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Loss of European silver eel passing a hydropower station

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Summary

The aim of this study was to assess escapement success of silver eels, *Anguilla anguilla* (L.), in a lowland river while passing a reservoir and a hydropower station. It was hypothesized that passage success would be lowest at the hydropower station and that survival and migration speed would be highest in the free-flowing river section upstream the reservoir. Forty-five female silver eels 56–86 cm in length were tagged with acoustic transmitters and released in November 2006. Their migration was monitored via automatic listening stations (ALS) in various sections of the river, covering a total migration distance of 64 km. Survival and progression rate of downstream migration was highest in the upstream river section and significantly lower in the reservoir. The eels apparently had trouble finding their way past the turbines and spent between 1.5 and 35 h in the forebay. The results show that within the study period, only 23% of the tagged eels reached the tidal limit, mainly due to difficulties in passing the hydropower dam. With such high loss-rates, the escapement goals set in the management plan cannot be achieved.

Introduction

The European eel population (*Anguilla anguilla* L.) has declined considerably over the past decades. The present recruitment of glass eels is only about 1–9% of the late-1970s level, indicating a historically low spawning stock in the Sargasso Sea (ICES, 2009). Consequently, the International Council for the Exploitation of the Sea (ICES) stated that the eel stock was beyond safe biological limits and recommended that anthropogenic activities affecting the stock be reduced as much as possible (ICES, 2001). This led to a proposed EU recovery plan for the eel populations (EU, 2007). As part of this plan, management measures must be implemented to meet a target of 40% silver eel escapement from individual river basins or eel management units.

Silver eel river migrations occur mainly during autumn, but some migration activity is also observed in the spring (Aarestrup et al., 2008). The timing of silver eel runs has been related to the increases in water discharge (Haraldstad et al., 1984; Vøllestad et al., 1986), lunar phases, and water temperature (Vøllestad et al., 1986; Tesch, 2003). Migration activity is, in general, nocturnal (Tesch, 2003).

To acquire knowledge on the behaviour and escapement of migrating silver eels, a series of studies was conducted in the River Gudenaa, Denmark. Previous studies investigated behaviour and survival in the lower river and estuary (Aarestrup et al., 2008, 2010). The present study focuses on the middle part of the river where downstream-migrating fish have to pass free-flowing river sections, a reservoir and a hydropower station.

The behaviour of downstream migrating eels at hydropower stations has been the subject of a number of studies (i.e. Haro et al., 2000; Behrmann-Godel and Eckmann, 2003; Durif et al., 2003; Gosset et al., 2005; Boubée and Williams, 2006; Calles et al., 2010). The general finding is that *A. anguilla* approaching a power station often hesitate to continue their migration, and only after repeated attempts may pass the hydropower station either through the turbines, spillways or the bypass passages. The two principal direct causes of mortality at hydropower stations are turbine-related mortalities and impingement on the screens (Monten, 1985; Calles et al., 2010). Carr and Whoriskey (2008) found 100% mortality of American eels (*Anguilla rostrata*) descending through turbines at a hydropower station. Winter et al. (2006) demonstrated that fishing and hydropower were the main causes for mortality of migrating eel in the River Meuse. Breteler et al. (2007) found that only 23% of silver eels had successfully migrated through the lower 300 km of the Rhine River.

The objective of this study was to assess overall escapement success of silver eels migrating through regular river sections, a reservoir and a hydropower station. For future eel management it is imperative that knowledge on escapement is available. It was hypothesized that passage success would be lowest at the hydropower station and that survival and migration speed would be highest in the free-flowing river section upstream the reservoir.

Materials and methods

The River Gudenaa (55°52′N, 9°33′E) is a lowland stream 160 km long with a catchment area of 2631 km^2 and a mean annual discharge of 32 m^3 s^{-1}. The river system is strongly influenced by human activities, including canalization, nutrient loading from agriculture, hydropower damming, and development. There are seven small hydropower stations on the River Gudenaa. The largest and lowermost is the Tange Hydropower station (Fig. 1) with a catchment of 1699 km^2 (65% of the total catchment) and a mean annual discharge of 21 m^3 s^{-1} at the station. The station is situated 35 km from the tidal limit and has three Francis turbines. The reservoir, Lake Tange, has a surface area of 537 ha, length of 8.5 km and with a depth of < 8 m.

To protect migrating fish, Danish legislation requires physical screens with a maximum bar distance of 10 mm to be installed in front of hydroelectric turbines. This is also the case at the Tange hydropower station, with 10 mm screens that should keep silver eels from entering the turbines. There are

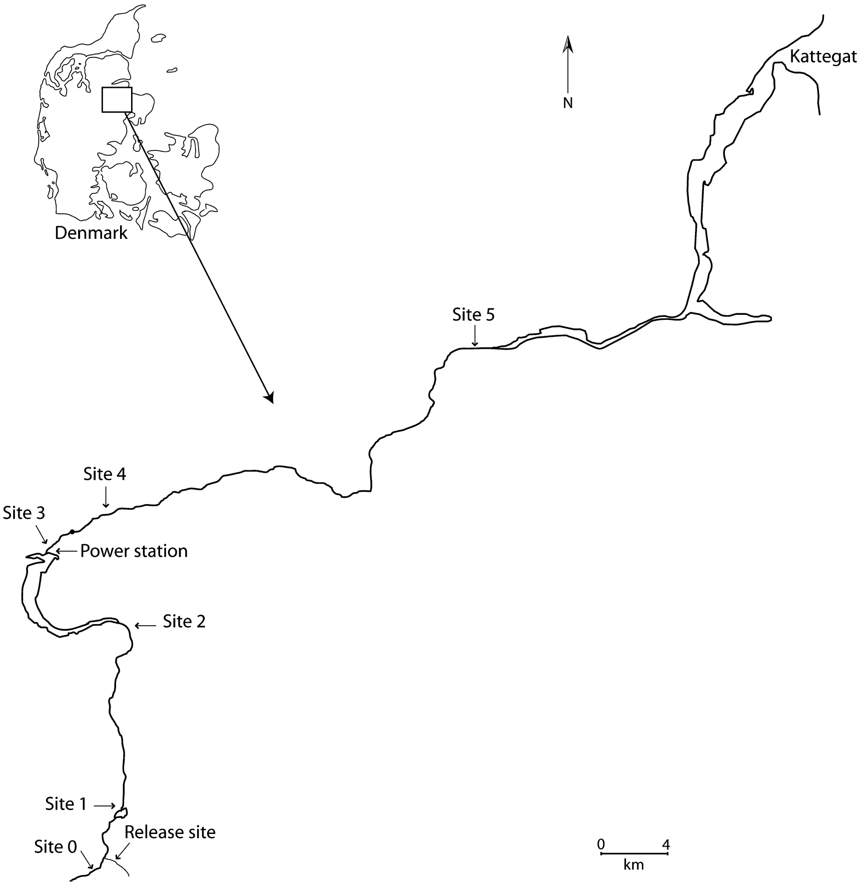

Fig. 1. Map of study area showing lower and middle part of River Gudenaa, Denmark. Automatic detection stations installed at all Sites 0–5. River width varies from 15 to 30 m. Mean annual discharge at Site 3 was 21 $m^3 s^{-1}$

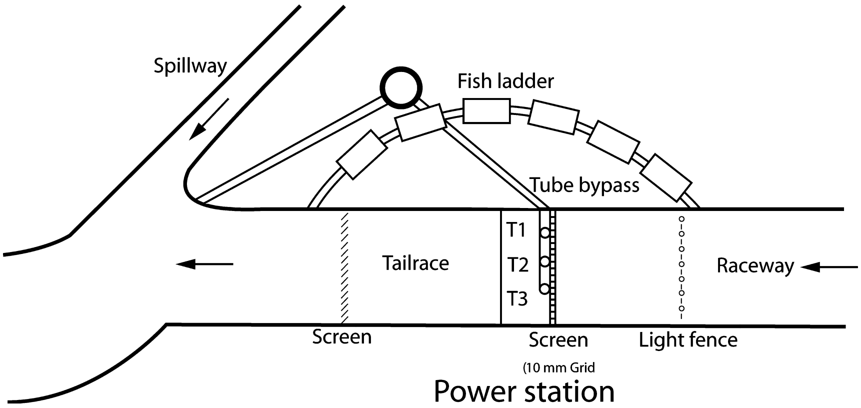

Fig. 2. Schematic diagram of Tange hydropower station with position of fish ladder and bypass in the deflecting screens in front of the three Francis turbines

two fish bypass facilities (Fig. 2), one is a Denil type fish ladder with resting pools and with an entrance situated approximately 200 m upstream the turbines (Fig. 2). The other bypass system consists of three (30 cm Ø) tube bypasses installed to help downstream-migrating fish, especially salmonid smolts, to bypass the turbines. One tube bypass is placed in each of the three turbine screens approximately 0.5 m below the water surface. Water discharge in the two different bypass systems fluctuates with the number of turbines in use. The bypass flow from each turbine in use is 150 L s^{-1}. In the fish ladder there is a constant flow of 150 L s^{-1}. When all three turbines are in use, the maximum discharge in the bypasses is 600 L s^{-1}, < 3% of the mean total discharge. A light fence is installed to guide eels to the fish ladder entrance (Fig. 1), but the effect of this has never been evaluated.

In the study area there is one commercial fisherman operating in the Tange reservoir using pound nets. Cormorants *Phalacrocorax carbo sinensis* can be observed foraging in the reservoir. The birds are possibly from a colony with 50–200 nests approximately 15 km from the reservoir.

The studied river stretch is 63.5 km. The study area was divided into five sections (Fig. 1). The first section covers a distance of 4.1 km of free flowing river. The second section is 14.2 km of river and ends at the inlet of the reservoir. The third section is the reservoir including the power canal (8.5 km). The fourth section is the area from the end of the inlet canal to the listening station 3.5 km downstream of the hydropower station. The fifth section goes to the tidal limit and is 33.3 km long.

Forty-five downstream migrating silver eels were captured in the autumn of 2006 in a permanent eel trap at the Vestbirk hydropower station approximately 30 km upstream the release site. Eels caught in the trap were kept in net-pens in the river for 1–7 days before tagging. Eels were transferred to the laboratory of DTU Aqua on 1–2 November and tagged by surgical implanting with THELMA Ltd., Norway, LP-9 acoustic transmitters (9 × 34 mm, weight in air of 5.3 g, weight in water of 3.3 g, guaranteed life time of 148 days) using the method described by Aarestrup et al. (1999). The tags had a programmed random interval range between transmitted signals. Mean body length of the tagged fish was 66.3 ± 7.2 cm (SD) (range 56–86 cm), mean body mass 551 ± 213 g (range 303–1309 g). After tagging the eels were kept in recovery tanks, from 1 to 8 h and by dusk released in a small tributary approximately 300 m upstream the confluence with the River Gudenaa. All tagged eels were released on 1–2 November.

Twelve hydrophone buoys (ALS, VR2; VEMCO Ltd., Canada) were placed pairwise at six sites (detection stations) in the river (Fig. 1). These were continuously in operation from 15 October 2006 to 25 March 2007. At each site, two hydrophones were moored in the river approximately 25 m apart. The ability of the VR2 to detect acoustic signals in a range wider than the river was tested on all stations. In the power-channel of the hydropower station significant acoustic noise occurs as a consequence of the turbines. Four VR2s were placed to cover the entire water column: two close to the surface and two at the bottom. A single VR2 was placed to detect upstream migration following release (Site 0, Fig. 1) and one VR2 was placed at the tidal limit (Site 5).

Migration (progression) speed was calculated as the time between first detection at site t and first detection at site $t + 1$ divided by distance (d).

Statistical analysis

To test whether progression speed in the river section 1 between the detection station 1–2 could explain survival of the eel to the tidal limit, a logistic regression with survived ⁄ dead as the dependent variable and progression speed in river section 1 as the predictor variable was performed, and body length and body weight were entered in the model as covariates.

Progression speed was compared between two river sections and the reservoir by repeated-measures ANOVA (r-m ANOVA) with one within-subject factor (compartment). R-m ANOVA was preferred to a profile analysis (MANOVA) that has lower statistical power (Maxwell and Delaney, 1990; Potvin et al., 1990). To compensate for violation of the sphericity assumption, the degrees of freedom were decreased by multiplication by the Huynh-Feldt epsilon, which is a less conservative adjustment than Greenhouse-Geisser and is recommended when sample sizes are small (Von Ende, 1993; SPSS, 1997). The data was log ($X + 1$) transformed to meet the requirements of parametric analysis (i.e. normality and homoscedasticity). Tests of within-subjects contrasts were achieved by a repeated design and Bonferroni adjusted (Von Ende, 1993).

Results

Two of the 45 tagged eels were not detected after release at any of the detection stations. Their fate is unknown and they are therefore omitted from further analyses.

Forty-three eels resumed downstream migration after release. Of these, 10 eels were detected at the tidal limit (Fig. 1, Table 1). Thus, during the study period (1 November 2006–25 March 2007), the observed overall passage ⁄ success of tagged eels entering the first station to the estuary is 23%. Eels were lost in the reservoir (n = 5) and in the last section of the river (n = 6), but the major loss occurred between Sites 3 and 4 where the eels had to pass the Tange Hydropower station. Here, 38 eels were detected in the inlet, but only 16 eels were detected at the next downstream station during the study period. Thus, 22 eels did not pass the power station and subsequently the loss was considerably higher at the station than at all other sections.

Following release, the tagged eels (n = 43) moved downstream after 0–38 days (mean 9.2 days). No tagged eels were detected at the upstream detection station Site 0. Seventeen eels quickly resumed migration and were detected at Site 1 within 24 h. One eel migrated on day two. Fourteen eels were detected between 7 and 12 days post release, and between days 12 and 38 the remaining 11 eels were detected at Site 1. Once having resumed migration, most eels (n = 40) moved quickly downstream to the reservoir at a mean speed of 3.4 km h^{-1} range (0.8–5.9 km h^{-1}). The majority of eels reached the reservoir within the same night as they resumed their migration. Three eels, however, spent 6, 10 and 14 days before they reached the reservoir (Site 2).

After arriving in the reservoir the migrants spent an average 8.2 days (range 0.2–34.8 days) (n = 38) before entering the power canal (Site 3). Most of the eels approached the station several times over several days before entering, and seven of the 38 eels detected in the canal reversed their direction of migration and passed back and forth between the inlet and the outlet of the reservoir (Sites 2 and 3), a distance of 8.5 km. After arriving at the power canal the second time, three individuals finally passed the hydropower station.

The eels clearly had problems locating ⁄ entering the bypass facilities, illustrated by the fact that they spent much more time passing the detection station in the canal than they did at the other stations (Table 1).

The 16 eels that succeeded in passing the hydropower station spent from 2 h to 63 days with a mean of 11 days 5 h before passing. The last 33.1 km to reach the tidal limit (Site 4–5) were completed on average in 1.3 days (range 0.42–6.35 days).

The logistic regression showed no effect of the progression rate in the river section between Sites 1 and 2, body length or body weight on the loss of eels ($P > 0.228$).

The r-m ANOVA revealed that the progression speed differed among the three sections Sites 1–2, 2–3 and 3–4 ($P < 0.0001$). Progression speed was not statistically dependent on body length or body weight ($P > 0.857$). None of the interaction terms was statistically significant ($P > 0.868$). The Within-Subjects contrast test showed that there was a significant difference between sections Sites 1–2 and 2–3 ($P < 0.0001$), and no significant difference between sections Sites 2–3 and 3–4, respectively ($P = 0.132$).

Table 1
Number of acoustic tagged silver eels (*Anguilla anguilla*) detected at downstream sections (Fig. 1), time spent and progression rate of downstream migration in each River Gudenå section. Mean length of time (minutes) spent within range of each detection station is given

River section	Release – Site 1	Site 1–2	Site 2–3	Site 3–4	Site 4–5
Habitat	River	River	Reservoir	Power station	River
No. of eels detected	43 (100%)	43 (100%)	38 (88%)	16 (37%)	10 (23%)
Mean time (h) (range; SD)	226 (4–918; 263)	21 (2–335; 65)	220 (5–881;224)	512 (25–1680; 545)	32 (10–152;43)
Mean progression rate (km h^{-1}) (range; SD)	0.24 (0.95–0.00; 0.3)	3.71 (5.25–0.04; 1.4)	0.16 (1.68–0.01; 0.3)	0.04 (0.14–0.00; 0.1)	1.05 (3.26–0.22; 1.1)
Distance from release site (km)	4.1	18.2	26.7	30.2	63.5
Mean time (min) for passing each detection station (range)	4.7 (1–22)	22.9 (1–260)	1179.5 (108–5760)	39.6 (1–600)	2.5 (1–6)

Discussion

Overall escapement to the tidal limit from the investigated 63.5 km river stretch was 23% in the autumn / winter 2006. This does not necessarily mean that the remaining 77% of the tagged eels died. It is a well-known fact that some silver eels halt their autumn migration and resume it the following spring or autumn (Winter et al., 2007; Aarestrup et al., 2008; Simon and Fladung, 2009). Own (unpublished) results from PIT-tagged eels in the Gudenaa show that approximately 10% resume migration the following spring. However, the observed 58% loss of silver eels during hydropower station passage is substantial, and in combination with other causes of loss, constitutes a major problem for the eel. Aarestrup et al. (2008, 2010) and found a 60–80% loss of *A. anguilla* moving through the Gudenaa estuary, presumably caused by fishing. The combination of hydropower station passage and estuarine fishing leaves very little chance for silver eels from the upper or middle Gudenaa catchment to reach the sea. The probability of reaching the estuary was not related to initial progression speeds observed at the first upriver section (Site 1–2). Progression speeds between sections varied and were found to be significantly different between river Site 1–2, the reservoir (Site 2–3), and the power station (Site 3–4). The differences in progression speeds were not related to size of the fish (length or weight); this is in contrast to movement monitored through the estuary where the larger eels did move faster (Aarestrup et al., 2010). Progression in the river was relatively fast, but slow through the reservoir. The delay at the reservoir and the hydropower station may increase the risk of predation from fishermen and cormorants and are likely causes of loss in the reservoir. The tags and tagging method used in this study have proven reliable in a number of studies already cited herein, but it cannot be ruled out that the adverse effects of capture, handling and tagging or transmitter malfunction could be reasons for the loss of some eels. However, earlier experience with the tags and studies of tagging effects (Baras and Jeandrain, 1998; Winter et al., 2005) gives reason to believe that it is not a problem.

A considerable number of eels (n = 22) did not pass the power station, suggesting that migrating silver eels have problems in locating the bypass openings. All eels spend a long time in the area in front of the entrance (power canal), as seen in the recordings from the station at Site 3 (Table 1). A number of eels (14) moved in and out of the power canal several times over a course of days - weeks before finally passing or disappearing. The opening of the bypass is at the surface, whereas silver eels migrate in midwater or near the bottom (Tesch, 2003). Consequently, the eels have to approach the surface to find the bypass. Haro et al. (2000) observed eels occupying a deep portion of a forebay, down to 10 m, but the eels made frequent excursions to the surface. Despite the fact that eels are known to be bottom-oriented, their vertical searching behaviour makes it possible for eels to locate and bypass hydroelectric stations through a surface bypass and spillway (Durif et al., 2003; Gosset et al., 2005; Watene and Boubée, 2005). The 10 mm bar spacing at the Tange power station prevents silver eels (down to approximately 35 cm length) from being sucked into the turbines. However, they can often be found impinged on the turbine screens; the proportion of eels that suffer this fate can be high (Calles et al., 2010). Gosset et al. (2005) found impingement to be related to the flow rate, and suggested a water velocity of less than 0.3 m s^{-1} to prevent impingement on 20 mm bar spacing on racks. The risk of impingement probably depends on the water temperature, eels being less likely to escape at low temperatures. Measurement of water velocity in front of the racks at Tange during low to moderate flow, showed values ranging from 0.26 to 0.48 m s^{-1}. During high flow, when eels are typically moving, values of up to 1 m s^{-1} can be expected. Eels that impinge on the turbine screens at Tange are subsequently removed (often dead or severely damaged) from the water with an automatic debris cleaner. Workers at the power station may spot eels among debris and subsequently release them downstream, or the eels will be trashed with the debris and die. Such releases of injured eels from the power plant may explain the relatively large proportion of eels (n = 6) lost in the last river section.

Combining the results from river loss in the present study with the loss in the estuary (Aarestrup et al., 2010) demonstrates a large loss of migrating silver eels in the Gudenaa system. The loss may be cumulative, with 10% or fewer *A. anguilla* reaching the sea. EU management goals for eels are thus not met in this system and action is required.

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