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Inter-annual variation in movements and passage of seaward migrating European eels at a shrouded Archimedean screw pumping station

Oliver J. Evans[a,b], Liam J. Carter[a], Thomas Hutchinson[a], Andrew Don[c], Rosalind M. Wright[d], Henrik Baktoft[e], Ine S. Pauwels[f], Jonathan D. Bolland[a,*]

[a] Hull International Fisheries Institute, University of Hull, UK
[b] Energy & Environment Institute, University of Hull, Hull HU6 7RX, UK
[c] Environment Agency, Rivers House, East Quay, Bridgwater, Somerset TA6 4YS, UK
[d] Environment Agency, Rivers House, Threshelfords Business Park, Inworth Road, Feering CO5 9SE, UK
[e] National Institute of Aquatic Resources, Technical University of Denmark, Silkeborg, Denmark
[f] Research Institute for Nature and Forest, Team Aquatic Management, Havenlaan 88/bus 73, 1000 Brussels, Belgium

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ABSTRACT

The construction of less damaging (here called fish-friendly) pumping stations has taken place in recent years, but it is unknown if they provide efficient and timely passage to migratory fish, such as European eel (*Anguilla anguilla* (L.)). The pump is often the only downstream passage route and operation, i.e., fish passage opportunity, is temporally variable depending on precipitation and prevailing river levels. Once the pumps are operating, eels must also consider the pumping station an attractive downstream passage route. Here, the movement of seaward migrating silver European eel ($n = 59$) upstream of a fish-friendly shrouded Archimedean Screw Pump (ASP) was assessed during three migrations (December–March in 2018/19, 2019/20 and 2020/21) with highly contrasting hydrology using acoustic telemetry. The overall passage rate was low (36.8 %) and minimum passage time was 65.2 days during a year with very little pump operation (2018/19), with seven eels tagged with long-life transmitters passing the pumping station the following year (2019/20). Furthermore, the median number of approaches to the pumping station was seven, with 36.8 % ($n = 7$) approaching more than 10 times. By contrast, passage rate was high (95.0 %), maximum passage time was 2.7 and 34.0 days (minimum = 3 min in both years) and all but one eel passed during the first approach during the two wettest years (2019/20 and 2020/21). Eels were almost exclusively nocturnal, regardless of pump operation, with 96.1 % of total approaches occurring between sunset and sunrise and no eels passed downstream during the day. Ultimately, limited eel passage opportunity during dry periods and a reluctance to pass when operational curtailed the effectiveness of these pumps to provide efficient and timely passage. Thus, measures are required to align pump operation with the timing of eel migration, especially in dry years, and reasons for retreat from the pumping station during operation must be identified and alleviated.

1. Introduction

Globally, waterways have been heavily modified in recent decades for numerous reasons including flood prevention, water retention for irrigation and human use and the generation of power (Grill et al., 2019). Consequently, many European rivers are now heavily obstructed, with a barrier every 1.5 km of stream in Great Britain, on average (Jones et al., 2019; Belletti et al., 2020). Obstructions vary in size from small structures such as low head weirs to pumping stations and hydropower facilities that span the full river width. Indeed, there are more than 150, 950 and 3000 pumping stations in Belgium, England, and the Netherlands, respectively (Environment Agency, unpublished data; Buysse et al., 2014). The modification and management of rivers has become a huge problem for diadromous fish species, particularly for seaward migrating adult silver European eel (*Anguilla anguilla* (L.)) (Feunteun, 2002; Bruijs and Durif, 2009).

The European eel has suffered severe decline since the early 1980's due to several reasons including migration obstructions (including passage through turbines), overfishing, habitat loss, pollution, parasites and marine events (Feunteun, 2002). Latest estimates of European eel

* Corresponding author.
E-mail address: j.bolland@hull.ac.uk (J.D. Bolland).

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recruitment as a percentage of 1960–1979 levels were 0.4 % (North Sea series) and 8.8 % (elsewhere Europe series) (International Council for Exploration of the Seas (ICES), 2023), hence eel now being classified as 'critically endangered' (Pike et al., 2020). Due to the severe decline of the European eel population the European Commission (EC) has established legislation (Regulation No. 1100/2007) meaning all member states with European eel habitat present must implement an Eel Management Plan (EMP). The objective of each EMP being to reduce anthropogenic mortalities, increasing the probability of escapement to the sea to a level of at least 40 % of the silver eel biomass relative to the best estimate of escapement that would have existed if no anthropogenic influences had impacted the stock (European Commission, 2016). It is also advised by ICES that all non-fisheries-related anthropogenic mortalities for European eel should be zero (ICES, 2022).

Fish-friendly pumps (FFPs) are structures which are less damaging to passing fish, which should have high survival rates and not change the fish's natural behaviour during passage. These have the potential to provide safe downstream passage at pumping stations, although evidence of high survival rates is still lacking (Bierschenk et al., 2018). Notwithstanding, it is also unknown if FFPs provide efficient and timely passage, which is subject to nuances that pumps do not always operate and there is often no alternative downstream route (e.g., 81 of 125 in Anglian region of England; Solomon and Wright, 2012). Consequently, eels must pass through the pumping station, and there is no downstream passage route when not operating. Pump operation, and therefore passage opportunity, is dictated by prevailing river levels depending on the amount of precipitation which can variably considerably between years, and thus pluriannual investigations into downstream passage are urgently needed. Furthermore, eels must consider the pumping station an attractive downstream passage route once the pumps are operating to ensure efficient and timely passage, especially as the pumps may only operate for a limited amount of time and they cannot choose to use a more attractive route. Elsewhere, Piper et al. (2015) found that the downstream passage route selected by eels was not proportionate to flow, as 67 % of river flow passed through a redundant hydropower facility but only 21 % of eels used this route, thus indicating eel chose the most attractive route (i.e., not the route with greatest flow).

To be considered effective, a high proportion of eels that approach the pumping station must pass downstream and do so with limited delay, as would occur in an unregulated river. Lucas and Baras (2001) suggested 90–100 % should be the desired passage rate for diadromous fishes. Elsewhere, it has been demonstrated that eels are reluctant to pass through pumping station weedscreens (also known as trashracks); Bolland et al. (2019) and Van Keeken et al. (2020) observed retreat rates of 76.7 % and 59.4 % using acoustic imaging, respectively. Bruijs et al. (2003) reported 25 % of tagged silver eels that approached at a hydropower station on the River Meuse, Netherlands, subsequently retreated upstream. While Calles et al. (2010) observed that radio-tagged eels approached hydropower station spill gates on the River Altran, Sweden, up to 35 times. Piper et al. (2015) proposed that increased water velocity / accelerated flows and noise emitted could cause eels to reject passing at anthropogenic infrastructure.

The use of tracking technologies has allowed the impact of retreat from and delay at anthropogenic infrastructure to be quantified. Behrmann-Godel and Eckmann (2003) reported eels exhibited a circling behaviour immediately upstream of a turbine on the River Mosel, Germany, with retreat distances of up to 1 km. Elsewhere, the additional distance swum by eels has been far more substantial; as much as 77.2 km at a single dam and a cumulative mean extra of 47.7 km over three dams in the River Fremur, France (Trancart et al., 2020). Further, 82 % of acoustic-tagged eels that approached a UK pumping station retreated up to 13.5 km (mean ± S.D. = 4.4 ± 3.6 km) (Bolland et al., 2019). Silver eels stop feeding and rely on fat reserves from the growth phase to complete the migration back to the Sargasso Sea to spawn (Balm et al., 2007), and thus increased swimming distance during retreat from anthropogenic infrastructure could result in a metabolic cost (i.e., deplete energy reserves) that impacts marine migration (Belpaire et al., 2009). Moreover, time delays can also be substantial; up to 49 days in the River Nive, France, (Gosset et al., 2005) and Bolland et al. (2019) reported 58.8 % of acoustic-tagged eels that approached a pumping station passed through after 9.5 ± 11.0 days (maximum = 31 days) and speculated that the remaining eels may have been predated or desilvered (e.g., Bašić et al., 2019). Likewise, Besson et al. (2016) observed migration delays for 75 % of tagged eels and 65 % of these were stopped by dams despite favourable environmental conditions. Ultimately, migration delays could cause eels to arrive outside the presumed spawning period (starting in spring) in the Sargasso Sea (Wright et al., 2022) or may not escape the catchment at all, but they are yet to be quantified at pumping stations with fish-friendly pumps.

1.1. *Aims and objectives*

The aim of this study was to analyse movements of seaward migrating silver European eels upstream of a pumping station with a fish-friendly pump (the only downstream passage route) over multiple years with highly contrasting hydrology. Specific objectives were to assess the approach, retreat and passage movements of tagged eels using both catchment-wide (3 years) and fine-scale (2 years) acoustic telemetry upstream of the pumping station. More specifically, solitary acoustic receivers enabled catchment-wide movements to be quantified while a dense array of receivers upstream of the pumping station enabled the fine-scale position during approach to be quantified (Hellström et al., 2022). Such information is urgently required to establish if fish-friendly pumps are a viable downstream passage solution for European eel in catchments regulated by a pumping station or if further remediation measures are required.

2. Materials and methods

2.1. *Study site*

Bells pumping station (51°22′13.5"N 0°51′24.2″E) is located on the Isle of Sheppey and provides flood protection to 34 km^2 of catchment. The pumping station has two fish-friendly shrouded Archimedean screw pumps (ASPs); 2.5-m screw diameter, 10.5-m screw length, 3500 L/s pumping capacity and 11.2–23.3 RPM (range). The pumping station is fronted by a 10-m long weedscreen. The reach upstream is fragmented by weirs on two tributaries, 0.92 km and 0.35 km from the pumping station (Fig. 1). The study was performed over three years with highly contrasting hydrology (between tagging and final eel passage); 2018/19 was a dry year with very little pump operation (mean ± S.D. = 1.75 ± 2.30 h per day) whereas 2019/20 (22.12 ± 3.65 h per day) and 2020/21 (13.56 ± 9.14 h per day) were wet years with more frequent pump operation.

2.2. *Eel capture and tagging procedure*

Fyke nets were used to catch seaward-migrating adult silver eels from the reach ~100 m upstream of Bells pumping station from the 19–30.11.2018, 17–19.12.2019 and 11–15.12.2020. Nets were emptied weekly and captured eels were transferred to 120 L holding barrels containing holes to allow for aeration and a flow of fresh water.

In 2018, V7-4L (n = 4; 21.5-mm long × 7-mm diameter, 2.1-g weight in air, 69 kHz, Pulse Position Modulation (PPM) delay = 33–57 s, tag life ~197 days; www.innovasea.com) and V9-2L (n = 15; 29-mm long × 9-mm diameter, 4.7-g weight in air, 69 kHz, PPM delay = 33–57 s, tag life ~512 days; www.innovasea.com) acoustic transmitters were used. In 2019 (n = 20) and 2020 (n = 20) V9–180 kHz acoustic transmitters (26.5-mm long × 9-mm diameter, 3.9-g weight in air, 180 kHz, PPM = 30–90 s and High Residence (HR) delay = 1–2 s, tag life ~320 days; www.innovasea.com) were used. Tag weight in air was less than 2 % of the eel mass (Winter, 1983). Prior to tagging in the field, acoustic

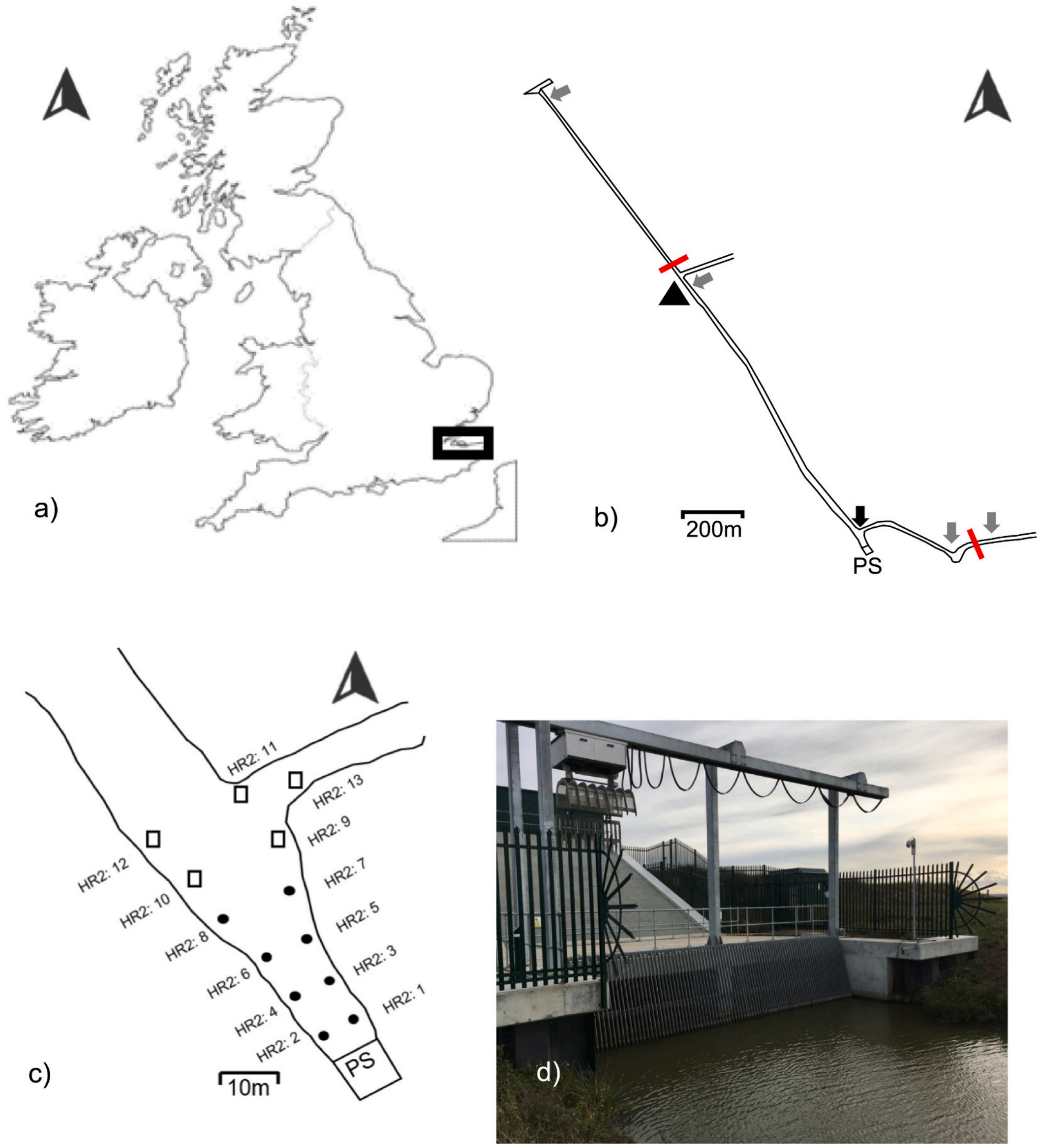

Fig. 1. a) The location of the Isle of Sheppey (black rectangle) in the United Kingdom, b) VR2W receiver locations (arrows), upstream limits (red lines), release location (black triangle) and Bells pumping station (PS), c) HR2 receiver locations (2019/20 = black circles and rectangles, 2020/21 = black circles) at Bells pumping station (PS) and d) upstream view of Bells pumping station. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

transmitters were activated, tested with a handheld receiver (Vemco VR100; www.innovasea.com) to verify that they were transmitting, disinfected with iodine, and rinsed with saline solution. Eels were anaesthetised using buffered tricaine methanesulphonate (MS-222; 0.16 g per 10 L of river water). Once anaesthetised, each eel was weighed (g) before being placed in a clean V-shaped foam support. Total length, left pectoral fin length, head width, left eye horizontal and vertical diameters (all in mm) were measured; all tagged eels (n = 59) were identified as female migrants using the silver index calculator (Durif et al., 2009). A ventro-lateral incision was made with a scalpel anterior to the muscle bed of the anal fins, an acoustic transmitter was implanted into the body cavity and the incision was closed with an absorbable monofilament suture. After surgery, eels were continuously monitored in a well-aerated tank of fresh river water and were released ~920 m upstream of the pumping station after full recovery (regained balance and actively swimming) (Table 1). There was no mortality due to tagging. All fish were treated in compliance with the UK Animals (Scientific Procedures) Act 1986, Home Office project licence number

Table 1
Year tagged, date tagged, number (n), length (mean ± SD (min-max), mm), weight (mean ± SD (min-max), g) and tag burden (mean ± SD (min-max), %) of tagged eels.

Year tagged	Date	Number	Length (mm)	Weight (g)	Tag burden (%)
2018	20.11.18	4	838 ± 61 (750–920)	128 ± 288 (875–1600)	0.17 ± 0.04 (0.13–0.24)
	03.12.18	15	777 ± 97 (630–1030)	1058 ± 321 (500–1625)	0.49 ± 0.17 (0.29–0.94)
2019	19.12.19	20	761 ± 71 (620–920)	869 ± 210 (475–1275)	0.48 ± 0.14 (0.31–0.82)
2020	17.12.20	20	752 ± 90 (560–930)	913 ± 214 (600–1305)	0.45 ± 0.11 (0.30–0.65)

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2.3. Catchment-wide and fine-scale acoustic receivers

Solitary acoustic receivers (presence/absence, VR2W; www.innovasea.com) were used to study the catchment-wide eel movements upstream of the pumping station in all three years (Fig. 1b). High residence acoustic receivers (positioning, HR2; www.innovasea.com) deployed in a dense array were used to study the fine-scale approach to and retreat from the pumping station in 2019/20 (n = 13) and 2020/21 (n = 8) (Fig. 1c).

2.4. Data analysis

Catchment-wide (VR2W) receiver data was uploaded to VUE (Vemco User Environment; www.innovasea.com) software and exported to Microsoft excel for analysis. Fine-scale (HR2) acoustic data was analysed in Fathom software (www.innovasea.com) and exported to Microsoft excel CSV files for use within R version 4.1.2 (Team R, 2023a) and in R Studio version 2022.02.3 (Team R, 2023b) in which tracks were created using the package Yet Another Positioning Solver (YAPS) (Baktoft et al., 2017). Track times and durations were exported and collated in Microsoft excel. A series of metrics were calculated for each eel (Table 2). Number of array visits, array visit duration, point of retreat and retreat duration could not be calculated after 09.01.2021 (error in data construction prevented fine-scale positions being created) for three eels that passed the pumping station on 14, 20 and 21.01.2021. Differences in passage time between years were compared using Kruskal-Wallis chi-squared test (Post-hoc Dunn's test) and differences in the proportion of eels that entered the fine-scale array between day and night (within 2019/20 and 2020/21) were compared using Fisher's exact test using R version 4.3.3 (Team, 2023a). It was not possible to statistically compare fine-scale movement data (e.g., array visit duration, point of retreat and retreat duration) between 2019/20 and 2020/21 due to differences in array size.

Table 2
Metrics used to analyse catchment-wide and fine-scale movements of acoustic-tagged eel at Bells pumping station.

Metric	Calculation
Catchment-wide acoustic telemetry	
Pumping station approach	Detected on the VR2W receiver closest to the pumping station (during pump operation), with subsequent approaches separated by detection on a VR2W receiver elsewhere in the catchment.
Passage	Detected on the most downstream VR2W receiver with no further detections on any VR2W receiver elsewhere in the catchment.
Passage time	Time between first approach to the pumping station (during pump operation) and final detection prior to passage.
Pumping duration between first approach and passage	Total amount of time pumps were operational between first approach to the pumping station (during pump operation) and passage.
Cumulative retreat distance	Distance moved during all retreats to VR2W receivers elsewhere in the catchment between first approach (during pump operation) and passage. For eels that passed the year after tagging, only movements prior to final pump operation in year 1 and following first approach (during pump operation) in year 2 were included.
Fine-scale acoustic telemetry	
Array visit duration	Time between passing the most upstream pair of HR2 receivers in a downstream direction and passing the most upstream pair of HR2 receivers during retreat in an upstream direction.
Point of retreat	The closest distance to the pumping station weedscreen prior to retreat during a visit to the HR2 array.
Retreat duration	Time between retreat from the HR2 array upstream of the pumping station and the subsequent visit to the HR2 array.

3. Results

3.1. Passage efficiency (all years; catchment-wide acoustic telemetry)

Of the 19 eels tagged in 2018, all ($n = 19$) approached the pumping station and 36.8 % ($n = 7$) of eels passed in 2018/19 and all (100 %) the remaining eels with long-life tags (n = 7) passed the following year (2019/20). The remaining eels (n = 5) were tagged with tags that expired before first pump operation in 2019/20 and therefore the fate was unknown. Of the twenty eels tagged in each of 2019 and 2020, 100 % ($n = 20$) and 95 % ($n = 19$) approached the pumping station and 95 % (n = 19) and 100 % (n = 19) of those that approached passed, respectively.

3.2. Passage times, relative to pump operation (all years; catchment-wide acoustic telemetry)

Pumping station passage occurred in February – March in 2018/19, December in 2019/20 and December – January in 2020/21 (Fig. 2). Median passage time (h:mm) was significantly different between years (Kruskal-wallis; $\chi^2 = 30.96$, d.f. = 2, $p < 0.001$), with eels tagged in 2018 (5811:14 (interquartile range (IQR) = 7130:28)) taking significantly

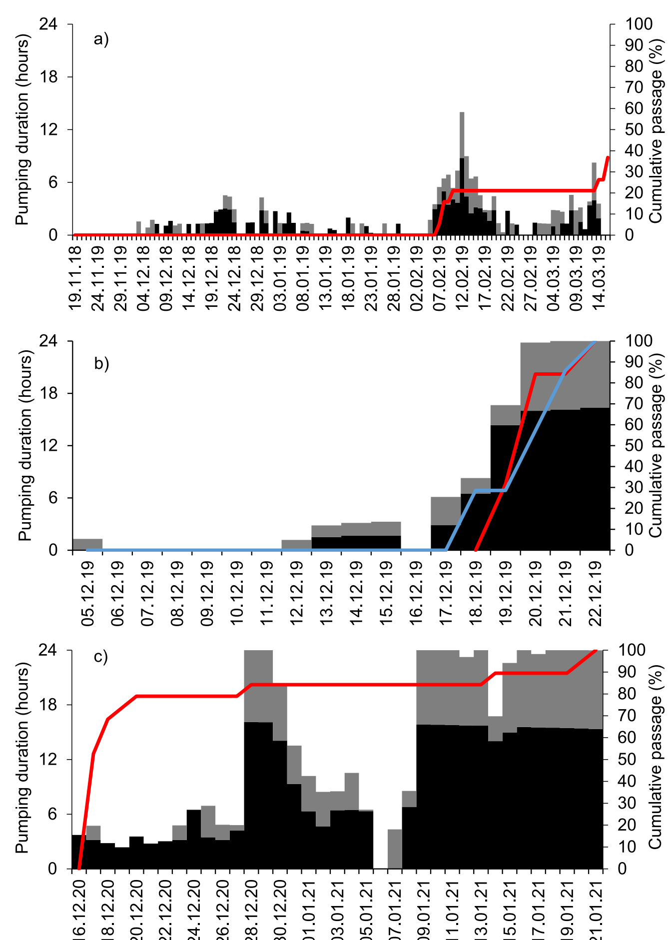

Fig. 2. Night (black) and day (grey) pump operation (hours) and cumulative passage for eels in a) 2018/19, b) 2019/20 and c) 2020/21. Red line = eels tagged that year and blue line = tagged in previous year (see Table 1 for tagging dates). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

longer to pass than eel tagged in 2019 (0:25 (IQR = 7:39); Post-hoc Dunn's test: z = 4.45, p < 0.001) and 2020 (0:09 (IQR = 0:10); Post-hoc Dunn's test: z = 5.28, p < 0.001) (Fig. 3a,b,c). These differences were attributed to the amount of pump operation between first approach and passage; 2.4–8.4 % in 2018/19, 98.9–100.0 % in 2019/20 and 63.5–100.0 % in 2020/21 (Fig. 3d).

3.3. Pumping station approach and cumulative retreat distance (all years; catchment-wide acoustic telemetry)

One eel tagged in 2018 approached the pumping station (during pump operation) once and 36.8 % (*n* = 7) approached more than 10 times (median = 7.0 (IQR = 15.5, min-max = 1–42)). The median (IQR, min-max) cumulative retreat distance (after first approach to the pumping station during pump operation) for eels tagged in 2018 that passed in 2018/19 (*n* = 7) was 6.5 km (16.6 km, 0.7–32.7 km) and in 2019/20 (*n* = 7) was 34.1 km (55.2 km, 14.7–87.5 km). By contrast, all but one eel tagged in 2019 approached the pumping station (during pump operation) once prior to passage in 2019/20 and the other eel approached twice (cumulative retreat distance = 3.24 km). In 2020/21, all eels passed during their first approach to the pumping station.

3.4. Fine-scale array entry and retreat (2019/20 and 2020/21; fine-scale acoustic telemetry)

Entry into the fine-scale array (during pump operation) was almost exclusively at night, with 96.4 % (*n* = 80/83) in 2019/20 (Fisher's exact test; p < 0.001) and 94.7 % (*n* = 18/19) in 2020/21 (Fisher's exact test; p < 0.001), and all pumping station passage occurred at night. Median number of array visits prior to passage was 1 in both 2019/20 (IQR = 3.5) and 2020/21 (IQR = 1), with 11 eels retreating from the array at least once and one eel approached 38 times (in 2019/20). Median array visit duration was 19 min in 2019/20, with 41.0 % (*n* = 34) less than 15 min (Fig. 4a), and 8 min in 2020/2021, with all 19 visits less than 15 min (Fig. 4b). The median point of retreat (m) during non-passage approaches were 11.4 m and 13.7 m upstream of the pumping station in respective years (Fig. 4c). Of eels that had multiple array visits, median retreat duration was 19 min and 313 min in respective years (Fig. 4d).

4. Discussion

Knowledge of silver European eel movements in pumped catchments are essential to understand if FFPs are a viable downstream passage solution, i.e., they provide efficient and timely passage. Here, the approach and passage of seaward migrating European eels at a pumping station with a FFP was assessed using catchment-wide and fine-scale acoustic telemetry over multiple years with contrasting amounts of pump operation. The annual passage rate was heavily influenced by the frequency and duration of pump operation, namely passage opportunity, but eels also retreated from the pumping station when pumps were operating.

Often, the only downstream fish passage route at a pumping station

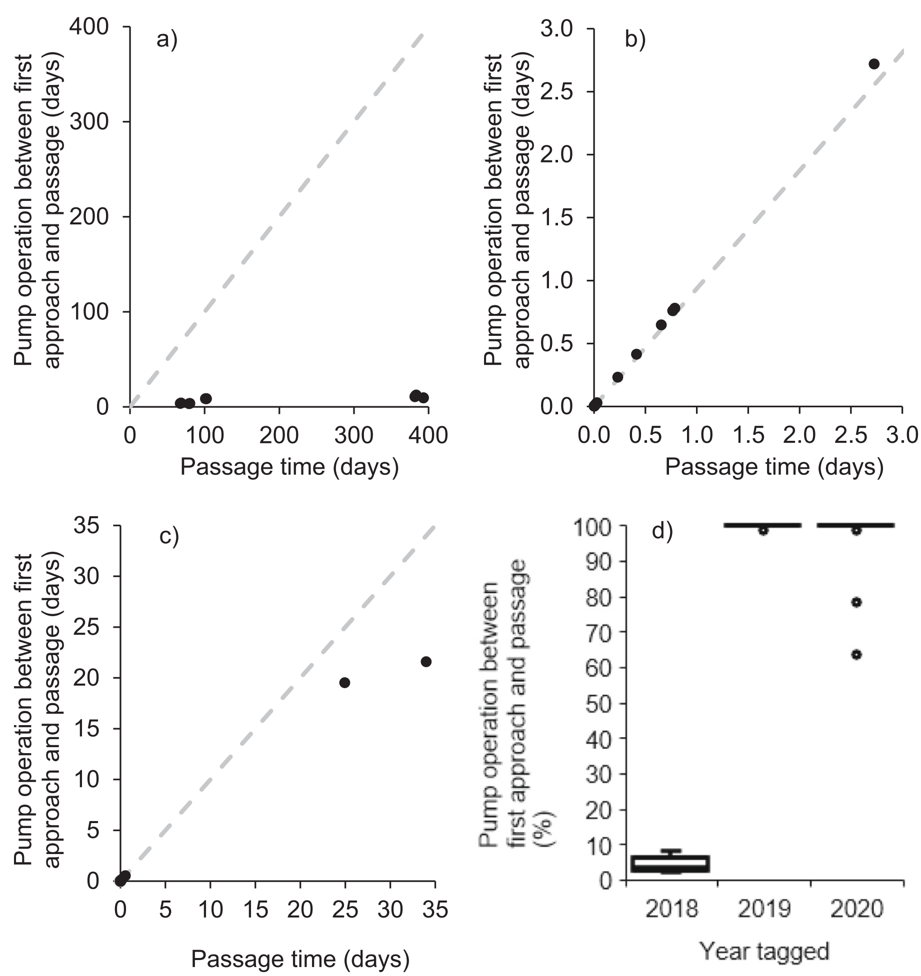

Fig. 3. Passage time (days) relative to amount of pump operation between first approach and passage (days) for European eel tagged in a) 2018, b) 2019, c) 2020, and d) the percentage of time the pump was operational between first approach and passage (days). Note; different x/y-axis scales and dashed grey line represents pump was operational for 100 % of the passage time (a-c).

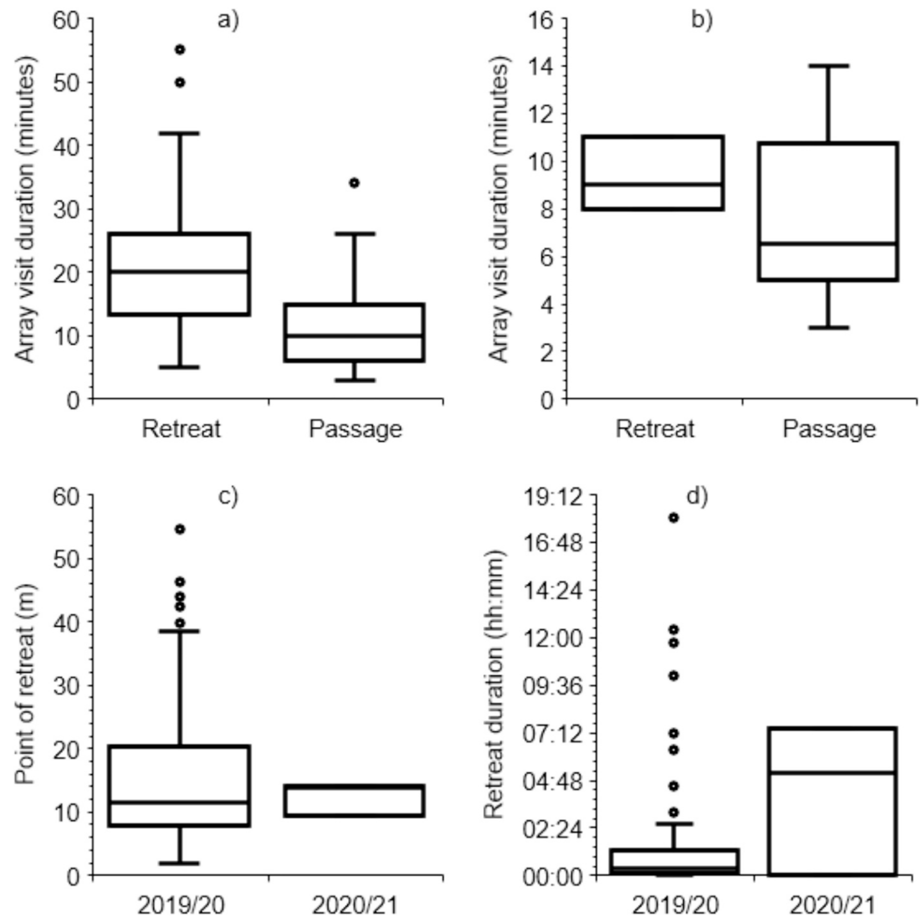

Fig. 4. Fine-scale array visit duration (minutes) prior to retreat and passage in a) 2019/20 (n = 83) and b) 2020/21 (n = 19), c) point of retreat in 2019/20 (n = 63) and 2020/21 (n = 3), and d) retreat duration in 2019/20 (n = 64) and 2020/21 (n = 3).

is through pumps, i.e., fish can only pass when the pump is operating, and the variation between dry and wet years in this study illustrated the importance of this. The overall passage rate was low (36.8 %) during a year with very little pump operation (2018/19) but high (95.0 %) during the two wettest years (2019/20 and 2020/21). All eels with long-life tags (n = 7) that failed to emigrate in 2018/19 survived within the river until the following year (2019/20) and passed the pumping station on similar dates to eels tagged in that year. Trancart et al. (2020) reported delays of up to 118.6 days were experienced by eels approaching overflow dams, but the findings presented here represent the first example of anthropogenic infrastructure delaying silver eel migration to the following year. Although it has been previously observed in an unregulated reach of River Imsa, with tagged eels recaptured the following migration season and unfavourable environmental conditions being the proposed explanation (Vollestad et al., 1994). Further, Westin (1998) described migration ceasing in October and recommencing the following July in the Baltic Sea as ‘hibernation’. Regardless, passage times of up to 393.2 days may have increased the likelihood of predation (e.g., Verhelst et al., 2018) but that was not found here. But it remains unknown if such passage delays could impact the onward migration of silver eels, as has been found for upstream migrating adult river lamprey (*Lampetra fluviatilis*; Jubb et al., 2023).

During the dry year (2018/19), the largest number of approaches to the pumping station was 42 and longest cumulative retreat distance was 87.5 km. Although it must be noted that retreat further upstream was prevented by man-made weirs and thus the potential maximum retreat distance was much shorter than in less impounded catchments. Elsewhere, Bolland et al. (2019) reported eels retreating from a pumping station moved a mean ± S.D. distance of 4.4 ± 3.6 km and up to a maximum of 13.5 km, while Trancart et al. (2020) reported eels approaching a dam covered up to 70 km of additional distance. Such retreat movements can increase energy expenditure and reduce body condition (Acou et al., 2008) but it was beyond the scope of this study to quantify the latter. By contrast, retreats from the pumping station during the wetter years were shorter duration and lower distance, and thus potentially have less effect than during dry years.

Thirty-eight of 39 eels that approached the pumping station when the fine-scale array was in situ (during the two wettest years; 2019/20 and 2020/21) passed downstream, but 11 eels retreated from the array at least once prior to passage and one eel approached 38 times (in 2019/20). These findings are consistent with those from other types of anthropogenic infrastructure, including up to 29 approaches to a pumping station with a gravity sluice (Baker et al., 2021) and 35 approaches to a hydropower plant (Calles et al., 2010). Here, the point of retreat was generally close to the pumping station, but ranged from within 10 m of the pumping station to >50 m away. At traditional pumping stations, weedscreens, accelerating flows and noise from pumps have been proposed as factors affecting eel passage / retreat (Bolland et al., 2019; Van Keeken et al., 2020) and thus could also be applicable to fish-friendly pumping stations. Ultimately, the cause of retreat movements at fish-friendly pumping stations must be better understood and minimised.

Understanding when European eels migrate in pumped catchments can provide evidence to change operations to maximise the likelihood of eel escapement, as has been described for a pumping station with a gravity sluice (Carter et al., 2023) and hydropower facilities (Schwevers and Adam, 2019). Eels were almost exclusively nocturnal during this study, with 96.3 % (n = 80/83) and 94.7 % (n = 18/19) of approaches between sunrise and sunset in 2019/20 and 2020/21, respectively, despite pumps also operating during daylight hours. Eels are known to be nocturnal during downstream movements (Stein et al., 2015), likely due to their photophobic nature, primarily moving on the darkest nights (i.e., new moon) (Lowe, 1952; Tesch, 2003), although cloud cover and turbidity lessen this effect (Travade et al., 2010; Sandlund et al., 2017). Thus, it is recommended that during periods when pumps do not run continuously, night-time pump operation at during the new moon should be prioritised to increase eel escapement.

4.1. Future research

This study is the first to quantify the movement of acoustic-tagged eels during approach to a pumping station with a FFP, doing so over three migration seasons. The overall passage efficiency was much lower when pump operation was less frequent in 2018/19 (only catchment-wide acoustic telemetry) than in 2019/20 and 2020/21 (both catchment-wide and fine-scale acoustic telemetry) during periods of heavy rainfall and consequently frequent pump operation. Thus, it remains unknown if the fine-scale movements of eels at the pumping station differed between dry and wet years. It is also known that temperature and lunar cycle have an influence on silver eel migration in unregulated rivers (Sandlund et al., 2017). Thus, further research is recommended to better understand the influence of a variety of environmental conditions on passage at pumping stations with FFPs. Furthermore, this study assessed one type of fish-friendly pump, a shrouded Archimedean screw, and thus it is recommended that further research into downstream passage is performed at more pumping stations and with a variety of FFP types (e.g., axial flow). Indeed, a greater understanding of the anthropogenic influences effecting eel passage (i.e., weedscreens, pump noise and accelerated flows) at pumping stations is urgently needed to inform future designs to improve effectiveness and increase eel escapement. It is also recommended that future research, where possible, should study the onward movements of eels which successfully pass pumping stations with fish-friendly pumps.

4.2. Management implications and context

This study uniquely showed that although fish-friendly pumping stations may have the potential to provide downstream passage for seaward migrating European eels, as per EC regulation 1100/2007 (establishing measures for the recovery of the stock of European eel; European commission, 2016) and Eels (England and Wales) Regulations 2009, but limited passage opportunity during dry periods and a reluctance to pass when operational curtail their effectiveness. Indeed, lowest annual passage rate was 36.8 % (2018/19), the longest passage time was 393.2 days and pumps operating for as little as 2.4 % of the time between first approach and passage. Therefore, it is recommended that fish-friendly pump operation must align with the seasonal (September – February), lunar (new moon) and circadian (night) timings of silver eel migration (see Carter et al., 2023) to improve the eel passage rates during dry periods. In addition, despite almost continuous pump operation in the wettest study year (2019/20), nearly half of the eels retreated from the pumping station at least once and up to as many as 38 times. Therefore, it is recommended that the reasons for retreat from fish-friendly pumping stations (e.g., interactions with weedscreens) are identified and alleviated to reduce passage delay (see Evans et al., 2024). Notwithstanding, all but two acoustic-tagged eels passed the pumping station, and the passage rate in the two wettest years was 95 %, which is within the desired range (90–100 %; Lucas and Baras, 2001). Thus, the shrouded Archimedes pumping station has the potential to remediate European eel escapement, provided that it can be confirmed (i.e., through health assessments or sensor deployments) that eels pass the structure unharmed.

CRediT authorship contribution statement

Oliver J. Evans: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Liam J. Carter:** Writing – review & editing, Methodology, Investigation. **Thomas Hutchinson:** Writing – review & editing, Methodology, Investigation, Formal analysis, Data curation. **Andrew Don:** Writing – review & editing, Resources, Project administration, Funding acquisition, Conceptualization. **Rosalind M. Wright:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. **Henrik Baktoft:** Writing – review & editing, Software, Formal analysis, Data curation. **Ine S. Pauwels:** Writing – review & editing, Resources, Methodology, Data curation. **Jonathan D. Bolland:** Writing – review & editing, Visualization, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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