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Research article

Timing is everything; operational changes at a pumping station with a gravity sluice to provide safe downstream passage for silver European eels and deliver considerable financial savings

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ABSTRACT

Catadromous European eel (*Anguilla anguilla*) are a critically endangered fish species due in part to in-river anthropogenic barriers (e.g., pumping stations, weirs, hydropower facilities). European legislation stipulates that safe downstream passage must be provided at hazardous intakes. Where present, gravity sluices have the potential to act as safe and low-cost downstream passage for seaward migrating silver eels at pumping station, but operational changes are required. This study used catchment-wide and fine-scale acoustic telemetry to investigate if operational changes (OC) at a pumping station (PS) with a co-located gravity sluice (GS) facilitated safe downstream passage for silver European eels. Specifically, night-time pump operations were ceased, river levels prior to sluicing were elevated and the GS was opened during key eel migration windows, i.e., at night during the new moon phase in autumn. No tagged eels passed through any pumps and the majority (2018 = 87.5%, 2020 = 88.9%) that approached the PS during OC passed downstream through the GS. Most eels approached during the first period of night sluicing after release (2018 = 73.9% and 2020 = 76.5%) and passed downstream during the first sluice event they experienced at the PS (2018 = 66.7% and 2020 = 75.0%). During the final approach prior to passage, very few retreats back upstream occurred at a median (IQR) distance of 34 (7.25) m from the GS and were predominantly a short distance (1–8 m). Overall, OC at a PS with a GS are considered a win-win-win, despite opening the sluice for <3% of the study period, given safe downstream passage was maximised, the financial benefits of sluicing water (~£14,670 in direct operational costs over two years) and the relative ease of implementation.

1. Introduction

Globally, many freshwater systems have been modified for water resource development needs, including agricultural irrigation, potable water supply, navigation, hydropower generation, flood risk management and land drainage (Nilsson et al., 2005; Piper et al., 2013; Harris et al., 2016; Wohl, 2017; Bolland *et al.*, 2019). Fluvial modifications disrupt natural hydrological flow regimes, which in turn impact fish community assemblages and impede free migratory movements (Rolls, 2011; Piper et al., 2013). In-river barriers are highly variable, ranging from low-head weirs to pumping stations that are complete barriers to longitudinal connectivity when not operational and renders the entire catchment upstream without flow. By contrast, the pumps are the only downstream passage route during operation, which is stochastic depending on rainfall and upstream water levels (Bice et al., 2023). The impact of in-river barriers on fish can vary between different types of structure and the prevailing community, and thus remediation measures must be tailored accordingly (Drouineau et al., 2018a,b).

Catadromous freshwater anguillid populations are in decline due to a suite of pressures acting on all life stages, including overfishing, pollution, parasitism, habitat loss and modification of river systems (Kirk, 2003; Dekker, 2003b; Bonhommeau et al., 2008; Acou et al., 2008; Aalto

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et al., 2016). Their complex lifecycle further confounds efforts to identify and implement protective measures (Tesch, 2003). Of the freshwater anguillid species, the European eel (*Anguilla anguilla*) has experienced one of the most drastic population declines, with recruitment reported to have reduced by over 90% since the 1980s (Dekker, 2003a; MacNamara and McCarthy, 2014). (Council Regulation No 1100, 2007) is enacted in England through (The Eels (England and Wales) Regulations, 2009) Statutory Instrument (Eels Regulations), which includes requirements for eel passage and screening of water intakes, including pumping stations, abstracting >20 $m^3 day^{-1}$, unless exempted by the Environment Agency (the regulator). Furthermore, the Eels Regulations also state that measures should aim to improve the escapement from river systems of seaward migrating adult eels (silver eels) to 40% of the potential biomass that would be achieved in unmodified river systems.

Pumping stations, hydropower plants, dams, and abstraction intakes fragment rivers and regulate flow that delays downstream silver eel migration, and in turn can increase predation and disease risk (Winter et al., 2006; Durif & Elie, 2008; Piper et al., 2013; Buysee et al., 2014). They also inflict physical damage or mortality through weed screen impingement and turbine/pumped passage (Buysse et al., 2014; Bierschenk et al., 2019; Geist, 2021; Mueller et al., 2022). Indeed, Bolland et al., 2019 reported high rates of lethal and sub-lethal injuries, particularly for eels that passed through the duty (electric) pumps, at the pumping station under investigation here. The best solution would be barrier removal, as occurs for defunct low-head weirs (Fjeldstad et al., 2011) and high-head dams (Catalano et al., 2007; Duda et al., 2021), but this is not feasible for operational pumping stations due to the ongoing need for flood risk management. Thus, in order to comply with legislation (EC 1100/2007), a safe downstream passage solution (e.g., retrofitting fish-friendly pumps, installation of a separate bypass) must be installed, often at considerable financial cost, which may be prohibitive. Existing infrastructure, such as a gravity sluice, has the potential to be a low-cost downstream passage solution at pumping stations but is seldom considered.

Migrant eels have been recorded passing downstream via spillways at hydroelectric facilities (Travade et al., 2010; Økland et al., 2019; Baker et al., 2020). For example, Egg et al. (2017) imaged 214 silver eels passing downstream using an undershot sluice gate at a hydroelectric facility. Providing safe downstream passage for eels at pumping stations is more challenging because these stations typically move water to a higher downstream level against gravity. However, some pumping stations are reported to have a co-located gravity sluice (85 of 447; Solomon and Wright, 2012) that can pass water downstream when upstream and downstream river levels allow. That said, Bolland et al., 2019previously found no acoustic tagged eels passed through the gravity sluice at the pumping station under investigation here during normal operations, i.e., to regulate river level and provide flood relief (rather than provide safe downstream fish passage). Baker et al. (2021) reported 28.6% of eels passed downstream via a sluice at a similar pumping station during the normal operating regime. This emphasises that further research is needed to maximise downstream silver eel passage through gravity sluices at pumping stations.

Fish-friendly operational management refers to a mode of operation adopted by hydroelectric facilities managers whereby turbine operation is reduced or ceased during fish migration events to minimise entrainment and maximise safe downstream eel passage (Schwevers and Adam, 2019). In theory, similar operational changes could be implemented at pumping stations with a suitable gravity sluice but are yet to be proven and, unlike hydropower, complete pump shutdown is not possible given the ongoing need to manage flood risk. Conversely, fish-friendly operational management is not economically desirable at hydroelectric facilities due to reductions in power generation but could represent considerable financial benefits at pumping stations. Indeed, cost savings would include reductions in energy consumed (i.e., diesel and electricity to power pumps) while reductions in pump operation will indirectly reduce on-going maintenance costs and extend pump life. Ultimately, to prevent entrainment and maximise safe downstream passage rates, operational changes (pump shutdown and sluice opening) must align with seasonal, lunar, and circadian rhythms of silver eel migration. Specifically, silver eels are known to migrate between late summer and early winter in response to lunar cycle (i.e., the new moon phase) and increased precipitation (which elevates river flow and turbidity), largely during hours of darkness (Tesch, 2003; Jansen et al., 2007; Piper et al., 2013; Bolland et al., 2019). River flow upstream of pumping stations with a gravity sluice could be modified to influence downstream eel migration, but remains to be proven, especially changes in water chemistry (e.g., elevated turbidity) caused by rainfall will not align.

During this investigation, an understanding of silver eel migration ecology led to pumps being operated exclusively during daytime hours (unless absolutely necessary, i.e., flood prevention) to prevent eel entrainment at night. Water was predominantly sluiced over a series of nights during the new (and full) moon phase of the lunar cycle, specifically for downstream eel passage. Pump and sluice operation prior to periods of eel specific night-time sluicing events were minimised to allow river levels to build (to simulate a flood) and maximise the amount of water sluiced. There was no flow in the catchment or downstream passage route at the pumping station when the pumps were off and the sluice was shut. As such, the overall aim of this investigation was to quantify the number of eels that approached and entered pump and gravity sluice (GS hereafter) passage routes during these operational changes (OC hereafter) at a pumping station (PS hereafter). Acoustic telemetry was employed to quantify the catchment-wide migration and fine-scale movement of seaward migrating silver European eel when approaching the PS.

Specific objectives of this investigation were to.

- Assess overall fate of acoustic-tagged eels during and after operational changes (both study years)
- Assess the influence of sluice timing on pumping station approach and sluice passage (both study years)
- Assess the influence of sluicing on pumping station approach, retreats and passage times (both study years)
- Assess fine-scale behaviour of acoustic-tagged eels during PS approach when the GS was open (2020), including the number and distance of fine-scale retreats

2. Methods

2.1. Study site

Hobhole PS (52°2′22.0″ N, 0°01′51.9″ E; Lincolnshire, UK) was commissioned in 1956, has a total pumping capacity of 36.7 m^3/s, regulates water level for drainage and flood defence of a 33,987-ha catchment area and discharges into the tidal River Haven (Fig. 1). As described in Bice et al. (2023), Hobhole PS prevents saltwater ingress and there is a prescribed upstream water level which varies between summer (May to September; −0.8 to −1.10m AOD) and winter (October to April; −2.0 to −2.2m AOD). The PS is the sole discharge point for the catchment and has three drainage routes, with operation dictated by prevailing upstream (stochastic depending on rainfall) and downstream (tidal estuary) river levels. There is no flow in the upstream catchment when the pumps are off and the sluice is shut.

- Four submersible axial flow Flygt 7,100,200-kw (267 HP) duty electric-powered pumps (installed in 1987) to regulate upstream river level. Each pump has a four-vane impeller (0.85 m diameter; 850 rpm) with a maximum pumping capacity of 2.1 m^3/s. The duty (electric) pumps are protected by a weed screen that is 10.8 m wide x 4.85 m deep with 10-mm thick bars and 55-mm gaps.
- Three mixed flow Allen T47 2-stroke, 770 HP diesel-powered pumps for flood relief operations (installed in 1957). Each pump has a three-vane impeller (2.23 m diameter; 100–106.7 rpm) with a maximum

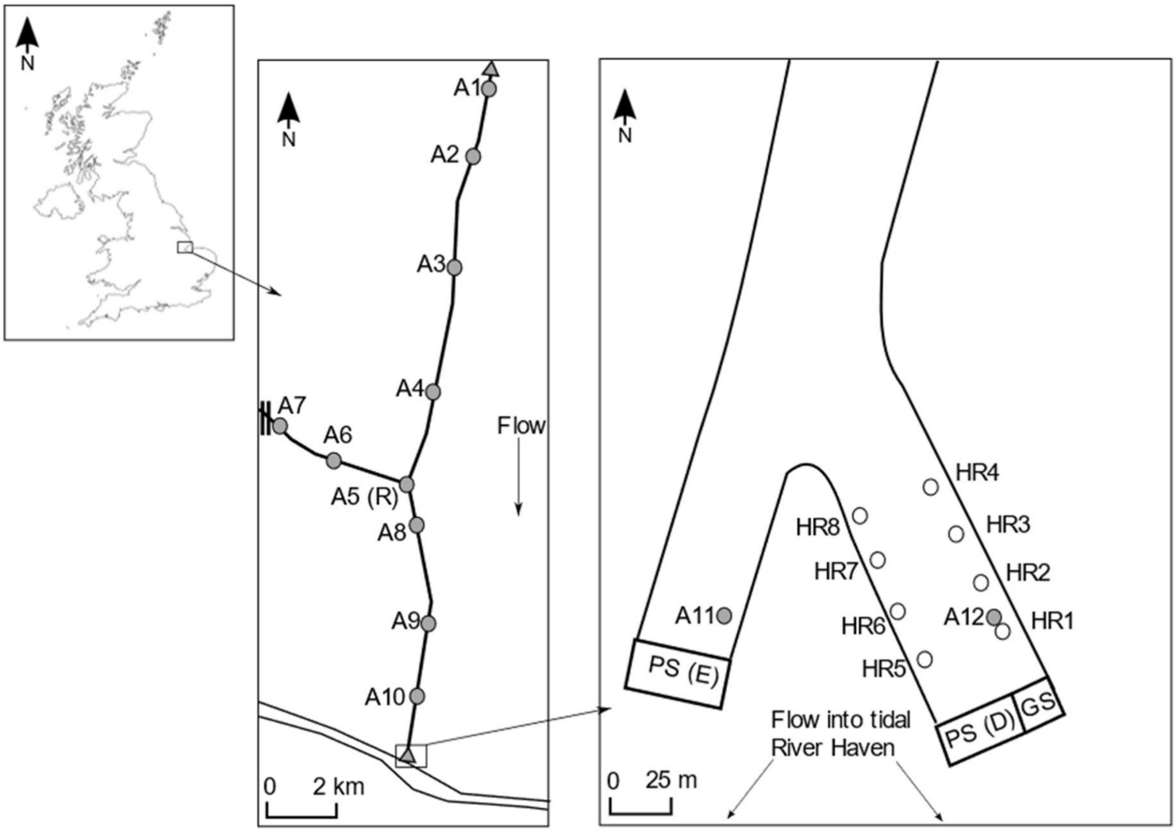

Fig. 1. A schematic of Hobhole Drain, including Hobhole pumping station (grey triangle), acoustic receivers (grey circles) and a spill over weir inlet (double black lines). The release site for acoustic-tagged eels is denoted with (R), PS (E) denotes duty (electric) pumps, PS (D) denotes diesel (flood) pumps and GS denotes gravity sluice. Note that in 2020, a high residence (HR) acoustic receiver array (open circles) was installed instead of the single receiver A12.

pumping capacity of 9.43 m^3/s. The flood (diesel) pumps are protected by a weed screen that is 20.8 m wide x 4.85 m deep with 25-mm thick bars and 90-mm gaps.

- A 5.2 m wide GS adjacent to the flood (diesel) pump intake (Fig. 1) with a cycloidal (inner) door that rotates upwards (under the weight of the water), a manually operated (outer) penstock door and no weed screen. The GS can be operated at low tide during largest spring and neap tides. A Sontek SL1500 side-looking (two horizontal beams with spreading widths of 1.4°) acoustic Doppler current profiler (ADCP; sampling rate = 1 s in pulse-incoherent mode) mounted at ~40% of the flow depth (accounting for the reduction in water level over the sluicing period) was used to assess discharge during a single sluicing event (Fig. S1); mean discharge = 18.0 m^3s^{-1}, peak discharge = ~23 m^3s^{-1} and total volume sluiced = 245,970 m^3.

2.2. Operational changes and sluicing procedures

Prior to this investigation, river level upstream of Hobhole PS was regulated by the duty (electric) pumps, water was sluiced during the day when upstream and downstream levels allowed, and flood (diesel) pumps provide flood relief (referred to as normal operations hereafter). During 2018, OC were implemented between 1 October to 22 December, i.e., the duty (electric) pumps only operated (if necessary) during daylight hours (07:00–17:00). River levels were allowed to build (to summer level) to simulate a flood event and maximise the volume of water that could be sluiced. The GS was opened specifically for eel passage at night during the new (dark) moon phase of the lunar cycle on low spring tides. A total of 10 night-time events occurred specifically for eel passage (total time sluice open = 41:20 h; average sluicing event = 04:10, min – max = 03:25–04:30) (Table 1). During 2020, OC were comparable to 2018 but occurred between 15 September and 16 November. There was a total of 16 night-time sluicing events; 12 during the new moon phase (total time sluice open = 49:30 h; average sluicing event = 04:07; min – max = 03:45–04:30) and four during the full moon phase (total time sluice open = 14:20 h; average sluicing event = 03:35; min – max = 02:30–04:00) (Table 1). There were also daytime sluicing and duty (electric) and flood (diesel) pumping events throughout both study periods (see Fig. S2). The study occurred in two non-consecutive years due to extreme flood relief pump operations in autumn 2019.

2.3. Acoustic tagging and tracking

Adult migrant silver eels were caught by commercial fishermen using fyke nets placed ~200 m upstream of the PS in both study years. To study catchment-wide movements in 2018, 37 eels were tagged with V9-2L acoustic transmitters (29 × 9 mm, 4.7 g weight in air, 69 kHz, Pulse Position Modulation (PPM) delay = 33–57 s; www.innovasea.com) and 1 eel (too small for a V9 transmitter) was tagged with V7-4L acoustic transmitter (21.5 × 7 mm, 2.1 g weight in air, 69 kHz, PPM delay = 33–57 s; www.innovasea.com) (see Table S1). To study catchment-wide and fine-scale movements in 2020, 24 eels were tagged with V9–2H acoustic transmitters (26.5 × 9 mm, 3.9 g weight in air, 180 kHz, PPM = 30–90 s and High Residence (HR) delay = 1–2 s; www.innovasea.com) (see Table S1). In all cases, the tag weight in air was less than 2% of the eel mass. All fish were treated in compliance with the UK Animals (Scientific Procedures) Act 1986, Home Office license number PPL PD6C17B56.

Prior to tagging, acoustic tags were activated, tested with a handheld receiver (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

Table 1
Night-time sluice event number (*n*), date, time of day, lunar phase, sluice opening width (cm) and duration (hours).

Sluice event (*n*)	Date	Lunar phase	Sluice opening width (cm)	Duration (hours)
1	November 05, 2018	New moon	61	04:30
2	November 06, 2018	New moon	61	04:30
3	November 07, 2018	New moon	61	04:15
4	November 08, 2018	New moon	61	04:15
5	November 09, 2018	New moon	61	04:30
6	December 05, 2018	New moon	61	03:45
7	December 06, 2018	New moon	61	04:00
8	December 07, 2018	New moon	61	04:00
9	December 08, 2018	New moon	61	03:25
10	December 09, 2018	New moon	61	04:30
1	September 15, 2020	New moon	46	04:15
2	September 16, 2020	New moon	46	04:15
3	September 17, 2020	New moon	61	04:00
4	September 18, 2020	New moon	46	04:15
5	September 30, 2020	Full moon	46	04:00
6	October 01, 2020	Full moon	61	04:00
7	October 14, 2020	New moon	46	04:00
8	October 15, 2020	New moon	46	04:30
9	October 16, 2020	New moon	76	04:30
10	October 17, 2020	New moon	76	03:45
11	October 29, 2020	Full moon	46	03:50
12	October 30, 2020	Full moon	76	02:30
13	November 13, 2020	New moon	76	04:00
14	November 14, 2020	New moon	76	04:00
15	November 15, 2020	New moon	46	04:00
16	November 16, 2020	New moon	46	04:00

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 (see Table S1). Maturation stage was later calculated following methods of Durif et al. (2009); all eels were determined to be in the migratory phase (Table S1). A ventro-lateral incision was made with a scalpel anterior to the muscle bed of the anal fins, an acoustic tag was implanted into the body cavity and the incision was closed with an absorbable monofilament suture.

After surgery, fish were continuously monitored in a well-aerated tank of fresh river water until fully recovered (regained balance and actively swimming) and released ~ 6 km upstream of the PS later that day, as was performed during Bolland et al., 2019. The distance (range = 3m to many kilometres) and time (range = the same night to 7 days) between release and data used to study silver eel interaction with anthropogenic infrastructure using telemetry is highly variable both within and between studies (e.g., Piper et al., 2015; Trancart et al., 2018; Calles et al., 2021; Huisman et al., 2023). Here, the mid-catchment release location (~6 km upstream of the study PS and ~7 km downstream of the next PS) at the confluence with the tributary (to avoid introducing a route choice bias) (Fig. 1) at least 24-h before a sluicing event were chosen to enable normal behaviour to resume prior to PS approach. In 2018, 26 of the 38 eels (68.4%) tagged were still active in the catchment when OC commenced (on 5 November) and are the focus for analysis here. In 2020, one eel was recaptured by the commercial eel fisherman and thus was excluded from all analysis.

The catchment-wide migration of silver eels was tracked using an array of acoustic receivers (2018 = 12, 2020 = 11 (A12 replaced with HR array); VR2W, www.innovasea.com) were installed throughout the 14.9 km reach of Hobhole Drain (to the next upstream pumping station) (Fig. 1). In addition, to study fine-scale movements of tagged eels, 8 high residence (HR) acoustic receivers (HR2-180 KHz, www.innovasea.com) were installed ~25 m apart in the channel beginning ~30 m upstream of the GS (Fig. 1). All receivers were anchored on steel fencing pins driven into the river bed. In all cases, the detection range was greater than the river width at the receiver deployment location. Detection efficiency calculations (using three sequential catchment-wide receivers (i.e. VR2W) to determine the efficiency of the middle receiver) revealed that missed detections accounted for less than 3.2% of silver eel movements between receivers. Rainfall data was manually collected at the pumping station at 9am daily (Fig. S2, Fig. S3). Temperature (°C) and turbidity (NTU) data were collected using a Sonde in 2018 but not in 2020 due to Covid-19 restrictions preventing access to the laboratory (Fig. S2).

2.4. Data and statistical analysis

Data were compiled, plotted and analysed using both Microsoft Excel and Rstudio (www.r-project.org). Data were tested for normality and homogeneity of variance by using Shapiro-Wilk-tests and Levene-tests. For non-normally distributed data, non-parametric tests were used. A series of metrics were calculated for each eel (Table 2). Wilcoxon rank sum tests were used to compare total number of approaches, passage time, total time at PS, total time GS was open between first approach and passage, total sluicing experienced and time to pass between years. Eel were classed as “retreating” when they were detected on receiver A10, 1.6 km upstream of the PS (Fig. 1).

Table 2
Metrics used to explore variation in catchment-scale movement of European eel after approach to Hobhole pumping station. OC denotes operational changes, PS denotes pumping station and GS denotes gravity sluice.

Metric	Calculation
Available fish	The number of eel that approached the PS during OC
Attraction efficiency	The proportion of eel that approached the PS during OC that approached the PS while the GS was open
Entrance efficiency	The proportion of eel that approached the PS while the gravity sluice was open that passed through the GS
Passage efficiency	The proportion of eel that approached the PS during OC that passed through the GS
Passage time	Time taken between first approach to the PS during OC and passage through the GS
Total time at PS	Total amount of time spent at PS during OC
Total time sluice open	Total amount of time the GS was open between first approach to the PS during OC and passage
Total sluicing experienced	Total amount of time the GS was open while an eel was at the PS
Time to pass	Time taken to pass through the GS during final approach to PS
Retreat extent	The most upstream receiver an eel was detected on after approach to the PS
Cumulative retreat distance	The total distance during all retreats from the PS for each eel
Duration of each retreat	Time between last and first detection at the PS during a retreat
Cumulative retreat time	Total amount of time spent in retreat from the PS for each for each eel

In 2020, the fine-scale positions of eels in the HR2 array upstream of the PS while the sluice was open were analysed using the Yet Another Positioning Solver (YAPS) package (https://cran.r-project.org/web/packages/yaps/index.html) (Baktoft et al., 2017) in RStudio v3.3.0 (R Core Team, 2020). Tracks for 4 of 11 (36.7%) non-passage visits to the array and 12 of 16 (75.0%) passage visits were produced. The beeline distance, i.e., the distance between the eel position and GS, was plotted against the backward path length, i.e., path taken by eels prior to passing downstream through the GS. Track tortuosity values were calculated by dividing distance eels swam within the array (m) (i.e., total track distance) by the distance eels were initially detected from the GS (m).

3. Results

3.1. *Eel fate*

In 2018, 24 of 26 acoustic-tagged eels approached the PS during OC, with 23 detected at the PS while the GS was open, i.e. attraction efficiency = 95.8%, and the majority passed downstream via the GS (*n* = 21); passage efficiency = 87.5% and entrance efficiency = 91.3% (Table 3). Three (12.5%) eels approached the electric PS while operational during the day during OC but no eels passed through. Although one eel that did not approach the PS during OC passed through the electric PS at night on February 11, 2019 following 32.3 mm of rainfall in the previous eight days. The remaining four eels were all detected at the PS, including one that first approached after OC, but were last detected in the catchment between November 24, 2018 and January 14, 2019 when no pump operation or sluicing was occurring.

In 2020, 18 of 23 acoustic-tagged eels approached the PS during OC, with 17 detected at the PS while the GS was open, i.e. attraction efficiency = 94.4% and the majority passed downstream via the GS (*n* = 16); passage efficiency = 88.9% and entrance efficiency = 94.1% (Table 3). Only one (5.3%) approached the electric PS while operational during the day during OC and did not pass through. Three eels first approached the PS after OC and passed through the electric pump at night on December 12, 2020 (10.6 mm of rain in previous two days) and one eel that approached the PS during OC passed through the electric pump at night on December 24, 2020 (38.8 mm of rain the preceding day). The remaining three eels, including one detected at the PS during OC, were last detected in the catchment between 17 September and October 23, 2020 when no pump operation or sluicing was occurring.

3.2. *The influence of sluice timing*

Of the 21 eels that passed through the GS in 2018, 19 (90.5%) did so during night-time sluicing events (specifically intended for eel passage) and 2 (9.5%) during daytime sluicing events (to regulate river level; *n* = 7) (Fig. 2; Table 4). All eels passed through the GS at night in 2020, despite 21 daytime sluicing events to regulate river level. Approach (64.4% and 40.0%), attraction (94.1% and 75.0%) and entrance (100% and 100%) efficiencies were all high at night during the new moon phase in both November and December 2018, respectively (Table 4). Likewise, approach (40.0%, 56.3% and 30.8%), attraction (100%, 88.9% and 100%) and entrance (100%, 100% and 100%) efficiencies were also high at night during the new moon phase in September, October and November 2020, respectively (Table 4). Only one eel approached the PS on the same day that water was sluiced at night during the full moon phase in 2020 (Fig. 2) but the sluice was closed when it approached and thus did not pass downstream (Table 4).

Table 3
Fate of acoustic-tagged eel (*n* (%)) at Hobhole pumping station (PS) during operational changes (OC) in 2018 and 2020. GS denotes gravity sluice.

Metric	2018	2020
At liberty during OC	26	23
Approached PS during OC, i.e., available fish	24	18
Detected at PS while GS was open, i.e., attraction efficiency	23 (95.8%)	17 (94.4%)
Passed through GS, i.e., passage efficiency and entrance efficiency	21 (87.5%/ 91.3%)	16 (88.9%/ 94.1%)
Detected at PS while duty (electric) pump was running (during OC); i.e., attraction efficiency	3 (12.5%)	1 (5.6%)
Passed through duty (electric) pump during OC, i.e., passage efficiency and entrance efficiency	0 (0%/0%)	0 (0%/0%)
Passed through electric pump after OC	1	4

3.3. *Pumping station approaches and retreats*

In 2018 and 2020, 39.1% (*n* = 9 of 23) and 47.1% (*n* = 8 of 17) eels that approached the PS while the GS was open did so during the first night-time sluice event after release, respectively (Fig. 3), and the majority approached during the first period of night sluicing after release (2018 = 73.9% and 2020 = 76.5%). All but one first approach to the PS was during night-time sluicing (97.5%) and the largest number of night-time sluice events before first approach was 10 in both years (Fig. 3). Most eels that passed through the GS experienced one sluicing event at the PS before passage (2018 = 66.7% and 2020 = 75.0%) (figure 2.3). Nineteen eels that passed through the GS in 2018 experienced only night-time sluicing events and two experienced sluicing during day and night, and both passed downstream during a daytime sluicing event on December 19, 2018 (following 21.6 mm of rain in the preceding four days).

Of all the eels that approached the PS during OC, 33.3% (*n* = 8 of 24) and 38.9% (*n* = 7 of 18) retreated back upstream in 2018 and 2020, respectively, the most approaches were four and six (Fig. 3), and the total number of approaches by each eel during OC was comparable between years (W = 14, *p* = 0.831). Eels that did not pass through the GS, approached the PS during OC one, two and four times in 2018 and one and six times in 2020 (Fig. 3). The total number of retreats from the PS during OC was 15 in 2018 (passed GS = 8 and did not pass GS = 7) and 16 in 2020 (9 and 7, respectively); all but four retreats were when the sluice was shut (87.1%). For eels that passed, the retreat extent ranged from 1.6 to 5.2 km upstream of the PS, the mean ± S.D. retreat distance was 2.7 ± 1.5 km (range = 1.6–5.2 km) and the mean ± S.D. cumulative retreat distance for each eel was 3.9 ± 2.7 km (1.6–10.3 km). The mean ± S.D. duration of each retreat from the PS was 48:34 ± 95:07 h (03:14 h–14 days) and the mean ± S.D. cumulative retreat time for each eel was 70:10 ± 6.44 h (10:54 h–14 days). All but three subsequent approaches occurred during night-time sluicing events (82.4%).

3.4. *Approach and passage times*

In 2018, 14 of 21 eels (66.7%) quickly passed through the sluice during the first sluicing event they experienced while at the PS (Fig. 4). Although three of these eels first approached the PS shortly after the GS closed the previous night (time = 00:21, 03:44 and 16:09) and thus while passage time (during OC) for these eels was almost a day (median (IQR) time = 21:55 (02:53)), the cumulative sluicing durations between first approach and passage (median (IQR) time = 01:40 (00:39)) were low and represented a small proportion of the passage time (1.1%, 10.6% and 4.3%). The most GS events experienced while at the PS prior to passage in 2018 was nine (5 nights and 4 days; number of approaches = 1), and thus the passage time (during OC) (923:42), amount of sluicing (13:35) and sluicing experienced (08:09) were all high. Three eels that approached the PS during OC in 2018 but did not pass through the GS experienced zero, eight and one sluicing events, spent 0, 447:07 and 27:17 h at the PS, the sluice was open for 0, 31:45 and 01:45 h between first and last approach to the PS and they experienced 0, 31:45 and 01:45 h of sluicing while at the PS, respectively.

In 2020, the longest passage time was over 60 h but corresponded to 02:02:37 (hh:mm:ss) of sluicing, which was also the largest amount of sluicing between first approach and passage. Overall, passage time

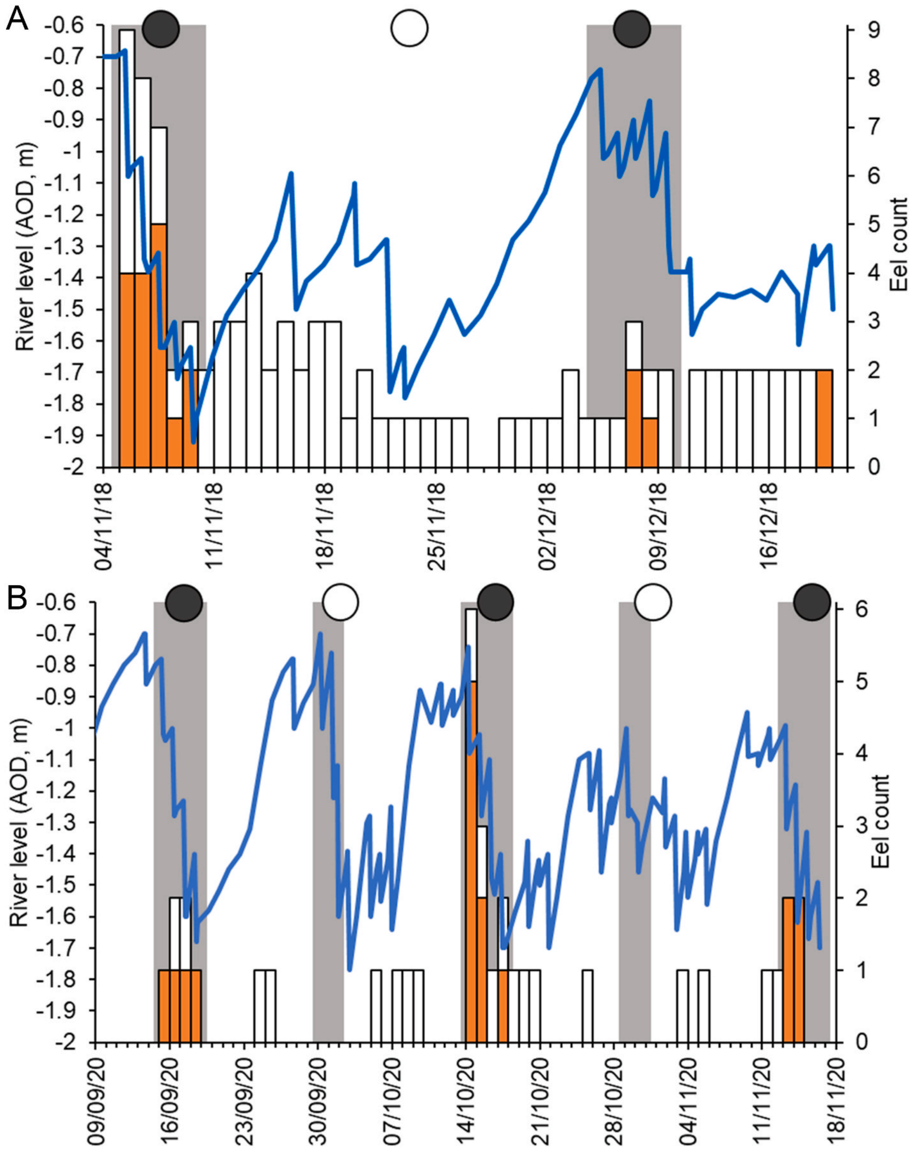

Fig. 2. Number (*n*) of tagged eels that approached (white bars) and passed (orange bars) Hobhole pumping station each day in 2018 (A) and 2020 (B) in response to river level (blue line). Grey shaded areas represent periods with sluice open at night, black circles represent new moon and open circles represent full moon. See Fig. S2 for details of daytime sluicing and pump operation that influenced river level.

Table 4
The number of eels at liberty and approached Hobhole pumping station (PS) during each period of night-time sluicing (available fish (%)), the number that approached while the gravity sluice (GS) was open (attraction efficiency (%)) and the number that passed downstream through the GS (entrance efficiency (%)/passage efficiency (%)).

Year	Month (date)	Moon phase	At liberty	Approached PS during sluice period (available fish (%))	Approached PS while GS open (attraction efficiency (%))	Passed through GS (entrance efficiency (%)/passage efficiency (%))
2018	Nov (5–9)	New	26	17 (64.4%)	16 (94.1%)	16 (100%/94.1%)
2018	Dec (5–9)	New	10	4 (40.0%)	3 (75.0%)	3 (100%/75.0%)
2020	Sept (15–19)	New	10	4 (40.0%)	4 (100%)	4 (100%/100%)
2020	Sept (30-1)	Full	6	0 (0%)	0 (–)	0 (–)
2020	Oct (14–17)	New	16	9 (56.3%)	8 (88.9%)	8 (100%/88.9%)
2020	Oct (29–30)	Full	8	0 (0%)	0 (0%)	0 (0%/0%)
2020	Nov (13–16)	New	13	4 (30.8%)	4 (100%)	4 (100%/100%)

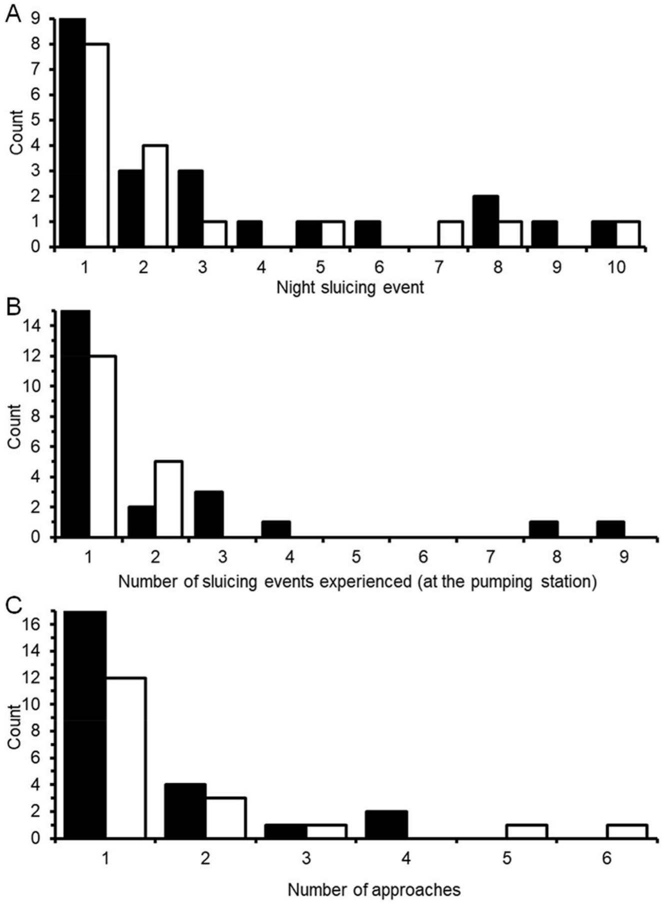

Fig. 3. The number of night-time sluicing events after release before first approach (A), number of sluicing events experienced at the pumping station before passage (B) and number of approaches (during operational changes) (C) at Hobhole pumping station in 2018 (black bars) and 2020 (white bars).

(during OC) (W = 177, $p = 0.794$), total time at the PS (W = 181, $p = 0.701$), total time GS was open between first approach and passage (W = 201, $p = 0.317$), total sluicing experienced (W = 207.5, $p = 0.23$) and time to pass (W = 273.5, $p = 0.877$) did not differ significantly between years (Fig. 4). In addition, two eels approached the PS during OC in 2020 but did not pass downstream through the sluice; they experienced two and zero sluicing events, spent 06:29 h and 01:37 h at the pumping station, the sluice was open for 09:00 h and 0 h between first and last approach to the PS and they experienced 00:49 h and no sluicing while at the PS, respectively.

3.5. *Fine-scale behaviour (2020)*

The majority (70.6%) of eels in 2020 passed through the GS during their first visit to the array, three did so during their second visit to the array (51,181, 52,038 and 52,043) and another did so during its third visit to the array (51,183). While one eel visited the array twice but subsequently passed through the electric pumping station (52,034) (Table S2, Figs. S4 and S5). The mean ± S.D. duration of visit to the array were 15:49 ± 11:40 (minutes:seconds) and the mean ± S.D. total time in the array was 21.23 ± 19.36 (minutes:seconds) (Table S2). The mean ± S.D. first retreat location during an array visit was 37.6 ± 25.0 m upstream of the GS and the extent of retreats (within the array) was 6.2 ± 6.0 m (Figs. S4 and S5). The location of all subsequent retreats during an array visit was 42.8 ± 33.6 m from the GS and extent of these retreats (within the array; 3 eels exited the array in an upstream direction) was 40.8 ± 50.7 m (Figs. S3 and S4). The tortuosity of the final visit to the array prior to GS passage was 0.82 ± 0.20 (Fig. S5).

4. Discussion

Methods to facilitate safe downstream passage for Anguillid eels at hazardous intakes are at the forefront of fish passage research. The present study demonstrated that operational changes (OC) can provide safe downstream passage for seaward migrating European silver eels at a pumping station (PS) with a co-located gravity sluice (GS) over two years. Here, we consider the influence of eel migration ecology and the management implications of the findings.

During this investigation, no eels passed through the duty (electric) pumps (operated exclusively during daylight) during OC, although some eels (2018 = 1 and 2020 = 4) passed through pumps once normal operations resumed. Previous research at this PS reported that 58.8% of acoustic-tagged eels passed through duty (electric) pumps during normal operations (Bolland et al., 2019), and thus OC resulted in vast improvement. Furthermore, 37 tagged eels safely passed downstream through the GS (2018 = 87.5% and 2020 = 88.9% of those that approached during OC), although Huisman et al. (2023) reported 100% passage efficiency for tagged eels ($n = 26$) at a tidal sluice. This represents a hugely encouraging result given that the GS was only operated when upstream and downstream river levels were conducive to gravity discharge, influenced by prevailing rainfall and tides. Indeed, all sluicing events equated to 2–5% of each month and those specifically intended to facilitate eel migration, i.e., at night during a new moon, equated to only 2.9% (2018) and 2.8% (2020). The final mode of operations at this PS closely resembled that described by Schwevers and Adam (2019) for hydropower facilities. However, the entrainment and passage rates presented here surpass those reported for seasonal turbine shutdown of five hydropower dams, which reduced cumulative mortality of American eel (*Anguilla rostrata*) from 63.3% to 37.3% (Eyler et al., 2016). Furthermore, the findings compare favourably with fish passes for other species (Noonan et al., 2012; Bunt et al., 2016) and were very close to the 90–100% passage rate desired for diadromous fishes (Lucas and Baras, 2001).

To date, no studies have implemented OC at a PS with a GS to provide safe downstream passage for seaward migrating silver eels; all previous research has merely reported low sluice passage rates during normal operations to regulate river levels and provide flood relief. Indeed, at the PS investigated here, Bolland et al., 2019, using multi-beam sonar, imaged no eels approaching or entering the GS when it was open during the day (7.7 h of sluicing over five different occasions). During this study, an implicit understanding of silver eel migration ecology from previous research (Jansen et al., 2007; Durif and Elie, 2008; Piper et al., 2013; Bultel et al., 2014; Sandlund et al., 2017; Bolland et al., 2019) helped inform the timing of sluicing events to maximise downstream passage. Indeed, it is known that eels are nocturnal and predominantly migrate during the new moon phase of the lunar cycle in the absence of floods. Consequently, the vast majority of eels that passed through the GS did so at night during the new moon phase of the lunar cycle (2018 = 90.5% and 2020 = 100%) despite water also being sluiced during the new moon phase of the lunar cycle (specifically for eel passage in 2020) and during the day (to regulate river level in both years). Thus suggesting the diurnal and lunar phase timing of sluice opening was fundamental for providing safe downstream eel passage.

In addition to the timing of sluice opening, river levels were allowed to build prior to sluicing events to simulate a flood and maximise the amount of water sluiced. It is well established that elevated river discharge influences the movements patterns and timing of silver eel migration (Teichert et al., 2020) and other species (Knott et al., 2020), with implications for adaptive management of anthropogenic infrastructure (e.g., hydropower turbines shutdown). The key difference here was that river level/discharge was artificially manipulated and thus was disconnected from changes in water chemistry (e.g., elevated turbidity) caused by rainfall. Conversely, there was no flow in the upstream catchment when the pumps were off and the sluice was shut. The

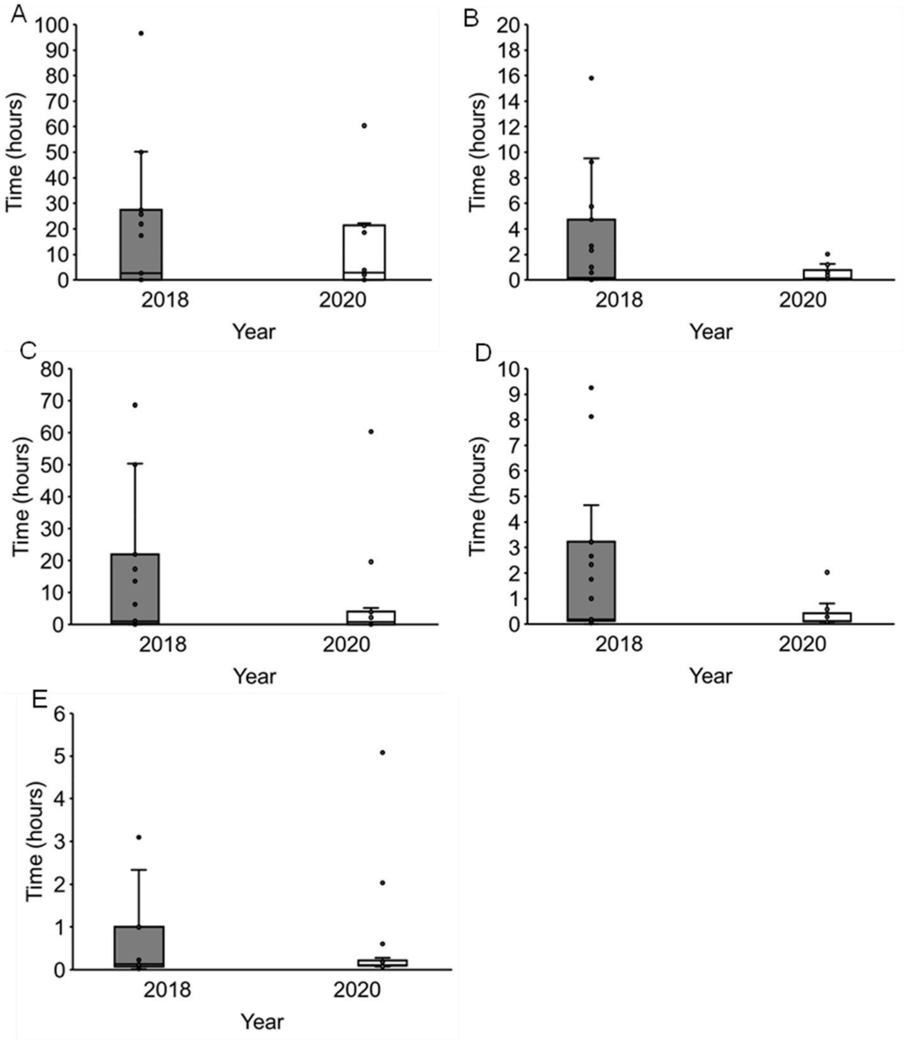

Fig. 4. Box plots for passage time (during OC) (A) (y-axis limit = 100), total time sluice was open between first approach and passage (B) (y-axis limit = 20), total time at the PS (C) (y-axis limit = 80), total sluicing experienced (while at the PS) (D) (y-axis limit = 10) and time to pass (E) (y-axis limit = 6) at Hobhole pumping station in 2018 and 2020.

propensity for eels to pass through the sluice at night may therefore be associated with the low turbidity, especially given two daytime sluice passages in 2018 occurred following heavy rainfall and a slight increase in turbidity. Huisman et al. (2023) reported similar observations, with 92.3% of eels passing through a tidal sluice at night. Notwithstanding, all movements through electric pumps after OC ceased also occurred at night.

During this investigation, only three eels that approached the PS during OC were last detected elsewhere within the catchment (2018 = 1 (4.2%)) or at the pumping station when no downstream passage route was in operation (i.e., no sluicing or pumps) (2018 = 1 (4.2%) and 2020 = 1 (5.6%)). These eels were considered to have been predated upon or ceased migration, i.e., de-silver and arrest migration despite being determined as silver migrants when tagged, as reported elsewhere (Tesch, 2003; Winter et al., 2006; Van den Thillart and Dufour, 2009; Piper et al., 2013; Bašić et al., 2019). Crucially, this number was considerably lower than reported by Bolland et al., 2019 at the same PS during normal operations (41.2%). Furthermore, the proportion of eels that retreated back upstream after approach to the PS reduced from 82.4% (Bolland et al., 2019) to 33.3% and 38.9% in 2018 and 2020, respectively, and were predominantly when the GS was shut (87.1%). Likewise, retreat distance reduced from 4.4 ± 3.6 km during normal operations (Bolland et al., 2019) to 2.7 ± 1.5 km during OC and passage time reduced from 9.5 ± 11.0 days to 2.7 ± 8.7 days. These reductions are important to reduce predation risk and migration delays, which should help increase the likelihood to migration success. Thus, improvements further emphasise that tailoring PS and GS operations holds promise regarding eel population and escapement management.

When approaching a structure, eels are known to display exploratory behaviour, actively searching for downstream passage routes (Piper et al., 2015) and typically retreat upstream should the downstream route be rejected or no downstream route be available (Bolland et al., 2019; van Keekan et al., 2020). For example, four non-passage approaches occurred when the GS was open and the location of first retreat was 37.6 ± 25.0 m upstream of the GS entrance, which may indicate hesitation to pass potentially due to flow acceleration (especially given there was no weed screen on the GS), as reported by Piper et al. (2015). Further, during the final visit to the pumping station prior to passage, six eels did not retreat, six eels retreated short distances (<8 m) and tortuosity was high (0.82 ± 0.20). These findings are contrary to previous studies that reported numerous approaches and retreat behaviour from eels when encountering structures (Brown et al., 2009; Bolland et al., 2019) and accelerating flow fields (Piper et al., 2015). But they do support the findings of Egg et al. (2017) who used multi-beam sonar to image 214 silver eels passing through an undershot sluice gate at a hydroelectric facility over two consecutive years. Conversely, Baker et al. (2021)

attributed the low passage rate (28.6% of 7 eels) of acoustic-tagged eels through a GS to limited flow over a surface-oriented weir. The GS in the present study was an undershot gate, further suggesting undershot sluice gates may provide attractive entrance flows for silver eels, especially since eels are predominantly bottom-oriented (Tesch, 2003). Although a more recent study demonstrated that downstream moving eels were often found in the upper part of the water column more centrally within the river ((Kjærås et al., 2022)Bolland et al., 2019). Overall, minor retreats within the array may indicate some hesitation, but these are of minor concern in terms of eels' overall lifecycle.

Although the primary objective of OC was to prevent entrainment and maximise safe downstream passage for seaward-migrating silver eels, ceasing pump operation and sluicing water had unintended financial benefits. Indeed, it was estimated that £14,670 in direct operational costs, i.e., electricity and diesel to power pumps, was saved during the study (across both years) (IDB staff, pers. comm., 2022). Indirect cost savings, such as reduced on-going maintenance costs and extended pump life, remain unquantified but are likely to be significant over many years. By comparison, the estimated cost for installing a rotating fine-mesh (2-mm) screen at this site was estimated at £5 million (cost estimates for other fish protection technologies, such as fish-friendly pumps, were not obtained). The cost savings are also in stark contrast to the economic cost (due to considerable loss of production) of turbine shutdown at hydroelectric facilities (Schwevers and Adam, 2019) and for restoring fish migration at water storage reservoirs (Xu et al., 2020). Furthermore, OC can, in theory, be implemented far quicker than engineered solutions. That said, the final operating regime implemented in 2020 was highly novel for infrastructure with a primary objective of managing flood risk and a consequence of seven years of silver eel entrainment research at the PS (e.g., Bolland et al., 2019). The annual knowledge gained was iteratively applied to operations the following year, with acceptance of change (e.g., institutional inertia) both aided and compromised by staff changes. Ultimately, eel protection coupled with financial benefits have now led to OC being permanently implemented, including outside the eel migration window (i.e., outside of night-time sluicing). It is also hoped that the lessons learned here can facilitate timely implementation elsewhere.

Operational changes are subject to the prevailing weather conditions, thus pump operation to prevent flooding may culminate in eel entrainment during exceptionally wet years, as occurred at this PS in 2019. Consequently, it is unlikely that OC in isolation will enable PS (with a GS) to prevent eel entrainment and fully comply with legislation (Council Regulation No 1100, 2007). However, such changes will contribute to minimising anthropogenic impacts on eels until alternative eel protection measures are installed, such as during a planned programme of works (as per current Environment Agency guidance). Furthermore, it is likely that the GS can provide a downstream passage solution if measures are implemented to prevent eel entrainment during pump operation (e.g., fine-mesh screening).

4.1. Future research

The fine-scale movement of eels during approach to the GS should be related to the hydrodynamics (e.g., using acoustic Doppler current profiler and computational flow dynamics) to further our understanding of conditions that downstream migrating silver eels find attractive/unattractive and to improve bypass attraction and entrance efficiencies. During this study, almost all eels approached and passed through the GS with the same opening height, thus further research should attempt to assess the influence of sluice opening on eel movements and passage rates. For example, Egg et al. (2017) reported significantly higher eel activity at an undershot sluice gate during the wider opening width tested (0.2m) compared to the narrower opening width ($\leq$0.1m). In addition, owing to the success of this study, attempts should be made to assess and review the features of pumping stations with gravity sluices elsewhere. Doing so would help identify key features (e.g. sluice type, size, location) to determine whether other pumping stations could implement similar OC to maximise silver eel escapement using existing infrastructure. If PS that could implement OC are found, further research should investigate if OC studied here yield comparable entrainment and passage rates or quantify non-tagged eel migration dynamics (using acoustic cameras), especially if the downstream watercourse is non-tidal and thus the window of opportunity to sluice water may be extended. Further research should also quantify both the direct and indirect cost savings of performing OC at a PS, given such information is likely to aid implementation elsewhere.

5. Conclusions and management implications

During this investigation, OC were uniquely implemented at a PS, i.e. ceasing night-time pump operations, (temporarily) elevating river levels prior to sluicing and opening the sluice when silver eels are known to migrate, to maximise safe downstream passage. The vast majority of eels quickly passed through the sluice at night during the new moon phase of the lunar cycle rather than during the day or the new moon, despite only opening for 2.8–2.9% of the study period. The entrainment and passage rates were a vast improvement on those reported for PSs (with GSs) during normal operations (including the site studied here), hydropower facilities and fish passage facilitates generally. There were also considerable operational cost savings and OC can be quickly implemented to minimise anthropogenic impacts on eels in the short-term until measures to prevent eel entrainment during pump operation are implemented in the long-term. The evidence provided here will help to develop effective remediation measures to maximise escapement of Anguillid eel species at hazardous intakes globally.

Author Contributions

Liam Carter: Investigation, Data curation, Visualisation, Formal analysis, Writing – original draft, Writing – review & editing. Jonathan David Bolland: Conceptualisation, Writing – review & editing, Funding acquisition, Supervision, Project administration. Oliver Evans: Investigation. Stephen Collier: Investigation. Rosalind Wright: Writing – review & editing, Resources. Leona Anne Murphy: Investigation. Jake Reeds: Investigation. Robert Thomas: Supervision, Writing – review & editing. Henrik Baktoft: Writing – review & editing, Software.

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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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2023.119143.

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