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RESEARCH ARTICLE

Mortality of silver eel (*Anguilla anguilla*) migrating downstream through a small hydroelectric plant on the Drawa River in northern Poland

Piotr Dębowski, Rafał Bernaś, Michał Skóra, Jacek Morzuch

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Abstract. The European eel, *Anguilla anguilla* L., is an endangered species. Barriers to its downstream spawning migration are one of the greatest threats this species faces. There are hundreds of hydroelectric plants (HEP) on rivers in Poland (> 600), and thousands throughout Europe. Eel that pass through HEP turbines as they migrate downstream suffer high mortality, but this depends mainly on local and technical conditions. Silver eel mortality was estimated and the possibility of the fish bypassing the turbines was studied between November 2013 and June 2014 at a typical HEP in northern Poland. Two telemetry methods were used with 49 eel: passive integrated transponder (PIT) system and acoustic telemetry. Fifty five percent of eel migrated downstream in fall 2013, soon after their release, and 45% migrated the next spring. The eel did not use the fish passes designed for upstream migration; thus, they were forced to go through the turbines, which resulted in 55% mortality. HEPs cause interruptions and delays in eel spawning migrations and are responsible for high eel mortality. This can make implementing an eel restitution plan difficult or even impossible in river systems with many barriers.

Keywords: eel, hydroelectric plant, mortality, spawning migration

Introduction

The European eel, *Anguilla anguilla* L., population has decreased dramatically in recent decades, and in the late 1990s, glass eel recruitment was less than 10% of that in the 1980s (Dekker 2003). This led to the development and implementation of the Eel Regulation by the European Union (Council Regulation (EC) No 1100/2007) that requires all member states to develop national eel management plans. The main requirement of these plans is to ensure escapement to the sea of at least 40% of the silver eel biomass relative to the estimate of reference amounts with no anthropogenic influences.

The presence of barriers in the downstream migration of adult eel is regarded as one of the main problems in implementing this plan. HEPs have an especially negative influence on migration, as they can delay or even entirely block it. In many HEPs, there is only one route downstream, which is blocked by turbines. Turbines cause injuries, and because of their shape eel are especially endangered (Larinier and Travade 2002). Eel mortality caused by turbines depends on many factors like the type of turbine, its size, rotation speed, and water flow (Čada 2001, McCleave 2001, Larinier and Travade 2002, Winter et al. 2006, Vowles et al. 2014). Turbines can cause

P. Dębowski [✉], R. Bernaś, M. Skóra, J. Morzuch
Department of Migratory Fishes in Rutki
Inland Fisheries Institute in Olsztyn, Poland
e-mail: p.debowski@infish.com.pl

100% mortality (Monten 1985, Carr and Whoriskey 2008), but this number is usually lower (Monten 1985, Jansen et al. 2007, Winter et al. 2007, Larinier 2008, Calles et al. 2010, Leonardsson 2012).

Lakes are the main environment for freshwater eel production in Poland. There are approximately 2600 km^2 of lakes; however, eel can migrate freely from only 630 km^2 (24%) (Dębowski and Bernaś 2010). One large lake complex in northwest Poland is drained by the Drawa River, the lower segment of which is dammed by a typical HEP. The HEP is equipped with a fish pass designed for the upstream migration of salmonid fish. The aim of this study was to discover if migrating silver eel used the fish pass and to assess the mortality rate of eel passing through the turbines.

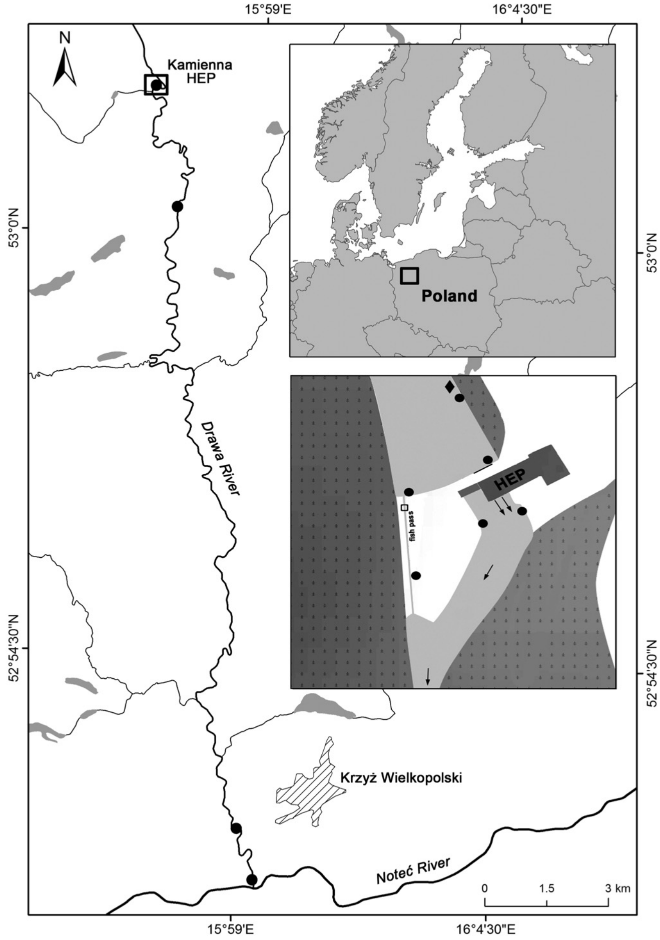

Figure 1. Map showing the location of the Drawa River catchment area (upper right), the Kamienna hydroelectric plant (HEP) in a lower course of the river, and the studied dam (lower right); the release point of the eel is denoted by a black rhombus, acoustic automatic receivers by black dots, and PIT antennae by a rectangle.

Study area

The Drawa River drains into the Noteć River, a tributary of the Warta River which drains into the Pomeranian Bay (southern Baltic Sea) via the Oder River. The Drawa River is 192 km long and its catchment area is 3291 km^2. There are around 105 km^2 of lakes in the area, of which 68% are upstream from at least one HEP. The Drawa River is dammed by four HEPs at 32, 89, 127, and 156 km from the mouth, and there are no other barriers between the mouth and the sea.

The dam on the Drawa River in the village of Głusko was constructed in 1903, and three years later a HEP was installed. The HEP has not experienced many breakdowns in its history. Water is dammed to 7.4 m and flows through two Francis turbines at 100 revolutions min^{-1} (Borkowska 1990). The power of the HEP is 960 kW, and the installed turbine flow is 21.4 m^3 s^{-1}. The average flow of the river from 1961 to 1999 according to the Institute of Meteorology and Water Management was 12.0 m^3 s^{-1} (Dębowski and Gancarczyk 2013).

The upper inlet into the fish pass is located at the right end of the dam around 50 m away from the HEP inlet (Fig. 1). It has two windows measuring 0.40 x 0.45 m each, one is at the bottom and one is at a surface. The fish pass is a typical concrete construction that is 83.4 m long with 19 chambers connected by two windows and a nominal flow of 0.430 m^3.

Material and methods

We used two telemetric methods to track the fish–acoustic telemetry to assess the mortality of fish passing through the turbines, and PIT (passive integrated transponder) tags (Prentice et al. 1990) to determine if the eel used the fish pass. We used 49 silver eel with total lengths (L) between 70.5 and 100 cm (L_{av} = 84.8, SD = 6.1) that had been caught in traps in the mouth of the Oder River. Judging from their size, they were females (Tesch 2003). Their maturity was estimated by the eye index (I) (Pankhurst 1982): $I = 100 \times (((0.25 \times (A + B)) \times 2\pi) \times L - 1)$; where A is the vertical eye diameter and B is the horizontal eye diameter. I was from 3.7 to 14.4 (I_{av} = 8.8, SD = 2.9).

All eel were tagged with PITs (OregonRFID 3.2 mm HDX), and 24 were fitted with acoustic transmitters (V9-2x, VEMCO, AMIRIX Systems Inc., Halifax, Nova Scotia, Canada). Both were surgically implanted into the body cavity of the fish (Baras and Jeandrain 1998). They were released November 7, 2013 into the main current of the reservoir 200 m upstream from the HEP inlet (Fig. 1).The PITs were detected by two loop antennae mounted in the upper part of the fish pass on the two windows between the second and third chambers (Fig. 1). Signals from the acoustic transmitters were detected by nine automatic receivers (VR2W, VEMCO, AMIRIX Systems Inc., Halifax, Nova Scotia, Canada): three in the reservoir above the HEP; one in the fish pass; two directly below the HEP outlet; three in the lower river segment (1.6, 7.2 and 31.9 km below the dam) (Fig. 1). The receivers were deployed until July, which was longer than predicted life span of the acoustic transmitters. The progression rates of the migrating of eel were calculated using the distances between receivers and the time between the last recorded signal in an upstream receiver and the first signal in a downstream receiver. All statistical analyses were done with STATISTICA 7.1. (StatSoft).

Results

Neither PITs nor acoustic tags were registered in the fish pass, which indicated that the eel did not use the fish pass. Almost all the fish with acoustic transmitters were recorded swimming in the reservoir after their release, visiting locations near the dam, and returning to the release location. Some fish did this more than once. Four fish did not swim downstream, but disappeared from the reservoir before winter (between November 22 and December 22). Twenty swam through the turbines. The first eel did so only three hours after release and the last did so seven months following release (Fig. 2). They began their downstream migration during the day and evening and avoided late night and morning hours (Fig. 3). Eleven fish swam downstream in fall–winter: seven in the first week and four in January, with the last leaving when the temperature was below 5°C. Nine eel emigrated in the spring: the first at the end of March after the temperature increased to 8°C, the rest, one by one, up to the beginning of June when the water temperature was 16°C (Fig. 2). River discharge during the study was stable, so no relation with this factor was noted (Fig. 2). The average lengths (85.6 vs 84.7 cm, t-test, P = 0.6782), or eye indices (10.2 vs 10.4, t-test, P = 0.8492) of the fall and spring migrants did not differ upon release.

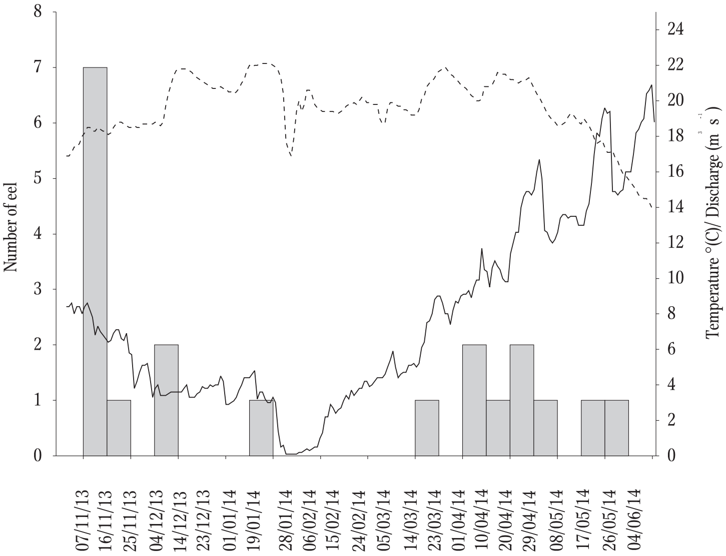

Figure 2. Number of eel (*A. anguilla*) passing through turbines (N), water temperature (T, °C, solid line) and discharge in lower Drawa River (Q, m^3s^{-1}, broken line).

Nine fish, six in fall and three in spring, reached the Drawa River mouth, 32 km below the dam (the

Table 1
Fate of eel (*A. anguilla*) with acoustic transmitters (numbers)

	Survivors-Uninjured	Injured	Dead	Total
Non-migrants	-	-	-	4
Spring migrants	3	4	2	9
Fall migrants	6	1	4	11
Total	9	5	6	24

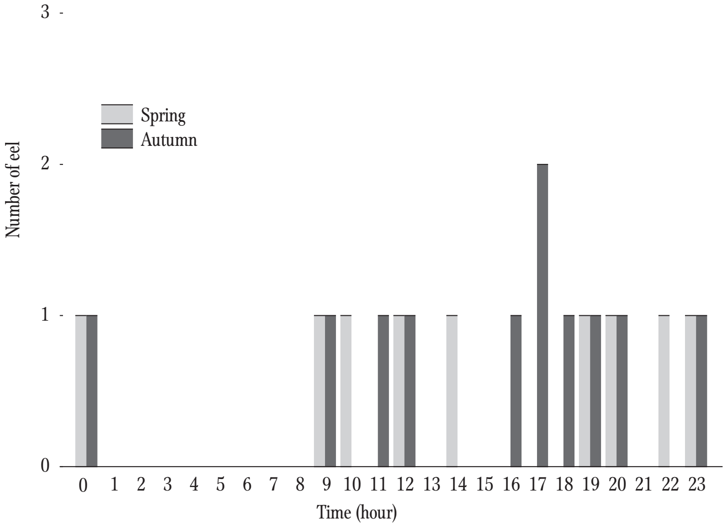

Figure 3. Number of migrating eel (*A. anguilla*) in relation to time of day in fall and spring.

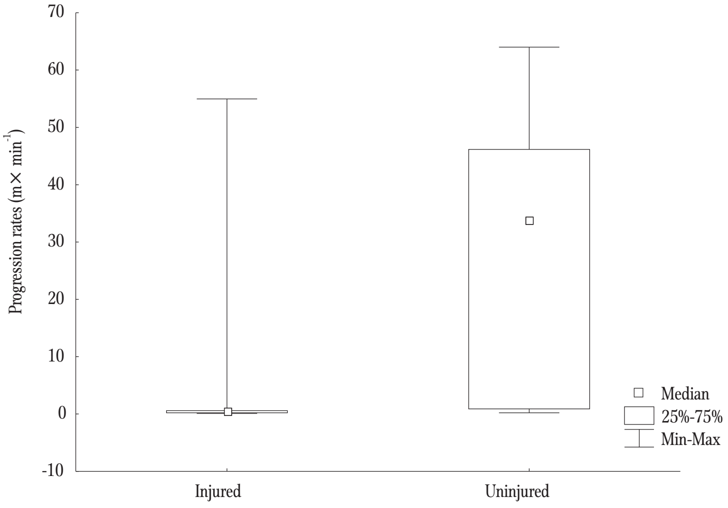

Figure 4. Progression rates (S, m min^{-1}) of injured and uninjured eel (*A. anguilla*) below the dam.

first group). Five fish, one in fall and four in spring, were registered 1.6 and/or 7.2 km below the dam, but did not reach the mouth (the second group). Six fish, four in fall and two in spring, were only registered directly below the outflow from the turbine (the third group). Eel from the third group were considered deceased, and eel from the first group were considered uninjured (Table 1). Fish from the second group were assumed to be injured and unable to migrate further. This assumption was supported by their lower progression rate below the dam in comparison with eel from the first group (Fig. 4) (insignificant difference: t-test, P = 0.2316). The total mortality (dead plus injured) of eel passing through the turbines was estimated at 55%.

There were no significant differences between the average lengths of the survivors and those that died (including injured): 84 vs 96 cm (t-test, P = 0.3783). The average progression rates of eel between the dam and the mouth ranged from 1 to 66 m × min^{-1}, with the fastest fish covering the distance in eight hours.

Discussion

Mature eel migrate throughout the year (Reckordt et al. 2014) with concentrated migration peaks occurring in spring and fall (Tesch 2003, Acou et al. 2008, Reckordt et al. 2014, Stein et al. 2014, 2015). Silvering is usually completed from September to November (van Ginneken et al. 2007), and migration is triggered by environmental cues. It is obviously regulated by water temperature (Verbiest et al. 2012, Reckordt et al. 2014, Stein et al. 2014, 2015); however, this relationship is not clear and can change depending on the location and the time of year (Durif et al. 2002, Tesch 2003, Carr and Whoriskey 2008). Eel usually do not migrate when the water temperature is below 4 and above 18°C (Vøllestad et al. 1986, Tesch 2003), and prefer the range of 10-14°C (Durif et al. 2002), but Reckordt et al. (2014) also observed migration below 5°C. The behavior of the eel in our experiment generally reflected these observations. Many authors emphasized that increased water levels trigger downstream eel migration (Durif et al. 2002, Behrmann-Godel and Eckmann 2003, Jansen et al. 2007, Acou et al. 2008, Travade et al. 2010, Verbiest et al. 2012, Stein et al. 2014, Barry et al. 2016). The flow of the Drawa River is very stable (Stachy et al. 1986), which mitigates this factor. Eel often interrupt migration after water temperature decreases in late fall and resume it in spring, when water temperatures increase (Acou et al. 2008, Stein et al. 2014, 2015). Half of the fish in our experiment exhibited this behavior.

Silver eel usually stop migrating when confronted with a barrier often swimming back and along dams, or they search for a path downstream (Haro et al. 2000, Behrmann-Godel and Eckmann 2003, Winter et al. 2006, Brown et al. 2007, Jansen et al. 2007, Acou et al. 2008, Travade et al. 2010, Pedersen et al. 2011, Piper et al. 2013, Calles et al. 2013, Stein et al. 2015). The eel in our experiment behaved similarly. The fish approached the vicinity of the fish pass, but the eel did not use the pass. Evidently, they were not attracted to this small outlet. Eels migrate in the main water current, and if they bypass turbines, they utilize high water to swim through spillways (Durif et al. 2002, Boubee and Williams 2006, Acou et al. 2008, Calles et al. 2010). Eel use fish passes designed for upstream migration sporadically (Jansen et al. 2007, Carr and Whoriskey 2008, Travade et al. 2010, Verbiest et al. 2012).

Eel usually migrate at night (Haro et al. 2000, Durif et al. 2002, Tesch 2003, Carr and Whoriskey 2008, Travade et al. 2010), and they only migrate during the day in turbid water (Durif et al. 2002, Travade et al. 2010). The fish in the present experiment did not avoid migrating during the day. Perhaps the light conditions in late fall and early spring were suitable. Regardless, they also preferred migrating during the early evening.

The character and severity of injuries sustained when eel passed through the turbines depended on many factors connected to the characteristics of both the turbines and eel, including size and behavior (Monten 1985, McCleave 2001, Leonardsson 2012). Some of the consequences of injury were immediate, while others appeared only after a period of time (Monten 1985, Richkus and Dixon 2003). Delayed consequences were not easy to assess with telemetric methods. Nevertheless, it appeared that the eel that swam actively for a distance of 32 km immediately after passing through the turbines could not have been injured.

Total mortality was estimated at 55%, which was high for a Francis turbine. In the majority of experiments carried out on this type of turbine, the mortality of eel was below 20% (McCleave 2001, Richkus and Dixon 2003). However, in some rates reached 60% (Calles et al. 2010) or even 100% (Monten 1985). Leonardsson (2012) estimated the average for 191 hydropower stations in southern Sweden to be 30%, and if omitting the largest rivers the predicted losses to 60-70%. The high mortality in our experiment could have stemmed from the large size of the eel.

Subject HEPs, and their characteristics are typical of Pomerania. Therefore, it can be assumed that the mortality of silver eel passing through other HEPs is similar. There are many HEPs on many rivers, and passing through three similar HEPs could result in 90% mortality for silver eel. This can make implementing an eel restitution plan difficult or even impossible in river systems with many barriers.

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Author contributions. P.D. designed the research; P.D., R.B., M.S., and J.M. performed the research; P.D. analyzed the data; P.D. and R.B. wrote the paper.

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