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RESEARCH ARTICLE

Route selection, migration speed, and mortality of silver eel passing through two small hydroelectric facilities

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Abstract. The European eel is a highly threatened species according the European Inland Fisheries Advisory Commission (EIFAC) and the Food and Agriculture Organization of the United Nations (FAO). The recruitment of this species has collapsed over the last fifty years primarily because of the destruction of free migration routes and overfishing. One of the most important factors linked to population decline is mortality during catadromous migration caused by hydroelectric facilities. The aim of the present study was to assess the mortality rate of silvers eel passing through two small hydroelectric facilities. Total mortality at the site was 5%, but it was 15% for fish passing through the two hydroelectric facilities. However, the cumulative mortality in the river basin studied, which has many hydroelectric facilities, indicated that silver eel escapement from the Słupia drainage basin was very low.

Keywords: silver eel migration, mortality, Francis turbine

Introduction

The European eel *Anguilla anguilla* (L.) is distributed throughout and exploited in most European countries and in large areas of African waters (Moriarty and Dekker 1997). This species undertakes a remarkable, catadromous spawning migration to the Sargasso Sea that is in excess of 5,000 km (Tsukamoto et al. 2002, Righton et al. 2016). In the Baltic Sea, the European eel is distributed in coastal waters and adjacent freshwater rivers, streams, and lakes (HELCOM 2013). The status of the European eel population is indicative of its prolonged decline: recruitment in the late 1990s was <10% of that in the 1980s (Dekker 2003) and this reached its minimum in 2011 of less than 1% of the mean 1960–79 levels in the continental North Sea, and less than 5% elsewhere in Europe (ICES 2016). Consequently, the European Union (EU) developed a recovery plan for the European eel population (EU 2007). According to this plan, management measures must be implemented in eel management units to meet a target of 40% silver eel escapement of the potential biomass that would be produced under conditions with no anthropogenic disturbance from fisheries, water quality, or migration barriers (EU 2007).

At the onset of the spawning migration, the appearance of adult eel changes with the fish becoming much darker, with white abdomens, and a greater eye surface area. Except for actual migration itself, these changes are the basis for identifying the various eel life stages (Durif et al. 2005). Most frequently,

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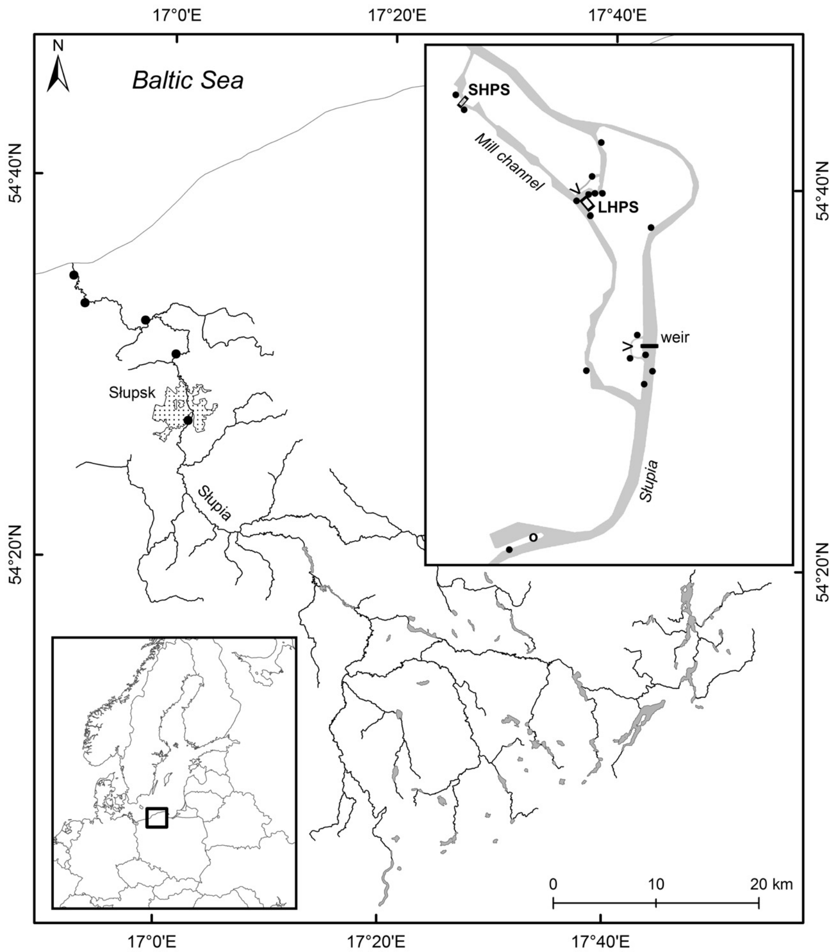

Figure 1. Map showing the location of the Słupia River catchment area, the hydrotechnical node in the Słupsk (upper right); the release point of the eel is denoted by empty circle, acoustic automatic receivers by black dots, PIT antennae by a >, SHPS=small hydro power plant, LHPS=large hydro power plant.

silver eel must negotiate through some barriers during catadromous migration. These barriers are of many types and range in size from small to very large, and some not only impede migration, but they are also directly responsible for eel mortality. Hydroelectric facilities and pump stations are first and foremost in this group. It is widely recognized and described in the literature that eel migrating downstream pass mainly through hydroelectric facility turbines (Haro et al. 2000), but the chosen route depends on the ratio between spill flow and turbine flow (Travade et al. 2010). Turbine mortality is highly variable and depends on fish size, the physical measurements of the turbines, their speed, and the characteristics of how they operate (Gibson and Myers 2002, Bernaś et al. 2017). Some mortality results from various injuries, including those inflicted by physical impact from moving or stationary turbine parts, sudden acceleration or deceleration, shear, very sudden variations in pressure, and cavitation (Larinier and Travade 2002). The WGEEL advice group, working under the auspices of the International Council for the Exploration of the Sea, indicated in recent annual reports that turbine mortality at hydroelectric facilities has the most significant non-fishery related impact on the European eel population and that this issue needs quantitative assessment (ICES 2018). In response to this statement, the main goal of the present study was to assess the mortality rate of silver eel passing through a site with two small hydroelectric facilities equipped with Francis turbines and their potential impact of delaying migration.

Materials and Methods

Study area

The Słupia River is a Pomeranian river located on the southern Baltic Sea coast (Fig. 1). It is 138.6 km in length with a catchment area of 1,623 km^2. The mean flow of the Słupia in its lower course is about 15 $m^3 s^{-1}$. Its source is located in moraine hills at an elevation of 178 meters above sea level. The river mouth is located in the small harbor of Ustka (16.8521°E, 54.5888°N). The Słupia drainage basin has 175 natural lakes mostly in the upper part of the basin (Marszelewski 2007). Many of these lakes have been stocked with eel. The last barrier in the river is 36 km from its mouth in the city of Słupsk, where the river is blocked by a weir with a height of 1.5 m (Fig. 1). Fifty meters downstream from the weir, to the left, is a mill channel that feeds two hydroelectric facilities: a large one 400 m down the channel and a smaller one 700 m farther at the end of the channel.

The system had two fish passes: the first was a pool and boulder pass at the weir, while the second was a technical fish pass at the large hydroelectric facility (Fig. 1). The large hydroelectric facility was equipped with two Francis turbines with a maximum flow of about 12 m^3. During the experiment, only one turbine was in operation. This turbine had a diameter of 0.7 m, a maximum paddle width of 0.3 m, and maximum rotatory speed of 600 rpm. The maximum power generated is 130 kW. The small hydroelectric facility had one Francis turbine with a diameter of 0.7 m, a blade width of 0.3 m, a speed of 350 rpm, and maximum power of 120 kW. The turbine intakes were protected by 30 mm screening racks.

Water flow during the experiment was measured with a RiverSurveyor S5 (SonTec, San Diego, USA). The flow in the main river channel was 2 ms^{-1} (about 0.5 through the fish passes and 1.5 through the weir), in the mill channel it was 11.4 ms^{-1} (the flow through the small hydroelectric facility was 1.6, while that through the large hydroelectric facility was 9.2; the flow through the fish pass next to it was approximately 0.3 (Fig. 1).

Sampling and telemetry

Eel were caught by commercial fishers using fyke nets in the mouth of the Oder River and transported in water to Słupsk. Before tagging, each fish was anesthetized with Propiscin (etomidate) at a concentration of 1 ml l^{-1}. Next, body length (L), weight (W), and the horizontal and vertical eye diameters were measured. All eel were classified by size as females (Vřllestad and Jonsson 1988). Silver eel were identified by the color of the back and abdomen, the presence of a well-defined lateral line, and the eye index (Pankhurst 1982, Durif et al. 2003). The Pankhurst (1982) eye index (EI) was calculated using the formula $EI = [\{(A+B)/4]^2 \times \pi/TL) \times 100$ where A is horizontal eye diameter (mm), B is vertical diameter (mm), and T L is total body length (mm). Two telemetry methods were applied: acoustic telemetry and passive integrated transponders (PIT) (Prentice et al. 1990). Altogether, 78 eel were tagged, and all the fish were tagged with PITs (Oregon RFID 3.2 mm HDX), while an additional 27 were also tagged with acoustic transmitters (V9-2x, VEMCO, AMIRIX Systems Inc., Halifax, Nova Scotia, Canada). The weight of tags in water was 0.8 g for PIT and 2 g for acoustic. Both types of tags were implanted surgically into the body cavity. The eel were then held for several hours to recover. They were released on November 16, 2012, upstream from the weir (Fig. 1).

The PITs were detected by two antennae mounted in each of the fish passes (Fig. 1). Signals from the acoustic transmitters were detected by 22 automatic receivers (VR2W, VEMCO, AMIRIX Systems Inc., Halifax, Nova Scotia, Canada) deployed at the fish release site and upstream from it, around the barrages, in the fish passes, and in the downstream river run (Fig. 1). The receivers were deployed until January 3, 2013. The speed of the migrating eel was calculated using the distances between receivers and the time between the last recorded signal from an upstream receiver and the first signal from a downstream receiver. Acoustic telemetry provided information about eel behavior after release, the migration routes they chose, and their further fates. The PIT system was used only to monitor eel passage through the fish passes. It was

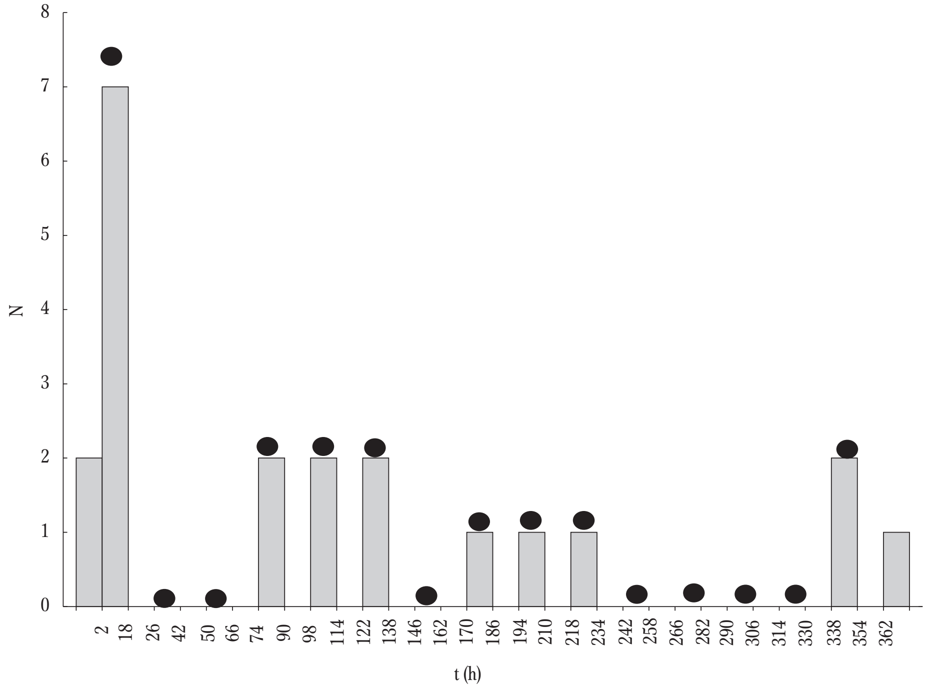

Figure 2. Time spent in the place of release. Black circles denote night hours.

assumed that the fish that swam to the sea (at a distance of 36 km) were undamaged by the turbines. When the speed of fish migrating deviated from that of other fish, and they only swam a short distance downstream from the barrier, they were considered to have been injured. All statistical analyses were performed with Statistica (StatSoft Inc., Tulsa, OK, USA).

Results

The mean length of tagged eel used in this study was 67.8 cm (range 56–87 cm), the mean weight was 544 g (range 405–810 g), and the mean eye index (EI) was 9.0 (5.0–15.1). Of the 27 eel tagged with acoustic tags, 21 swam downstream, three swam upstream, and three disappeared after release (Table 1). The specimens that swam downstream did not differ significantly from the other eel either in terms of body length (t-test; P= 0.242) or eye index (t-test; P = 0.882). The time the tagged fish spent at the release site ranged from immediate migration to 15 days (Fig. 2).

Additionally, except for the first two specimens, all the other eel began migrating between sunset and sunrise. The time spent at the release site did not depend on eel length or eye index (Pearson correlation; P = 0.371 and P = 0.238). Twelve fish swam through the right channel with a flow of 2 $m^3 s^{-1}$ toward the weir, while nine eel migrated through the left mill channel with a flow of 11.4 $m^3 s^{-1}$ toward the hydroelectric facility. The specimens from these groups did not differ significantly in body length (t-test; P = 0.242), eye index (t-test; P = 0.886), or in the amount of time they remained at the release site (t-test; P = 0.154).

Table 1
Routes chosen by eels with acoustic transmitters

	Non-migrants	Weir	Large HPS	Small HPS	Total
Total	6	12	7	2	27
Injured	?	0	1	0	1

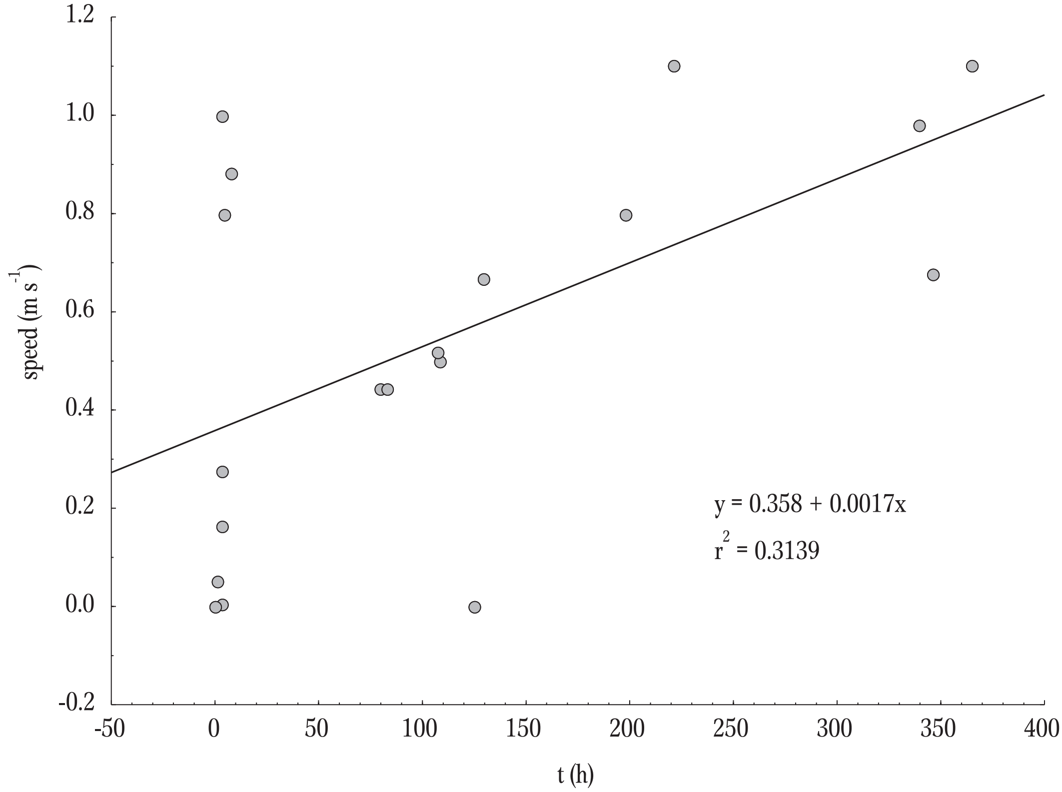

Figure 3. The dependence of speed of the fish on the first 0.5 km and time spent at the release site.

The eel swam the first river section from the release site to the weir (0.5 km) at speeds of 0.003 to 1.104 m s^{-1} (average 0.549, SD = 0.385). This did not depend significantly on the fish route (right or left) (t-test; P = 0.445), body length (t-test; P = 0.230), or eye index (t-test; P = 0.111). However, speed was related to the amount of time spent at the release site, and values were higher for fish that started migrating later (Pearson correlation; P = 0.013) (Fig. 3).

The acoustic and PIT telemetry tags showed that no eel migrated through the fish passes. Among the specimens that moved downstream, those that chose the route toward the weir swam downstream from the upper spill or through some leaks in the weir near the river bank. Nine eel that took the mill channel passed through the turbines-seven at the large hydroelectric facility and two at the small one (Table 1).

All of the fish that swam downstream through the weir reached the sea after 36 km of migration. The fastest eel did this in 10 h, while the slowest took 31 d. The rest of fish migrated through the hydroelectric facilities and reached the sea after periods of time ranging from 10 h to 3 d (Fig. 4). One of them (68.5 cm long) that passed through the large hydroelectric facility was finally detected 1.6 km downstream after 30 h, and it was assumed that this fish had been damaged by the turbine.

In the river section downstream from the barriers, which was 2 km downstream from the weir, 1.6 km downstream from the large hydroelectric facility, and 1.3 km downstream from the small hydroelectric facility, the eel swam downstream at speeds ranging from 0.002 to 0.964 m s^{-1} (average 0.598, SD = 0.365). There was no relationship between speed and fish length (Pearson correlation; P = 0.677) or fish speed upstream from the barrier (Pearson correlation; P = 0.584). Fish migrating through the mill channel were faster (0.758 m s^{-1}) than the fish migrating through the weir (0.470 m s^{-1}). However, this difference was caused by one very slow fish and was not significant (t-test; P = 0.096).

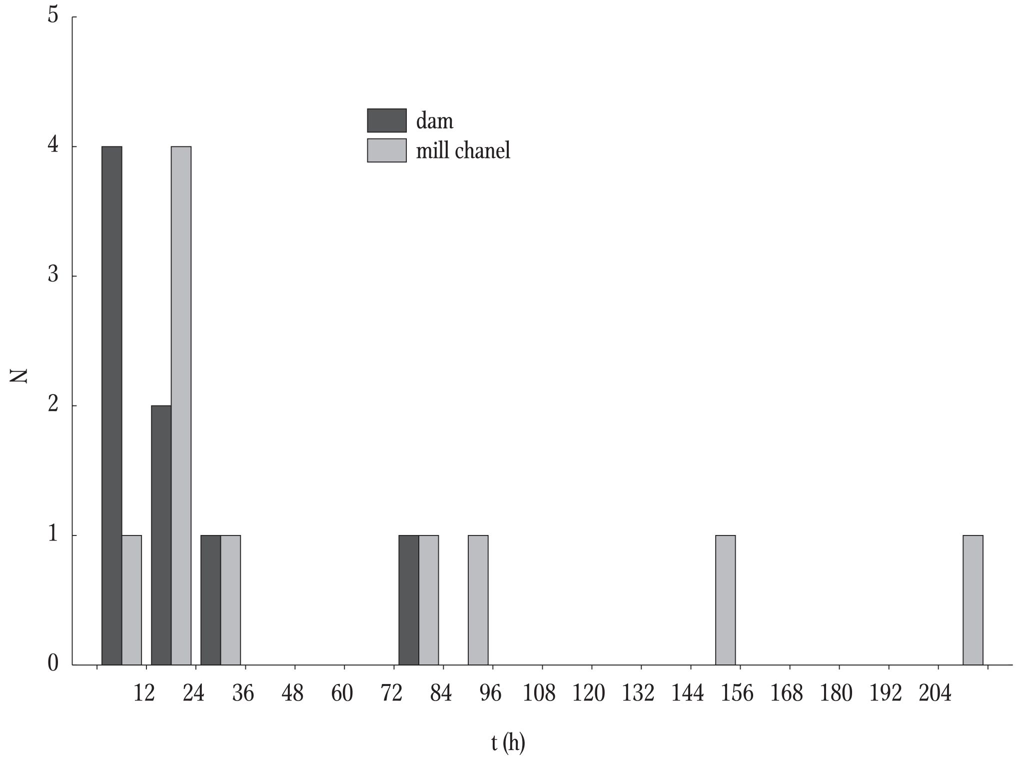

Figure 4. Migration time from the barriers to the sea.

In the next river section, from the connection of the channels to the sea (34.5 km), the eel swam downstream at speeds ranging from 0.023 to 1.007 m s^{-1} (average 0.581, SD = 0.345). This speed did not depend on fish length (t-test; P = 0.580), on the speed in the sections mentioned above (t-test; P = 0.531), or the on route chosen by the fish (t-test; P = 0.531).

The overall mortality of the eel migrating downstream in this segment of the Słupsk River was 5% and 14% for specimens that passed through the large hydroelectric facility turbine. None of the 78 eel with PIT tags was registered in any of the two fish passes.

Discussion

All tagged and released eel began their migrations during the night, which is typical behavior that has been reported in many experiments (e.g., Vøllestad et al. 1986, Aarestrup et al. 2010, Bernaś et al. 2017). The routes chosen were not related to the main river flow. Among the eel that swam downstream, 44% of those released chose the route through the weir where the flow rate was significantly lower than it was in the mill channel. While it is a fact that the silver eel were distributed over alternate migration routes regardless of water discharge proportion, this is not easy to interpret, especially since several studies report the opposite (e.g., Jansen et al. 2007, Larinier 2008). However, disproportion was also observed (Calles et al. 2010); migration speed was not related to the route the eel chose or body length or eye index. However, it was related to the time spent at the release site. This observation suggests that the specimens that recovered for a longer period after tagging and release had better migration potential. That none of the 78 eel swam downstream through the fish passes is characteristic of this species. Similar situations were observed in other experiments performed in northern Poland (Dębowski et al. 2016), and it appears that fish pass entrances are not attractive to eel. The turbine intakes on both of the hydroelectric facilities are protected by 30 mm screening racks, which potentially permitted all of the tagged eel to swim through the turbines according to the formula in Turnpenny (1989). The body length of the fish used for the experiment was close to the typical silver eel migrants in northern Poland (Robak 2005). Therefore, the mortality obtained should be well balanced in terms of this important factor (Larinier and Travade 2002). Mortality rates in Francis turbines vary widely from nearly 0 to 100% (McCleave 2001, Larinier and Travade 2002, Dębowski et al. 2016, Bernaś et al. 2017), although rates of 10–50% are more common (Jansen et al. 2007, Larinier 2008). The mortality rate at the large hydroelectric facility in this experiment should be considered as moderate. However, from a management perspective it was important and significant. Twelve hydroelectric facilities are in operation in the Słupia River system, and some (Konradowo, Krzynia) are large with steep slopes and numerous Francis turbines. All of the important large lakes are located in the upper reaches of the drainage basin, and most eel migrating downstream must pass through at least five to six of them. If cumulative mortality is considered here, silver eel losses would be as high as 80–90%, and when this is added to natural mortality, fishing, and predation, eel escapement from the Słupia drainage basin is very low.

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