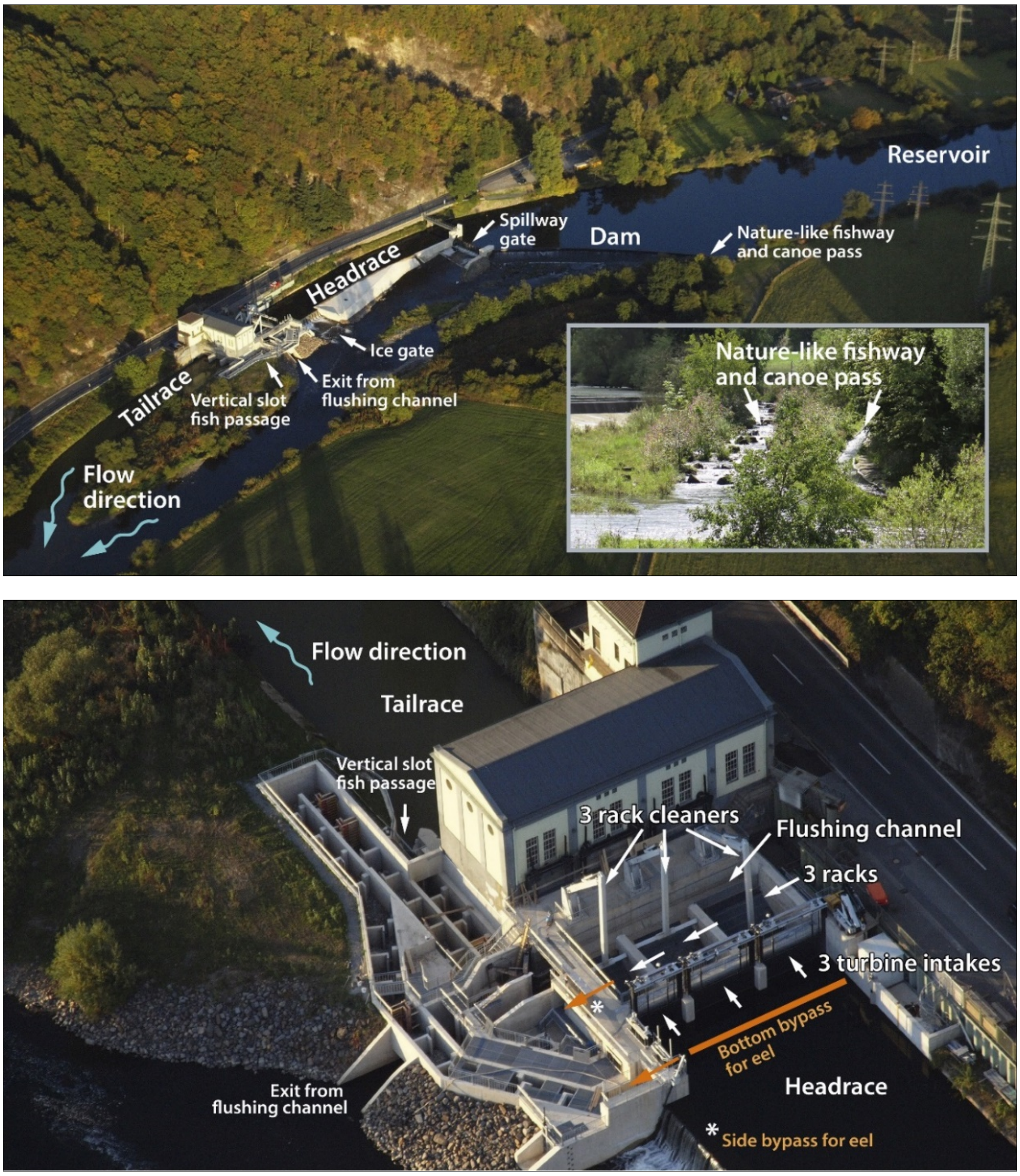

Figure 3.2. Unkelmühle power station with the different passages where downstream migrating fish can pass. The upper panel shows an overview of the power station area, and the lower panel shows the power station in more detail. The different migration routes past the power station are further described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

Ten migration routes can be used by downstream migrating fish past the power station (**figures 3.2-3.6**). 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. The spillway gate was frequently open during the study period, except in periods with low water discharge. The ice gate was occasionally opened during the winter, mainly during large floods (ice gate discharge capacity is approximately 30 m^3s^{-1}).

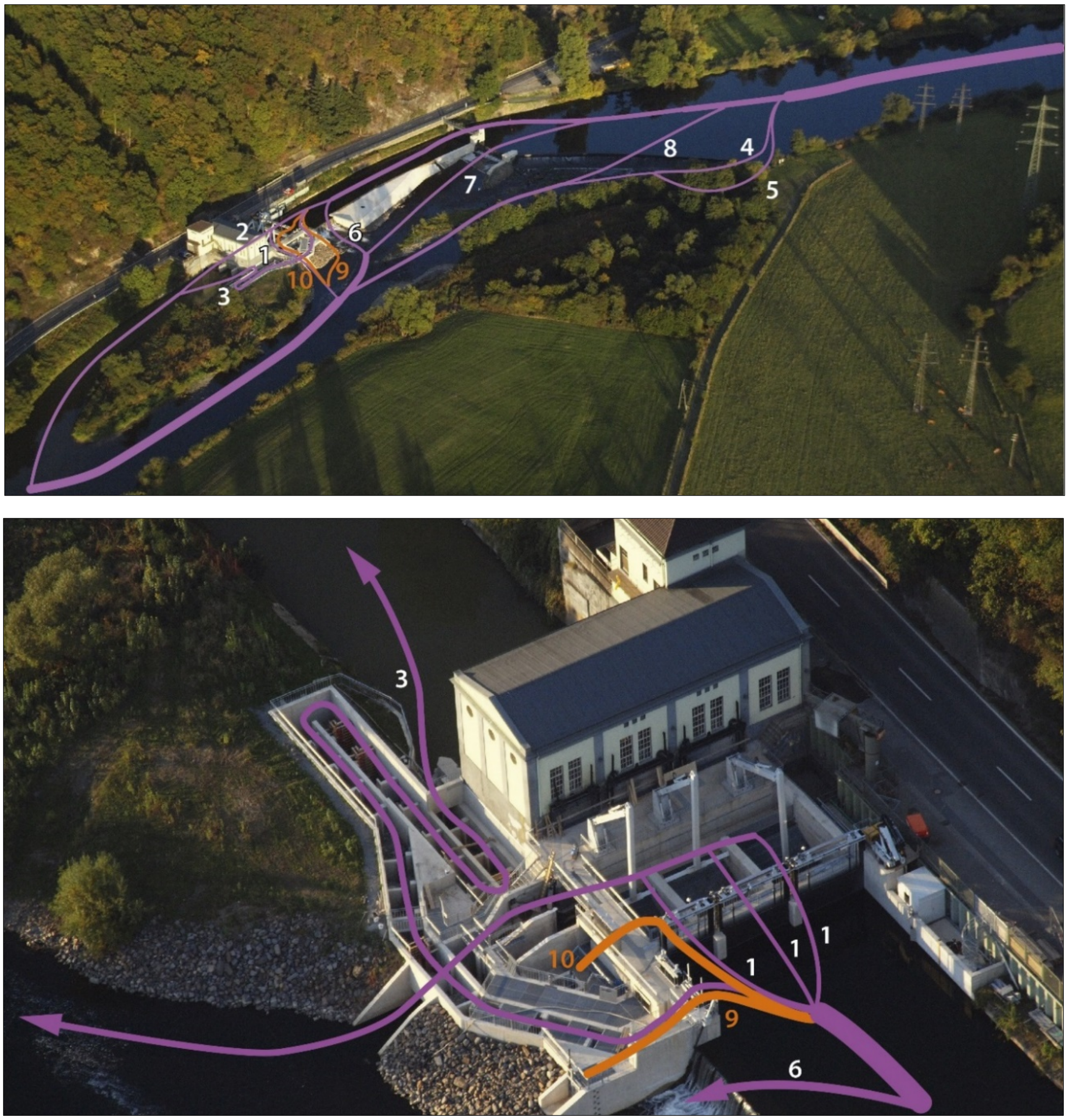

Figure 3.3. The different routes downstream migrating fish can use to pass the Unkelmühle power station: 1) via custom-made openings in the racks that leads fish to a route outside the turbines via the flushing channel, 2) through turbines if they slip through the bar spacing of the racks, 3) through 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, which was 12 August - 17 December 2014 and 24 August - 15 December 2015). 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 fish to bypass the turbines via the flushing channel (**figure 3.3, 3.4**). Fish could move from the flushing channel and be guided back to the river outside the turbines via the same channel as debris were flushed out when the rack cleaners were in operation. In periods during the Atlantic salmon smolt run in the spring, fish were guided to holding tanks where they were collected for monitoring purposes. The position of a movable valve determined if the fish were guided back to the river or to the holding tanks.

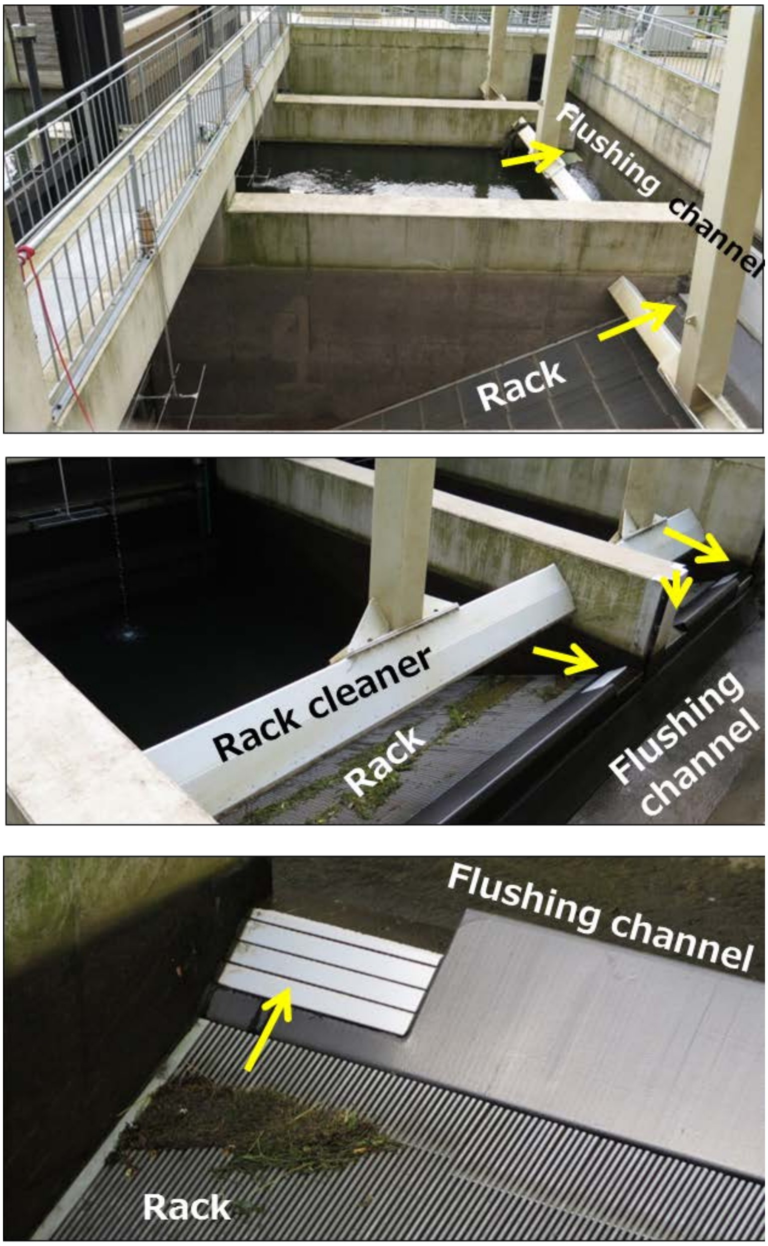

Figure 3.4. Details from the turbine intake at the Unkelmühle power station.

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 enter the flushing channel can follow a migration route past the power station outside the turbines (shown in **figure 3.3**) continuously when the water discharge exceed the capacity of the turbines (27 m^3s^{-1}), but only when the rack cleaners are operating at lower water discharges. However, this migration route is always available during the smolt run period in the spring, regardless of water discharge. When the turbines were operating during this study, the water level covered the racks, openings and flushing channel. However, 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

In autumn, fish could move from the flushing channel when the water discharge exceed the capacity of the turbines (27 m^3s^{-1}), but only when the rack cleaners were in operation at lower water discharges. In spring, they could move freely from the flushing channel at all times. When the rack cleaners were in operation, fish could also pass over the racks between the surface openings and into the flushing channel. The frequency of rack cleaner operation depends on amount of debris. During periods of high water discharge and increased debris transport, the rack cleaners are continuously operating.

Eels can also pass the power station via custom made side bypasses for eel. These consist of three 20 cm diameter holes in the sidewall at the turbine intake, situated about 0.3, 2.0 and 3.2 m below the water surface (near the exit for the bottom bypass for eels **figure 3.2, 3.3** and **3.5**). They were connected to holding tanks for eels at the other side of the wall by 20 cm diameter tubes. Eels using the side passes were supposed to be captured in the holding tanks and moved manually back into the river in a safe site below the turbines.

The bottom bypass (BOTTOM GALLERY ®) is another custom made bypass solution for eels installed at this power station, which attempts to collect eels that may have reached the racks in front of the turbines, but decide to turn around and try to escape upstream again against the current, following the bottom (**figure 3.6**). Eels exhibiting this behaviour are supposed to swim into a sill-like structure constructed across the bottom of the head race (6.8 m from the bottom end of the racks in front of the turbines), and if they hide in it, they will be captured when the trap door is automatically closed. The sill is connected to a bypass pipe at the side, which leads eels into a holding chamber. From the holding chamber they can be manually moved and released at a safe site in the river below the turbines. In 2014, the bottom gallery was operated 24 hours per day. For a 20-min period the gallery was open and eels could swim into it and be captured, then the gallery openings closed for 10 minutes, after which the cycle was repeated. The bypass pipe from the bottom gallery that enabled eels to swim into the holding chamber was open at all times.

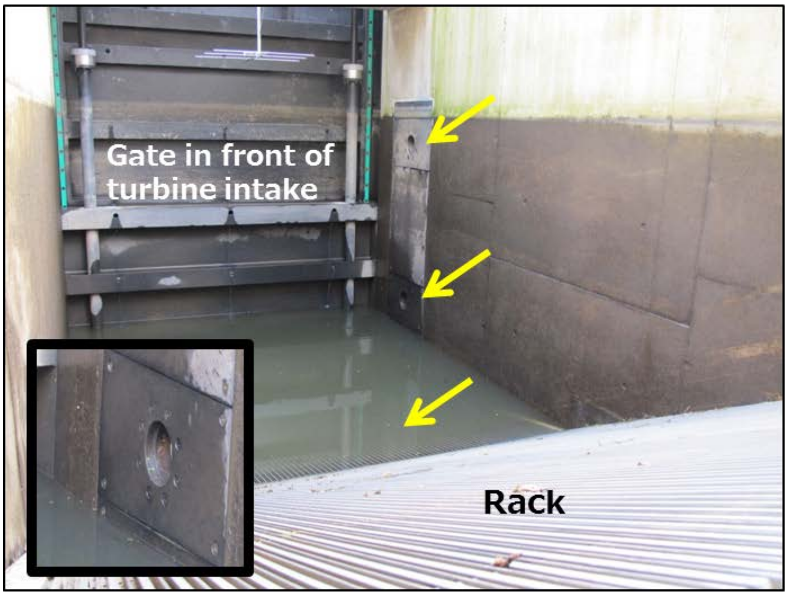

Figure 3.5. Left panel: Side bypasses for eel at Unkelmühle power station, which are three holes (indicated by yellow arrows) in the concrete wall at one of the turbine intakes. When the photo was taken, the turbine was not running and the gate in front of the turbine intake was closed. When the turbine is running, the gate is open and the intake including the rack and the holes, are covered by water. Inserted photo to the left shows close-up of one of the holes. Right: Holding tanks where eel enter and are collected if they use the side bypasses (one tank for each of the three holes). The holding tanks are placed where there is an asterisk in **figure 3.2**. Photos: Finn Økland.

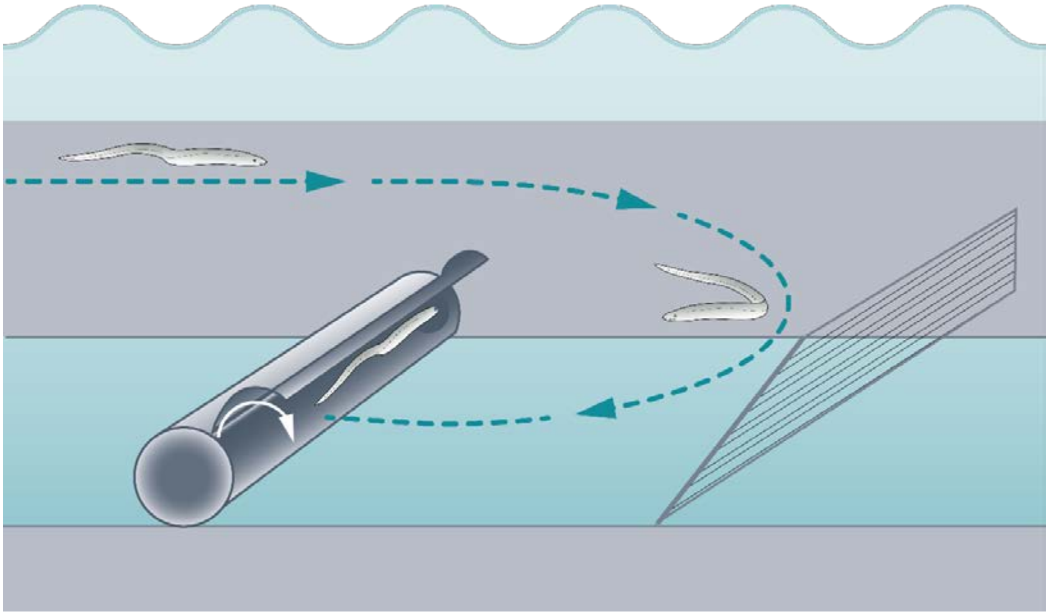

Figure 3.6. The bottom bypass (BOTTOM GALLERY ®) for eel, which attempts to collect eels that may have reached the racks in front of the turbines, but decide to turn around and try to escape upstream again along the bottom. Eels exhibiting this behaviour will swim into the bottom bypass construction, and if they hide in it, they will be captured when the trap door is automatically closed. The sill is connected to a bypass pipe, which leads eels into a holding chamber (not shown in the figure) from where they can be manually moved and released downstream of the turbine intakes.

Detailed behaviour of radio tagged fish at the power station was recorded by using multiple antenna data loggers (total of 5 data loggers and 18 antennas, **figure 3.7**). Antennas had reception ranges covering different areas, enabling identification of the migration routes and speeds of individual fish.

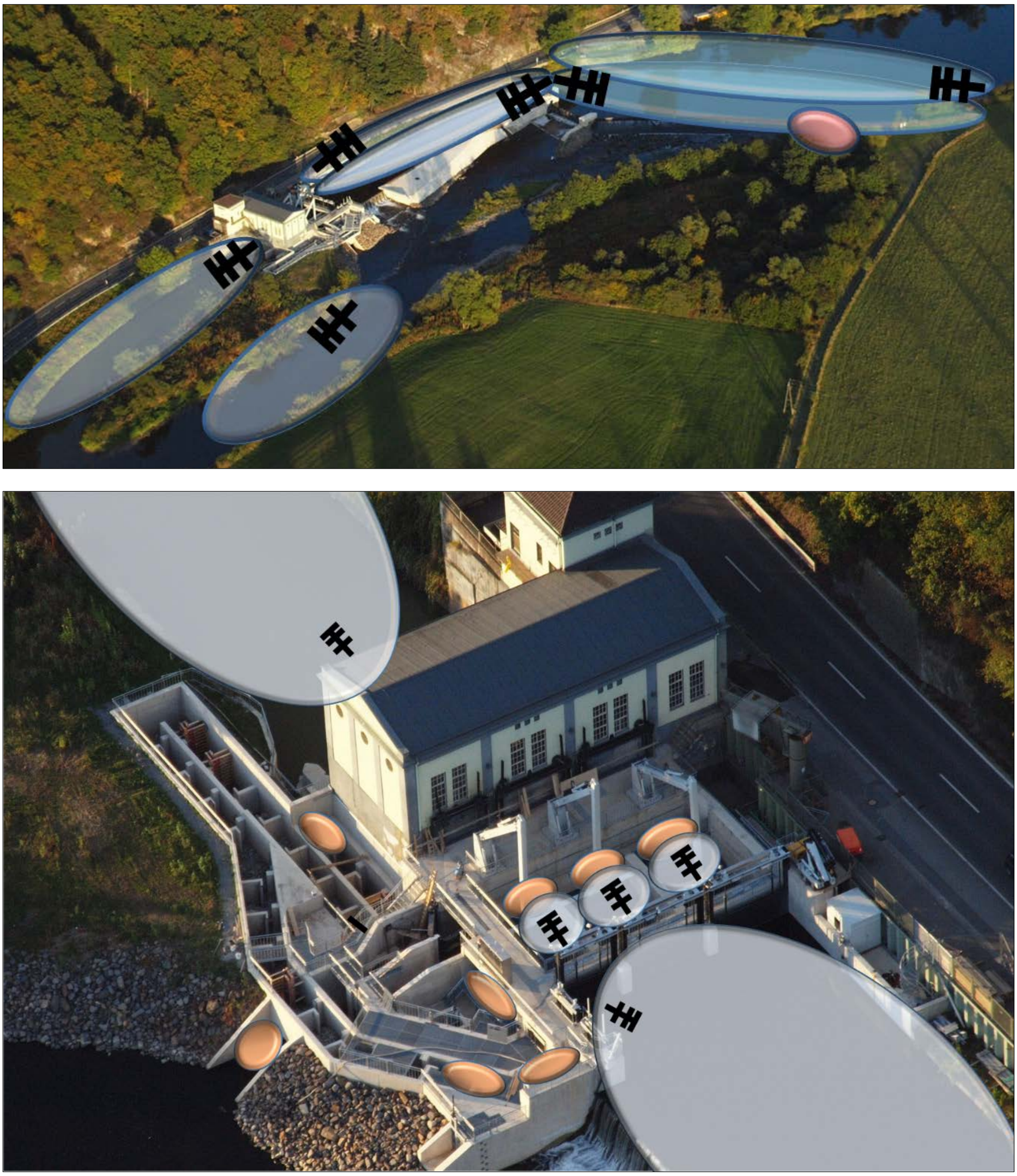

Figure 3.7. Overview of radio antennas and their approximate detection ranges used to record signals from radio tagged eels at Unkelmühle power station in 2014 and 2015. Approximate detection ranges for aerial Yagi antennas are shown with blue bubbles and co-axial underwater antennas with pink bubbles. **Upper panel:** Overview of the power station area. **Lower panel:** Power station area in more detail. Photos: Wikimedia Commons.

3.2 Gengenbach power station in the Kinzig

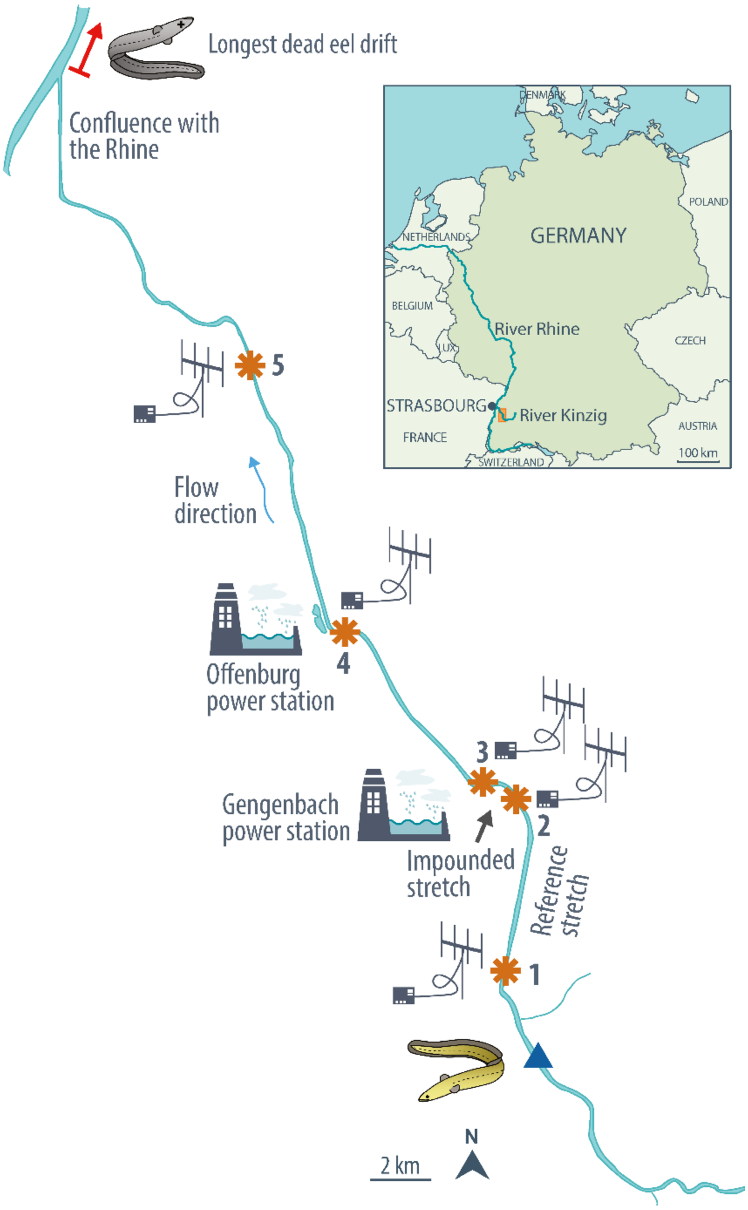

Figure 3.8. Study area in the Kinzig showing the release site of European eels tagged with radio transmitters (blue triangle), receiver sites where they were recorded when passing (orange stars, denoted with site numbers 1-5) and the power station in Gengenbach at site 3. The receiver at site 4 was installed immediately upstream of the power station at Offenburg. Some radio tagged dead eels released at the power station drifted past the confluence with the Rhine (red arrow). Distance downstream from the release site was 1.7 km for site 1, 8.9 km for site 2, 10.2 km for site 3, 17.7 km for site 4 and 26.3 km for site 5.

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 3.8, 3.9**). A movable Kaplan bulb turbine (maximum capacity of 20 m^3s^{-1}, **figure 3.10**) is installed in the dam, which exploits a drop of 3.2 m. A similar power station is installed 7.5 km further downstream in the river, at Offenburg (**figure 3.8**).

Downstream migrating fish can choose between six different routes when they pass the power station (**figure 3.11**). 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 3.9. 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}.

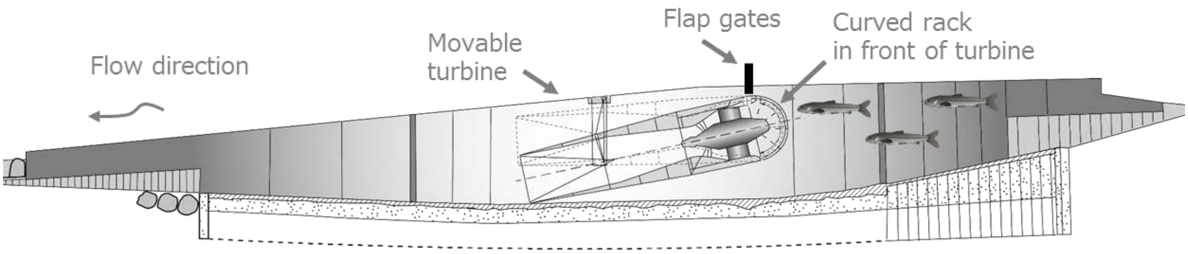

Figure 3.10. The movable bulb turbine installed in the dam at Gengenbach, in the Kinzig.

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 between 0.2 m to 2.5 m above the bottom at higher flows, when the discharge exceeds the turbine capacity of about 20 m^3s^{-1}. During the present study (8 October 2015 – 23 May 2016), the turbine was elevated 12 times, each time for a median[1] duration of 2.3 days (range 0.6-8.3 days). It was elevated for a total time of 35 days. Fish (and sediments) can pass under the turbine tube when it is elevated, but not when it is lowered. Independent of position, some water spills over the turbine, and downstream migrating fish can also pass over it (**figure 3.9, 3.10**).

[1] Median can be used to describe data instead of the mean. The median is the middle value of a data set. For example, if the data set consists of the values 1, 1, 3, 5, 5, 8 and 9, the median is 5. The median is the "typical" value of the data set, and it is often less skewed by extremely large or small values than the mean.

When the water discharge is low and the turbine lowered, an automatic bar rack cleaner operates every 10th hour. During each cleaning operation, which lasts for about 2 minutes, the flap gates are lowered. Between cleaning operations, fish passing over the turbine has to pass through an opening between the flap gates (**figure 3.9**). When the water discharge increases and the turbine is elevated, the flap gates are constantly lowered. During high water discharge, frequent cleaning operations are usually not needed.

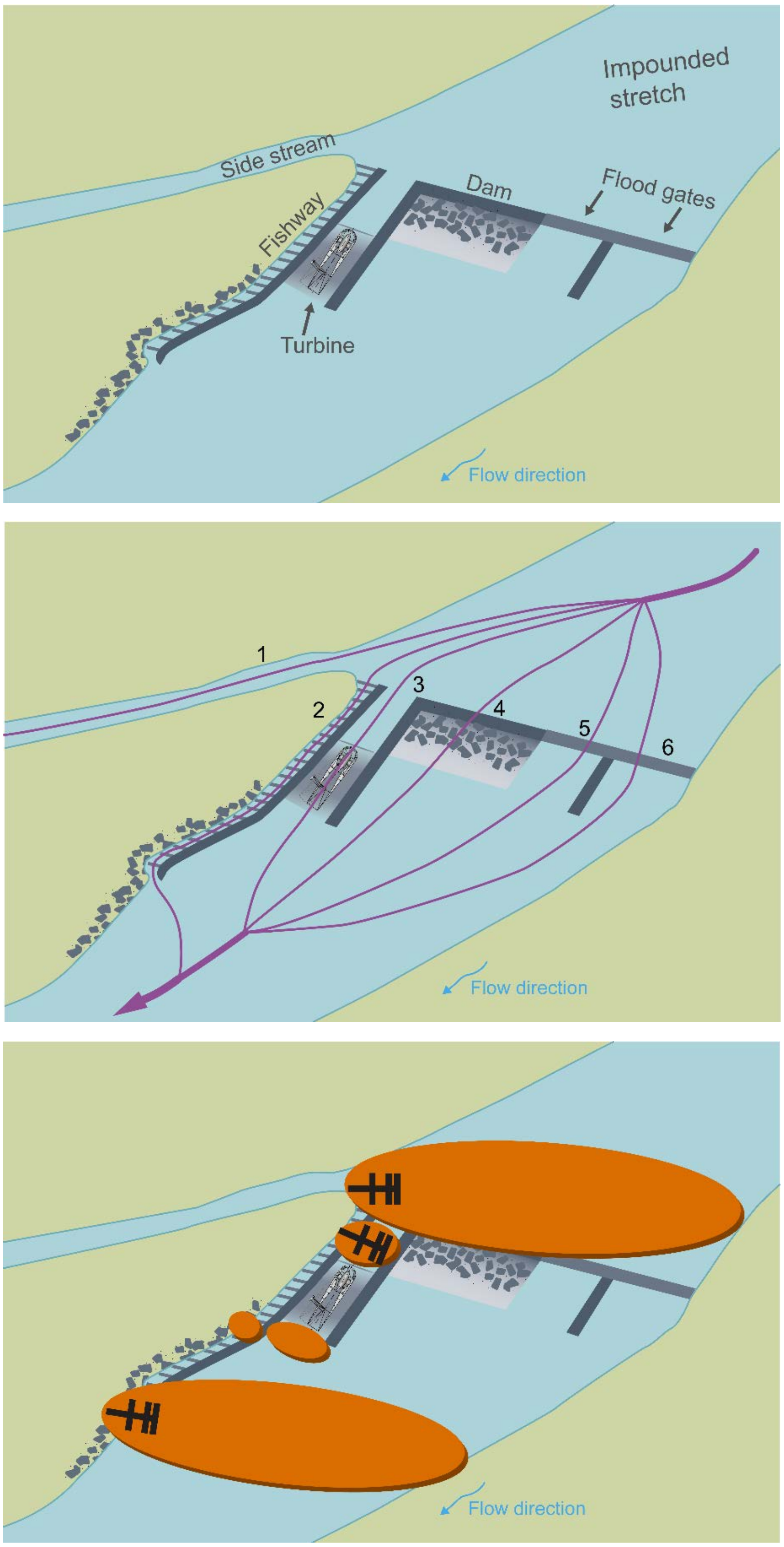

Figure 3.11.

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 side stream, 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 side stream 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. Water discharge in the side stream was 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

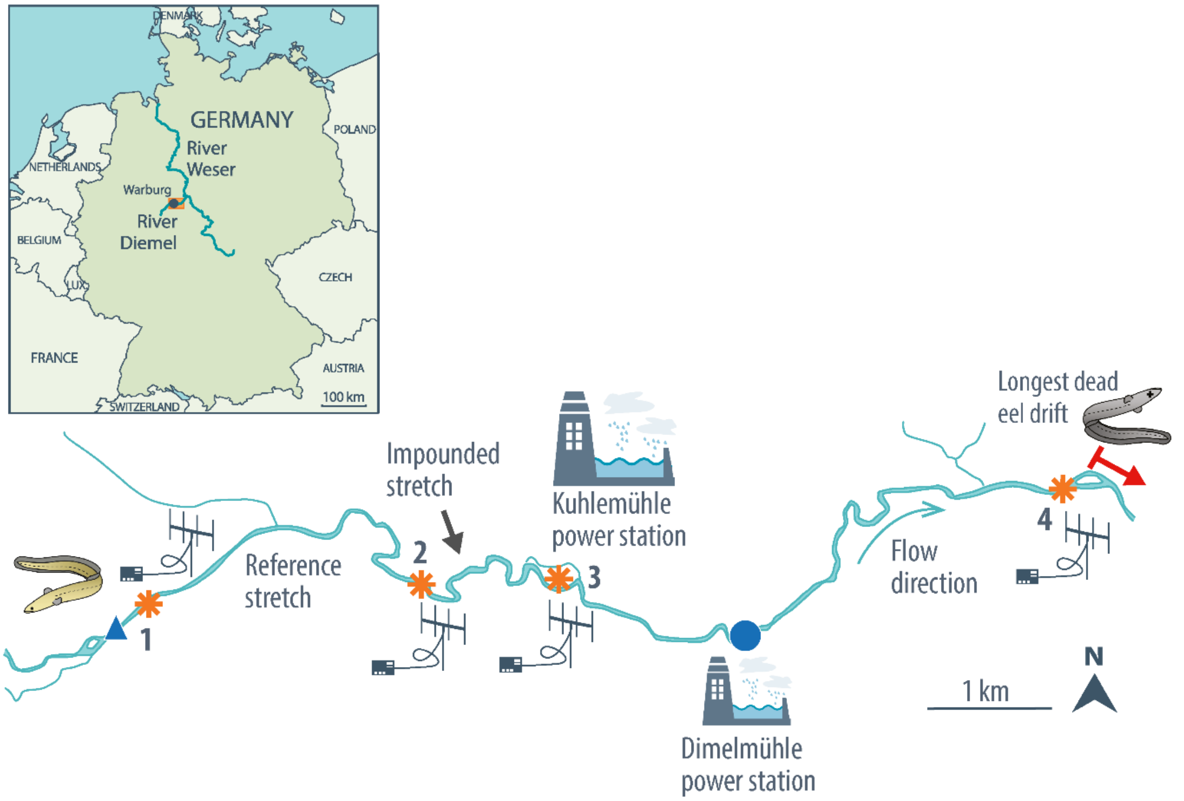

Figure 3.12. Study area in the Diemel showing the release site of European eels tagged with radio transmitters (blue triangle), receiver sites where they were recorded when passing (orange stars, denoted with site numbers 1-4) and the Kuhlemühle power station at site 3. Diemelmühle power station is also shown on the map, but no receivers were installed to monitor tagged fish at this site. The longest drift of radio tagged dead eels released at the power station was past site 4 (red arrow). Distance downstream from the release site was 0.3 km for site 1, 3.0 km for site 2, 4.7 km for site 3 and 9.9 km for site 4.

Kuhlemühle is a run-of-the river power station on the Diemel, 4 km downstream from the town Warburg (**figure 3.12, 3.13**). A 4-bladed Archimedes screw turbine is installed (3.4 m diameter and 7 m long, **figure 3.14**), 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 3.15**).

Downstream migrating fish can choose between six different routes when they pass the Kuhlemühle power station (**figure 3.13, 3.15, 3.16**). 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 3.12**). Fish can potentially be damaged or killed also at this site, but monitoring at this site was not part of the study.

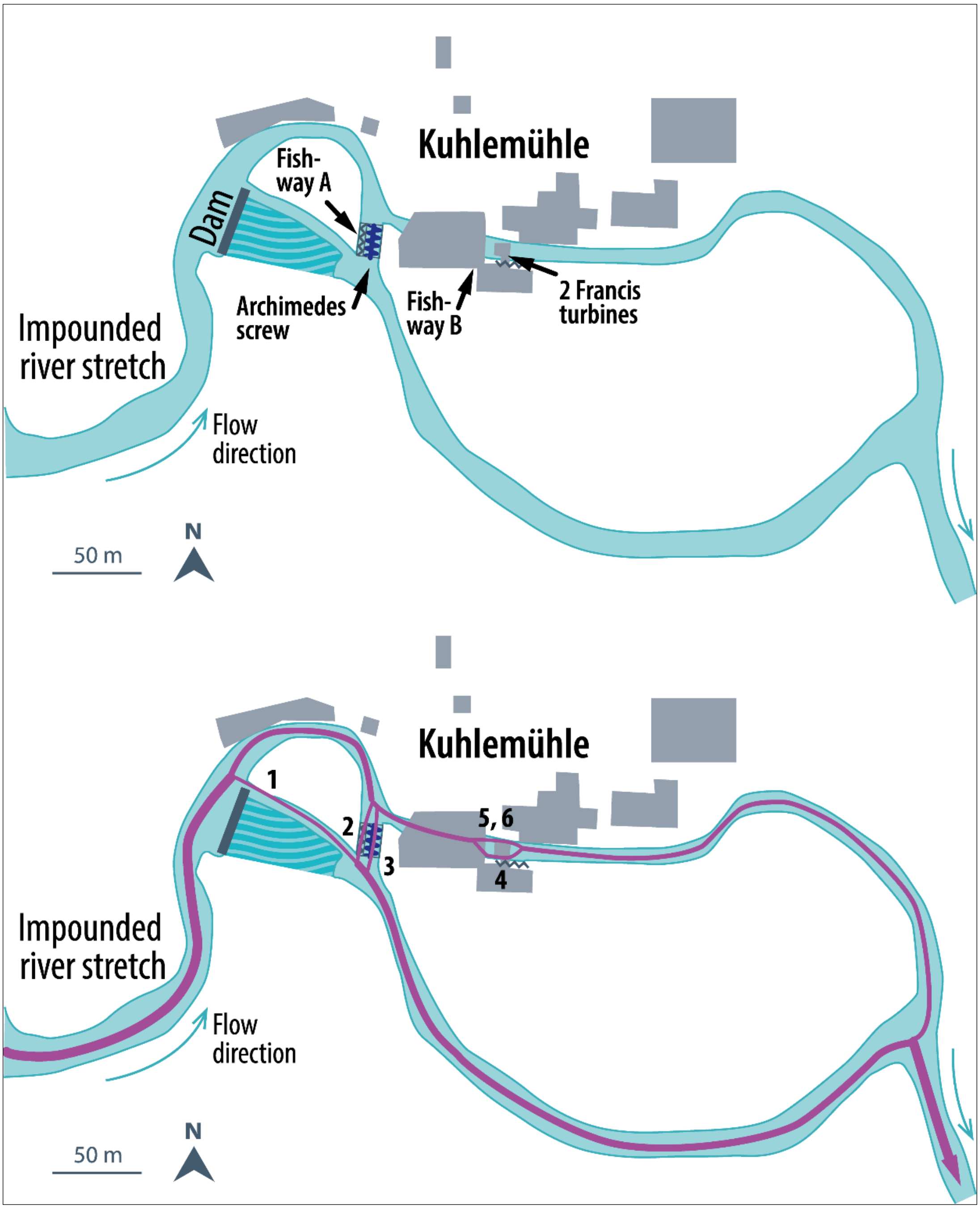

Figure 3.13. Kuhlemühle power station. **Upper panel:** Turbines and fishways. **Lower panel:** The different routes downstream migrating fish can use to pass: 1) over the dam and outside the area with hydropower installations, but only when the water discharge is large enough for excess water to flow over the dam crest (> 12 m^3s^{-1}), or when a gate is opened to get debris past (which occurred 5 times in the autumn 2014), 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 at irregular intervals during October and November 2014, but seemed to operate at more stable intervals in 2015.

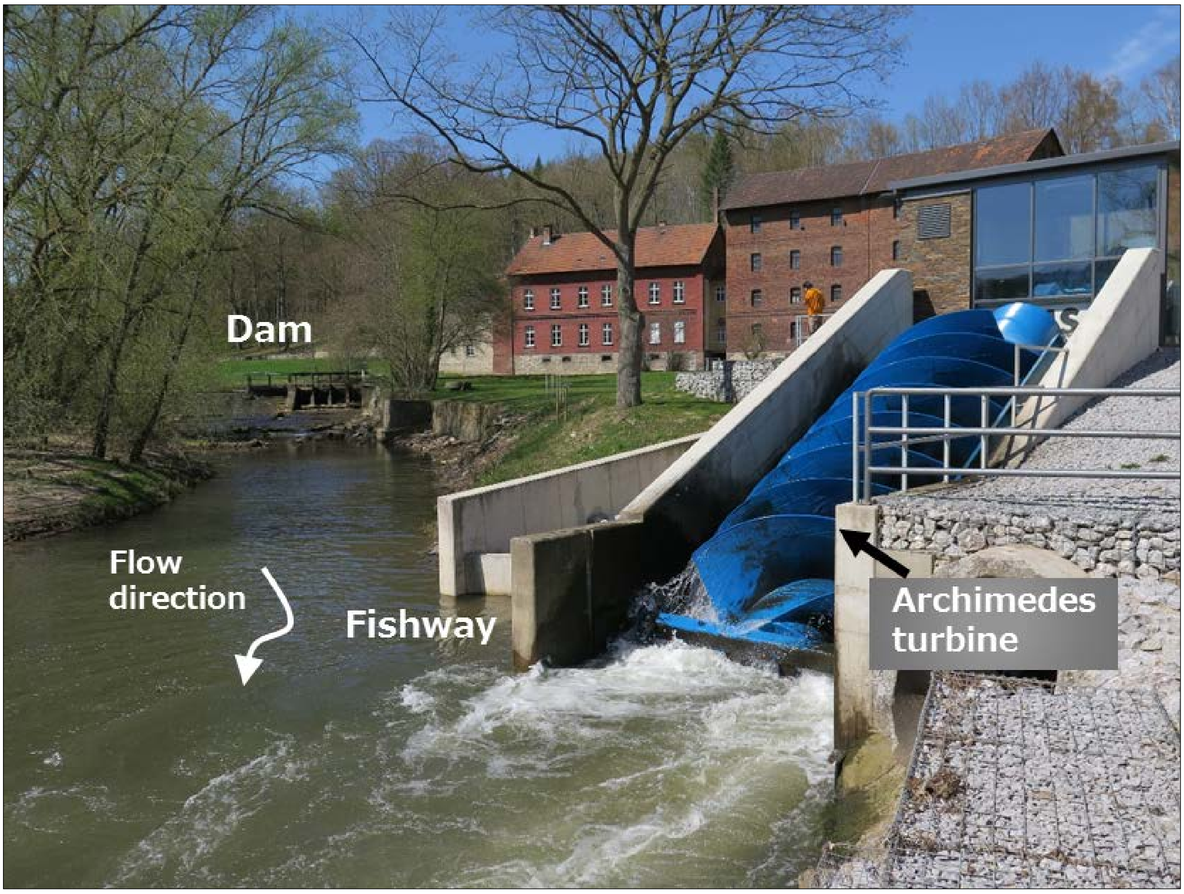

Figure 3.14. Archimedes screw turbine at Kuhlemühle. Photo Torgeir B. Havn.

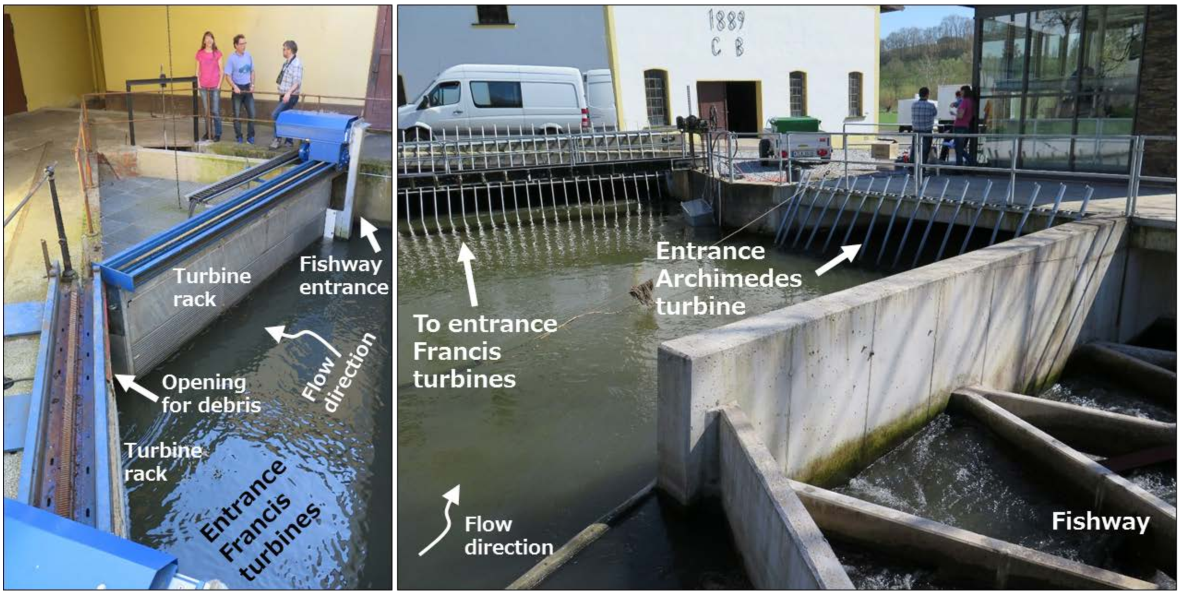

Figure 3.15. Entrance to Francis turbines and Archimedes screw turbine at Kuhlemühle. Photos Torgeir B. Havn.

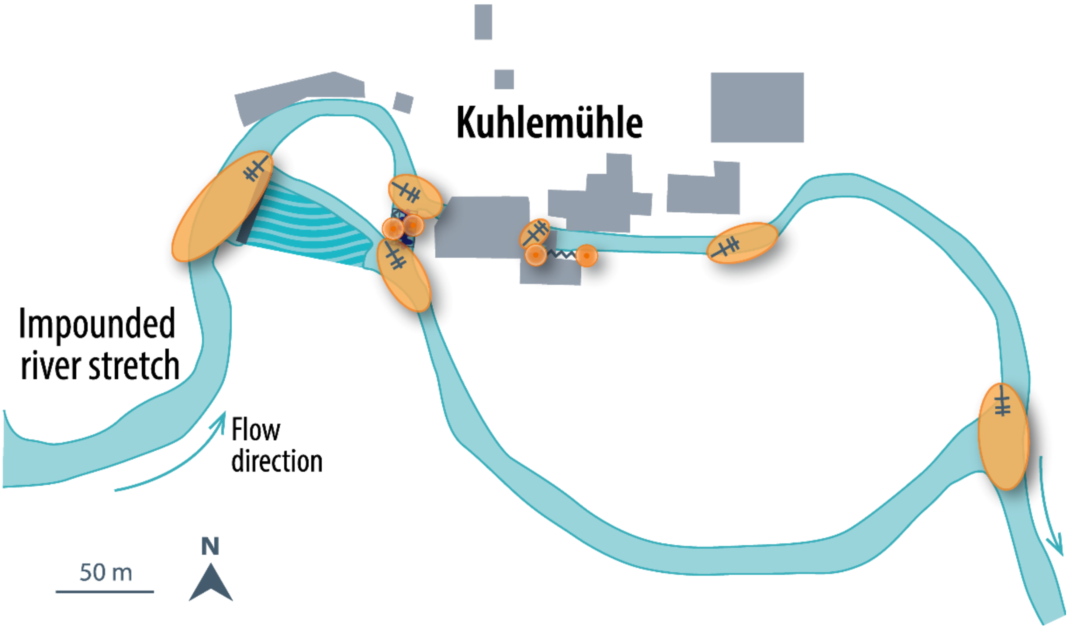

Figure 3.16. Overview of radio antennas and their approximate detection ranges (in orange) used to record signals from radio tagged fish at Kuhlemühle. Ranges with antenna symbols indicate the use of Yagi antennas, whereas ranges without antenna symbols indicate the use of coaxial antennas (in the fishways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

4 Results

4.1 Unkelmühle power station

Summary

Downstream migration of European eel was studied by tagging a total of 270 silver eels with radio transmitters during 2014 and 2015. They were released 10 km upstream of the power station. Of these, 222 eels (82%) passed the power station, primarily in October and November (76% of the eels), although some descended during the subsequent winter and spring.

Most of the eels that passed the power station did so over the spillway gate (59% and 49% in the two study years), or followed the migration route towards the bar racks in front of the turbines (24% and 27%), where they were guided to a route outside the turbines via the flushing channel. No eel slipped through the bar racks and passed through the turbines, as expected due to the narrow spacing between the bars (10 mm). Some eels used the vertical slot fish passage (12% and 8%), whereas few used the nature-like fishway or canoe pass (2% and 4%).

Few eels were captured in the bottom bypass (2% and 8%) and none in the side bypasses, which were custom-made bypasses for eels. Some individuals entered the bottom and side bypasses, but did not remain in the collecting tanks, and instead returned via the bypasses back into the headrace. If eels using these bypasses had not been able to return from the tanks, a total of 1% of the eels in each year had passed the power station via the side bypasses, and 5% and 9% via the bottom bypass.

At least 96% of the eels tagged in 2014, and 92% of the eels tagged in 2015, likely survived passing the power station. For the remaining eels, we do not have data to determine whether they were dead or alive after passing. No direct turbine mortality occurred, since no eel passed through the turbines. Therefore, if some eels died during passage of the power station, this must have been related to injuries in the bypass routes or increased predation risk.

The headrace entrance, spillway gate and dam at the Unkelmühle power station in the Sieg.
Photo by Eva B. Thorstad.

4.1.1 Fate of eels after tagging and release

For eels tagged in 2014, 122 of 136 eels (90%) had passed the power station when the study ended 3 July 2015. For eels tagged in autumn 2015, 100 of 134 eels (75%) had passed when the study ended 20 May 2016.

Of the 14 eels tagged in 2014 that did not pass the power station, 5 eels (36%) had shown upstream movements at some stage, which may indicate that they were alive, 5 eels (36%) remained in the release area or moved downstream and became stationary, and 4 eels (29%) disappeared from tracked stretches (of which one had most likely been taken by a predator, and three were either taken by a predator - or had moved upstream of tracked stretches) (**appendix 1**).

Of the 34 eels tagged in 2015 that did not pass the power station, 23 eels (68%) had shown upstream movements at some stage, which may indicate that they were alive, 6 eels (17%) moved downstream and became stationary, and 5 eels (15%) disappeared from tracked stretches (of which one had most likely been taken by a predator, and four were either taken by a predator - or had moved upstream of tracked stretches).

It should be noted that even though upstream movements may be indicative of an eel being alive, results from release of dead eels showed that scavengers can sometimes bring dead eels upstream in the river (7% of all released dead eel, see Havn et al. 2017). Using upstream movements as an indication that an eel is alive may therefore not always be correct.

4.1.2 Timing of passing the power station

Most of the tagged eels passed the power station in October-November in the same year as they were released, but some eels also descended during the subsequent winter and spring (**figure 4.1**). Of the 122 eels tagged in 2014 that passed the power station, 93 eels (76%) passed in October-November, whereas 23 eels (19%) passed in December and 6 eels (5%) in April-June. No eel passed the power station in January-March. Of the 100 eels tagged in 2015 that passed the power station, 75 eels (75%) passed in October-November, whereas 17 eels (17%) passed in December, 1 eel (1%) in January-March, and 7 eels (7%) in April-June.

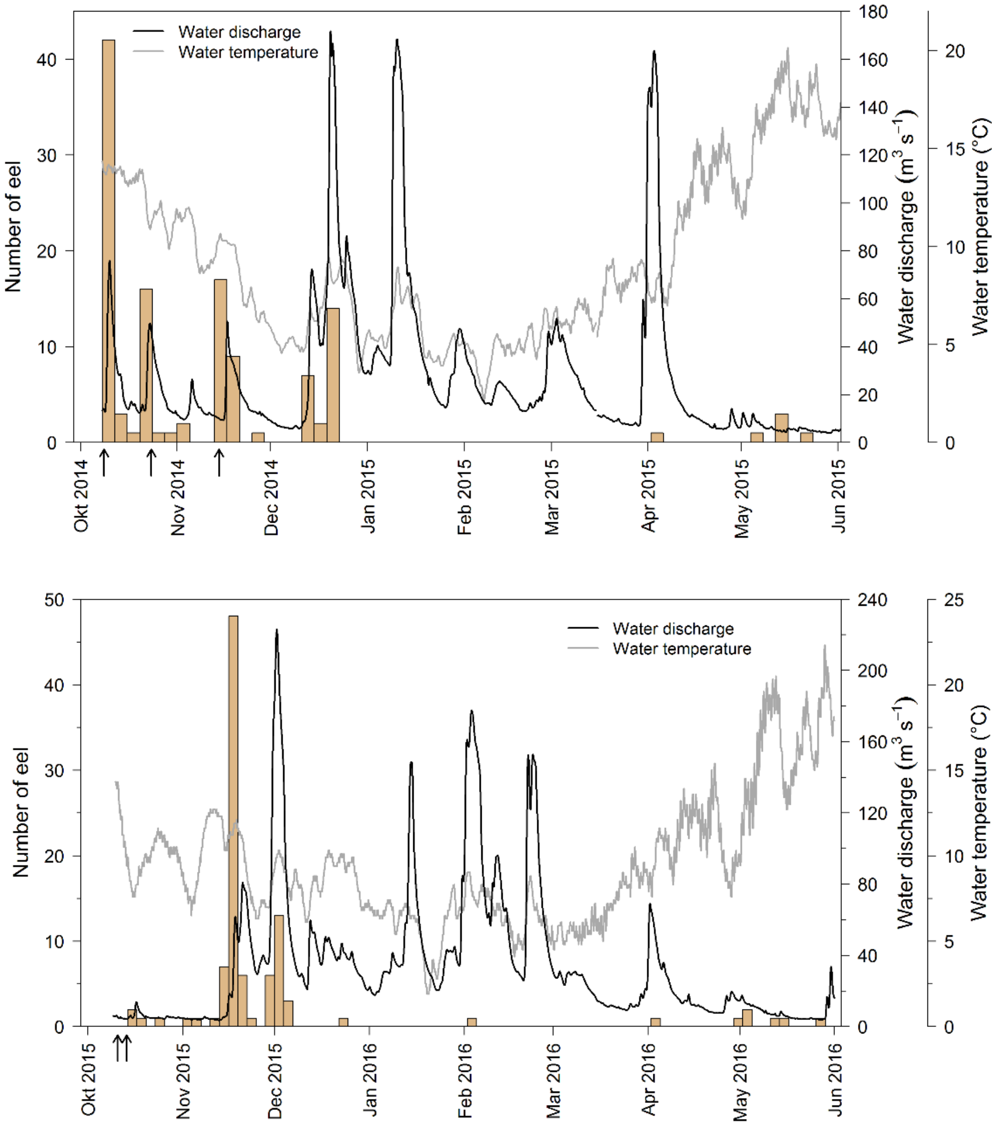

Figure 4.1. Number of eels (bars) passing the power station at different dates for eels tagged and released in 2014 (upper panel, n = 122) and 2015 (lower panel, n = 100). Water discharge (black line) and water temperature (grey line) recorded at Unkelmühle are also shown. Arrows indicate dates when the eels were released in the river.

4.1.3 Migration routes used when passing the power station

Of eels tagged in 2014 and 2015, 91 and 74 eels passed the power station along a known route. The reasons for not having recorded migration route for all eel passing the power station were technical problems with one of the receivers for a period, that receivers were uninstalled during a flood, and that some eels passed during the winter when some stations were uninstalled.

Most of the eels that passed the power station passed over the spillway gate (59% and 49% in the two study years), or followed the migration route towards the bar racks in front of the turbines (24% and 27%) (**figure 4.2**), where they were guided to a route outside the turbines via the flushing channel. These were the migration routes with the largest proportion of the total water flow. No eel slipped through the bar racks and passed through the turbines, as expected due to the narrow bar spacing (10 mm). Three eels (4%) tagged in 2015 passed when the ice gate was open, and for these we could not separate whether they migrated through the spillway gate or ice gate.

Some eels used the vertical slot fish passage (12% of those tagged in 2014 and 8% of those tagged in 2015), whereas few used the nature-like fishway or canoe pass (2% and 4%) (**figure 4.2**). For the eels that used the nature-like fishway or canoe pass, we cannot determine which of these two closely related routes they used.

Few eels were captured in the bottom bypass (2% of those tagged in 2014 and 8% of those tagged in 2015). No eel was captured in the side bypasses. However, some individuals entered the bottom bypass (3 of those tagged in 2014 and 1 of those tagged in 2015) and side bypasses (1 of those tagged in each year), but did not remain in the tanks where eels using these migration routes were supposed to remain until collected by the crew monitoring fish at the power station. Instead, these eels returned from the collection tanks and via the bottom or side bypasses back into the headrace and later used other migration routes past the power station. If the eels using the bottom or side bypasses had not been able to return, a total of 1% of the eels in each year had passed the power station via the side bypasses, and 5% of those tagged on 2014 and 9% of those tagged in 2015 had passed via the bottom bypass.

Figure 4.2. Number of eels tagged in 2014/2015 that used the different migration routes when passing the power station. Total number of eels passing along a known migration route was 91 in 2014 and 74 in 2015. Most of the eels passed over the spillway gate, or followed the migration route towards the bar racks in front of the turbines, where they were guided to a route outside the turbines via the flushing channel. Some eels used the vertical slot fish passage, the bottom bypass and the nature-like fishway or canoe pass. Three eels in 2015 passed when the ice gate was open, and for these we were not able to separate whether they migrated past the spillway gate or ice gate.

4.1.4 Fate of eels after passing the power station

Of the 222 eels that passed the power station during the two study years, no eel became stationary in the power station area, indicative of being dead. Further, no direct turbine mortality occurred, since none of the tagged eels passed through the turbines. It is still possible that eels died and drifted downstream, became injured in the different bypass routes past the power station, or experienced increased predation at the power station. We therefore analysed the fate of the eels also after they had passed the power station.

Among 35 tagged dead eels released at Unkelmühle, the longest drift downstream from the power station of any dead eel was 21 km. This indicates that eels becoming stationary within 21 km downstream of the power station could theoretically be eels that had died at the power station and drifted downstream.

With all likelihood, minimum 96% of the eels tagged in 2014 and 92% of the eels tagged in 2015 survived passing the power station[2] (**table 4.1**). This survival estimate for eel passing the power station is based on the assumption that potentially dead eel did not float longer than the dead eel released below the power station, and that all upstream movements of eel released alive were caused by the eels swimming upstream and not by predators moving the tag upstream. However, cormorants are known to predate on both undamaged eel and turbine damaged eel below power stations (Doherty & McCarthy 1997), and our releases of dead eels showed that a few dead eels were brought upstream in the rivers by scavengers. These assumptions may therefore not always be valid, and there is an uncertainty due to the possibility that there can be dead eel included in this survival estimate.

For the four eels (4%) tagged in 2014 that were not classified as likely survived in the paragraph above, we do not have data to determine whether they were dead or alive after passing the power station. These four eels became stationary upstream of receiver site 5 (7.5 km downstream from the power station, *i.e.*, within the stretch dead eels were shown to potentially drift from the power station) and might be dead. However, stationary eels can potentially also be alive, so we cannot conclude whether they were alive or dead. Two of these eels passed the power station via the surface bypass in the trash racks (route 1), one passed via the vertical slot fish passage (route 3), and for one the route is unknown (**table 4.1**).

For the seven eels (8%) tagged in 2015 that were not classified as likely survived, we do not have data to determine whether four of the seven were dead or alive after passing the power station, because they became stationary in the river below the power station. Three of the seven had recordings indicating that they were taken by predators between the power station and site 5. For those likely taken by predators, it is difficult to know if this was related to the power station, because they could have died at the power station and been taken out of the river by predators, they could have been injured at the power station and been taken by predators, or they could have been uninjured but taken by predators anyway. Of those taken by predators, one had passed via the spillway gate, one via the spillway gate or ice gate, and for one the route is unknown. Of those becoming stationary, one had passed the power station via the vertical slot fish passage, one had passed via the spillway gate and for two the route is unknown (**table 4.1**).

A higher proportion of the fish passing over the weir (*i.e.*, through the spillway gates, canoe pass or natural like fishway) were classified as likely survived (56 of 56 eels) compared to

[2] Eels that passed between 15 December to 20 February in 2014 and after 15 March in 2015 were not monitored downstream of the power station and were therefore, together with eels captured in the bottom gallery, not included in this analysis. The sample size for this analysis was therefore 106 eels in 2014 and 87 eels in 2015.

those passing via the headrace (*i.e.*, through the surface bypass or vertical slot, 30 of 33 eels) in 2014 (Fisher's exact test, P = 0.05). However, due to the uncertainty of the fate of the eels that were not classified as likely survived, and the low sample sizes of eels in this group, these results do not necessarily indicate that there was a difference in survival for eels using the different migration routes at the power station in 2014. Further, in 2015, the proportion of fish classified as likely survived after passing the power station did not differ between the groups (25 of 26 of those passing via the headrace and 39 of 42 of those passing over the weir, Fisher's exact test, P = 1).

Table 4.1. Number and proportion of eels that passed the power station and fates in relation to migration route for eels tagged in 2014 and 2015. Eels with an uncertain fate are those that became stationary within the stretch dead eels were shown to potentially drift from the power station (n = 4 in 2014 and n = 4 in 2015). Three eels were likely taken by predators in 2015.

	Migration route						
Fate	**Surface bypass** (route 1)	**Vertical slot** (route 3)	**Canoe pass or natural-like fishway** (route 4)	**Spillway gate** (route 7)	**Spillway gate or ice gate** (route 6 or 7)	**Unknown** (due to technical problems or passing when stations were removed)	**Total**
Eels tagged in 2014:							
Likely survived	20 (91%)	10 (91%)	2 (100%)	54 (100%)	0 (0%)	16 (94%)	102 (96%)
Uncertain	2 (9%)	1 (9%)	0 (0%)	0 (0%)	0 (0%)	1 (6%)	4 (4%)
Total	**22**	**11**	**2**	**54**	**0**	**17**	**106**
Eels tagged in 2015:							
Likely survived	20 (100%)	5 (83%)	3 (100%)	34 (94%)	2 (67%)	16 (84%)	80 (92%)
Uncertain	0 (0%)	1 (17%)	0 (0%)	1 (3%)	0 (0%)	2 (11%)	4 (5%)
Taken by predator	0 (0%)	0 (0%)	0 (0%)	1 (3%)	1 (33%)	1 (5%)	3 (3%)
Total	**20**	**6**	**3**	**36**	**3**	**19**	**87**

4.1.5 Migrations speeds

There were large differences in the times spent on different stretches among individual eel, and some differences among stretches (**table 4.2**). In particular, eels spent longer time in the release area (from release to passing receiver site 1) than on the other stretches, and eels tagged in 2015 also spent a long time on the free-flowing reference stretch (receiver site 1 to 2).

Table 4.2. Time spent on passing the different river stretches (time from first detection at one receiver site to first detection at the next receiver site, ignoring movements back into another stretch). Length of the different river stretches is also given. Site numbers refer to the map in **figure 3.1**. Sample sizes for each stretch may be lower than the actual number of fish passing due to missing detections on arrival or exit. See **appendix 1** for correct numbers on how many fish that passed each stretch.

Stretch	Number of eels	Mean (hours/km h^{-1})	Median (hours/km h^{-1})	Minimum-maximum (hours)	Minimum-maximum (km h^{-1})
Eels tagged in 2014:					
Release area, 1.5 km	117	492 / 0.20	51 / 0.03	0.87-5267	<0.01-1.79
Reference stretch, 5.8 km	108	95 / 2.65	2.3 / 2.48	0.86-1230	0.01-6.76
Reservoir, 2.3 km	107	83 / 2.36	0.8 / 2.79	0.50-4224	<0.01-4.54
Power station, 0.2 km	104	110 / 1.03	0.3 / 0.70	0.05-1217	<0.01-3.67
Power station to site 5, 7.5 km	94	38 / 4.74	1.3 / 5.71	1.02-897	0.01-/ 7.38
Eels tagged in 2015:					
Release area, 1.5 km	112	501 / 0.18	115 / 0.01	1.3-3680	<0.01-1.22
Reference stretch, 5.8 km	94	693 / 0.93	212 / 0.03	0.9-5186	<0.01-6.43
Reservoir, 2.3 km	81	105 / 1.72	1.3 / 1.75	0.4-1299	<0.01-6.23
Power station, 0.2 km	71	104 / 0.9	1.3 / 0.15	0.03-3900	<0.01-6.18
Power station to site 5, 7.5 km	59	83 / 3.62	1.7 / 4.53	1.0-3307	<0.01-7.76
Site 5 to site 6, 12.2 km	57	42 / 3.35	2.7 / 4.45	2.0-938	0.01-6.07
Site 6 to site 7, 21.8 km	66	78 / 4.22	4.1 / 5.38	2.5-3668	0.01-8.62

Eels tagged in 2014 spent median 0.29 hours in passing power station (mean 110 hours, range 0.05-1217) and eels tagged in 2015 spent median 1.3 hours (mean 104 hours, range 0.03-3900, **figure 4.3**). The distribution of times spent passing the power station was highly skewed among individuals, with most individuals moving fast and some individuals moving much slower (which is the reason for the difference between the median and mean values). Most eels moved past the power station within 24 hours (77% of those tagged in 2014 and 73% of those tagged in 2015).

The migration speed in passing the power station differed among migration routes (Kruskal Wallis tests, 2014: χ^2 = 17.4, P = 0.02, 2015: χ^2 = 10.5, P = 0.03, **figure 4.3**). Eels passing via the spillway gate were the fastest in both study years. Of eels tagged in 2014, those with an unknown migration route were also among the fastest. However, migration speed past the power station differed among routes for eels that passed within 24 hours after arriving at the power station (2014: χ^2 = 22.1, P < 0.001, 2015: χ^2 = 16.9, P < 0.001), but not for eels that passed more than 24 hours after arriving (2014: χ^2 = 3.7, P = 0.16, 2015: χ^2 = 3.4, P = 0.34) (tests include only eels with a known migration route).

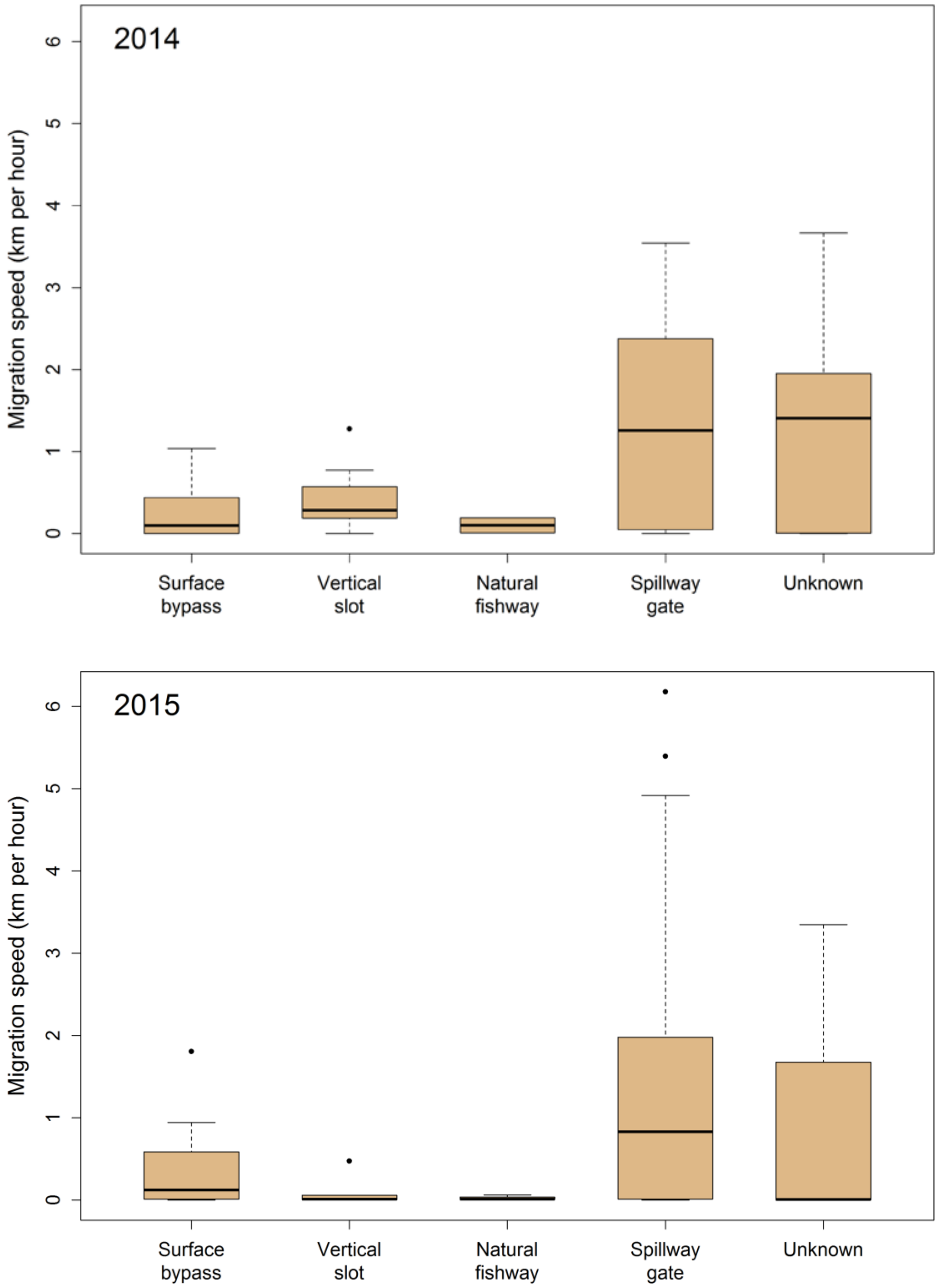

Figure 4.3. Migration speeds when passing Unkelmühle for fish using the different migration routes shown as a box plots for eels tagged and released in autumn 2014 (upper panel, n = 104) and 2015 (lower panel, n = 71). The boxes show the median and interquartile range (*i.e.*, half of the individual values are within the boxes) and the whiskers and dots show values outside this range.

4.2 Gengenbach power station

Summary

Downstream migration of European eel was studied by tagging 136 silver eels with radio transmitters in 2015. They were released 10 km upstream of the power station. Of these, 102 eels (75%) passed the power station, primarily in October and November (66% of the eels), although some descended during the subsequent winter and spring.

Most of the eels (65%) that passed the power station passed through the section where the turbine is installed, whereas some eels (23%) moved over the dam or via the flood gates. Few eels used the side stream (9%) or fishway (3%). Of the eels that passed through the section where the turbine is installed, half of them (52%) passed when the turbine was lifted and one third (36%) when it was lowered. Data on the turbine operation was not available when the remaining fish passed.

Of the 102 eels that passed the power station, no eel became stationary, indicative of being dead, at the power station. However, for survival estimates at the power station, there is an uncertainty because eels may drift downstream the river after they are dead.

We have data on the fate of 87 eels after passing the power station (the remaining passed in the winter when they were not monitored). Of these, 73 eels (84%) either showed upstream movements (n = 2), or passed the receiver 16 km downstream and moved into the Rhine (n = 71), which indicate that they might have survived passing the power station. However, there is an uncertainty, since several dead eels released at the power station were also shown to drift this far. Two eels (2%) were likely taken by predators. The 12 remaining eels (14%) were still recorded in the Kinzig in the spring. These could be eels that died or became injured when passing the power station, but they could also potentially be alive and uninjured, because some eels may cease migration and delay migration until a later year.

The fishway, section where the turbine is installed, dam and flood gates at Gengenbach power station in the Kinzig. Photo by Eva B. Thorstad.

4.2.1 Fate of eels after tagging and release

When the study ended in May 2016, 102 of 136 (75%) tagged eels had passed the power station. Of the 34 eels that did not pass the power station, 15 eels (44%) had shown upstream movements at some stage, which may indicate that they were alive, 7 eels (21%) moved downstream from the release area and became stationary, 8 eels (24%) remained in the release area, and 4 eels (12%) disappeared from tracked stretches (of which two most likely had been taken by a predator, and two were either taken by a predator - or had moved upstream of tracked stretches) (**appendix 1**). One of the eels that moved upstream was later recaptured by anglers.

It should be noted that even though upstream movements may be indicative of an eel being alive, results from release of dead eels showed that scavengers can sometimes bring dead eels upstream in the river (7% of all released dead eel, see Havn et al. 2017). Using upstream movements as an indication that an eel is alive may therefore not always be correct.

4.2.2 Timing of passing the power station

Most of the tagged eels passed the power station in October-November, but some eels also passed during the subsequent winter and spring. Of the 102 eels that passed the power station, 68 eels (66%) passed in October-November, 17 eels (17%) in December, 3 eels (3%) in January-March, and 14 eels (14%) in April-June (**figure 4.4**).

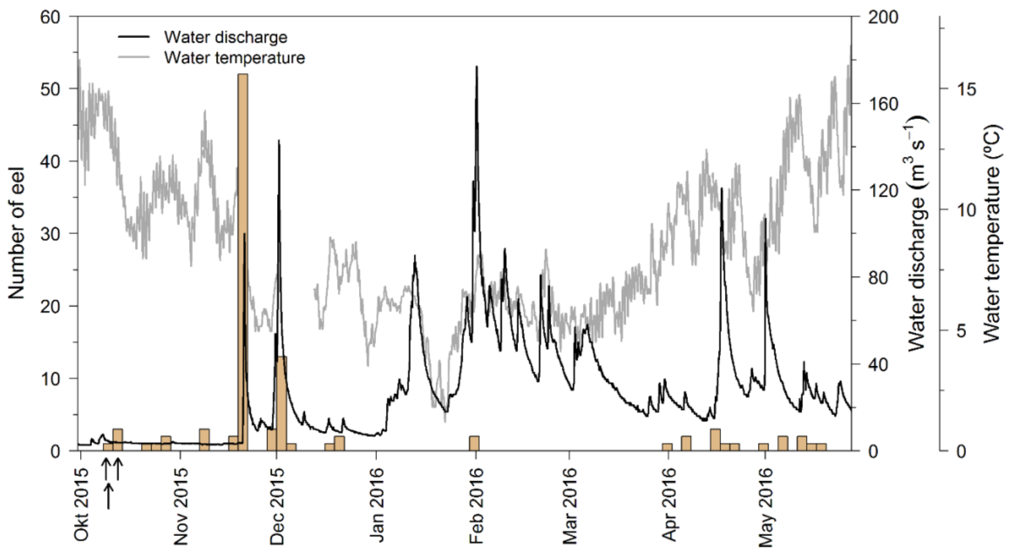

Figure 4.4. Number of eels (bars) passing the power station at different dates (n = 102). Water discharge (black line) recorded at Schwaibach gauging station and water temperature (grey line) recorded at Gengenbach power station are also shown. Arrows indicate dates when the eels were released in the river.

4.2.3 Migration routes used when passing the power station

Of the 102 eels that passed the power station, the largest proportion passed through the section where the turbine is installed (66 eels, 65%, **figure 4.5**). Further, 24 eels (23%) migrated over the dam or via the flood gates, three eels (3%) moved through the fishway and nine eels (9%) used the side stream. Of the 66 eels that passed through the section where the turbine is installed, 34 eels (52%) passed when the turbine was lifted, 24 eels (36%) when it was in the lowered position and for 8 eels (12%) it is unknown which position the turbine was in when they passed due to missing data on the turbine operation.

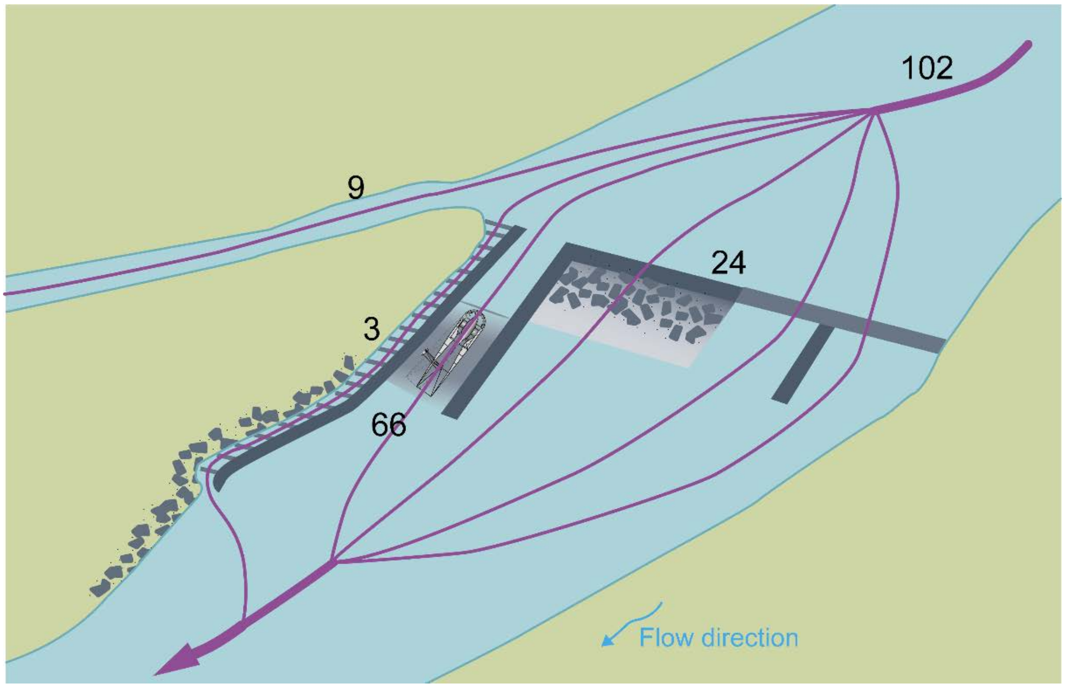

Figure 4.5. Numbers of eel that used the different migration routes past the power station. In total, 102 tagged eels passed the power station area.

4.2.4 Fate of eels after passing the power station

Of the 102 eels that passed the power station, no eel became stationary, indicative of being dead, at the power station. However, eels may drift downstream the river after they are dead. Among 10 dead eels released at Gengenbach, the longest drift downstream from the power station of any dead eel was more than 30 km, into the Rhine. Hence, dead eels could potentially drift downstream within and out of the study area, which made it difficult to assess power station mortality of the eels released alive.

Of the eels that passed the power station, we have data on the fate of 87 eels (15 eels passed in the winter, when there was limited monitoring) (**table 4.3**). Of these, 73 eels (84%) either showed upstream movements (n = 2, 2%), or passed the receiver 16 km downstream of the power station and moved into the Rhine (n = 71, 82%), which indicate that they might have survived passing the power station. However, there is an uncertainty since three of the dead eels also drifted this far, so we cannot exclude the possibility that there could have been eels killed at the power station among those passing.

Two eels (2%) were likely taken by predators below Offenburg power station. It is difficult to know if this was related to any of the power stations, because these eels could have died at any of the two power stations and been taken out of the river by predators, they could have been injured at one or both power stations and then been taken by predators, or they could have been uninjured but taken by predators anyway. The 12 remaining eels (14%) were still recorded in the Kinzig when the study ended in the spring. These could be eels that had died or become injured when passing the Gengenbach or Offenburg power station (half of them had passed Offenburg power station before they became stationary), but they could also potentially be alive, as some eels may cease migration and rather migrate downstream towards the ocean in a later year.

Table 4.3. Number and proportion of eels that passed the power station and fates in relation to migration route. Eels that are judged to might have survived are those that showed upstream movements (n = 2) or passed the receiver downstream of the power station and moved into the Rhine (n = 71), and uncertain fish (n = 12) are those that remained on the monitored stretch below the power station when the study ended. Two fish were likely taken by predators.

	Migration route				
Fate	**Side stream** (route 1)	**Fishway** (route 2)	**Section where turbine is installed** (route 3)	**Over dam or flood gate** (route 4 or 5)	**Total**
Might have survived	7 (78%)	1 (33%)	48 (84%)	17 (94%)	73 (84%)
Uncertain	2 (22%)	1 (33%)	8 (14%)	1 (6%)	12 (14%)
Taken by predator	0 (0%)	1 (33%)	1 (2%)	0 (0%)	2 (2%)
Total	**9**	**3**	**57**	**18**	**87**

4.2.5 Migration speeds

There were large differences in the times spent on different stretches among individual eel, and some differences among stretches (**table 4.4**). In particular, eels spent longer time in the release area (from release to passing receiver site 1) and on the free-flowing reference stretch (receiver site 1 to 2) than on the other stretches.

Table 4.4. Time spent on passing the different river stretches (time from first detection at one receiver site to first detection at the next receiver site, ignoring movements back into another stretch). Length of the different river stretches is also given. Site numbers refer to the map in **figure 3.8**. Sample sizes for each stretch may be lower than the actual number of fish passing due to missing detections on arrival or exit. See appendix 1 for correct numbers on how many fish that passed each stretch.

Stretch	**Number of eels**	**Mean (hours/km h^{-1})**	**Median (hours/km h^{-1})**	**Minimum-maximum (hours)**	**Minimum-maximum (km h^{-1})**
Release site, 1.7 km	107	707 / 0.10	941 / <0.01	1.1-2220	<0.01-1.49
Reference stretch, 7.2 km	91	231 / 2.66	23 / 0.31	0.7-1705	<0.01-10.18
Impounded river stretch, 1.2 km	89	81 / 3.21	0.5 / 2.51	0.1-1581	<0.01- 8.96
Power station, 0.08 km	91	218 / 2.02	0.05 / 1.67	0.01-3551	<0.01- 8.00
Power station to site 4, 7.5 km	72	25 / 5.35	1.2 / 6.21	0.8-1245	0.01-9.48
Site 4 to site 5, 8.6 km	71	14 / 3.78	1.8 / 4.71	1.1-385	0.02-7.70

Eels spent a median time of 0.05 hours in passing the power station (mean 218 hours, range 0.01-3551). The distribution of times spent passing the power station was highly skewed among individuals, with most individuals moving fast and some individuals moving much slower (which is the reason for the difference between the median and mean values). Most eels (71%) moved past the power station within 24 hours.

The migration speed in passing the power station differed among migration routes (Kruskal Wallis test $\chi^2 = 8.1$, $P = 0.02$). Eels passing over the dam or via the flood gate were the fastest, and those using the fishway the slowest (**figure 4.6**). However, migration speed past the power station differed between routes for eels that passed the power station within 24 hours after arriving ($\chi^2 = 4.0$, $P = 0.04$), but not for eels that passed more than 24 hours after arriving ($\chi^2 = 2.8$, $P = 0.2$).

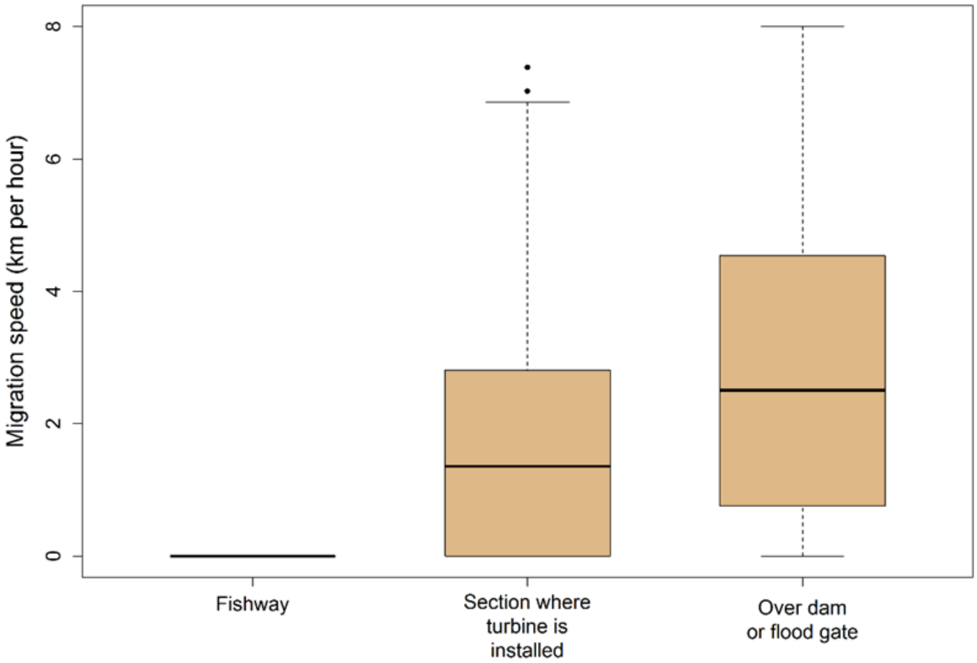

Figure 4.6. Movement speeds when passing Gengenbach power station for fish using the different migration routes shown as a box plots (n = 91). Movement speed past the power station was not available for nine eels using the side stream and for two fish that passed through the section where the turbine is installed. The boxes show the median and interquartile range (*i.e.*, half of the individual values are within the boxes) and the whiskers and dots show values outside this range.

4.3 Kuhlemühle power station

Summary

Downstream migration of European eel was studied by tagging 136 silver eels with radio transmitters in 2014. They were released 4.6 km upstream of the power station. Of these, 111 eels (82%) passed the power station, primarily in October-December (59% of the eels), but many also descended during the subsequent winter and spring.

A large proportion of the eels passed through the Archimedes screw turbine (41%). The rest migrated over the dam (11%), used the fishway at the Archimedes screw (17%), moved through the Francis turbines, or were flushed through the opening for debris at the Francis turbines (17%, we cannot separate between these two routes), or used the fishway at the Francis turbines (14%).

We have data on the fate of 78 eels after passing the power station (the remaining passed in the winter or other periods when the receiver at site 4 was not operating). Of these, 3 eels (4%) for sure survived passing the power station because they were later recaptured by fishers, and 56 eels (72%) might have survived based on either upstream movements, or that they passed the receiver site 5 km downstream. However, there are uncertainties with this estimate, because we cannot rule out that there could have been dead eels in this group that were either brought upstream by scavengers, or drifted dead out of the study area. One eel (1%) was likely predated. Further, 18 eels (23%) became stationary on river stretches downstream of the power station. These could be eels that died or became injured when passing the power station, but they could also potentially be alive and uninjured, because some eels may cease migration and delay migration until a later year.

Lower end of the Archimedes screw at the Kuhlemühle power station in the Diemel.
Photo by Eva B. Thorstad.

4.3.1 Fate of eels after tagging and release

When the study ended in July 2015, 111 of 136 (82%) tagged eels had passed the power station. Of the 25 eels that did not pass, 11 eels (44%) had shown upstream movements at some stage, which may indicate that they were alive, 7 eels (28%) moved downstream and became stationary, 1 eel (4%) remained in the release area, and 6 eels (24%) disappeared from tracked stretches (of which at least 2 had likely been taken by predators, and the rest had either moved upstream of tracked stretches or been taken by predators) (**appendix 1**).

It should be noted that even though upstream movements may be indicative of an eel being alive, results from release of dead eels showed that scavengers can sometimes bring dead eels upstream in the river (7% of all released dead eel, see Havn et al. 2017). Using upstream movements as an indication that an eel is alive may therefore not always be a correct.

4.3.2 Timing of passing the power station

Half of the tagged eels passed the power station in October-November, and half of them passed during the subsequent winter and spring. Of the 111 eels that passed the power station, 57 eels (51%) passed in October-November, 9 eels (8%) in December, 24 eels (22%) in January-March, and 21 eels (19%) in April-May (**figure 4.7**).

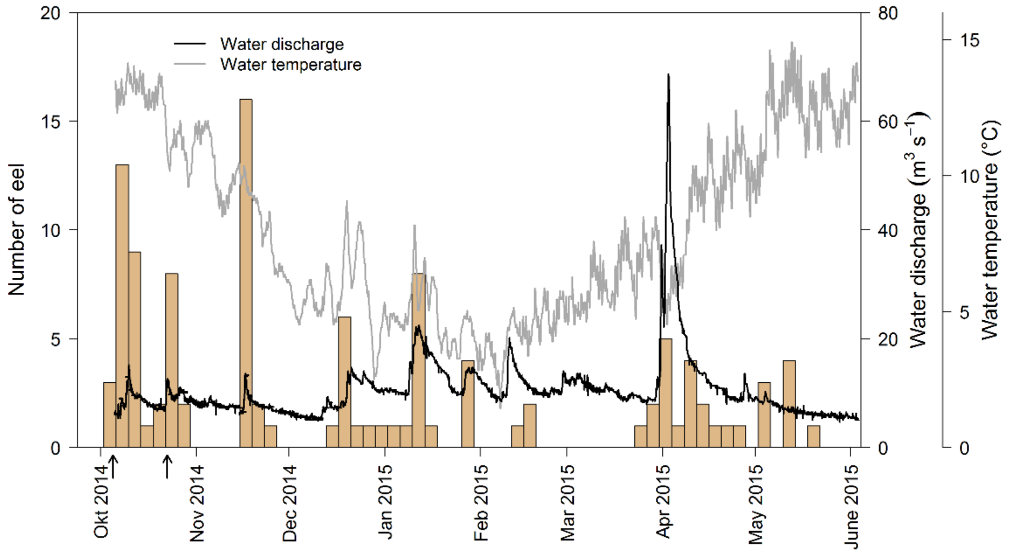

Figure 4.7. Number of eels (bars) passing the power station at different dates (n = 111). Water discharge (black line) and water temperature (grey line) recorded at Kuhlemühle are also shown. Arrows indicate dates when the eels were released in the river.

4.3.3 Migration routes used when passing the power station

Of the 111 eels that passed the power station, the largest proportion passed through the Archimedes screw turbine (45 eels, 41%, **figure 4.8**). Further, 12 eels (11%) migrated over the dam, 19 eels (17%) used the fishway at the Archimedes screw, 16 eels (14%) used the fishway at the Francis turbines and 19 eels (17%) either moved through the Francis turbines or were flushed through the opening for debris at the Francis turbines (we cannot separate between these two routes).

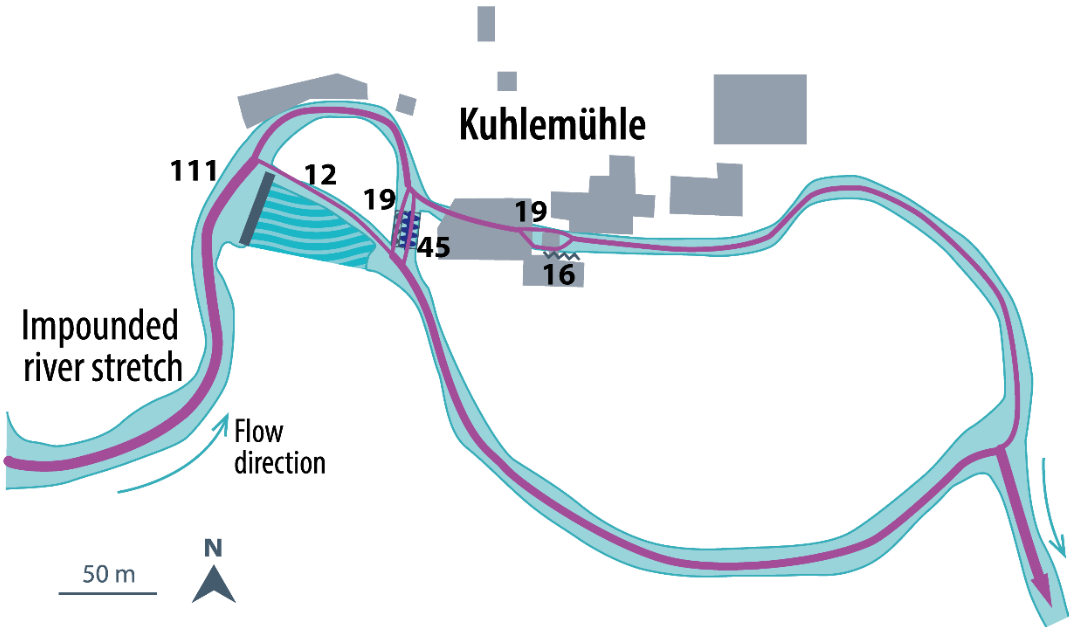

Figure 4.8. Numbers of eel that used the different migration routes past the power station. In total, 111 tagged eels passed the power station area.

4.3.4 Fate of eels after passing the power station

Of the 111 eels that passed the power station, no eel became stationary, indicative of being dead, at the power station. However, for survival estimates at the power station, there is an uncertainty because eels may drift downstream the river after they are dead. Of 10 dead eels released at Kuhlemühle, at least one drifted past receiver site 4, 5 km downstream of the power station. Three more dead eels might also have been doing so, because they disappeared from tracked stretches during a period when this receiver was not operating. Hence, dead eels could potentially drift downstream within and out of the study area, which made it difficult to assess power station mortality of the eels released alive.

Of the eels that passed the power station, we have data on the fate of 78 eels (33 eels passed the power station in the winter or other periods when the receiver at site 4 was deinstalled or out or function for other reasons) (**table 4.5**). Of these 78 eels, 22 eels (28%) might have survived because they showed upstream movements after passing the power station (15 might also have survived passing Diemelmühle, because upstream movements were recorded downstream of Diemelmühle). However, since it is shown that dead eels can be brought upstream by scavengers, we cannot rule out that some of the eels shown to move upstream were dead. Thirty-four eels (44%) might also have survived because they passed receiver site 4 and moved out of the study area, and few dead eels moved this far. However, we cannot conclude for sure that all these fish survived passing the power station because there could be some fish killed at the power station that potentially drifted this far. Eighteen eels (23%) were still located on the monitored river stretches downstream of the power station when the study ended in June 2015, and we do not know whether they were dead or alive (none of them were recoded with any upstream movements). Seven of them were located upstream and eleven downstream of receiver site 4. Fifteen of these eels had passed Diemelmühle power station before they became stationary, so if there was power station related mortality among eels in this group, it is difficult to know whether they might have been killed or injured at Kuhlemühle, Diemelmühle, or at both power stations. One eel (1%) was likely predated by a bird. Three eels (4%) for sure survived passing the power stations Kuhlemühle and Diemelmühle, because they were recaptured by fishers further downstream in the watershed.

Table 4.5. Number and proportion of eels that passed the power station in relation to migration route and fate. Eels that are judged to might have survived are fish that moved upstream (n = 22), moved out of the study area (n = 34) or were recaptured (n = 3), and uncertain fish (n = 18) are those that remained on the monitored stretch below the power station when the study ended. One fish was likely taken by a predator.

	Migration route					
Fate	**Dam** (route 1)	**Fishway at Archimedes screw** (route 2)	**Archimedes screw** (route 3)	**Fishway at Francis turbines** (route 4)	**Through Francis turbines or opening for debris** (route 5 or 6)	**Total**
Might have survived	7 (78%)	9 (56%)	26 (90%)	10 (83%)	7 (58%)	59 (76%)
Uncertain	2 (22%)	7 (44%)	3 (10%)	2 (17%)	4 (33%)	18 (23%)
Taken by predator	0 (0%)	0 (0%)	0 (0%)	0 (0%)	1 (8%)	1 (1%)
Total	**9**	**16**	**29**	**12**	**12**	**78**

4.3.5 Migration speeds

Eels spent a median time of 1.7 hours in passing the power station area (mean 184 hours, range 0.03-3932). The distribution of times spent passing the power station was highly skewed among individuals, with most individuals moving fast and some individuals moving much slower (which is the reason for the difference between the median and mean values). Most fish (73%) moved past the power station within 24 hours.

The migration speed in passing Kuhlemühle differed among migration routes (Kruskal Wallis test, $\chi2 = 12.9$, $P = 0.01$, **figure 4.9**), with the fish passing the dam and the Archimedes screw having the fastest migration speeds. Fish passing the Archimedes screw spent median 0.3 hours from entering the dam upstream of Kuhlemühle until being recorded in the Archimedes screw (0.25 km, mean 68 hours, range 0.07-782 hours), and median 0.07 hours from being recorded the Archimedes screw until the last detection on the antenna covering the tailrace (0.1 km downstream, mean 6 hours, range 0.01-167 hours).

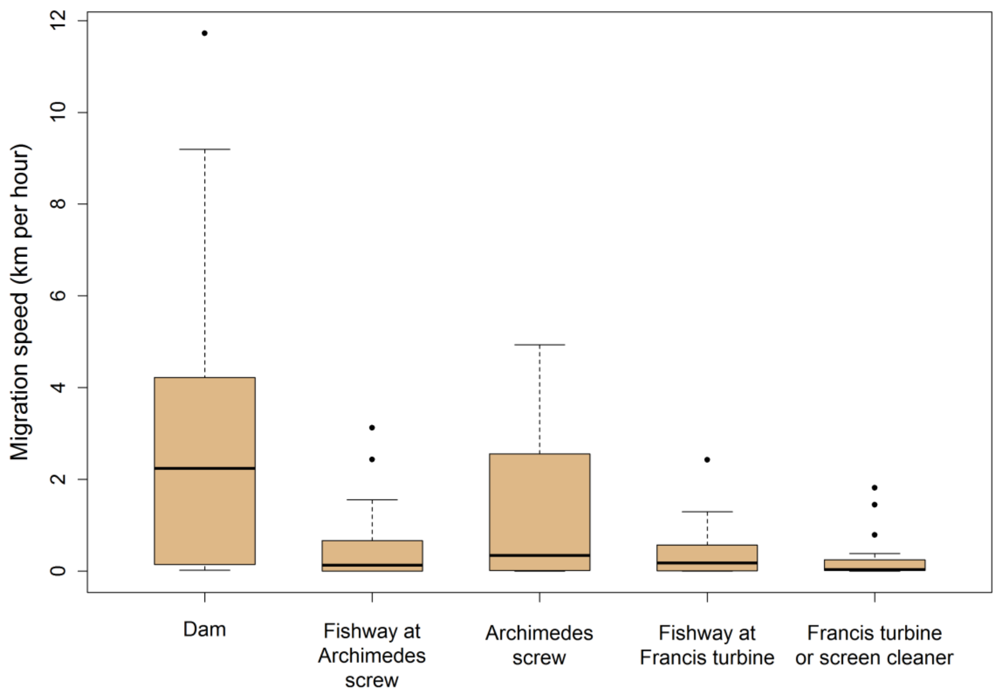

Figure 4.9. Movement speeds when passing Kuhlemühle power station for fish using the different migration routes shown as a box plots (n = 109). The boxes show the median and interquartile range (*i.e.*, half of the individual values are within the boxes) and the whiskers and dots show values outside this range.

5 Discussion

5.1 Unkelmühle power station

This study showed a low mortality (0-4% and 0-8% in the two study years) for downstream migrating eels when they passed the Unkelmühle power station. This shows that it is possible to obtain low mortalities for migrating eels by using special protection measures at power stations to facilitate migration and reduce mortality for downstream migrating fish. At Unkelmühle, racks have been installed to prevent fish from entering the turbines, and there are several bypass routes that can be used by downstream migrating fish. No direct turbine mortality occurred, as no eel slipped through the bar racks in front of the turbines. This was as expected, since a bar spacing of 10 mm should prevent eels larger than approximately 33 cm body length to slip through (Adam et al. 2005), and the smallest tagged eel was 60 cm.

The reason that we give mortality estimates as a range (0-4% and 0-8%), is that the fate of some tagged individuals after passing the power station is unknown, which makes it difficult to determine if they were alive or dead after passing. Further, three individuals had recordings indicating that they were taken by birds, but it is not known whether they were dead at the power station and taken by bird predators, injured by passing the power station and therefore taken by predators, or whether they were uninjured but taken by predators anyway. The estimates given as ranges take this uncertainty into account, and imply that the mortality of tagged eels passing the power station could have been zero in both study years, but the mortality could also have been up to 4% in the first study year and up to 8% in the second study year.

If there was some mortality linked to passing Unkelmühle power station, this must have been due to injuries caused by the bypass routes, or to increased predation at the power station. Increased predation may occur if fish are injured and thereby easier prey. It is also possible that due to presence of injured fish of different species, power stations may attract predators, such that the likelihood of being taken by a predator increases also for uninjured fish. There are for instance great black cormorant (*Phalacrocorax carbo*) colonies in the area, and cormorants are known to be able to predate on large eel. In an Irish study, great black cormorants were feeding on eel below a power station, and the eels eaten had mean body length 62 cm (maximum length about 90 cm) (Doherty & McCarthy 1997). The cormorants in their study were preying on both undamaged eel and turbine-damaged eels below the power station (Doherty & McCarthy 1997).

Eels mainly used the two migration routes with the largest proportion of the water flow, which were the spillway gate and a bypass route leading fish from the bar racks in front of the turbines into the flushing channel, and back to the river via a route outside the turbines. Only two eels used the custom-made side bypasses for eels, and only a small proportion of the eels (<10%) used the custom-made bottom bypass

5.2 Gengenbach and Kuhlemühle power stations

No eel became stationary, indicative of being dead, neither at the Gengenbach or Kuhlemühle power station. However, for survival estimates at these power stations, there are uncertainties because eels may drift downstream in the river after they are dead. Release of dead eels showed that eels that potentially died when passing the Gengenbach or Kuhlemühle power station could have drifted a longer distance than we recorded them by stationary receivers and manual tracking. The survival estimates at Unkelmühle were more certain, because the fish were followed over a longer stretch, and there were fewer individuals with an uncertain fate after passing the power station.

Some eels became stationary on river stretches below the power stations, and could be suspected to be dead (14% and 23% of the eels that passed the Gengenbach and Kuhlemühle, respectively). However, eels may cease migration and migrate downstream another year (Winter et al. 2006, Simon et al. 2012), so an eel becoming stationary may not necessarily be dead. The presence of power stations only a few kilometers further downstream (7.5 km from Gengenbach and 2.1 km from Kuhlemühle) also complicated survival estimates, because for fish being predated or becoming stationary below the second power station, possibly being dead, it is difficult to know which of the power stations, or maybe both, that may have inflicted injury.

When passing the power stations, the eels mainly used migration routes with a large proportion of the water flow, and fewer eels used the routes with little water discharge, such as fish passages and a side stream. At Gengenbach, the largest proportion of eels passed through the section where the moveable turbine was installed, and at Kuhlemühle, the largest proportion passed through the Archimedes screw turbine.

The Archimedes screw turbine was not equipped with a bar rack to prevent fish from entering, so all fish that had used this route passed through the turbine. However, the Francis turbines at Kuhlemühle were equipped with a bar rack with 20 mm spacing between the bars. According to Adam et al. (2005), a bar spacing of 20 mm should prevent eels larger than approximately 67 cm body length to slip through. The eels tagged at Kuhlemühle had body lengths 60-114 cm, so the smallest tagged fish could have slipped through the racks and passed through the turbine, but most of the tagged eels were too large to slip through this rack. The movable turbine at Gengenbach power station had a rack with 15 mm bar spacing, which should prevent eels larger than approximately 50 cm to slip through (Adam et al. 2005). Here, tagged eels had body lengths 65-101 cm, which means that none of them should have slipped through the bar spacing. This means that eels passing through the section where the turbine is installed, most likely passed below or above the turbine (but this cannot be differentiated by the telemetric design in this study).

5.3 Archimedes screw turbine at Kuhlemühle

Archimedes screw turbines are often regarded as less harmful to fish than other hydropower turbines, and reported damage and loss rates are usually low (Potter et al. 2012, Økland et al. 2016). 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). In contrast to many other turbine designs, there are no racks in front of the Archimedes screw to prevent fish from entering the turbine, and fish can pass the turbine without leaving the main river flow through blocks of water at slow speed down the screw. However, there is generally little knowledge on the effects of Archimedes screw turbines on fish, and there is particularly an absence of scientifically evaluated knowledge.

The most likely damage to fish from passage through Archimedes screw turbines may be mechanical injuries, in particular blade striking and grinding (Potter et al. 2012). There is low risk of immediate mortality for fish travelling through the turbine according to the few studies done, but injuries can lead to delayed mortality (Potter et al. 2012). According to our results, mortality of radio tagged Atlantic salmon smolt passing the Archimedes screw turbine in Kuhlemühle was less than 8%, but the extent of scale loss and other injuries possibly causing delayed mortality for these fish is not known (Økland et al. 2016).

Another potential negative effect by Archimedes screw turbines on fish may be migration delays, either upstream if they hesitate to enter the turbine, or downstream due to having passed the turbine. Such delays can potentially increase the predation rate, or affect the overall migration rate. However, most eels migrated fast through the Archimedes screw turbine in this study, and did not hesitate or stop the migration either upstream or downstream of the turbine (median time spent upstream of the turbine after entering the power station area was 0.3 hours on a 0.25 km long stretch, and downstream of the turbine 0.07 hours on a 0.1 km stretch). In fact, eels migrating through the Archimedes screw turbine or over the dam passed the power station area faster than eels using the other routes. Hence, eels were not markedly delayed in their downstream migration by using the Archimedes screw. However, there was large individual variation, and some individuals spent a long time in passing the power station via the Archimedes screw.

5.4 Conclusion

Overall, we recorded low mortality for downstream migrating silver eels at the power stations in the present study. However, there are uncertainties linked to the survival estimates, particularly at Gengenbach and Kuhlemühle. There could also have been some additional long-term mortality, or additional mortality due to predation in the reservoir or impounded stretch, that we were not able to record. A problem in many rivers is that eels have to pass several power stations and other barriers where they can be killed or injured, and there are usually also other causes of mortality and reduced production of eels due to anthropogenic impacts (*e.g.* habitat loss, fishing, pollution). In such cases, the cumulative mortality may become large, even though the mortality at each site is relatively low. The total effects of several power stations can potentially also lead to larger effects than just adding the impacts by each site, because an already injured fish may have a reduced tolerance to new injuries, as well as an increased susceptibility for diseases and predation.

Power stations may also delay the downstream migration of eels, which may lead to reduced spawning success, for instance if they do not reach the ocean and the spawning area at the right time, or if delays lead to increased mortality (for instance larger likelihood of being predated). The passage of the power stations did not seem to largely delay the eels in this study, although there were some individuals that spent much longer time than the others to pass. A proportion of the eels stopped their migration, either upstream or downstream of the power station, which is also known from other, similar studies of eels (Winter et al. 2006, Simon et al. 2012). However, it is difficult to know if such behavior is normal in eel, or whether the presence of power stations, or perhaps also the handling and tagging, resulted in a reduced motivation to migrate in some individuals.

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7 Appendix

Appendix 1: Movements of tagged European eel released in the different rivers and years (table 2.1.). Numbers of eel entering (Eel In) and leaving (Eel Out) the different stretches are given, as well as the number of eel that remained in or had disappeared from each stretch at the end of the study period. An eel ceasing migration is not necessarily dead, especially when an upstream movement was recorded, which may indicate that the eel was alive.

Stretch	**Eel In**	Eel last detected in stretch		Eel disappeared from stretch because of		Eel captured in bypass galleries	**Eel Out**
		with upstream movement	without upstream movement	predation	uncertain¥		
Sieg 2014/15							
Release area	136	3	2		2		129
Reference stretch	129	1	1				127
Reservoir	127	1	2	1	1		122
Power station	122					2	120
Power station to site 5	106*	1	3				102
Site 5 to end of monitored stretch	102		1				101 ##
Sieg 2015/16							
Release area	134	5	1		2		126
Reference stretch	126	11	2		1		112
Reservoir	112	6	3	1	1		101
Power station	101	1				6	94
Power station to site 5	87*		3	3			81
Site 5 to site 6	81	2	1				78
Site 6 to site 7	78		1		7		70
Diemel 2014/15							
Release area	136	3	1		1		131
Reference stretch	131	4	4	1	1		121
Impounded river stretch	121	4	3	1	2		111
Power station	111						111
Power station to site 4	78*		7	1			70
Site 4 to end of monitored stretch	70	4	11				55 ###
Gengenbach 2015/16							
Release area	136	11 #	8		2		115
Reference stretch	115	1	6	1			107
Impounded river stretch	107	3	1	1			102
Power station	102						102
Power station to site 4	87*	1	6				80
Site 4 to site 5	80	1	4	2			73
Site 5 to end of monitored stretch	73		2				71

¥ It is uncertain why the fish disappeared, and often several reasons are possible (*e.g.*, de-installation of recording stations after the main monitoring period, temporarily failure of stations, predation, upstream movement out of the reach of manual tracking, and less likely malfunctioning of transmitter)

* "Eel In" reduced because eel passed the power station after monitoring below the power station was suspended

Each # denotes an eel that was later captured by fishers

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