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Improving European Silver Eel (*Anguilla anguilla*) downstream migration by undershot sluice gate management at a small-scale hydropower plant

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ABSTRACT

Hydropower plants have been linked with high mortality and passage impairments during Silver Eel (*Anguilla anguilla*) downstream migration, but there is still a lack of effective and economically viable management options for safe power plant passage. This study used an Adaptive Resolution Imaging Sonar (ARIS) to investigate how undershot sluice gate management at a small-scale hydropower plant affects Silver Eel behavior during downstream migration. Not a single eel out of 1323 counts used the eel bypass system, which is currently considered a technical standard. Instead, Silver Eels approached the opening of an undershot sluice gate and effectively used this corridor during their downstream migration. The opening size of the undershot sluice gate and the resulting higher current velocities in front of this corridor were identified as the most important triggers. Migration occurred primarily at night and peaked with rising discharge. This study suggests that undershot sluice gates can be used as a cost-effective downstream migration pathway and should be operated at night on rising discharge during the peak migration period for eels.

1. Introduction

Migrating fish species are considered the most critically imperiled faunal elements in aquatic ecosystems (Dudgeon et al., 2006). In particular, populations of long-distance migrating diadromous fish species such as the European Eel (*Anguilla anguilla* L. 1758) have had strong population declines, often beyond sustainable levels (Limburg and Waldman, 2009). This prompted the IUCN to classify the species as critically endangered (Jacoby and Gollock, 2014). After hatching in the Sargasso Sea, *A. anguilla* undertakes one of the longest migrations in the animal kingdom, to the European continent (approximately 6000 km) (Schmidt, 1922; van Ginneken and Maes, 2005). After several years in freshwater habitats, mature European Eels (Silver Eels) migrate back to the Sargasso Sea for the completion of their life cycle, where all specimens die after spawning. During the past centuries, migration routes within most rivers have strongly decreased in longitudinal connectivity due to the construction of hydropower plants (HPP) and other barriers. Some authors have directly linked the observed decline in eel populations to Silver Eel damage during turbine passage (MacNamara and McCarthy, 2014). Due to their elongated body shape, Silver Eels are much more susceptible to turbine blade impingement compared to other species, resulting in reported cumulative Silver Eel mortalities after multiple turbine passage of up to 100% (Doenni et al., 2001; Dumont, 2005, 2006). As a means of conservation, the European Parliament issued an Eel Management Plan (Regulation Council of the European Union, 2007). According to this plan, the escapement rate of Silver Eels should be at least 40% of the potential biomass a river system could produce in the absence of anthropogenic modification. Strategies to fulfill this plan and to facilitate downstream migration of Silver Eels currently include a diversity of management options such as the catching of Silver Eels and their transportation to the sea (“Trap-and-Truck”) (McCarthy et al., 2008), identifying activity patterns at the onset of migration (“Migromat”) (Adam, 2000; Bruijs et al., 2009) for shutting down turbines, as well as technical measures to facilitate downstream movement (e.g. “Hassinger tube system”) (Hassinger and Huebner, 2009). However, to date there is a lack of information on the usefulness of many of those approaches. Some of the options such as shutting down turbines during migration or “Trap-and-Truck” approaches are either costly or not sustainable and thus not well accepted. Moreover, several factors that govern migration

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patterns and eel behavioral responses are not yet fully understood. For instance, management of sluice gates at existing hydropower facilities is a currently unexplored management option to facilitate downstream migration of eels that could be easily realized with little or no cost due to the comparatively small water volumes needed. Most of the existing hydropower plants are equipped with sluice gates, which are primarily used for spilling of debris, offering a great potential for fish conservation if they were effective in attracting and guiding downstream migrating fish.

An evidence-based aquatic conservation approach requires evaluating different management options against predefined criteria to identify optimal solutions (Geist, 2015). Thus, we tested if undershot sluice gate management affects Silver Eel behavior and downstream migration at an existing small-scale HPP considering season, daytime versus nighttime, and different flow conditions. Additionally, the functionality of the installed eel bypass system was tested during the migration period of *A. anguilla*. Specifically, we hypothesized that (i) Silver Eels recognize and use an undershot sluice gate as migration corridor, (ii) and that attraction of Silver Eels to this migration corridor depends on the opening width of the undershot sluice gate. Conversely, we hypothesized (iii) that Eel Activity in front of the fish protection screens upstream of the turbines decreases with the opening of the undershot sluice gate due to the attraction of *A. anguilla* to this alternative corridor.

2. Materials and methods

2.1. Study site

This study was conducted at a HPP at the Franconian Saale in Bad Kissingen in Bavaria, Germany (N50°10’47.5” E10°04’24.8”). As a tributary of the Main, the Franconian Saale belongs to the Rhine catchment, which is part of the natural distribution area of *A. anguilla*. The Franconian Saale is an anthropogenically modified river with a mean low water discharge of $2.9\,m^3\,s^{-1}$, a mean discharge of $12.1\,m^3\,s^{-1}$ and a mean flood discharge of $114.0\,m^3\,s^{-1}$ recorded at the nearest water gauge in Bad Kissingen (10 km downstream of the HPP: N50°10’47.5” E10°04’24.8”). The hydrograph of the river is characterized by floods in fall and late winter, as well as periods of low water during summer. The entire river (136 km) is regulated by 17 weirs. The small-scale HPP is equipped with a Kaplan turbine with a maximum capacity of 280 kW and a horizontal fish protection screen with a gap size of 15 mm. During the eel migration events recorded in this study, the turbine was run at a mean capacity of 157.3 ± 95.7 kW. The HPP is equipped with an eel bypass system in front of the horizontal fish protection screen (Hassinger and Huebner, 2009), which is intended to guide the eels unharmed into the tail water of the HPP. The Silver Eels can potentially enter this structure through holes in a zig-zag shaped tube, which is placed on the ground of the river in front of the fish protection screen. After swimming through this structure, the Silver Eels reach the tailwater of the river by sliding down a flume. In close proximity to the turbine intake, a sluice gate exists (length: 6.25 m, height: 3.75 m). This undershot sluice gate is additionally equipped with an overshot spillway in order to lead floating debris into the tail water. The undershot sluice gate only operates during high flow conditions to guide large floating debris into the tail water. The water level of the headwater is regulated by a 17.65 m wide shutter weir on the orographical right side of the Franconian Saale. Since the turbine intake is limited to a maximum discharge of $10.0\,m^3\,s^{-1}$, any additional water in the river is lead over the top of the shutter weir. This results in almost constant current velocity conditions in front of the fish protection screen during rising flood levels. The study was carried out in two consecutive years (2015 and 2016).

The study was performed during a period of low flow conditions in late summer (Reference I: 28 September 2015 and 01 October 2015) and during the expected Silver Eel migration period, initiated by the first flood in late fall 2015 (Event I: 20–21 November 2015). Subsequently, during low flow conditions in fall 2016 (Reference II: 07–09 November 2016 and Reference III: 11–12 November 2016) and during high flow conditions (Event II: 24–26 October 2016 and Event III: 16–18 November 2016). The weather situation and the lunar phase were recorded during the study period and are illustrated in Fig. 2. Daytime was defined from sunrise to sunset (summer: Day = 07:01 a.m.–07:00 p.m.; Night = 07:01 p.m.–07:00 a.m.; fall: Day = 07:31 a.m.–4:30 p.m.; Night = 4:31 a.m.–07:30 a.m.). At the study site, the Silver Eels could only use two possible corridors for their downstream passage (eel bypass system and the opened undershot sluice gate) (Fig. 1).

The opening width of this gate can be regulated and was manipulated in this study to test the effects of different opening widths on Silver Eel migration. Due to the installed fish protection screen (gap size 15 mm), no Silver Eels could enter the turbine passage.

2.2. Environmental variables

Current velocity [ms^{-1}] in front of the fish protection screen was recorded with an electromagnetic water flow meter (Ott MF pro, Ott, Kempten, Germany) 10 cm below water surface, in the middle of the fish protection screen and 10 cm above the river bottom twice a day. To be able to link eel behavior with current velocities in the undershot sluice gate, sonar measurements were used to calculate the specific current conditions of the different flow treatments in front of the undershot sluice gate. For this reason, the mean current velocity for each 0.25 h sample was calculated by the entrained debris, which passed this corridor, using the Software Echoview 6.0 (Myriamax, Hobart, Australia). Links between current velocity and Eel Migration intensity through the undershot sluice gate was then explored by correlation analyses. For a general characterization of the environmental conditions, different additional abiotic parameters were measured: turbidity [NTU] (Turbidity meter, WTW, Weilheim, Germany), oxygen [$mg\,L^{-1}$], pH-value, conductivity [$\mu S\,cm^{-1}$] and temperature [°C] (Multimeter, WTW, Weilheim, Germany) twice a day at three measuring points in the head water of the HPP. The weather conditions (air temperature [°C], air pressure [hPa], rainfall [mm]) were recorded during the study period for every day by using the data of the meteorological station of the city of Bad Kissingen.

2.3. Acoustic detection of eels

Activity and downstream passage of Silver Eels were recorded with an imaging sonar (ARIS Explorer 3000, Soundmetrics, Bellevue, USA) placed in two positions in front of the horizontal screen and the undershot sluice gate. The imaging sonar unit was operated with a horizontal beam angle of 28°, a vertical beam angle of 14° and a frequency of 1.8 MHz. The sonar was fixed on a small vessel (Carolina Skiff J14, Carolina Skiff LLC, Waycross, USA). The boat was swapped between the two different positions (Fig. 1). The sonar was mounted 1.20 m under the water surface. The sonar provides video data which were saved in the field and subsequently analyzed.

2.3.1. Eel activity

The first position (P1) was in front of the horizontal screen in order to record the Eel Activity (Fig. 1). In this position the pitch was set to −16.4° and the tilt was set to −1.4°. Eel Activity was defined as follows: Every appearance of an eel inside of the ARIS video window was counted as one Eel Activity record. In order to test for diurnal patterns of the Eel Activity and the detected Eel

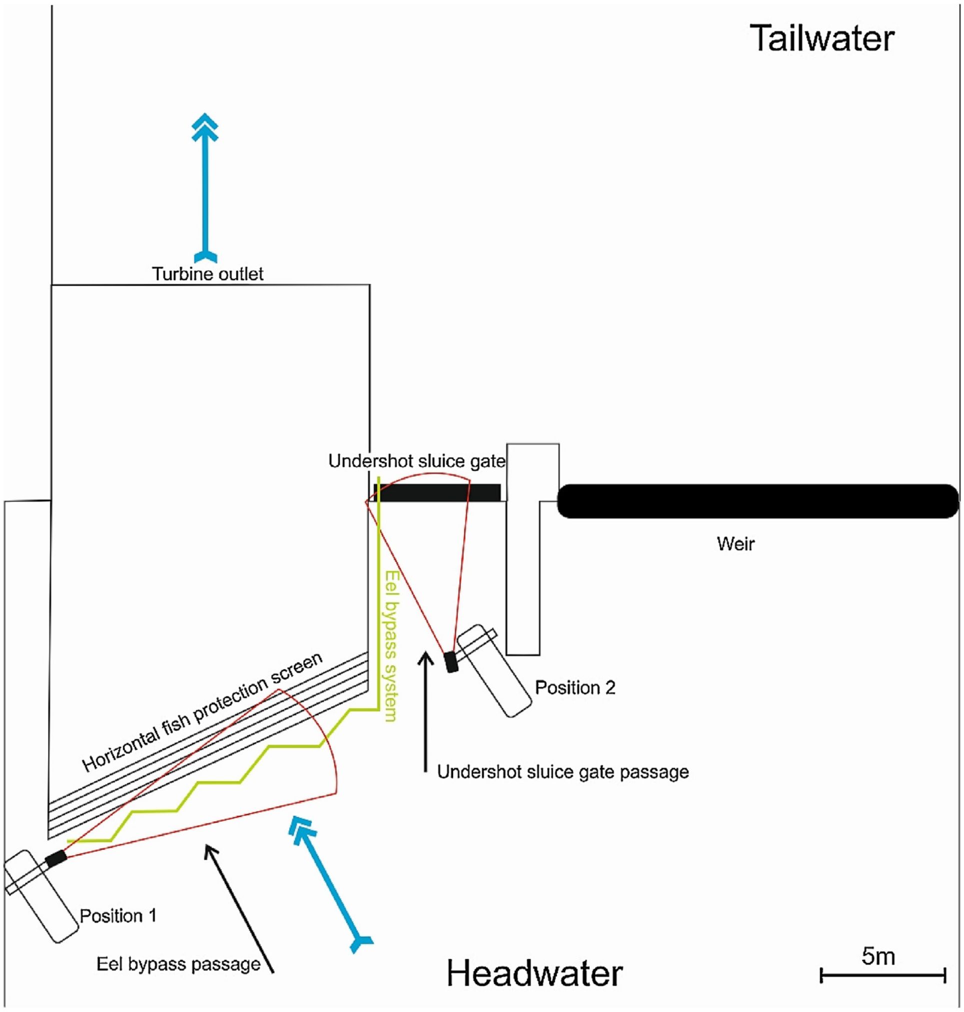

Fig. 1. Top view of the study site (eel bypass system with the fish protection screen, undershot sluice gate and weir). Blue arrow = main current. Note that the fish protection screen is installed directly upstream of the turbine intake. Head (drop height) = 3.34 m. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Migration, both were recorded during daytime and nighttime. The Eel Activity in front of the screen was observed while the undershot sluice gate was closed during day and night in two consecutive years (2015 and 2016). In order to detect changes in the Eel Activity, the same area was recorded while the undershot sluice gate was opened during day and night in both study years. Due to the observed marginal Eel Activity during daytime, we only compared the different treatments (opened and closed undershot sluice gate) during nighttime. In order to validate the functionality of the eel bypass system, eels were counted visually and net-based with a fixed fyke net at the outlet of the tube slide, where the shallow water level allowed emptying the net. Visual observations at the tube slide were made for 0.25 h intervals every 1.50 h during the total observation period. For the visual observation, every Silver Eel was counted that was sliding down the tube slide.

2.3.2. Eel migration

The second boat position (P2) was located directly in front of the undershot sluice gate in order to detect potential passing of Silver Eels (Fig. 1). In this position, the pitch was set to -24.9° and the tilt was set to -29.3°. Eel Migration was defined as follows: Every eel on the video passing through the gap between the river bottom and the undershot sluice gate was counted as one Eel Migration record. Since no backward movement of the eels was detected through the undershot sluice gate, double counts can be excluded. The Eel Migration was observed during two phases of different opening widths in 2015 (20 cm and $\leq$10 cm) resulting in different current velocity conditions. Due to the lower discharge conditions in 2016 the undershot sluice gate operated only $\leq$10 cm opening width.

2.4. Analysis of the sonar data

The total observation period (157.75 h) was subdivided into 0.25 h sample interval units (N = 631). Eel Activity and the numbers of migrating eels were determined by an independent visual counting by four experts in order to eliminate personal bias. As a high consistency among the counts with no significant differences among observers was evident, the mean value of the four counts was used for the following analysis. Every expert watched the data independently with the Software ARIScope (Soundmetrics, Belleview, USA) and counted the Eel Activity and the Eel Migration. As a result, the study comprised 631 sample units of 0.25 h observation periods each (Table 1). However, technical constrains at the study site and the changing water level during the expected migration period of *A. anguilla* produced an uneven sample size among the different treatments. A total of 52 sample units were recorded for the Eel Activity in 2015, comprising 23 sample units during daytime when the undershot sluice gate was closed and 23 sample units during nighttime when the undershot sluice gate was closed. Additionally, 3 sample units during daytime when the undershot

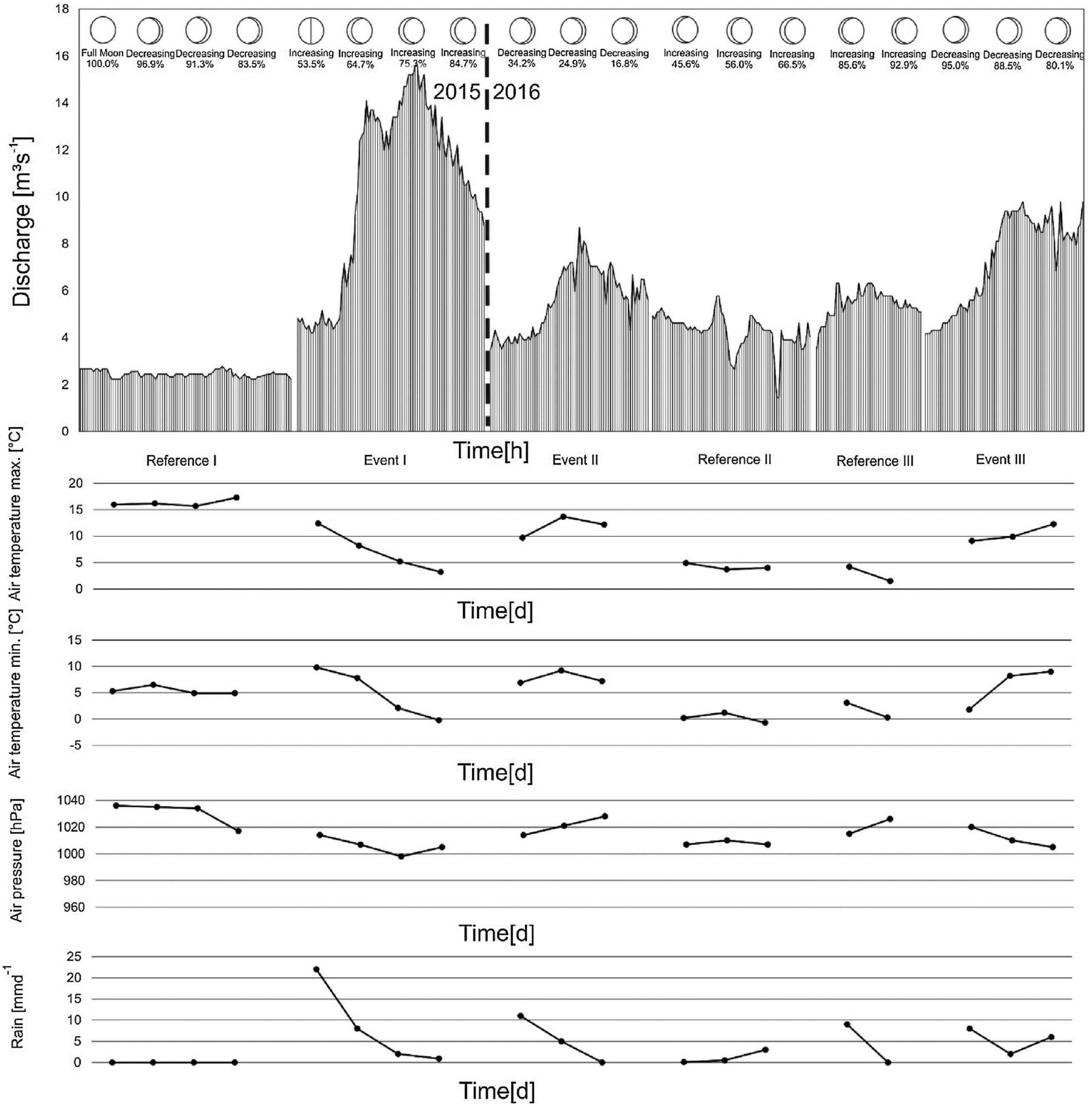

Fig. 2. Lunar phase (percentage of the illuminated moon [%]) is shown on top of the figure. Discharge of the Franconian Saale during the study period.

Table 1
Replicates of the different treatments.

Treatment	2015	2016
Eel Activity Night 0 cm	23	125
Eel Activity Night 10 cm	3	17
Eel Activity Day 0 cm	23	187
Eel Activity Day 10 cm	3	3
Eel Migration Night 10 cm	42	176
Eel Migration Night 20 cm	3	–
Eel Migration Day 10 cm	9	17

sluice gate was opened and 3 sample units during nighttime when the undershot sluice gate was opened. Fifty four sample units of 0.25 h observation periods each were recorded for Eel Migration in 2015, comprising 9 sample units during daytime, 42 sample units during nighttime when the opening width of the undershot sluice gate was $\leq$10 cm and 3 sample units during nighttime when the opening width of the undershot sluice gate was 20 cm.

In 2016, a total of 332 sample units were recorded for the Eel Activity, comprising 125 sample units during daytime when the undershot sluice gate was closed and 187 sample units during nighttime when the undershot sluice gate was closed. Additionally, the study comprised 3 sample units during daytime when the undershot sluice gate was opened and 17 sample units during nighttime when the undershot sluice gate was opened. One hundred ninety three sample units of 0.25 h observation periods each were recorded for Eel Migration in 2016, comprising 17 sample units during daytime and 176 sample units during nighttime. Due to the lower discharge conditions in 2016, the undershot sluice gate was not opened more than 10 cm. For the analysis of the actual eel migration, only the sample units were used which could be clearly identified as a migration event. An actual migration event was defined by the first appearance of a Silver Eel.

2.5. Statistical analyses

In order to detect differences between the treatments we used univariate statistics. The dataset was analyzed with the software R (www.r-project.org). Each dataset was tested for normality and homogeneity of variance by using the Shapiro–Wilk-test and the Levene-test. The *t*-test was used if the data showed normal distribution. When data were not normally distributed, the Mann–Whitney-*U*-test was used to test for differences between the treatments. Spearman-Rank correlation and Power regression models were used to test for correlation between the mean velocity and the number of migrating Silver Eels in 0.25 h intervals. In all statistical testing, significance was accepted at $p < 0.05$.

3. Results

3.1. Observed silver eel migrations

A total number of 191 Silver Eels was recorded using the undershot sluice gate in 2015 (Event I: 20–21 October 2015). The great majority of them (96%) migrated during nighttime with a peak migration of up to 28 eels/0.25 h. During this migration peak, the water temperature reached 9.9 ± 0.4 °C (mean ± standard deviation) and turbidity reached 17.3 ± 9.5NTU. At the onset of the observed migration event the weather situation changed, with a 9 °C decrease in air temperature, a 16 hPa decrease in air pressure and a 21 mm increase of rainfall within a day (Fig. 2). The moon was in the first quarter of its phase with an up to 75.3% illuminated circle (Fig. 2). Eel fishermen at the River Main, of which the Franconian Saale is a major tributary, confirmed that our study period exactly matched the predominant Silver Eel migration (Personal communication C. Schaetzl). In the following year, two migration events were recorded (Event II: 24–25 October and Event III: 17–18 November). During the first migration event in 2016 (Event II), a total of 23 Silver Eels were recorded using the opened undershot sluice gate. In this event, every Silver Eel migrated during nighttime (100%), with a peak migration of up to 6 eels/0.25 h. During this migration peak, the water temperature reached 9.3 ± 0.4 °C and turbidity was 8.6 ±0.2NTU (Table 2). At the onset of the observed migration event the weather situation changed, with a 4 °C increase in air temperature, a 15 hPa increase in air pressure and a 9 mm increase of rainfall (Fig. 2). The moon was in the last quarter of its phase with an up to 34.2% illuminated circle (Fig. 2). During the last observed migration event in 2016 (Event III) a total of 18 Silver Eels were recorded using the opened undershot sluice gate. As in Event II, every Silver Eel migrated during nighttime (100%) with a peak migration of up to 3 eels/0.25 h. During this migration peak, the water temperature reached 4.8 ± 0.2 °C and turbidity reached 4.9 ± 1.3NTU (Table 2). At the onset of the observed migration event the weather situation changed, with an 11 °C increase in air temperature, a 26 hPa decrease in air pressure and a 7 mm decrease of rainfall within a day (Fig. 2). The moon was in the third quarter of its phase with an up to 95.0% illuminated circle (Fig. 2).

Eel Activity as an indicator of an upcoming eel migration event revealed differences between the periods of low discharge and floods. During Reference I the Eel Activity in front of the fish protection screen was significantly lower (0.1 ± 0.4 eels/0.25 h) compared to Event I (64.2 ± 55.4 eels/0.25 h; Mann–Whitney-*U*-test: W = 9600; $p < 0.001$). During Event I in late fall the abiotic parameters changed, with a 1.8 °C decrease in water temperature, three-fold higher turbidity, four-fold higher current velocity above bottom and a four-fold increase in discharge (Table 2).

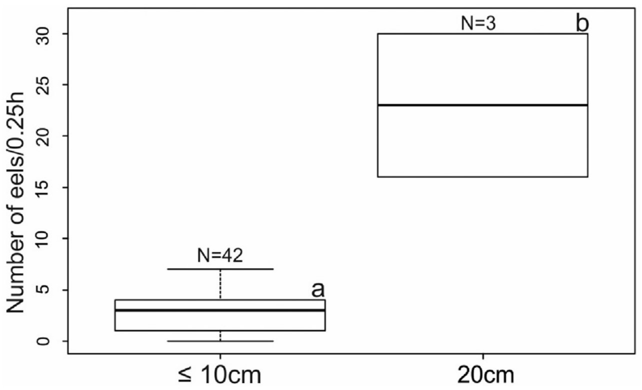

Fig. 3. Boxplot of the detected Eel Migration/0.25 h through the undershot sluice gate with an opening width of ≤10 cm and an opening width of 20 cm during Event I. Box: 25% quantile, median, 75% quantile; whisker: minimum and maximum value. Significant differences were visualized by different letters (a,b).

As in 2015, during Reference II and Reference III the Eel Activity in front of the protection screen was significantly lower (0.0 ± 0.0 eels/0.25 h) compared to Event II and Event III (8.4 ± 7.4 eels/0.25 h; Mann–Whitney-*U*-test: W = 7772; $p < 0.001$). Event II showed a 3.0 °C higher water temperature compared to Reference II and III, two-fold higher turbidity, two-fold higher current velocity above bottom and a 1 m^3 increase in discharge. Furthermore Event III showed different abiotic parameters compared to Reference II and Reference III conditions. Water temperature fell down to 4.8 °C, turbidity raised up to 4.9NTU, current velocity above bottom showed a three-fold increase and a 2.4 m^3 s^{-1} increase in discharge.

3.2. Opening width of the undershot sluice gate

In line with our hypothesis, eels predominantly used the undershot sluice gate as a passage corridor in both years, with eel detections strongly depending on the opening width of the undershot sluice gate during Event I (opening width = 20 cm: 23.4 ± 5.5 eels/0.25 h; opening width ≤10 cm: 2.7 ± 1.6 eels/0.25 h). Despite a comparable low number of replicates (N = 3) with an opening width of 20 cm, the detected Eel Migration was significantly higher at an opening width of 20 cm compared with an opening width of ≤10 cm (Mann–Whitney-*U*-test: W = 0; $p < 0.001$) (Fig. 3).

Caused by the greater opening width of the undershot sluice gate, current velocity in front of this corridor increased by 26% during an opening width of 20 cm compared to an opening width ≤10 cm (opening width 20 cm: 0.5 ± 0.1 ms^{-1}; opening width ≤10 cm: 0.4 ± 0.0 ms^{-1}). Current velocity was positively correlated with the amount of migrating Silver Eels/0.25 h (Spearman Rank correlation: S = 9811.202; $p < 0.05$; rho = 0.3537). Additionally the results of the Power regression model ($R^2 = 0.5545$) supported this outcome (Fig. 4). The power regression model was mostly determined by the highest current velocity events at which the greatest Silver Eel passage occurred.

3.3. Screen approaches and gate operation

The analysis of nighttime Eel Activity in front of the fish protection screen of Event I revealed a response of *A. anguilla* to the opening of the undershot sluice gate. Following the opening of the undershot sluice gate, Eel Activity in front of the fish protection screen decreased (before opening of the sluice gate = 131.7 ± 15.9 eels/0.25 h; after opening of the sluice gate = 102.5 ± 20.1 eels/0.25 h) since eels were attracted to the alternative corridor. Due to the small number of replicates, the difference observed in 2015 was not statistically significant (*t*-test:

Table 2
Abiotic habitat characteristics during the study period. All values are given as arithmetic mean ±standard deviation.

Date	Reference I	Event I	Event II	Reference II	Reference III	Event III
Temperature [°C]	11.67 ± 0.69	9.91 ± 0.42	9.23 ± 0.38	6.77 ± 0.04	5.73 ± 0.04	4.82 ± 0.20
Dissolved oxygen [mg L^{-1}]	10.17 ± 0.32	9.63 ± 0.15	10.45 ± 0.06	10.60 ± 0.10	11.28 ± 0.02	11.31 ± 0.08
Electric conductivity [μS cm^{-1}]	1135.83 ± 30.65	916.25 ± 171.49	1138.66 ± 5.90	1129.33 ± 10.84	1051.00 ± 0.00	1079.33 ± 15.52
pH	8.15 ± 0.09	7.86 ± 0.02	9.03 ± 0.48	9.34 ± 0.24	8.94 ± 0.01	9.00 ± 0.26
Turbidity [NTU]	6.19 ± 1.70	17.27 ± 9.45	8.61 ± 0.19	3.87 ± 0.38	3.97 ± 0.25	4.91 ± 1.33
Current velocity near surface [ms^{-1}]	0.07 ± 0.03	0.35 ± 0.17	0.13 ± 0.05	0.07 ± 0.03	0.11 ± 0.02	0.16 ± 0.01
Current velocity middle [ms^{-1}]	0.10 ± 0.04	0.42 ± 0.13	0.20 ± 0.07	0.10 ± 0.02	0.15 ± 0.03	0.29 ± 0.08
Current velocity above bottom [ms^{-1}]	0.11 ± 0.03	0.49 ± 0.13	0.21 ± 0.04	0.10 ± 0.03	0.15 ± 0.03	0.35 ± 0.07
Discharge [m^3 s^{-1}]	2.45 ± 0.13	10.32 ± 3.79	5.60 ± 1.37	4.25 ± 0.78	5.46 ± 5.5	7.26 ± 1.92

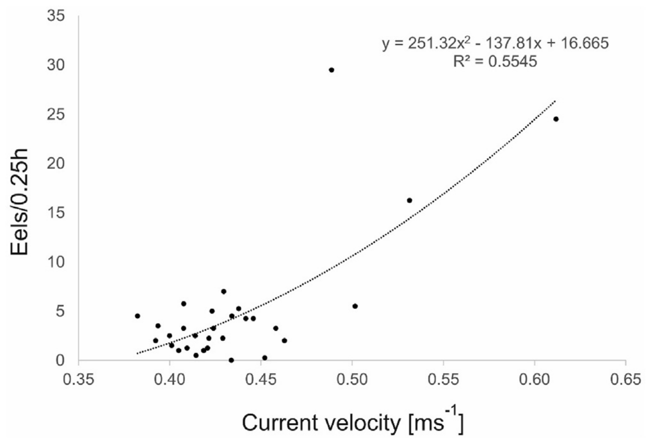

Fig. 4. Power regression between the current velocity (x-axis) and the recorded number of migrated eels (y-axis). Each data point represents a 0.25 h time interval.

$t = 1.6094$; $df = 3.809$; $p > 0.05$). In contrast, the analyses of Event II and Event III in 2016 revealed a significant response of *A. anguilla* to the opening of the undershot sluice gate (Mann–Whitney-*U*-test: $W = 269$; $p < 0.05$). The Eel Activity in front of the fish protection screen decreased significantly after the opening of the undershot sluice gate (before opening of the sluice gate = 10.6 ± 6.9 eels/0.25 h; after opening of the sluice gate = 5.6 ± 3.3 eels/0.25 h) (Fig. 5).

3.4. *Diurnal patterns of the observed eel migration*

The results of this study revealed diel patterns of Eel Activity and Eel Migration over all migration events. During nighttime (117.1 ± 33.7 eels/0.25 h) the recorded Eel Activity in Event I was significantly higher compared to daytime (11.3 ± 3.5 eels/0.25 h; Mann–Whitney-*U*-test: $W = 0$; $p < 0.001$) (Fig. 6). During an opening width of ≤ 10 cm, significantly more Silver Eels migrated through the opened undershot sluice gate during nighttime (2.6 ± 1.6 eels/0.25 h) compared with daytime (0.9 ± 1.1 eels/0.25 h; Mann–Whitney-*U*-test: $W = 1682.5$; $p < 0.001$) (Fig. 7). In the following year, the Silver Eels revealed the same diel preferences. During Event II and Event III the recorded nocturnal Eel Activity was significantly higher compared to daytime (nighttime: 10.6 ± 6.9 eels/0.25 h; daytime: 0.6 ± 1.3 eels/0.25 h) (Mann–Whitney-*U*-test: $W = 10.5$; $p < 0.001$) (Fig. 6).

As in 2015, significantly more Silver Eels migrated through the opened undershot sluice gate during nighttime in 2016 (nighttime: 1.0 ± 1.0 eels/0.25 h; daytime: 0.0 ± 0.0 eels/0.25 h) (Mann–Whitney-*U*-test: $W = 45$; $p < 0.01$) compared with daytime (Fig. 7).

3.5. *Eel bypass system*

In contrast to the current perception on using the zig-zag shaped eel bypass tube as a technical standard to facilitate eel downstream migration, not a single Silver Eel out of a total eel count of 1323 over both years used this corridor. This finding was unexpected, particularly since 775 (in 2015) and 548 (in 2016) counts were recorded in front the fish protection screen which is located directly adjacent to the entrance of the eel bypass tube.

4. Discussion

The results of this study support that management of Silver Eel migration should primarily target a narrow time window during late fall and at nighttime, specifically during periods of increased water flow and increased turbidity. Undershot sluice gate management, which is currently hardly considered in facilitating the downstream migration of *A. anguilla*, appears to be a promising management approach at small-scale HPPs, since our data clearly suggest that the opening of these structures attracts Silver Eels.

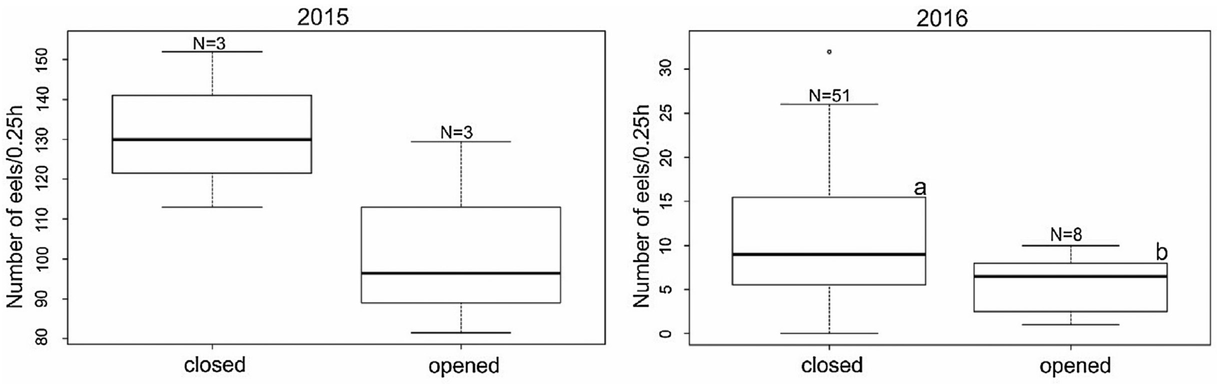

Fig. 5. Boxplots of the recorded Eel Activity/0.25 h in front of the fish protection screen for the opened and closed undershot sluice gate conditions during 2015 and 2016. Box: 25% quantile, median, 75% quantile; whisker: minimum and maximum value. Significant differences were visualized by different letters (a, b).

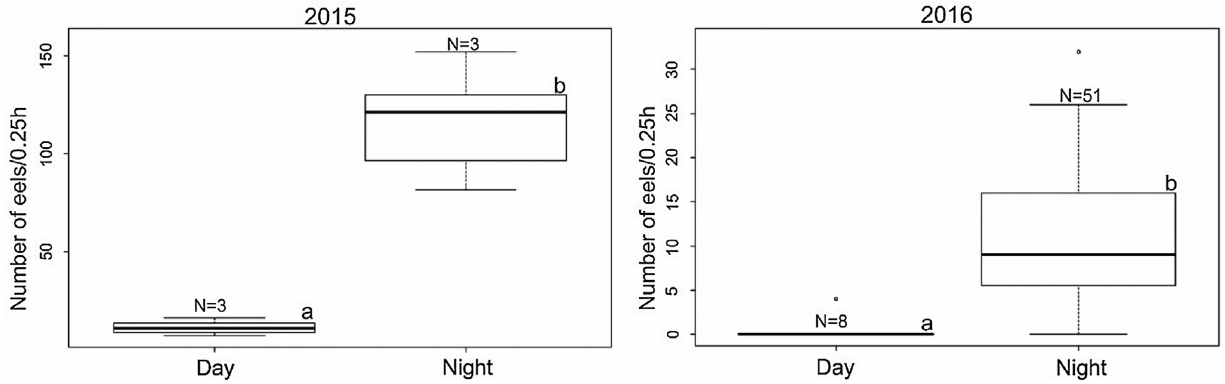

Fig. 6. Boxplots of the recorded Eel Activity/0.25 h in front of the fish protection screen during time period in 2015 and 2016. Box: 25% quantile, median, 75% quantile; whisker: minimum and maximum value. Significant differences were visualized by different letters (a, b).

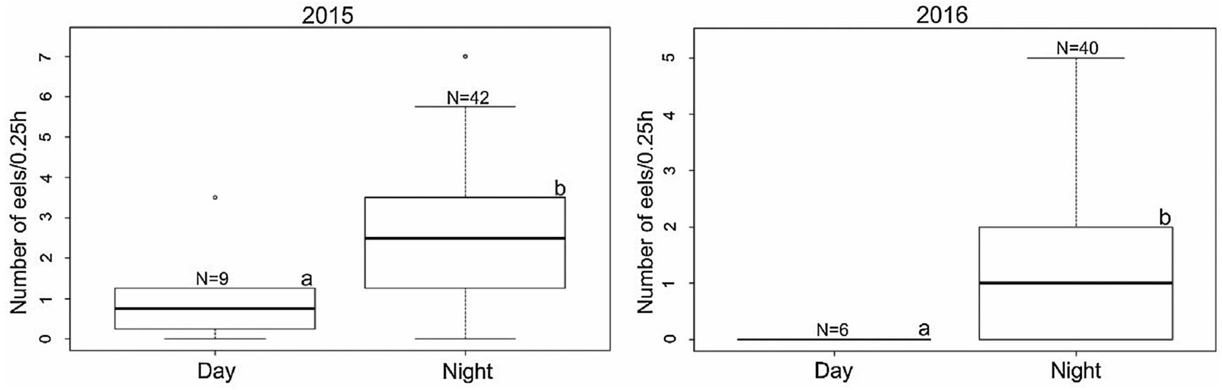

Fig. 7. Boxplots of the recorded Eel Migration/0.25 h through the undershot sluice gate during time period in 2015 and 2016. Box: 25% quantile, median, 75% quantile; whisker: minimum and maximum value. Significant differences were visualized by different letters (a, b).

The opening width of the sluice gate and the resulting change in current velocity in front of this structure were the main parameters affecting its effectiveness as a migration corridor for Silver Eels. In contrast to the Silver Eel management approach proposed herein, currently used alternative management options, such as the methodology of "Trap and Truck", the "Migromat" and eel bypass systems (Bruijs et al., 2009MacCarthy et al., 2008) are economically disadvantageous under most circumstances.

Silver Eels are generally known to follow the main current during their downstream migration (Gosset et al., 2005; Jansen et al., 2007; Travade et al., 2010) which can also explain the high activity of Silver Eels in front of the horizontal screen where the main discharge is located. The eel bypass system was originally expected to be a main corridor for the downstream migration of Silver Eel since previous laboratory studies by Hassinger and Huebner (2009) had suggested passage rates of >90% through this type of system. However, none of the Silver Eels used this corridor at the field site studied herein, questioning the general applicability of this bypass. Based on our sonar observations, it is likely that the major reason for this is clogging by leafy debris, which is mobilized during flood events in fall. This debris accumulated in front of the entrance holes of the eel bypass system, in turn reducing the functionality of this corridor for the downstream migration of Silver Eels.

In contrast to the current perception that the orientation of the Silver Eels is restricted to the main current flow, the results of this study suggest that Silver Eels were able to detect and effectively use the opened undershot sluice gate as an alternative corridor, even though the discharge of this corridor was low compared to the main current. In this context, current velocity can play an important role for the detectability of alternative corridors by migrating Silver Eels as shown by Carton (2001). According to Baker and Montgomery (1999), Montgomery et al. (1995) and Montgomery et al. (1997) fishes are able to detect minimal changes in the current velocity with their lateral line. This is in line with the findings of this study, where a higher current velocity at the undershot sluice gate resulted in a higher number of Silver Eels using this corridor. After reaching the barrier of the fish protection screen, the Silver Eels started to actively search for alternative corridors and responded immediately to the opening of the undershot sluice gate.

According to Calles and Bergdahl (2009) and Adam et al. (2002), the maximum gap size of a screen should be 18 mm in order to prevent Silver Eels from entering the turbine passage. In addition to the narrow bar spacing of the screen, the positioning of the alternative corridor in direct spatial proximity to the main current can ensure optimal detectability for the migrating eels. The increase in migration activity with increasing opening size of undershot sluice gates likely results from the observed increase in current velocity, which acts as a trigger for Silver Eels to be attracted away from the main current. Consequently, it does not appear necessary to relocate the main current to the sluice gate, but the creation of an additional attraction flow seems to be advantageous, especially when combined with a fish protection screen that prevents Silver Eels from entering the turbine passage. According to Tudorache et al. (2015) the critical swimming capacity of mature *A. anguilla* (0.94 ms^{-1}) was not exceeded at the opened undershot sluice gate in this study (max. 0.61 ms^{-1}). Thus it can be assumed that the Silver Eels actively choose this corridor. In addition to their ability to detect changes in current velocity, fishes and especially *A. anguilla,* are also able to register minor changes of sound patterns (Purser et al., 2016; Slabbekoorn et al., 2010). Thus, a response of the Silver

Eels to this signal can be an alternative explanation for the observed behavior.

Because a permanent opening of the sluice gate may be rarely possible, it would be beneficial to know over what environmental ranges the sluice may be best operated to maximize passage. Previous studies identified many factors (e.g. lunar circle, daytime, turbidity, temperature, and discharge) that were correlated with Silver Eel downstream migration (Reckordt et al., 2014; Barry et al., 2015; Behrmann-Godel and Eckmann 2003). Miyai et al. (2004) observed that the downstream migration occurred during new moon or in the moons last quarter. In line with this finding, the two migration events in 2016 (Event II and Event III) took place in the decreasing half of the moon phase. However, the migration event with the highest numbers of migrating Silver Eels in this study (Event I) was during the moon's first quarter. Thus, it can be assumed that the lunar phase is not a major trigger for the Silver Eels to start their migration. Similar to this finding, no trend could be detected for air pressure as a trigger for the seaward migration of Silver Eels. According to Okamura et al. (2002) atmospheric depressions might be a major trigger for Silver Eels to start their migration (Fig. 2). While Event I and Event III occurred during phases of decreasing air pressure, Event II took place in a phase of increasing air pressure. According to the present study, the increase in discharge and turbidity seem to be the most crucial triggers for the Silver Eel downstream migration at the Franconian Saale. Euston et al. (1997), Durif et al. (2003) and Behrmann-Godel and Eckmann (2003) also propose that the Silver Eel migration starts with the first increase of discharge in fall. Additionally, Silver Eels are supposed to reach a maximum migration rate at 9 °C, whereas the migration rate decreases in both directions of higher and lower temperatures (Vollestad et al., 1986). This is partially supported by the findings of the present study, considering the discharge of the Franconian Saale and the mean temperature of Event I (9.2 °C) and Event II (9.4 °C). However, Silver Eels also migrated during Event III, when the mean water temperature reached 4.7 °C. Consequently, it can be assumed that the migration period of *A. anguilla* is not strictly limited by lower water temperatures, even though the number of migrating Silver Eels was much lower compared to Event I and Event II. Since the ideal combinations of discharge and temperature only occur during narrow time windows throughout the year, the management of Silver Eel migration by opening undershot sluice gates can be limited to a few days per year and site, resulting in minimum disturbance of hydropower plant operation. Besides the measurement of environmental factors to predict eel migration events, visual observations of eel behavior using the Migromat system (Adam, 2000) can improve the accuracy of the prediction of eel migration. Vollestad et al. (1994) showed that the migration of tagged Silver Eels is faster after sunset. According to Bruijs et al. (2003) and Miyai et al. (2004) most of the Silver Eels migrate during the night. This is also supported by our study, where Eel Activity as well as Eel Migration was higher during nighttime, indicating that undershot sluice gate management during the night could be sufficient to facilitate successful Silver Eel migration. Due to the increased water flow during a Silver Eel migration event, the additional water, which is anyway not useable for electric power production in the HPP, can be passed through an undershot sluice gate at no additional costs for the hydropower company. Boubèe and Williams (2006) recommend the opening of an alternative corridor during the whole migration period of the Silver Eels. Whereas an automated undershot sluice gate opening at rising water levels at nighttime during fall is likely to improve the successful migration of Silver Eel at the study site, and possibly elsewhere. Therefore, additional studies (e.g. net or telemetric based) should be carried out to validate the results of this study at different HPP's. However, it has to be considered that differences in water pressure caused by height differences at sluice gate structures have the potential to cause fish damage as detected in Baumgartner et al. (2006) for fish larvae. Therefore, additional assessments of critical pressure differences should be carried out and compared to the potential damage of turbine passages. Additionally, an adequate downstream depth of plunge pools might be advantageous in order to dissipate energy and reduce the risk of striking downstream structures.

5. Conclusion

The approach of guiding Silver Eels through already existing technical structures of HPPs, revealed the potential to significantly improve the downstream migration of *A. anguilla*, at comparatively low economical cost. According to this study, Silver Eels used the opened undershot sluice gate as a corridor during their downstream migration in two consecutive years. After the opening of the undershot sluice gate, Eel Activity in front of the fish protection screen decreased. This leads to the conclusion that migrating Silver Eels were able to recognize the additional corridor, even if the main flow runs through the turbine passage. The detectability of the corridor was strongly dependent on the opening width of the structure and the resulting higher flow conditions in front of the alternative migration corridor. However, it is necessary to hinder the Silver Eels from entering the turbine passage. For that reason it is crucial that this corridor is blocked by an adequate fish protection screen (15 mm in this case). The results of this study confirmed that the migration of Silver Eels is a nocturnal event and measures with the aim of ensuring their migration should concentrate during nighttime. Additionally, the study identified discharge, the resulting increase of turbidity and the water temperature as the main triggers for the start of the migration. Management plans of HPP's should consider the opening of undershot sluice gates during the main migration period of *A. anguilla* at rising water levels, at night and during fall months.

Geolocation information

The study was carried out at a hydropower plant at the Franconian Saale in Bad Kissingen in Bavaria, Germany (N50°10'47.5" E10°04'24.8").

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