Mortality of Silver Eels Migrating Through Different Types of Hydropower Turbines in Lithuania

Running Head: Mortality of Silver Eels

Justas Dainys^{1*}, Saulius Stakėnas², Harry Gorfine³, Linas Ložys¹

¹ Nature Research Centre, Laboratory of Marine Ecology, Vilnius, Lithuania

² Nature Research Centre, Laboratory of Ecology and Physiology of Hydrobionts, Vilnius,
Lithuania

³ School of BioSciences, University of Melbourne, Parkville Campus, Victoria, Australia

* Corresponding author

E-mail: dainys@ekoi.lt

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Abstract

Hydropower plants (HPP) are considered to be one of the major threats to the survival of European eels when they migrate downstream along inland water bodies during the early part of their annual journey to the spawning area in the Sargasso Sea. There are 98 HPPs in Lithuania and thousands throughout Europe. Numerous studies describe HPP induced mortality rates among European eels as variable depending on local, environmental and technical factors. This heterogeneity in effect complicates theoretical extrapolation to eel mortality arising from specific types of HPP, necessary for effective management of local stocks. Silver eel mortality was estimated for four different HPPs in Lithuania. Mortality was estimated using RFID (PIT) tags and acoustic telemetry in a large HPP (>100 MW) with Kaplan turbines, a small HPP (<1 MW) with a Kaplan turbine and a fish passage, and for the first time in two small HPPs (<1 MW) with CINK turbines. The results supported a hypothesis that the mortality rate of migrating eels depends mainly on the type and size of the turbine. HPP induced mortality varied from 100% in a small CINK turbine down to 25% in the large HPP with Kaplan turbines. The importance of simple mitigation measures was highlighted by 34% of all tagged eels bypassing one of the HPP via an adjacent fish passage constructed for upstream migration of salmonids. The observed differences in mortality provide essential information for long term strategies designed to restore depleted eel populations in Lithuania and other European countries.

Key words: *Anguilla anguilla*, hydropower, eel migration, Kaplan turbine, CINK turbine

Introduction

Steep declines in European eel *Anguilla anguilla* recruitment started in the 1980s and since then eel population abundance has fallen below its minimum safe biological limit (Dekker, 2004; ICES, 2006). This population crash happened over the entire range of this species' distribution without a single obvious root cause, but a number of different reasons such as changes in the Gulf Stream, migration barriers, fishing pressure, habitat loss, parasites or pollution have been postulated (Dekker, 2004; Wirth, 2003). Despite all these factors contributing to the decline in eel populations there is no consensus on their relative importance. Results from previous studies (e.g. Winter et al., 2006; Bruijs and Durif, 2009; Aarestrup et al., 2010) demonstrated that substantial mortality during downstream migration of eels, which in Lithuania is most intensive during spring (Ložys et al., 2008), could dramatically reduce the number of spawners. Fisheries exploitation and loss from passage through hydropower plants (HPPs) are often considered to be the main causes of eel mortality in rivers (Winter et al., 2006). The two direct causes of mortality at HPPs are turbine-related trauma and impingement on protective screens (Monten, 1985; Calles et al., 2010).

It has been generally assumed that turbine related mortality of migrating fish decreases with increasing turbine size (Calles et al., 2010). However, eel mortality rates in HPPs are variable depending on the site, river physiography, associated hydrological conditions, and the type of migration barriers installed (ICES, 2007). Eels tend to have four to five times higher mortality rates compared with juvenile salmonids when transiting HPPs (Hadderingh and Bakker, 1998), mostly due to mechanically-induced injuries because of their elongated morphology (Monten, 1985; Larinier and Travade, 2002). Previous studies have demonstrated negative impacts of hydropower structures on migrating eels, with mortalities ranging from 5 to 100%. Kaplan turbines are the most commonly used in Europe (Bruijs and Durif, 2009) and according to Larinier and Travade (2002) the range of reported turbine-induced mortality among eels is between 15% and 30% in large Kaplan turbines, and from 50% to 100% in the smaller turbines used in most small-scale HPPs (Monten, 1985; Hadderingh and Bakker, 1998). We did not find any studies on the rates of eel mortality in cross-flow turbines (e.g. Banki, CINK, Ossberger). However, mortality rates of other fish species passing through cross-flow turbines are significantly higher (up to 75%; Gloss and

Wahl, 1983; Dubois and Gloss, 1993) compared to that in Kaplan or Francis turbines. Many behavioural studies (e.g. Calles et al. 2010; Behrmann-Godel and Eckmann 2003; Durif et al., 2003) suggest that eels approaching HPPs and dams often hesitate to continue with their migration, thereby extending their migration time. Pedersen et al. (2012) reported that some of the eels spent weeks moving in and out of the power canal before finally passing through it or disappearing beyond the detection range. In that study only 23% of the tagged eels reached the tidal limit within the study period, mainly due to difficulties in traversing the hydropower dam.

Global production of hydroelectricity has grown steadily by about 3% per year on average since 1980 (Moller, 2016). The role of hydropower, along with other renewable energy sources, is expected to become increasingly important in the future. The fastest rates of hydropower expansion are expected in developing countries with high but unexploited hydropower potential, e.g. parts of Eastern Europe (Voigtländer et al., 1999). Thus, the negative impact of HPPs on migrating fish is likely to increase in the future.

The main objective of this study was to assess mortality rates of silver eels passing low-head HPP turbines of two types: Kaplan (large and small) and CINK (small). An additional aim of the study was to estimate the importance of fish passages for bypassing HPP during downstream eel migration.

Study area

The study area encompassed part of the Nemunas River catchment and several of its tributaries in which a total of eight HPP are located, four of which were included in this study (Fig. 1). The Nemunas River is the largest river in Lithuania, with a total length of 937 km and a catchment area of 98 200 km². The Kaunas water reservoir of 63.5 km² created by a dam on the Nemunas River is situated above the Kaunas HPP. The HPP with its four Kaplan turbines was constructed in 1960 and there are no other barriers to fish migration between it and the Baltic Sea situated 290 km away (Table 1).

The Siesartis River (Fig. 1) is 64 km long and it has a catchment area of 616 km². This river is dammed by the Valtūnai HPP at 11 km from its confluence with the Nemunas River (377 km from the Baltic Sea) (Table 1); there are no other fish migration barriers between this HPP and the Baltic Sea.

The Strėva River is 74 km long and its catchment area is 759 km²; this river drains to the Kaunas water reservoir above the Kaunas HPP. The Bagdononys HPP with one cross-flow CINK turbine is situated 60.5 km from the mouth of the Strėva River and 412 km from the Baltic Sea (Table 1, Fig. 1). The Strėva River is dammed by five HPPs at 9, 30.4, 40.5, 56.6, and 60.5 km from the river's mouth.

The Dubinga River is 17.8 km long and its catchment area is 410.4 km². The Pabradė HPP (Table 1) is located 1.4 km from the mouth of the Dubinga River and 540 km from the Baltic Sea (Fig. 1) with no other fish migration barriers between the HPP and the Baltic Sea.

Materials and Methods

Small turbine induced mortality

Eel mortality in the small CINK (Bagdononys HPP and Pabradė HPP) and Kaplan (Valtūnai HPP) turbines was assessed from eels tagged with 12 mm passive integrated transponders (PIT tags). Eels migrating downstream were captured above each HPP using a fyke net located at the nearest suitable reach in terms of river width and depth. The numbers of eels caught and tagged were 52 at Bagdononys, 26 at Pabradė, and 64 at Valtūnai. Due to the large impoundments at Bagdononys and Pabradė the fyke nets were set 2 km and 2.5 km upstream from their respective HPPs. Immediately after capture the eels from these two locations were anaesthetised with 2-phenoxy ethanol (0.8 ml l⁻¹) for 5–10 minutes and fitted with PIT tags injected into the peritoneal cavity. After allowing sufficient recovery time (c. 30 min) following transportation to each release site, tagged individuals from each batch of captured eels were successively released at five minute intervals directly into the

intake of each HPP as described by Oliveira and Pressiat (2011). This release strategy was used to avoid losses of tagged eels above the HPP due to cessation of migration or predation.

Unlike the other two small HPP, the Valtūnai HPP does not have a water reservoir above the dam wall but it does have a fish passage that was installed for upstream migration of salmonids. In this instance tagged eels were able to be released just below the site of capture - approximately 0.8 km upstream from the HPP. This release strategy enabled the eels to use the fish passage as an alternative means of migrating downstream.

After their release, the eels were recaptured either in a fyke net placed with its opening facing towards a narrow outflow structure directly below the three HPP, or below the fish passage bypassing the Valtūnai HPP. In all instances the fyke nets set below and above the HPP were checked every 30 minutes to remove trapped eels and were only removed from the rivers after all of the PIT tagged eels had been recaptured.

Large turbine induced mortality

To assess mortality rates of eels migrating downstream through large Kaplan turbines installed at the Kaunas HPP, 25 silver eels were caught using a fyke net in a small tributary of the Nemunas River upstream of the HPP. Immediately after capture the eels were translocated to the release site (c. 60 km) near the Kaunas HPP in plastic transportation bags supplied with water and oxygen. Then the eels were placed in submerged cages to allow full recovery after transportation prior to surgery. Eels were anaesthetised as described previously. A 12–15 mm incision for Vemco V9 tags (weight 4.7 gram in air, length 29 mm, estimated tag life 159 days) and a 18–22 mm incision for Vemco V13 tags (weight 11 gram in air, length 36 mm, estimated tag life 262 days) was made on the mid-ventral line, in the posterior quarter of the body cavity. V9 tags were used to tag eels between 352 and 550 g while V13 tags were used for tagging eels >550 g. Tag-to-body weight ratios varied between 0.6 and 1.9%. The transmitter was inserted into the intra-peritoneal cavity and positioned 30–40 mm anterior of the incision. Surgery took 5–6 minutes to complete and the incision was then sutured with 4/0 Vicryl® Polyglactin absorbable surgical thread and treated with

antiseptic *Methylrosanilinni chloridum* 2% solution. After this surgery the eels were transferred back to the cages for recovery from anaesthesia for c. 30 minutes. Despite its relatively big size the V13 tag has been previously used to successfully tag silver eels (Westerberg et al. 2007, Béguer-Pon et al. 2014) without causing an increase in mortality rates (Winter et al., 2005; Heupel et al., 2007). After recovery, the tagged eels were released into the reservoir near the Kaunas HPP intake (N=13 on May 30, N=3 on June 13 and N=9 on October 7, 2014) between 10 a.m. and 12 a.m. There is no fish passage installed on the Kaunas HPP and its spillway operates only during extreme flooding events ensuring that all migrating eels had to pass directly through the turbines.

The eel silvering stage was determined as described by Durif et al. (2009). Specifically, both FIV and FV stages represent silver female eels; FV is the final silvering stage, whereas FIV refers to the earlier, nevertheless migrating, silvering stage. Fulton's condition factor (FCF) was calculated as described by Ricker (1975). All silver eels >55 cm were considered to be females (Tesch, 1977).

Four VR2W receivers were installed in the area of Kaunas HPP water intake to detect eels entering turbines; four receivers were installed just below the Kaunas HPP to detect eels that had passed through the turbines. Data from the receivers were downloaded monthly. The maximum time taken to pass through the turbines was calculated as the time-lag between the last detection of an eel upstream of the HPP and the first detection below the HPP. To detect eels that successfully migrated downstream, four additional receivers were installed on the navigational buoys within the Nemunas Delta.

To locate eels that passed through the Kaunas HPP but potentially suffered lethal injuries, a section of the Nemunas River 25 km below the HPP was scanned on a single occasion over a period of c. 10 hours with two VR2W receivers installed on an inflatable boat prior to the end of transmitter's estimated battery life. The boat drifted at a speed of approximately 2–3 km per hour.

Fish passage mitigation of turbine mortality

In contrast to the three other HPP included in this study, the presence of a fish passage adjacent to the Valtūnai HPP provided an opportunity to find out what proportion of eels were likely to use the passage to avoid transiting the turbine, thereby increasing their chance for survival. After their release, eels that migrated downstream via the fish passage were recaptured and their PIT tag ID numbers recorded. The eels were then compared with those recaptured at the HPP outlet in the previously described experiment investigating small turbine mortality at this location.

Laboratory analysis

Immediately after recapture eels were euthanized by an overdose of anaesthetic. After euthanasia the eels were scanned for their ID number and transported to the Lithuanian Nature Research Centre for further analyses. Injuries were considered to be lethal if an eel's spine or skull were fractured or if the internal organs had showed evidence of severe trauma. Other fish species, if any, caught below HPP were also examined for injuries.

Morphometric parameters total length (TL) and weight (W), Fulton's condition factor (FCF) and the silvering stage of eels were estimated for each turbine and the fish passage (Table 2.).

Statistical analyses

Eel survival rate was calculated as the ratio between the number of tagged eels that passed through the turbines and the number of eels which survived without suffering lethal injury.

As the data for eel length, weight and FCF were non-normally distributed (Shapiro–Wilk's W tests, $p < 0.05$) and sample sizes were relatively small, the non-parametric Mann-Whitney test was used to test for the effect of length on eel survival during passage through the turbine, and differences in size and condition between those passing through turbine and the ones that used the fish passage, as well as the effects of length and weight on migration success from Kaunas HPP to the Nemunas Delta.

The effects of length, weight and FCF on the likelihood that eels would use the fish passage instead of passing through the turbine were tested by logistic regression. The generalised linear model procedure in the R version 3.3.2 statistical package (R Core Team, 2016) was applied to the data for tagged eels released at the Valtūnai HPP, with the dependent binary response being whether a tagged eel was recaptured below the fish passage (value=1) or below the turbine (value=0). The coefficients of the three predictor (explanatory) variables in the model were exponentiated to obtain their respective odds ratios i.e. the proportional change in probability of using the fish passage for one unit increase in each predictor (UCLA, 2017). The same analysis was repeated to determine effect of the three explanatory variables on the probability of surviving passage through the small Kaplan turbine. Model-fit statistics were estimated by computing the Akaike Information Criterion (AIC), chi-squared test between the residual (full model) and null deviances (intercept only), and the maximum log-likelihood (MLL).

Results

Small turbine induced mortality

All 52 eels released upstream from Bagdononys HPP (CINK turbine) passed through the turbine immediately after release, suffering lethal injuries prior to their recapture below the HPP. Other fish caught below the Bagdononys HPP also suffered 100% mortality. These included Roach (*Rutilus rutilus*) N=12, mean TL 8.8 ± 1.1 cm; Tench (*Tinca tinca*) N=1, TL 7.5 cm; and Bleak (*Alburnus alburnus*) N=6, mean TL 11.3 ± 0.2 cm.

Laboratory examination revealed that the tagged eels suffered fractures of the spine and injuries to their internal organs; most eels (N=44, 84.6%) suffered lacerations of skin and muscles; and 34 eels (65.4%) sustained skull fractures. Marks from the turbine runner were evident over the entire body surface and the mean number of spinal fractures was 12 ± 2 per eel.

None of the 26 eels released immediately above the Pabradė HPP (CINK turbine) water intake pipe were recaptured below the HPP.

Eel mortality in the small Kaplan turbine at the Valtūnai HPP was estimated to be 52.4% because 22 out of 42 eels suffered lethal injuries while passing through the turbine. During the same period, out of 29 salmonid juveniles ($TL=12.8\pm1.2$ cm) that were caught below the Valtūnai HPP, eight (27.6%) suffered lethal injuries during their turbine passage, while the rest were without any visible injuries.

Laboratory examination indicated that 20 (48%) out of the 42 eels that migrated through the turbine suffered fractures of the spine, 14 eels (33%) suffered injuries to their internal organs, and 18 eels (43%) had lacerations of their skin and muscles. Two eels (5%) had skull fractures. Marks from the turbine's runner (absence of scales or small scratches) were visible on 38 out of 42 eels (90.6%), but in only 22 cases (52%) were these injuries lethal.

There were no significant differences ($p>0.05$) in mean length, weight and FCF between eels that suffered lethal injuries ($N=22$; $TL=67.3\pm7.6$ cm, $W=494\pm131$ g, $FCF=0.16\pm0.02$) and those which passed through the Kaplan turbine successfully ($N=20$; $TL=64.8\pm4.5$ cm, $W=458\pm77$, $FCF=0.17\pm0.01$). Logistic regression showed that none of these three variables had a significant effect on the probability of survival when passing through the small Kaplan turbine.

Large turbine induced mortality

Out of 25 eels released upstream of the Kaunas HPP water intake area, 21 (84%) moved downstream through the turbines and were detected below the HPP. Although 12 eels migrated within 24 hours after release, nine others took between one to 47 days to pass through. Three of this latter group remained close to the HPP water intake zone prior to passing through the turbines, whereas the remaining six eels were moving actively in and out of the water intake area prior to passage. Four eels did not migrate downstream and remained in the water reservoir until the end of the lifespan of the tag transmitter batteries. A majority of eels (76%, $N=16$) migrated through the HPP during daylight hours between 9.00 a.m. and 8.00 p.m., whereas another 5 eels (24 %) migrated during night-time between 10.00 p.m. and 5.00 a.m. The mean TL of those eels failing to migrate and remaining instead within the Kaunas Reservoir was 69.0 ± 7.1 cm, and their mean W

was 534 ± 65 g, whereas eels detected below the Kaunas HPP were substantially larger at 77.5 ± 9.3 cm in length with a mean weight of 967 ± 398 g. Despite these numeric differences, there were no statistically significant differences detected ($p > 0.05$) in TL and FCF between these two eel groups, whereas eels that did not migrate through turbines had significantly lower W ($p < 0.05$). Time taken to pass the Kaplan turbines was diverse and varied between 35 seconds and almost ten hours, but more than half of all eels ($N=12$, 57%) passed through the turbines within 5 minutes. Statistical analysis demonstrated that there was no significant difference between time taken to pass the turbines when comparing eels which reached the Nemunas Delta and those which have not.

Out of 21 eels which migrated through the turbines, 11 (52.4%) were detected in the Nemunas Delta (212 km downstream from Kaunas HPP). Transmitters showed that five eels (23.8%) remained stationary in close proximity to the Kaunas HPP (from 0.5 km to 6.2 km) until the battery was discharged. As a consequence it was concluded that these eels had died. The fate of the remaining five eels after passing through the HPP turbines remains unknown because the transmission signal ceased between the scanned sector 25 km downstream from the HPP and the Nemunas Delta where they were not detected.

Eels that successfully reached the Nemunas Delta were slightly smaller (mean TL = 76.2 ± 8.4 cm and W = 874 ± 281 g), compared with eels that migrated through turbines but did not reach the Nemunas Delta before the transmitter battery expired (mean TL = 79.0 ± 10.4 cm and W = 1070 ± 491 g). This difference was not significant and neither was the difference in W between the two groups. Four (36.4%) out of 11 eels detected in the Nemunas Delta were at the silvering stage FIV, while the other seven eels (63.4%) were at the silvering stage FV. Four (80%) out of five eels that suffered lethal injuries during passage through the Kaplan turbines were at the silvering stage FV and one (20%) at silvering stage FIV. Three (60%) out of five eels that disappeared between the scanned sector downstream of the Kaunas HPP and the Nemunas Delta were at the silvering stage FV and two (40%) at the silvering stage FIV.

Fish passage mitigation of turbine mortality

Following release, all of the tagged eels (N=64) passed from above to below the Valtūnai HPP during the same night. The most intense transit was observed between 0.30 a.m. and 4.30 a.m. when 83% (N=53) of the eels were recaptured below either the HPP or the fish passage. All recaptured eels had implanted PIT tags and no untagged eels were caught. Forty two eels (66%) migrated through the turbine, while the remaining 22 eels (34%) were caught after passing through the fish passage. Eels caught passing through the fish passage were significantly larger ($p < 0.001$, mean $TL = 72.0 \pm 7.2$ cm, $W = 681 \pm 188$ g) than those eels passing directly through the turbine (mean $TL = 66.1 \pm 6.4$ cm, $W = 476 \pm 109$ g); their FCF was also significantly larger ($p < 0.001$, mean $FCF = 0.18 \pm 0.02$) when compared with eels passing directly through the turbine (mean $FCF = 0.16 \pm 0.02$).

Logistic regression confirmed that TL, W and FCF all were significant ($p < 0.01$) predictors of the likelihood of eels using the fish passage thereby avoiding the turbine. The model fitted the data well (AIC = 51; Chi Sq = 39, df = 3, $p < 0.001$; MLL = -21, df = 4). Examination of the odds ratios showed that in contrast to the non-parametric results each unit increase in TL decreased the probability of using the fish passage by about 10%, whereas each increase in unit weight increased the probability by 12% and the effect of FCF was negligible.

Discussion

Results of this study support conclusions from similar studies (e.g. Hadderingh and Bakker, 1998; Verbiest et al., 2012) that show the occurrence of substantial mortality among silver eels due to injury when passing through HPP. It is apparent that HPP are among the main factors liable for decline in eel stocks.

Successful eel migration through small cross-flow CINK turbines was virtually impossible with 100% mortality recorded at the Bagdononys HPP. This HPP does not have a fish passage, thus all eels passed through the turbine suffering lethal injuries as a consequence. We conclude that cross-flow CINK turbines should be considered as the most hazardous type for migrating eels.

None of the 26 eels released at the Pabradė HPP water intake pipe were recaptured below the HPP. After the field experiment was conducted, it was found out that the HPP was equipped with an additional protective screen in the water intake pipe with a bar interval of c. 10 mm. This protective screen was not included in the initial HPP construction design and could not be reasonably known in advance of this study. The presence of the protective screen was only discovered after the field experiment during attempts to identify a reason for the 'disappearance' of all tagged eels guided into intake of the turbine.

Eel mortality rates in HPPs can be considerably reduced by the installation of fish passages. A substantial proportion of eels (34%) at Valtūnai HPP migrated through the fish passage thereby avoiding the injuries suffered by those which had passed through the Kaplan turbine. Our findings contrast with studies reporting only sporadic usage of fish passages (originally designed for fish upstream migration) by eels migrating downstream (Verbiest et al., 2012; Jansen et al., 2007). Eels caught during transit via a fish passage were significantly larger and had higher FCF in comparison with those passing directly through a turbine, although only weight was a significant predictor of an increased probability of preferentially using a passage. This is presumably caused by protective 35 mm metallic mesh screens at the HPP water intake zone which prevent larger eels from entering the turbine. Fish with elongated morphology tend to have higher mortality rates compared with other morphologies (e.g. salmonids) (Monten, 1985; Larinier and Travade, 2002), implying that larger eels were also expected to suffer higher mortality rates. However, there were no significant length and FCF differences between eels which suffered lethal injuries during passage through the small Kaplan turbine and those that survived. Length variation among eels which passed through the turbine was relatively small (from 57.5 to 85 cm) in our study, hence small males that usually grow up to 35 cm (Bauchot, 1986) are likely to have lower mortality rates. Effectiveness of the screens in deterring or preventing entry would be expected to be related more to girth and hence weight than length, or FCF. The lack of significance of length and FCF in predicting the use of the fish passage can be explained by heterogeneity in eel allometry, such that weight is a better indicator of girth than length or FCF which is a coefficient of the weight: length relationship.

In accordance with national regulatory measures to protect fish from small hydropower plants, each small HPP in Lithuania must have turbine screening by metal grids with bar intervals $<35\text{mm}$, but in practice the grids are not less than 35 mm. Our results indicate that such screening is insufficient for protection of eels and approximately two thirds of eels at the Valtūnai HPP passed directly through the turbines. ICES (2007) recommends that small male silver eels require bar intervals $<9\text{ mm}$ for protection, whereas females may be prevented from entering turbines by bar intervals $<15\text{ mm}$. Different screens and trash racks in front of water intakes have also been known to cause damage if fish become impinged and pressed against the racks by strong water currents (Adam and Bruijs, 2006; Calles et al., 2010), however flow rates of Lithuanian lowland rivers are typically slow and in conjunction with large bar intervals of c. 35 mm, impingement on screens should be negligible or absent except under extreme conditions such as those associated with exceptionally high rainfall events. Installation of effective screens at HPP in combination with fish passages may reduce eel mortality rates to negligible levels, but in Lithuania only three new fish passages have been installed during the past nine years. This is clearly insufficient to substantially reduce eel mortality rates. If such improvements were more widespread, then more water bodies may become suitable for restocking and restoration of depleted eel populations.

The majority of the 98 HPPs built on Lithuanian rivers ($N=67$, 68%) use Kaplan turbines, as with the rest of the Europe (Bruijs and Durif, 2009). According to the Bruijs and Durif (2009) review, eel mortality in Kaplan turbines at large ($>10\text{ MW}$) HPPs typically ranges from 20% to 38%, thus the results of the current study fall within the expected mortality range. Out of 21 eels which passed through the Kaplan turbines in the Kaunas HPP, five eels (23.8%) remained stationary below the HPP until their transmitter batteries expired, suggesting that the likelihood of them still being alive was negligible. The fate of the other five eels, which disappeared somewhere between the scanned sector 25 km downstream of the HPP and the Nemunas Delta, remains unknown. Winter et al. (2006) and Aarestrup et al. (2010) suggest that some migrating eels cease migration for lengthy periods, thus it is possible that those eels survived. Tag-induced morbidity and mortality are also considerations when tracking migrating eels. Jepsen et al. (2002) suggested that tag size should be minimized as much as possible. Cottrill et al. (2006) demonstrated that swimming capacity of silver

American eels was unaffected by the presence of telemetry transmitters and concluded that surgically implanting transmitters is the preferred method of affixing telemetry transmitters, especially for long-term telemetry studies. Despite the V13 acoustic tags being relatively large, we reasonably assumed that they had no significant negative impact on eel swimming performance and behaviour because Westerberg et al. (2007) and some more recent studies (e.g. Besson et al. 2016) have successfully tagged eels with higher tag to body mass ratios ($>2.5\%$).

The considerably higher mortality rate for eels passing through the Kaplan turbines installed in the Valtūnai HPP was likely caused by the smaller size of the turbine, given that turbine related mortality is expected to be decreasing with increasing turbine size (Marmulla, 2001).

Despite eels being typically nocturnal animals (Tesch, 1977) more than half of the eels passed through the Kaunas HPP turbines during the daytime. This was unlikely to have been a consequence of time of release because a proportion of those released at the same time during daylight hours did not transit the HPP until after nightfall or during the following day. Durif (2003) states that eel migration during daytime is related to increased water turbidity and water flow rate. The mean depth of the Kaunas Reservoir is approximately 12 m and its water turbidity is relatively high, therefore even under daylight conditions eels from this location were exposed to a relatively dark environment during passage through the turbines, which are located near the bottom of the reservoir at ~15 m depth. This daytime behaviour was observed only in the Kaunas HPP. In the small rivers with shallower depths (Siesartis, Dubinga and Strėva) eels were captured only during the night-time. Previous behavioural studies (Behrmann-Godel and Eckmann, 2003; Durif et al., 2003; Gosset et al., 2005; Calles et al., 2010) suggested that HPPs and dams may have indirect negative effects on eel migration: migrating eels often delay their passage through an obstacle and consequently the duration of their migration becomes extended. Results of the current study support this observation as 36% of eels released upstream from the Kaunas HPP also delayed passing through the turbines for periods from one to 47 days, while 16% of eels did not migrate at all. The remaining 48% of tagged eels passed through the turbines of the Kaunas HPP within 24 hours after their release.

We conclude that all eels passing through the small CINK turbines suffered lethal injuries resulting in 100% mortality, whereas Kaplan turbines caused lower mortality rates ranging from c. 25% to 52% depending upon size of the turbine. Results from this study suggest that 34% of eels migrating downstream used fish passages originally designed for upstream migration of salmonids. Installation of fish passages, especially in combination with effective screening, may be an effective measure to substantially reduce mortality rates among migrating eels. The results of our study demonstrate that HPPs may significantly threaten escapement targets specified in eel management plans if re-stocking is conducted in water bodies upstream from HPPs in the absence of any mitigation.

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Table 1. Main technical parameters of studied hydropower plants (HPP) (Lithuanian hydropower association, 2011).

River	HPP	Turbine	Water head, m	Installed power	Mean annual river flow at HPP, m³ s⁻¹
Nemunas	Kaunas HPP	Kaplan	15	101 MW	375
Siesartis	Valtūnai HPP	Kaplan	3.8	170 kW	5
Strėva	Bagdononys HPP	CINK	10.9	90 kW	0.8
Dubinga	Pabradė HPP	CINK	10.5	315 kW	3.4

Table 2. Morphometric parameters (TL - total length; W – weight; FCF - Fulton's condition factor) and tagging method of eels used for evaluation of mortality rates caused by CINK and Kaplan turbines

HPP	Turbine	N	Tagging method	TL, mm (±SD)	W, g (±SD)	FCF (±SD)	Silvering stage
Bagdononys HPP	CINK	52	PIT	681±84	576±153	0.18±0.04	FIII (N=20) FV (N=32)
Pabradė HPP	CINK	26	PIT	691±51.9	629±139	0.19±0.04	FIII (N=6) FIV (N=1) FV (N=19)
Valtūnai HPP	Kaplan	64	PIT	681±73	545±174	0.17±0.02	FV (N=64)
Kaunas HPP	Kaplan	25	Acoustic VEMCO	761±93	897±398	0.19±0.03	FIV (N=7) FV (N=18)

Figure Legend:

Figure 1. Location of Pabradė (CINK turbine), Bagdononys (CINK turbine), Valtūnai (Kaplan turbine) and Kaunas (Kaplan turbine) HPPs, and others within the catchments which were not included in this study.

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Author/s:

Dainys, J;Stakenas, S;Gorfine, H;Lozys, L

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