

The influence of passive wedge-wire screen aperture and flow velocity on juvenile European eel exclusion, impingement and passage

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ABSTRACT

The European eel (*Anguilla anguilla*) is a critically endangered catadromous fish. The decline has partly been attributed to water management infrastructure that abstract water from rivers for potable and industrial water supply, irrigation, hydroelectric power generation and flood defence; eels can be impinged on weedcreens and trashracks and entrained in pumps and turbines. The Eel Regulations (England and Wales) 2009 stipulates measures are required to provide safe (upstream and downstream) passage of eels past such hazardous intakes. Preventing impingement and entrainment of upstream migrating (glass eel and elver) and river-resident (yellow) juvenile eels at hazardous intakes may require fine-mesh aperture screens and low approach velocities due to eels' small size and relatively poor swimming capacity but quantitative evidence is lacking. Here, passive wedge-wire screen aperture (1, 2, 3 and 5 mm) and depth-averaged flow velocities (0, 0.1, 0.15 and 0.2 m·s⁻¹) both influenced the fate (i.e., impingement or passage) and behaviour (i.e., migratory separation or behavioural avoidance) of two size classes of juvenile eels (60–80 mm glass eels and 100–160 mm elvers) in an experimental flume. One and 2 mm aperture screens were required to physically exclude 60–80 mm and 100–160 mm, respectively. Up to 90% and 100% of the 60–80 mm and 100–160-mm size class eels were impinged at 0.2 m·s⁻¹ depth-averaged flow velocity, which also positively influence number of screen contacts per eel and time to eel fate (from first contact). A small proportion of 60–80 mm eels (9.2%) did not approach the screen due to migratory separation (i.e., positive rheotaxis) and eels narrower than the screen aperture did not always pass through the screen, and thus other biological or hydraulic processes may also influence screen passage. It is hoped that these findings help improve screening guidance for regulators, key stakeholders and water abstraction managers to further improve protective measures required for critically endangered eels.

1. Introduction

Freshwaters provide many essential goods and services and thus are among the most extensively altered ecosystems globally (Carpenter et al., 2011). Water resource management can lead to in-stream structures that control, divert or raise water levels, and has contributed to over one million barriers fragmenting river systems in Europe alone (Belletti et al., 2020). Anthropogenic infrastructure often abstract water from rivers for potable and industrial water supply, irrigation, hydroelectric power generation and flood defence (“hazardous intakes” hereafter). For example, in England and Wales there are some 48,000 licensed water abstractions (Environment Agency, 2011) and total

surface water (rivers, reservoirs and lakes) abstracted in 27 EU Member State countries in 2019 was 155,540 million m³ (European Environment Agency, 2022). Furthermore, there has been a global proliferation of hydropower installations in the pursuit of renewable energy (Couto and Olden, 2018) and the potential for further developments is considerable (Xu et al., 2023). However, there is considerable debate over whether hydropower can be regarded as ‘green energy’ due to impacts on freshwater fauna (Geist, 2021).

Worldwide, temperate freshwater anguillids have some of the widest geographic ranges of any naturally occurring freshwater genus but have experienced significant population declines, particularly in the northern hemisphere (Dekker, 2003a; Jellyman, 2021). For example, juvenile

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European eel (*Anguilla anguilla*) recruitment has reduced by 98% over the last four decades (ICES, 2019) and the species is now critically endangered (Jacoby and Gollock, 2014). Anguillid eel decline has been attributed to numerous pressures at all life history stages, including freshwater habitat loss and migration barriers, parasites and diseases, overfishing, oceanic changes, and pollution (Dekker, 2003b; Acou et al., 2008; Aalto et al., 2016; Jellyman, 2021). Water management structures in particular have a profoundly negative impact on eel due to habitat fragmentation, and hazardous intakes can impinge eels against screens at and entrainment them in pumps and turbines, which can lead to injury and mortality (Nilsson et al., 2005; Piper et al., 2012; Buysse et al., 2014; Bolland et al., 2019).

In 2007, the EU established a management framework for eel (EC Regulation No. 1100/2007) and in 2009 the UK government introduced the Eel Regulations (2009) Statutory Instrument. These regulations specifically require measures to provide safe (upstream and downstream) passage of eels past hazardous intakes using eel passes, screens and by-washes (O'Keefe and Turnpenny, 2005; Environment Agency, 2011). Preventing impingement and entrainment of juvenile eels at hazardous intakes may require fine-mesh aperture screens and low approach velocities (Larinier and Travade, 2002), which may pose challenges for operators. Indeed, decreased open screen area, increased head losses and increased cost of raw materials and infrastructure have operational and financial implications (Clough et al., 2014). Thus, screening guidance must be informed by quantitative evidence. Research into the effectiveness of protection measures at intakes has largely focused on seaward migrating adult (silver) eels (Egg et al., 2017; Deleau et al., 2019; van Keekan et al., 2020). Thus, knowledge is lacking for upstream migrating (glass and elver) and river-resident (yellow) juvenile eels, including whether upstream migrating eels (positive rheotaxis; Laffaille et al., 2007) approach hazardous intakes. Indeed, Clough et al. (2014) concluded that research to assess impingement and entrainment risk at fine mesh screens is urgently required.

To physically exclude fish at a hazardous intake, the screen aperture must be narrower than the widest part of the target species (at a given life-stage); which is typically the bony part of the head (i.e., screen aperture should prevent attempts for eels to force themselves through). Indeed, a recent study at five real-world hydropower sites identified that fish can squeeze through screen apertures narrower than body dimensions (Knott et al., 2023). In England, passive wedge-wire screens (i.e., flat facing triangular bars; see Bromley et al., 2014) are recommended for juvenile life-stages (O'Keefe and Turnpenny, 2005) and regulatory guidance stipulates that screening at hazardous intakes (21–90° to the flow) should have 1–2 mm mesh size/bar spacing for glass eels and elvers (up to 140 mm) and 3 mm for yellow eels (between 140 and 300 mm) (Environment Agency, 2011). Environment Agency guidance was informed by Knights (1982) who analysed the relationship between farmed eel body weight and mesh size/bar spacing (for grading purposes) and determined a weight-length relationship to infer the length of excluded eels. Specifically, 1, 2 and 3-mm grid bar spacing and 2 and 3-mm mesh would exclude 69, 110 and 145 mm and 80 and 112 mm eels, respectively. While the study of Knights (1982) was informative, there is uncertainty surrounding the shape and size of mesh and grid apertures, the transferability of findings from grading farmed eels to screening intakes, the comparability of farmed and wild eel body morphology and the necessity to infer eel length from two relationships. Consequently, quantitative evidence of juvenile eel body morphology (i.e., total length and head width) physically excluded by fine-mesh screen apertures is urgently required to inform screening guidance.

To prevent fish impingement at physical screens, the approach velocity (also referred to as flow velocity) must be low enough for the fish to swim away (also referred to as the escape velocity), i.e., fish should be able to swim fast enough and for long enough to return to the main river or enter a bypass, with swimming performance influenced by fish length and temperature (e.g. Clough et al., 2003). Due to their small size and

relatively poor swimming capacity (McCleave, 1980; Langdon and Collins, 2000; Harrison et al., 2014), low screen approach velocity may be necessary to enable juvenile eels to escape and prevent impingement. Environment Agency regulatory guidance stipulates screens (21–90° to the flow) should have a $0.1 \text{ m}\cdot\text{s}^{-1}$ approach velocity for glass eels and elvers (up to 140 mm) and $0.15 \text{ m}\cdot\text{s}^{-1}$ for yellow eels (between 140 and 300 mm) (Environment Agency, 2011). The approach velocities stated in the guidance are based on the sustained swimming capabilities of fish in swim-tunnel experiments (Barbin and Krueger, 1994; Clough et al., 2003). Notwithstanding, a further consideration is that an eel moving downstream (in a head first orientation) must first change swimming direction, i.e., from positive to negative rheotaxis, either during approach to or after contact with the screen, in order to swim away. Therefore, quantitative evidence of rates of eel impingement linked to eel contact with and retreat from small aperture screens at different approach velocities, including whether they can escape once impinged on a screen, are also urgently needed to inform guidance.

The overall aim of this flume-based investigation was to quantify the influence of passive wedge-wire screen aperture (1, 2, 3 and 5 mm) and depth-averaged flow velocities (0, 0.1, 0.15 and $0.2 \text{ m}\cdot\text{s}^{-1}$) on behaviour (i.e., migratory separation or behavioural avoidance; defined in methodology) and fate (i.e., impingement or passage; defined in methodology) of two size classes of juvenile eels (i.e., glass eels (60–80 mm) and elvers (100–160 mm)). Knights (1982) reported that head width for eels below 20–25 g in weight (i.e., all glass eels and elvers used in this study) was more critical in limiting passage through mesh screens in comparison to their trunks. Given this, the initial objective was to quantify eel head width relative to eel length to understand the proportion of eels that would theoretically pass through 1–5 mm screen apertures. The influence of screen aperture and hydraulic flow conditions on time to first screen approach and time to eel fate was also assessed. The number, rate, eel orientation and type of screen contact was quantified for 60–80 and 100–160 mm eels during 1 and 2 mm aperture screen trials, respectively. Although juvenile glass eels and elvers are primarily nocturnal (Glova and Jellyman, 2003; Piper et al., 2012; Geffroy et al., 2015; Fukuda et al., 2016), the influence of prevailing light (i.e., day and night) was also studied (2 mm aperture, all flow velocities) to further understand biotic and abiotic influences on eel behaviour and fate. These highly novel findings will improve the understanding of physical, hydraulic and biological influences on small eel exclusion at hazardous intakes, leading to improved screening guidance and fish protection.

2. Materials and methods

2.1. Experimental setup

The experiment was conducted between 4 May and 13 August 2021, in an indoor flume ($4.9 \times 1.0 \times 0.4 \text{ m}$ length x width x depth) filled with water to a depth of 0.1 m (Fig. 1). Flow straighteners composed of 8 mm diameter, 150 mm long polycarbonate tubes in a honeycomb configuration were installed at the upstream end of the flume to encourage wall-parallel uniform flow conditions in the experimental section (2.1 m long section with glass walls 0.71 m downstream from the flume inlet). Fine mesh screens (0.7 mm square mesh, open area = 44%) were located at the upstream end of the experimental section and downstream of the screen under investigation to prevent eels from escaping. All passive wedge-wire study screens had a 34SB profile ($2.8 \times 5 \text{ mm}$ width x deep), vertical apertures and were orientated vertically at 90° to the flow. Screen apertures of 1 mm (open area = 26.3%), 2 mm (41.7%), 3 mm (51.7%) and 5 mm (64.1%) were investigated.

Depth-averaged approach velocities of the flow of 0, 0.1, 0.15 and $0.2 \text{ m}\cdot\text{s}^{-1}$ were studied, corresponding to Reynolds numbers of 0, 7733, 11,600, 15,467 for the studied water temperature (i.e., flows were fully turbulent; Pope, 2000). This reflected current guidance in England, i.e. $0.1 \text{ m}\cdot\text{s}^{-1}$ approach velocity for glass eels and elvers (up to 140 mm) and $0.15 \text{ m}\cdot\text{s}^{-1}$ for yellow eels (between 140 and 300 mm) (Environment

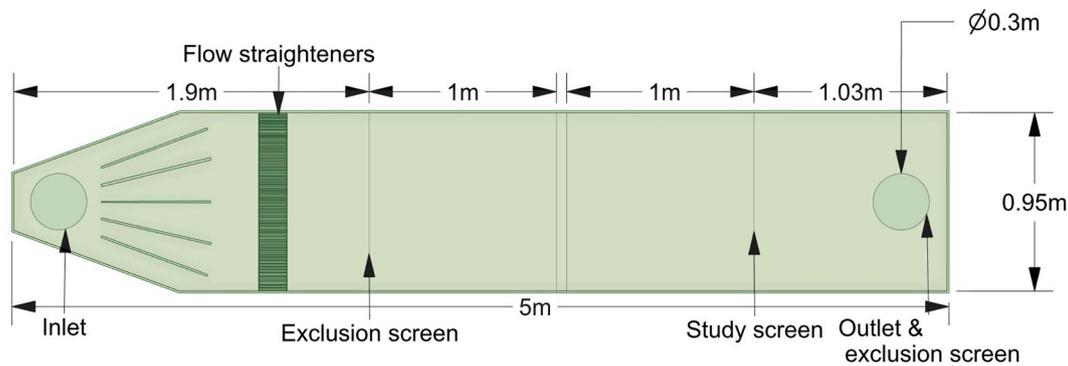


Fig. 1. An overhead schematic of the experimental flume, showing the water inlet flow straighteners, upstream exclusion screen, passive wedge-wire screen (study screen) and outlet with exclusion screen.

Agency, 2011). Flow was controlled with a variable speed inline propeller pump (Minn Kota, Weedless wedge propeller, Model 4.3HP/S) in a re-circulatory pipe (4.5×0.3 m length \times diameter) situated underneath the main tank. Experiments at night (between 18:00–02:00) were performed in a dark room to replicate periods when eels are active, with two infrared lamps above the flume to improve video quality and a red LED strip light under the flume for health and safety purposes. Five overhead infra-red video cameras (Hikvision 5MP IP POE H265 30 m IR 2.8 mm D150H) connected to desktop software (iSpy v7.2.6.0; www.ispyconnect.com) were used to monitor and record eel behaviour during trials.

Velocity profiles to assess flow development were collected using a profiling Nortek Acoustic Doppler Velocimeter (ADV) sampling at 100 Hz for 180 s. For the 0.2 m s^{-1} case, flow profiles comprising 30 mm sub-profiles overlapped by 10 mm were collected from bed to water surface at seven sampling locations (0.10, 0.30, 0.50, 0.75, 1.00, 1.25 and 1.50 m) upstream of the study screen along the centerline of the tank. Data

were post-processed using the TSNCQUAL dealiaser (Parkhurst et al., 2011), phase-space threshold filter (Wahl, 2003) and an 80% correlation threshold filter in MATLAB. The resulting profiles indicate that flows were fully developed at least 0.5 m upstream of the study screen (Fig. 2).

2.1.1. Fish husbandry

The 60–80 mm eels were caught from the River Parratt, Southwest England, on 26 April 2021 and 100–160 mm eels were caught from the River Wensum, Southeast England, on 16 July 2021. Following collection of captured eels, a sample from the rivers Parratt ($n = 30$) and Wensum ($n = 30$) were transported to the Environment Agency National Fish Lab in Bampton, UK for health assessments. All eels were deemed healthy and representative of a normal eel population. The remaining study eels were transported in chilled river water to the University of Hull. Eels were held in holding tanks filled with recirculating-freshwater in the flume room, with sections of PVC pipe provided as shelters. The temperature in the flume room, and thus the water temperature, was

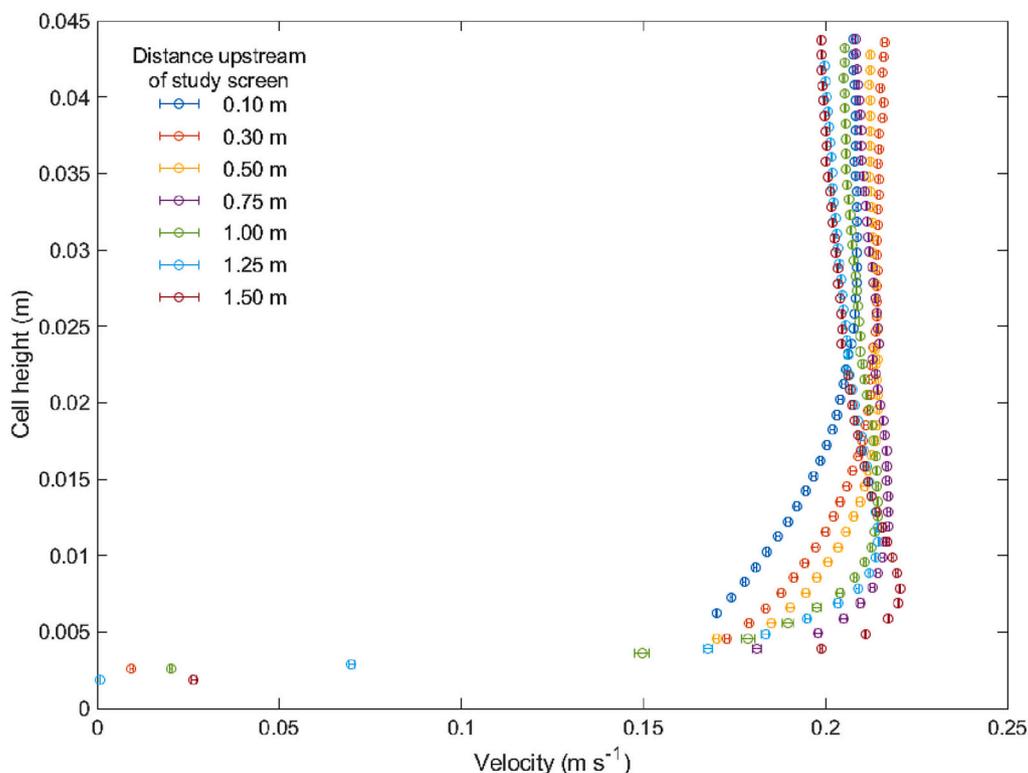


Fig. 2. Vertical hydrodynamic profiles at seven sampling locations (0.10, 0.30, 0.50, 0.75, 1.00, 1.25 and 1.50 m) upstream of the study screen using a Nortek Vectrino Profiler (ADV). Error bars denote the 95th percentile confidence intervals and were estimated using the equation given by Garcia et al. (2006).

10–12 °C. Eel holding tanks were visually inspected daily. Artificial lighting in the room was switched on between 06:00–18:00. Eels were held for a minimum of 48 h prior to commencing the investigation to facilitate acclimation and recovery from capture and handling.

2.2. Experimental trials

Two experiments were performed:

- (1) Screen apertures of 1 mm, 2 mm, 3 mm and 5 mm were investigated for 60–80 mm eels (Table 1) and apertures of 2 mm, 3 mm and 5 mm were investigated for 100–160 mm eels (Table 2) at all flow velocities (0, 0.1, 0.15 and 0.2 m·s⁻¹).
- (2) To investigate if any prevailing light (day and night) influenced eel behaviour and fate, 60–80 mm eel were investigated at 2 mm screen aperture (Table 1) and 100–160 mm eels were investigated at 3 mm screen aperture (Table 2) at all approach velocities (0, 0.1, 0.15 and 0.2 m·s⁻¹) in daylight conditions.

2.2.1. Experimental procedure

Screen aperture and approach velocity treatment order for each size class was determined through random selection. For each treatment, eels were randomly selected by dip netting individuals from the holding tank, studied in isolation and studied only once. Each eel was placed centrally within the experimental section in a vessel gently tipped in the downstream direction, enabling the eel to shelter from the flow at the beginning of the trial. Once the eel had entered the flow, the vessel was removed. Eels that sheltered and did not move around the experimental section were removed and excluded from further analysis. Each trial was performed until either the eel was entrained (herein referred to as “passed” or “passage”) through the test screen, became impinged on the test screen for 10 s, or 15 min had elapsed. After each treatment, the eel was removed from the flume and held in isolation. At the end of the trials, all eels were alive, actively swimming and exhibited no external signs of injury or stress. Eels were sedated (buffered tricaine methanesulphonate (MS-222)) <12 h later and total body length (mm), head and body width and height (mm), and total body mass (g) were measured using digital callipers and photographed for morphometric analysis. After taking photographs and morphometric measurements, eels were allowed to recover before being placed in a separate holding tank to unstudied eels. At the end of the experiment, all eels were returned to the site of capture. During the study, a total of 40 h and 48

min of trial footage was recorded. Footage was later reviewed by two reviewers to both corroborate and establish eel behaviour and fate. Mean (\pm SD) flume water temperature, measured prior to the start of each trial, was 10.4 \pm 0.1 °C. All eels were treated in compliance with University of Hull ethical procedures, with investigation specific approval provided by Faculty of Science and Engineering Ethics Committee (FEC_2021_89 and FEC_2021_53).

2.3. Data analysis

Metrics to analyse eel behaviour (i.e., migratory separation or behavioural avoidance) and fate (i.e., impingement or passage) were calculated for each eel (Table 3). Throughout, specific consideration was given to whether eels remained exclusively at the upstream end of the flume, defined here as migratory separation. Eels that made contact with the screen (< 10 s) but remained free-swimming for the full trial were deemed to have performed behavioural avoidance while impinged eels were stationary on the screen for ten seconds. Both these groups of eels were separated into those that could and could not pass through the screen to disentangle physical exclusion from other processes.

Data were compiled, plotted and analysed in both Microsoft Excel and Rstudio (R Version 4.1.2; www.r-project.org) using base R functions. Data were tested for normality (Shapiro-Wilk-test) and homogeneity of variance (Levene test). When data were normally distributed, parametric tests were used. When data were not normally distributed, non-parametric tests were used. Unpaired *t*-tests were used to compare head width and total length between 60 and 80 mm eels that either passed or became impinged on the 5 mm aperture screen. A Wilcoxon rank sum test was used to compare first screen contact time between swim direction upon release for both size classes. Kruskal-Wallis tests were used to compare time to first contact screen across each depth-averaged flow velocity tested and time from first screen encounter to impingement for each size class across flow treatments. Post-hoc pairwise comparisons were performed using Dunn’s test with Holm *p* adjustment. Two-proportions *Z* tests were used to compare (1) screen approach orientation of eels that became impinged on 1 mm (60–80 mm size class) and 2 mm (100–160 mm size class) aperture screens and eel fate proportions between light and dark treatments, (2) proportions of screen contacts in different approach orientations for 1 and 2 mm aperture screens for 60–80 mm and 100–160 mm size classes across flow treatments, respectively, and (3) proportions of total screen contacts, impingements <10 s, and impingements (> 10 s, eels removed) for 1 and 2 mm aperture screens for 60–80 mm and 100–160 mm size classes

Table 1

Experimental conditions (aperture size, depth-averaged flow velocity and light conditions) and 60–80 mm eel geometric characteristics (mean \pm S.D. (range), mm).

Aperture (mm)	Velocity (m·s ⁻¹)	Light	n	Total length (mm)	Head width (mm)	Head length (mm)	Head height (mm)	Body width (mm)	Body height (mm)
1	0.2	Night	10	67.7 \pm 3.6 (60.1–72.5)	2.3 \pm 0.1 (2.2–2.5)	1.9 \pm 0.3 (1.5–2.3)	2.6 \pm 0.2 (2.2–2.9)	2.1 \pm 0.2 (1.9–2.4)	2.6 \pm 0.2 (2.2–3.0)
1	0.15	Night	10	67.9 \pm 3.5 (61.7–73.6)	1.8 \pm 0.1 (1.5–1.9)	1.4 \pm 0.2 (1.2–1.7)	1.7 \pm 0.1 (1.5–1.8)	1.4 \pm 0.2 (1.2–1.7)	2.1 \pm 0.1 (1.8–2.3)
1	0.1	Night	10	68.0 \pm 0.1 (62.2–72.2)	1.8 \pm 0.1 (1.6–2.1)	1.5 \pm 0.1 (1.4–1.7)	1.7 \pm 0.1 (1.5–1.9)	1.5 \pm 0.2 (1.3–1.8)	2.1 \pm 0.3 (1.8–2.6)
1	0	Night	10	67.3 \pm 3.0 (61.6–69.6)	1.8 \pm 0.1 (1.6–1.9)	1.5 \pm 0.2 (1.3–1.7)	1.7 \pm 0.1 (1.5–1.9)	1.4 \pm 0.2 (1.1–1.6)	2.1 \pm 0.2 (1.7–2.4)
2	0.2	Night	10	68.7 \pm 5.1 (61.8–74.7)	1.8 \pm 0.1 (1.6–2.0)	1.3 \pm 0.2 (1.0–1.5)	1.7 \pm 0.2 (1.4–2.0)	1.4 \pm 0.1 (1.2–1.7)	2.2 \pm 0.2 (1.9–2.5)
2	0.15	Night	10	68.2 \pm 3.0 (65.4–75.1)	1.7 \pm 0.1 (1.6–1.9)	1.3 \pm 0.2 (1.0–1.6)	1.8 \pm 0.1 (1.6–1.9)	1.4 \pm 0.2 (1.1–1.8)	2.0 \pm 0.1 (1.7–2.1)
2	0.1	Night	10	68.4 \pm 4.7 (62.9–79.4)	1.8 \pm 0.2 (1.5–2.1)	1.5 \pm 0.1 (1.2–1.7)	1.7 \pm 0.2 (1.4–1.9)	1.4 \pm 0.1 (1.2–1.6)	2.1 \pm 0.3 (1.9–2.7)
2	0	Night	10	69.7 \pm 3.3 (62.8–73.3)	1.9 \pm 0.1 (1.7–2.0)	1.6 \pm 0. (1.5–1.6)	1.8 \pm 0.1 (1.5–2.1)	1.7 \pm 0.2 (1.4–2.0)	2.3 \pm 0.3 (2.0–3.1)
3	0.2	Night	10	69.3 \pm 4.7 (61.4–79.4)	1.8 \pm 0.2 (1.5–2.1)	1.3 \pm 0.1 (1.1–1.7)	1.6 \pm 0.2 (1.4–1.9)	1.5 \pm 0.1 (1.2–1.6)	2.1 \pm 0.3 (1.9–2.7)
3	0.15	Night	10	67.4 \pm 3.3 (63.7–73.3)	1.7 \pm 0.1 (1.5–2.0)	1.3 \pm 0. (1.0–1.6)	1.7 \pm 0.1 (1.5–2.1)	1.4 \pm 0.2 (1.1–2.0)	2.1 \pm 0.3 (1.8–3.1)
3	0.1	Night	10	69.3 \pm 3.2 (62.2–73.6)	1.9 \pm 0.3 (1.7–2.5)	1.5 \pm 0.3 (1.1–2.3)	1.9 \pm 0.4 (1.7–2.9)	1.5 \pm 0.3 (1.3–2.4)	2.2 \pm 1.6 (1.4–2.5)
3	0	Night	10	67.8 \pm 4.3 (64.0–79.3)	2.0 \pm 0.1 (1.9–2.0)	1.6 \pm 0.1 (1.3–1.7)	2.0 \pm 0.1 (1.5–1.9)	1.8 \pm 0.3 (1.3–2.3)	2.2 \pm 0.3 (1.8–3.1)
5	0.2	Night	10	67.7 \pm 3.8 (61.1–73.0)	1.8 \pm 0.2 (1.6–2.1)	1.3 \pm 0.2 (1.0–1.6)	1.3 \pm 0.2 (1.4–2.1)	1.6 \pm 0.2 (1.4–2.2)	2.1 \pm 0.4 (1.7–3.1)
5	0.15	Night	10	66.6 \pm 3.0 (61.0–70.2)	1.8 \pm 0.2 (1.5–2.1)	1.3 \pm 0.4 (0.2–1.7)	1.7 \pm 0.4 (0.7–2.0)	1.5 \pm 0.2 (1.1–1.8)	2.1 \pm 0.2 (1.7–2.6)
5	0.1	Night	10	69.2 \pm 5.7 (57.1–76.4)	2.0 \pm 0.3 (1.6–2.3)	1.4 \pm 0.3 (0.8–1.7)	2.0 \pm 0.1 (1.8–2.2)	1.7 \pm 0.4 (1.1–2.2)	2.2 \pm 0.4 (1.6–2.9)
5	0	Night	10	66.4 \pm 4.6 (58.5–72.5)	1.9 \pm 0.2 (1.6–2.3)	1.4 \pm 0.3 (0.8–1.8)	1.9 \pm 0.2 (1.5–2.2)	1.8 \pm 0.2 (1.6–2.1)	2.1 \pm 0.2 (1.7–2.4)
2	0.2	Day	10	68.9 \pm 4.3 (65.5–79.3)	1.9 \pm 0.1 (1.8–2.0)	1.5 \pm 0.2 (1.3–1.7)	1.7 \pm 0.1 (1.4–1.9)	1.5 \pm 0.3 (1.3–2.3)	2.3 \pm 0.3 (2.0–3.1)
2	0.15	Day	10	66.8 \pm 4.1 (61.9–75.0)	1.9 \pm 0.1 (1.8–1.9)	1.5 \pm 0.2 (1.3–1.9)	1.8 \pm 0.1 (1.6–2.0)	1.5 \pm 0.2 (1.2–1.8)	2.2 \pm 0.4 (1.9–3.1)
2	0.1	Day	10	66.4 \pm 4.0 (59.6–72.8)	1.9 \pm 0.1 (1.8–2.0)	1.6 \pm 0.1 (1.4–1.8)	1.7 \pm 0.1 (1.6–1.9)	1.5 \pm 0.2 (1.2–1.7)	2.2 \pm 0.1 (2.0–2.4)
2	0	Day	10	66.7 \pm 4.4 (56.4–72.5)	1.9 \pm 0.1 (1.7–2.0)	1.5 \pm 0.1 (1.3–1.7)	1.7 \pm 0.2 (1.4–2.0)	1.5 \pm 0.2 (1.2–2.1)	2.2 \pm 0.2 (1.9–2.5)

Table 2

Experimental conditions (aperture size, depth-averaged flow velocity and light conditions) and 100–160 mm eel geometric characteristics (mean ± S.D. (range), mm).

Aperture (mm)	Velocity (m·s ⁻¹)	Light	n	Head width (mm)	Head length (mm)	Head height (mm)	Body width (mm)	Body height (mm)	Head width (mm)
2	0.2	Night	10	115.3 ± 8.1 (104.2–127.3)	3.2 ± 0.2 (3.0–3.8)	2.9 ± 0.3 (2.4–3.3)	3.1 ± 0.3 (2.5–3.8)	3.1 ± 0.4 (2.8–4.2)	4.1 ± 0.5 (3.4–5.2)
2	0.15	Night	10	117.8 ± 13.1 (108.0–153.7)	3.3 ± 0.4 (3.1–4.3)	2.9 ± 0.3 (2.6–3.5)	3.2 ± 0.3 (2.8–3.8)	3.3 ± 0.3 (2.9–3.9)	3.9 ± 0.6 (3.1–5.3)
2	0.1	Night	10	115.2 ± 7.3 (106.1–127.6)	3.1 ± 0.4 (2.6–4.1)	3.0 ± 0.4 (2.6–3.8)	3.2 ± 0.3 (2.7–3.9)	3.1 ± 0.8 (2.3–5.0)	3.8 ± 0.6 (3.2–5.1)
2	0	Night	10	113.1 ± 5.6 (106.4–119.8)	3.1 ± 0.1 (2.9–3.2)	2.9 ± 0.2 (2.6–3.2)	3.0 ± 0.2 (2.7–3.2)	2.9 ± 0.3 (2.5–3.3)	3.5 ± 0.5 (2.6–4.5)
3	0.2	Night	10	116.0 ± 11.4 (100.0–135.0)	3.1 ± 0.3 (2.6–3.5)	2.8 ± 0.4 (2.5–3.5)	3.0 ± 0.4 (2.5–3.6)	3.1 ± 0.6 (2.3–4.3)	3.8 ± 0.5 (3.1–4.4)
3	0.15	Night	10	117.0 ± 5.9 (102.9–122.10)	3.1 ± 0.2 (2.9–3.5)	2.9 ± 0.2 (2.5–3.1)	3.2 ± 0.2 (2.7–3.6)	3.2 ± 0.4 (2.7–3.8)	3.9 ± 0.4 (3.4–4.7)
3	0.1	Night	10	114.7 ± 6.4 (102.6–122.0)	3.1 ± 0.1 (2.9–3.3)	3.0 ± 0.2 (2.5–3.3)	3.2 ± 0.2 (2.9–3.4)	3.0 ± 0.2 (2.8–3.5)	3.8 ± 0.6 (2.9–4.5)
3	0	Night	10	113.8 ± 6.6 (103.6–124.5)	3.1 ± 0.1 (2.8–3.2)	2.8 ± 0.2 (2.5–3.2)	3.1 ± 0.1 (2.9–3.3)	3.0 ± 0.1 (2.7–3.2)	3.7 ± 0.3 (3.2–4.2)
5	0.2	Night	10	117.0 ± 6.7 (105.8–126.6)	3.2 ± 0.2 (2.9–3.5)	2.9 ± 0.2 (2.6–3.4)	3.2 ± 0.1 (3.0–3.4)	3.3 ± 0.4 (2.7–3.9)	3.7 ± 0.3 (3.2–4.1)
5	0.15	Night	10	117.3 ± 8.1 (106.5–128.5)	3.3 ± 0.2 (2.9–3.6)	3.0 ± 0.4 (2.5–3.5)	3.3 ± 0.4 (2.6–3.7)	3.2 ± 0.4 (2.7–3.7)	3.9 ± 0.7 (3.0–5.0)
5	0.1	Night	10	115.0 ± 6.4 (106.4–123.1)	3.1 ± 0.2 (2.9–3.4)	2.8 ± 0.2 (2.4–3.1)	3.1 ± 0.1 (2.9–3.3)	3.1 ± 0.2 (2.7–3.4)	3.7 ± 0.4 (3.1–4.3)
5	0	Night	10	119.0 ± 5.1 (107.4–124.1)	3.2 ± 0.1 (3.1–3.4)	3.1 ± 0.2 (2.8–3.5)	3.2 ± 0.1 (3.0–3.4)	3.2 ± 0.2 (2.9–3.5)	3.8 ± 0.3 (3.5–4.6)
3	0.2	Day	10	121.0 ± 14.6 (100.0–144.5)	3.1 ± 0.3 (2.7–3.5)	3.1 ± 0.4 (2.4–3.6)	3.2 ± 0.3 (2.9–3.5)	3.2 ± 0.3 (2.6–3.5)	5.6 ± 6.1 (3.0–23)
3	0.15	Day	10	125.5 ± 13.3 (106.7–143.5)	3.2 ± 0.3 (2.8–3.7)	3.0 ± 0.4 (2.4–3.6)	3.1 ± 0.3 (2.8–3.9)	3.1 ± 0.4 (2.6–3.9)	3.7 ± 0.7 (3.0–5.5)
3	0.1	Day	10	131.2 ± 17.6 (108.6–157.5)	3.3 ± 0.3 (2.9–3.7)	3.3 ± 0.5 (2.5–4.1)	3.2 ± 0.3 (2.8–3.8)	3.1 ± 0.3 (2.7–3.6)	4.0 ± 0.9 (3.1–5.4)
3	0	Day	10	119.8 ± 16.2 (100.0–147.7)	3.0 ± 0.3 (2.6–3.5)	3.1 ± 0.5 (2.4–3.8)	3.0 ± 0.4 (2.5–3.7)	2.9 ± 0.5 (2.4–4.0)	3.6 ± 0.8 (3.0–5.0)

Table 3

Metrics to analyse eel behaviour and fate.

Metric	Calculation
Release orientation	Eel swimming direction following release, i.e. upstream or downstream
	Behaviour
Migratory separation	Exclusively approached the upstream end of the flume for the full trial
Behavioural avoidance	Encountered the screen but remained free-swimming upstream for the full trial
	Fate
Impingement	Stationary on the screen for at least 10 s
Passage	Passed downstream through the screen

across flow treatments, respectively. Spearman’s rank correlation analysis was used to assess the relationship between number of screen contacts and eel body length for 1 and 2 mm aperture screens for 60–80 and 100–160 mm size classes between flow treatments, respectively.

3. Results

3.1. Eel head width and total length

Of all 60–80 mm eels ($n = 200$), 0%, 60.5% ($n = 121$) and 100% had a head width (HW) <1, 2 and 3 mm, respectively (Fig. 3a). Of all 100–160 mm eels ($n = 160$), 0%, 14.4% ($n = 23$), 85.6% ($n = 137$), and 100% had a head width <1, 2, 3, and 5 mm (Fig. 3b). The longest eel with a head width < 2 mm was 79.3 mm (HW = 1.9 mm) and < 3 mm was 122.1 mm (HW = 3.0 mm). Conversely, the shortest eel with a head width > 2 mm was 60.1 mm (HW = 2.2 mm) and > 3 mm was 103.58 mm (HW = 3.0 mm).

3.2. Eel behaviour (migratory separation, behavioural avoidance) and fate (impingement, passage)

The lowest rates of passage (0%) were for 1 and 2 mm screens for the 60–80 and 100–160 mm eels, respectively (Table 4); all eels had a head wider than the screen aperture. Impingement rates were high for both eel size classes, with 50%, 60%, and 90% of the 60–80 mm eels and 90%, 90%, and 100% of the 100–160 mm eels impinged at 0.1, 0.15, and 0.2 m·s⁻¹ approach velocities, respectively. For the 60–80 mm eels, 20% of eels in each of the 0.1 and 0.15 m·s⁻¹ approach velocities did not approach the 1 mm aperture screen and thus experienced migratory separation (Table 4).

For the 60–80 mm eels, 10% of eels in each of the 0.1, 0.15 and 0.2 m·s⁻¹ flow treatments did not approach the 2 mm aperture screen, i.e., migratory separation (Table 4). One eel (10%) in the 0.1 m·s⁻¹ flow treatment and 2 (20%) eels in the 0.2 m·s⁻¹ flow treatment (including 1 eel with a head wider than the screen aperture; HW = 2.06 mm) were free swimming at the end of the trial, despite encountering the screen, i.e., behavioural avoidance, in contrast to 60% of eels in the 0 m·s⁻¹ flow treatment (including 1 eel with >2 mm head width; HW = 2.01 mm). During 0.1, 0.15 and 0.2 m·s⁻¹ flow treatments, 70%, 40% and 50% of eels were impinged on the screen, respectively; only one eel (HW = 2.04 mm) during 0.2 m·s⁻¹ flow treatment had a head wider than the screen aperture. Across all approach velocities, 30% of eels (of which 100% had <2 mm head width) passed through the 2 mm screen, with 40%, 10%, 50% and 20% of eels passing for approach velocities of 0, 0.1, 0.15 and 0.2 m·s⁻¹, respectively.

All 60–80 mm eels had a head narrower than the 3 mm aperture screen (mean ± S.D. = 1.84 ± 0.16 mm, range = 1.52–2.24 mm) but 100% passage only occurred during 0 m·s⁻¹ approach velocity. Migratory separation was found for 10% of eels at 0.15 m·s⁻¹ and behavioural avoidance was found for 10% of eels for depth-averaged flow velocities of 0.15 m·s⁻¹ and 0.2 m·s⁻¹. The highest impingement (80%) and passage (60%) rates were found for 0.1 and 0.2 m·s⁻¹ depth-averaged flow velocities, respectively. In contrast, 40% ($n = 16$) of the 100–160 mm size class of eels were free swimming at the end of the trial and all these eels encountered the screen; 81.3% ($n = 13$) had a head wider than the 3 mm screen aperture and thus were physically excluded while 19.7% ($n = 3$) had a head narrower than the 3 mm screen aperture but did not pass and avoided impingement, i.e., behavioural avoidance. For the 100–160 mm size class, 40%, 60%, and 70% of eels were impinged during the 0.1, 0.15 and 0.2 m·s⁻¹ approach velocities, and 0%, 33.3% and 14.3% had a head width narrow enough to fit through the screen, respectively.

All eels in the 60–80 mm (mean ± S.D. = 1.9 ± 0.2 mm, range = 1.5–2.5 mm) and 100–160 mm (3.2 ± 0.2 mm, 2.6–4.3 mm) size classes had a head narrower than the 5 mm screen aperture. Despite this, 100% passage was only found for the 60–80 mm eels for a depth-averaged flow velocity of 0 m·s⁻¹ and 100–160 mm eels for all depth-averaged flow velocities. Across all flow velocities, 10% of 60–80 mm eels were free swimming at the end of the trial; 7.5% of eels did not approach the screen (migratory separation), and 2.5% of eels encountered the screen but did not pass and avoided impingement (behavioural avoidance). In addition, 17.5% of eels (HW: mean ± S.D. = 2.0 ± 0.2 mm, range = 1.8–2.2 mm; TL: 69.3 ± 2.1 mm, 67.0–73.1 mm, respectively) were impinged on the 5 mm aperture screen (0.1 m·s⁻¹ = 20%, 0.15 m·s⁻¹ = 40% and 0.2 m·s⁻¹ = 10%). The head widths of these eels were significantly larger than the 72.5% ($n = 29$) eels that passed through the screen (mean ± S.D. = 1.8 ± 0.2 mm, range = 1.5–2.3 mm) ($t = 2.4625$,

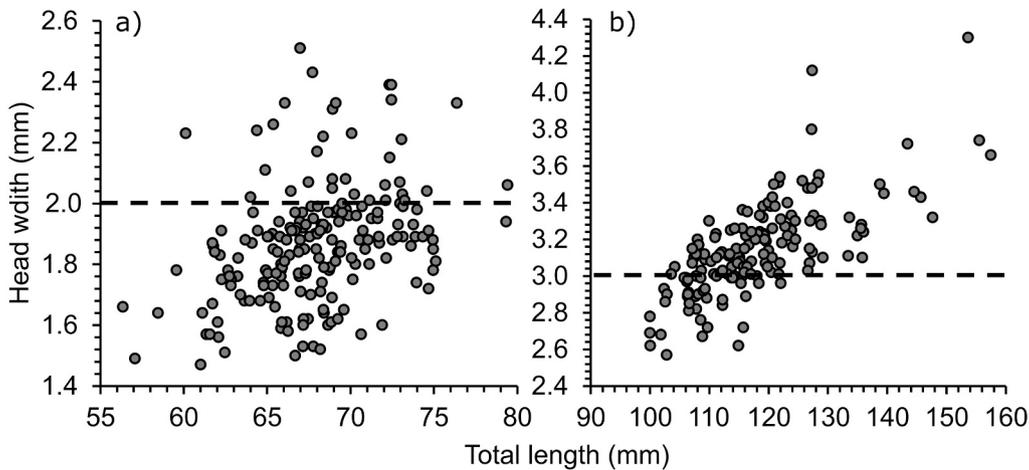


Fig. 3. Head width against total length for 60–80 (A) and 100–160 mm (B) eels. Dashed line in figures denote a head width of 2 and 3 mm, respectively. Please note differing x and y scales.

Table 4

The behaviour (migratory separation (MS), behavioural avoidance (BA)) and fate (impinged (I), passed (P)) of 60–80 (left) and 100–160 mm (right) eel for 1, 2, 3 and 5 mm screen apertures and 0, 0.1, 0.15 and 0.2 m·s⁻¹ approach velocities. Darker colours denote larger numbers. Numbers in brackets represent eels that had a head wider than the screen aperture, and thus could not pass through the screen. Dashes denote that it was not possible for eels to be impinged during the no flow treatment.

Aperture (mm)	Velocity (m s ⁻¹)	60–80 mm				100–160 mm			
		MS	BA	I	P	MS	BA	I	P
1	0.2	0	1 (1)	9 (9)	0				
1	0.15	2 (2)	2 (2)	6 (6)	0				
1	0.1	2 (2)	3 (3)	5 (5)	0				
1	0	2 (2)	8 (8)	-	0				
2	0.2	1	2 (1)	5	2	0	0	10 (10)	0
2	0.15	1	0	4	5	0	1 (1)	9 (9)	0
2	0.1	1 (1)	1	7 (1)	1	0	1 (1)	9 (9)	0
2	0	0	6 (1)	-	4	0	10 (10)	-	0
3	0.2	0	1	3	6	0	1	7 (6)	2
3	0.15	1	1	5	3	0	3 (2)	6 (4)	1
3	0.1	0	0	8	2	0	3 (2)	4 (4)	3
3	0	0	0	-	10	0	9 (9)	-	1
5	0.2	2	0	1	7	0	0	0	10
5	0.15	1	0	4	5	0	0	0	10
5	0.1	0	1	2	7	0	0	0	10
5	0	0	0	-	10	0	0	-	10

df = 12.254, $p = 0.029$), although total lengths (67.1 ± 4.7 mm, 57.1–76.4 mm) were comparable ($t = 1.8694$, $df = 22.71$, $p = 0.074$).

3.3. Time

3.3.1. First screen approach time

For 60–80 mm eels, the first screen approach time (s) (median (Inter Quartile Range: IQR) = 35 (72) s) was significantly lower for eels that swam downstream upon release ($n = 93$ (58.1%)) rather than upstream (median (IQR) = 200 (300) s; $n = 67$ (41.9%)) ($w = 4399$, $p \leq 0.001$).

For eels that swam downstream upon release, the median (IQR) first screen approach time (for all screen apertures) was 61 (103), 30 (13), 27 (17) and 40 (178) seconds for depth-averaged flow velocities of 0, 0.1, 0.15 and 0.2 m·s⁻¹, respectively, and differed significantly ($\chi^2 = 11.341$, $df = 3$, $p = 0.01$) (Fig. 4a). Post-hoc pairwise comparisons revealed there was a significant difference between flow velocities of 0 m·s⁻¹ and 0.15 m·s⁻¹ ($p = 0.009$). For eels that swam upstream, first screen approach

time was 122 (124), 280 (584), 281 (204) and 169 (350) seconds for flow velocities of 0, 0.1, 0.15 and 0.2 m·s⁻¹, respectively, and did not differ significantly ($\chi^2 = 6.8427$, $df = 3$, $p = 0.077$) (Fig. 4a).

For 100–160 mm eels, the first screen approach time was significantly lower for eels that swam downstream upon release (median (IQR) = 15 (6) s; $n = 56$; 46.7%) rather than upstream (median (IQR) = 98 (92) s; $n = 64$; 53.3%) ($w = 3444.5$, $p \leq 0.001$).

For eels that swam downstream, the median (IQR) first screen approach time (all screen apertures) was 17 (9) s, 17 (6) s, 16 (6) s and 13 (3) s for depth-averaged flow velocities of 0, 0.1, 0.15 and 0.2 m·s⁻¹, respectively, and were statistically comparable ($\chi^2 = 6.8621$, $df = 3$, $p = 0.076$) (Fig. 4b). For eels that swam upstream, median (IQR) first screen approach time (all screen apertures) was 62 (31), 99 (86), 105 (95) and 144 (108) s for depth-averaged flow velocities of 0, 0.1, 0.15 and 0.2 m·s⁻¹, respectively, and differed significantly ($\chi^2 = 15.677$, $df = 3$, $p = 0.001$) (Fig. 4b). Post-hoc pairwise comparisons revealed a significant difference between 0 m·s⁻¹ and 0.2 m·s⁻¹ ($p \leq 0.001$).

3.3.2. Time to eel fate (from first screen contact)

Time from first screen contact to passage or impingement for both size classes of eels was highly variable both within and between different screen apertures and depth-averaged flow velocities (Fig. 5). The strongest trend was an increase in time from first screen encounter to impingement for 60–80 mm ($n = 20$; $\chi^2 = 4.1772$, $df = 2$, $p = 0.129$) and 100–160 mm ($n = 28$; $\chi^2 = 0.85101$, $df = 2$, $p = 0.653$) eels at 1 and 2 mm aperture screens, respectively, as depth-averaged flow velocity increased, although neither were significantly different (Fig. 5).

3.4. Screen contacts

3.4.1. 60–80 eels for 1 mm aperture screen

For 60–80 mm eels (1 mm aperture screen), there were 91 screen contacts across the three flow treatments, with a median (IQR) number of screen contacts of 1.0 (2.0), 1.5 (2.0), and 5.5 (4.5) for depth-averaged velocities of 0.1, 0.15, and 0.2 m·s⁻¹, respectively (Fig. 6a). The number of screen contacts (within each flow treatment) was not influenced by eel body length (Spearman rank correlation $p > 0.05$). Median (IQR) rate of screen contacts fish⁻¹ min⁻¹ was 0.89 (1.59), 0.17 (1.1) and 0.67 (0.83) for depth-averaged velocities of 0.1, 0.15 and 0.2 m·s⁻¹, respectively (Fig. 6c). The proportion of screen contacts in a headfirst orientation ($\chi^2 = 3.0333$, $df = 2$, $p = 0.219$) were comparable between flow treatments, however, there were proportionally more screen contacts in side-on orientation ($\chi^2 = 38.954$, $df = 2$, $p \leq 0.001$) at 0.2 m·s⁻¹ in comparison to 0.1 and 0.15 m·s⁻¹ (Fig. 6e). Only one eel made contact with the screen in a tail first orientation at 0.2 m·s⁻¹.

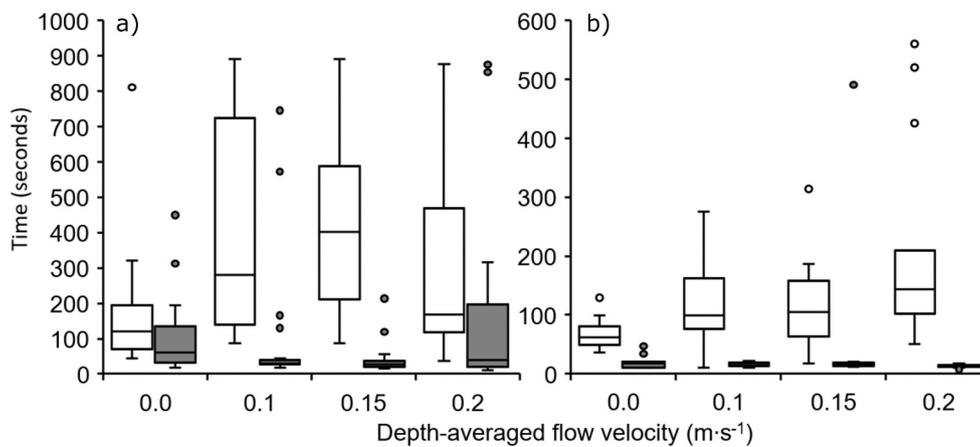


Fig. 4. First screen approach time (seconds) for A) 60–80 mm and B) 100–160 mm eels that swam upstream (white) and downstream (grey) for 0, 0.1, 0.15 and 0.2 $\text{m}\cdot\text{s}^{-1}$ depth-averaged flow velocities.

There were proportionally more screen contacts ($\chi^2 = 45.044$, $df = 2$, $p \leq 0.001$) and impingements under 10 s ($\chi^2 = 6.7989$, $df = 2$, $p = 0.033$) at a depth-averaged velocity of 0.2 $\text{m}\cdot\text{s}^{-1}$ compared to 0.1 and 0.15 $\text{m}\cdot\text{s}^{-1}$, but the proportion of impingements were comparable ($\chi^2 = 1.4028$, $df = 2$, $p = 0.495$) (Fig. 6g).

3.4.2. 100–160 mm eels for 2 mm aperture screen

For 100–160 mm size class eels (2 mm aperture screen), there were 72 screen contacts across the 3 flow treatments, with a median (IQR) number of screen contacts of 1.0 (1.0), 2.0 (3.8) and 2.0 (1.8) for 0.1, 0.15 and 0.2 $\text{m}\cdot\text{s}^{-1}$, respectively (Fig. 6); the number of screen contacts (within each flow treatment) was not influenced by eel body length (Spearman rank correlation $p > 0.05$). Median (IQR) rate of screen contacts $\text{fish}^{-1} \text{min}^{-1}$ was 0.70 (0.60), 0.65 (0.47) and 0.88 (0.97) for depth-averaged velocities of 0.1, 0.15 and 0.2 $\text{m}\cdot\text{s}^{-1}$, respectively (Fig. 6). The proportion of headfirst ($\chi^2 = 1.037$, $df = 2$, $p = 0.595$) and side-on screen contacts ($\chi^2 = 2.5455$, $df = 2$, $p = 0.28$) were comparable between flow treatments (Fig. 6). The proportion of screen contacts ($\chi^2 = 2.265$, $df = 2$, $p = 0.269$), impingements under 10 s ($\chi^2 = 2.4905$, $df = 3$, $p = 0.287$) and proportion of impingements ($\chi^2 = 6.8621$, $df = 3$, $p = 0.959$) were comparable across flow treatments (Fig. 6).

3.5. Influence of prevailing light (day and night)

For 60–80 mm eels (2 mm aperture screen) across all depth-averaged flow velocities, migratory separation (light = 32.5%, dark = 7.5%; $\chi^2 = 6.3281$, $df = 1$, $p = 0.011$) and passage (light = 40.0%, dark = 30.0%; $\chi^2 = 0.49451$, $df = 1$, $p = 0.481$) were higher during the day while behavioural avoidance (light = 0%, dark = 22.5%; $\chi^2 = 8.0125$, $df = 1$, $p = 0.004$) and impingement (light = 27.5%, dark = 40.0%; $\chi^2 = 0.89448$, $df = 1$, $p = 0.344$) were higher at night, although not significantly (Table 5).

All 100–160 mm eels tested against the 3 mm aperture screen between day and night approached and encountered the screen at least once i.e., no migratory separation (Table 5). Behavioural avoidance (L:D = 47.5%:40%; $\chi^2 = 0.20317$, $df = 1$, $p = 0.652$), impingement (L:D = 22.5%:42.5%; $\chi^2 = 2.792$, $df = 1$, $p = 0.094$) and passage (L:D = 30%:17.5%; $\chi^2 = 1.1044$, $df = 1$, $p = 0.293$) rates were largely comparable between light and dark treatments. Impingement rates increased as depth-averaged flow velocity increased, with no impingements at a velocity of 0.1 $\text{m}\cdot\text{s}^{-1}$ during light treatments whereas 4 eels were impinged under the same velocity during dark treatments. Of the 9 eels impinged during light treatments, all of them had a head width < 3 mm and would have been able to pass through the screen. Conversely, 10 of the 17 eels impinged at night had a head width > 3 mm and thus were

unable to pass through the screen.

4. Discussion

Knowledge of juvenile eel exclusion, impingement and passage at physical screens is urgently required to understand and mitigate the impacts of hazardous intakes (e.g., hydropower plants, water abstraction sites and pumping stations). During this study, passive wedge-wire screen aperture and depth-averaged flow velocities both influenced the fate (i.e., impingement or passage) and behaviour (i.e., migratory separation or behavioural avoidance) of two size classes of juvenile eels (60–80 mm glass eels and 100–160 mm elvers). Eel head width (relative to eel length) was also quantified to understand the proportion of eels that would theoretically be excluded by different screen apertures but eels narrower than the screen aperture did not always pass through. Here, we discuss the influence of physical, hydraulic and biological influences on small eel exclusion, impingement and passage to help improve screening guidance and fish protection at hazardous intakes.

Prior to this study, the relationship between farmed eel weight during grading and weight-length relationship published in Knights (1982) has been used to infer the length of eels excluded by mesh and grid bars. However, there was insufficient knowledge about juvenile eel head width to determine screen apertures to physically exclude eels. This study confirmed that 2 and 3 mm apertures did not provide physical exclusion for 60–120 and 121–300 mm size classes of eels, respectively, as currently stated in Environment Agency guidance (2011). Furthermore, eels narrower and slightly wider than screen apertures passed through screens. Eels with a head wider than the screen aperture may have passed through because of measurement errors, given their small size and intention to avoid causing injury (although they were anaesthetised), but fish are also known to force themselves through small apertures (Knights, 1982; Sheridan et al., 2014; Knott et al., 2023). That said, between 85.7 and 100% of 60–80 mm eels and 18.2% of 100–160 mm eels that did not pass through screens had a head narrow enough to do so. This demonstrates that while physical exclusion is an important consideration when screening intakes, other biological and/or hydraulic processes may also influence passage.

Glass eel and elver life-stages migrate upstream into rivers (Laffaille et al., 2007; Piper et al., 2012). During this study, eels were caught during their upstream migration and were of a size known to perform upstream migration; Imbert et al. (2010) found juvenile eels up to 240 mm had a tendency to migrate upstream but this tendency decreased with increasing body length. Thus, it was speculated that eels may not approach the screen because flows would induce upstream migratory instincts, i.e., migratory separation. However, only a small proportion of

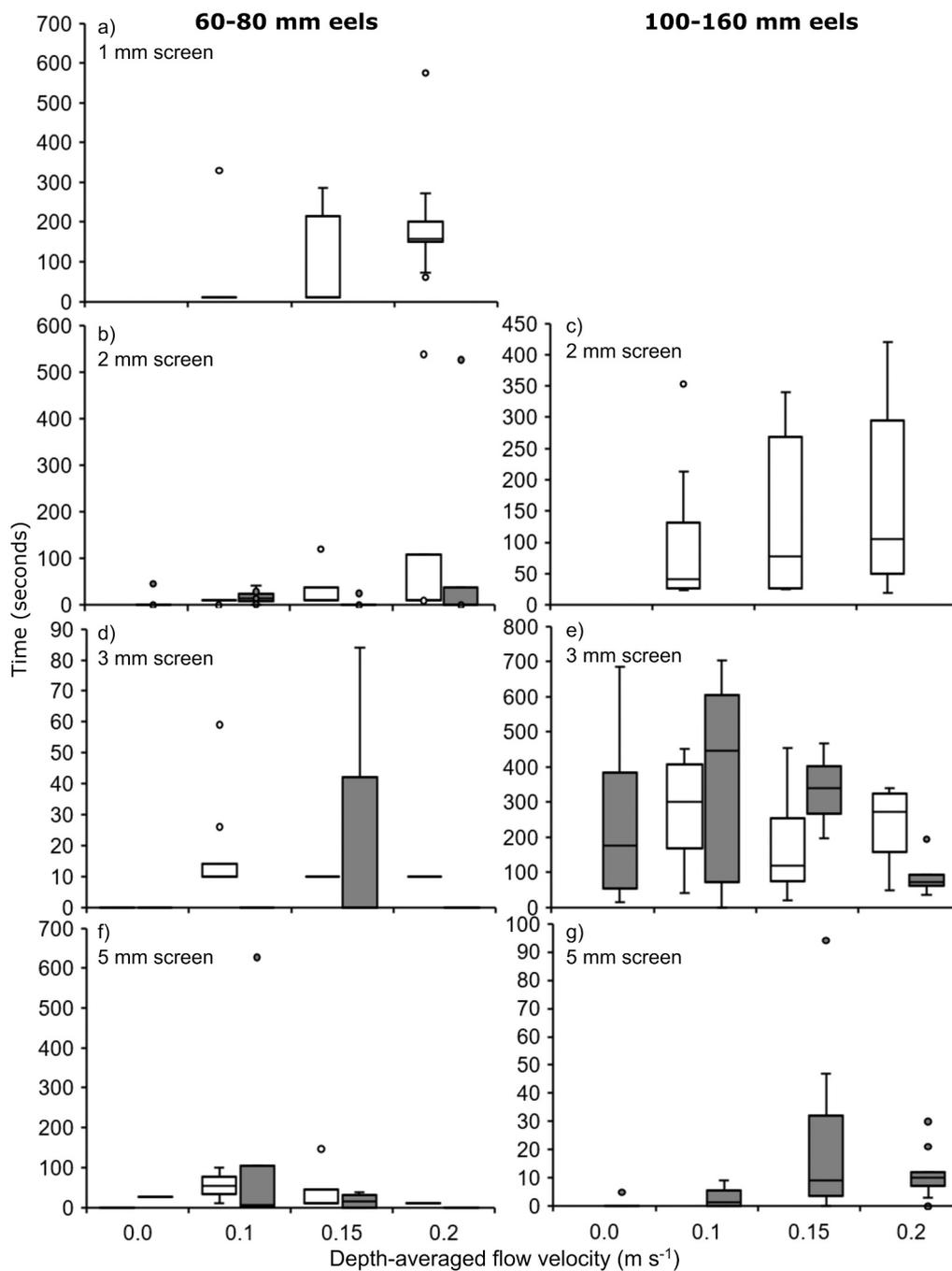


Fig. 5. Time from first screen contact to eel fate (seconds) for 60–80 mm (A,B,D,F) and 100–160 mm (C,E,G) eel that were impinged (white) and passed (grey) for each screen aperture (1, 2, 3 and 5 mm; top to bottom) and depth-averaged flow velocity (0, 0.1, 0.15 and 0.2 $\text{m}\cdot\text{s}^{-1}$).

60–80 mm eels (8.3%) and no 100–160 mm eels (0%) exclusively approached the upstream end of the flume at night. The contrasting behaviour between the two size groups of eels remains unknown but Poletto et al. (2018) attributed contrasting behaviour between two size groups of juvenile green sturgeon (*Acipenser medirostris*) near screens to ontogenetic influences on morphology, behaviour or physiology. Unexpectedly, given juvenile eels are primarily nocturnal (Glova and Jelliman, 2003; Piper et al., 2012; Geffroy et al., 2015), the proportion of 60–80 mm eels that exclusively approached the upstream end of the flume was higher during the day (32.5%) than at night (7.5%), but the reason for this remains to be determined. It is possible that transferring the eels to the flume caused some of them to cease their upstream migration, but is considered unlikely given flume investigations have

been performed to study upstream migration (Podgorniak et al., 2016).

Impingement was found for both size classes of eel for all apertures and all depth-averaged flow velocities, except 100–160 mm eels and the 5 mm aperture screen (100% passage). The proportion of 60–80 mm eels impinged during the 1 mm aperture study increased as approach velocity increased, which is consistent with impingement of juvenile golden perch (*Bidyanus bidyanus*) during increased approach velocities (Stocks et al., 2019). However, high rates of impingement (at least 90%) also occurred for the larger size class of eels (100–160 mm) at 2 mm screen aperture during all approach velocities and the number of screen contacts was not related to body length of the eels. Thus, neither impingement nor screen contact were necessarily a consequence of higher approach velocities exceeding the swimming capabilities of

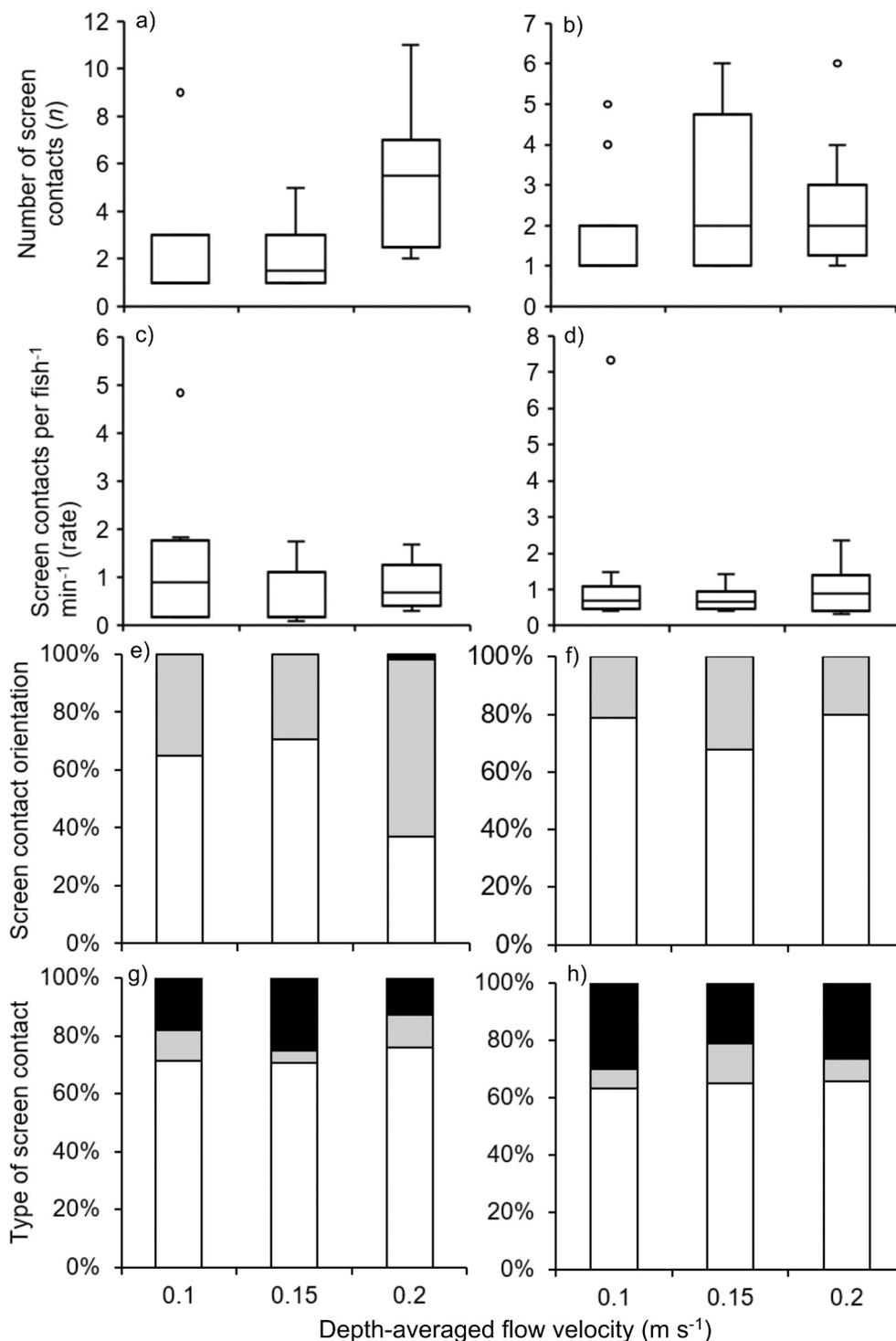


Fig. 6. Number of screen contacts (n) and contacts $\text{fish}^{-1} \text{min}^{-1}$ (rate), and stacked bar charts for screen contact orientation (white = headfirst; grey = side-on; black = tail first) and the type of screen contact (white = screen contact; grey = impingements <10 s; black = impingements >10 s) for 60–80 mm eels and 1 mm aperture screen (A, C, E, G) and 100–160 mm eels and 2 mm aperture screen (B, D, F, H) for each depth-averaged flow velocity (0.1, 0.15, 0.2 m s^{-1}).

smaller eels. This finding is in contrast to Peake (2004), who reported a positive relationship between juvenile Northern pike (*Esox lucius*) size and the ability to avoid contact and impingement (prolonged contact). Furthermore, in our study only one eel made contact with the screen in a tail first orientation, although there were significantly more screen contacts in side-on orientations for 60–80 mm eels at 0.2 m s^{-1} , and thus eels were not drawn onto the screen as they tried to escape.

Once screen contact has been made, impingement can occur when a

fish is either unwilling or unable to swim off the screen. Here, the median number of screen contacts per eel increased as approach velocity increased (significantly so for 60–80 mm eels for a depth-averaged velocity of 0.2 m s^{-1}), the rate of screen contacts remained consistent and time to eel fate (from first contact) increased. In a similar study, Swanson et al. (2004) speculated that the ability of juvenile Chinook salmon (*Oncorhynchus tshawytscha*) to avoid screen contact at low flow was related to their “level of effort” rather than swimming capabilities,

Table 5

Behaviour (migratory separation (MS), behavioural avoidance (BA)) and fate (impinged (I) and passed (P)) of 60–80 mm (left) and 100–160 mm (right) eels for 2 and 3 mm screen apertures, respectively, across all depth-averaged flow velocities (0, 0.1, 0.15 and 0.2 m·s⁻¹) during dark and light treatments. Darker colours denote larger numbers. Numbers in brackets represent eels that had a head wider than the screen aperture, and thus could not pass through the screen. – denotes it was not possible for eels to be impinged during the no flow treatment.

Light	Velocity (m s ⁻¹)	60–80 mm 2 mm screen aperture				100–160 mm 3 mm screen aperture			
		MS	BA	I	P	MS	BA	I	P
Dark	0.2	1	2 (1)	5	2	0	1	7 (6)	2
Dark	0.15	1	0	4	5	0	3 (2)	6 (4)	1
Dark	0.1	1	1	7 (1)	1	0	3 (2)	4	3
Dark	0	0	6 (1)	–	4	0	9	–	1
Light	0.2	3	0	4	3	0	2	5	3
Light	0.15	4	0	5	1	0	4	4	2
Light	0.1	2	0	2	6	0	6	0	4
Light	0	4	0	–	6	0	7 (3)	–	3

since increased water velocity resulted in less frequent screen contact. Likewise, [Boys et al. \(2013\)](#) reported juvenile golden perch avoided approaching an experimental screen by engaging in positive rheotactic behaviour, which was enhanced as velocity increased (up to 0.4 m·s⁻¹). Therefore, impingement during this investigation was probably a consequence of both behavioural and hydraulic processes during contact with the screen. More specifically, impingement at lower approach velocities may be related to eels being unwilling to swim off the screen, while impingement at higher approach velocities was possibly caused by eels being unable to swim off the screen during final contact. However, the behavioural responses to flow velocity and screens are poorly understood, with [Poletto et al. \(2014\)](#) reporting highly contrasting findings between two closely related sturgeon species. Ultimately, in contrast to current UK Environment Agency guidance (2011), depth-averaged screen approach velocities of 0.1 and 0.15 m·s⁻¹ do not necessarily prevent impingement of 60–120 and 121–300 mm eels, respectively. That said, lower approach velocities decrease the requirement for elevated swimming activity to avoid screen contact or impingement, and thus are recommended.

Impingement rates at day and night were comparable for both size classes of eels at all approach velocities. It was previously reported that eels supplement their rheotactic response to flow with a visual response to the screen to guide their behaviour during the day ([Swanson et al., 2004](#)). For example, [Boys et al. \(2013\)](#) reported that fish were more likely to contact a screen in darkness and suggested that visual cues were important to avoid screen contact. However, for 60–80 mm eels, no eels exhibited behavioural avoidance during the day.

4.1. Further research

Further research is required to understand the hydraulic and biological processes that occur before and during screen contact for the apertures and approach velocities tested here. Water temperature was kept at 10 °C and thus future investigations should incorporate a range of water temperatures given its influence on eel swimming capabilities ([Edeline et al., 2006](#)). Future investigations may also incorporate alternative screen angles, both with and without a downstream bypass channel to assess the influence of sweeping flows on exclusion, impingement and guidance, as has been performed for other species ([de](#)

[Bie et al., 2021](#); [Harbicht et al., 2022](#)) and life stages of European eel ([Russon et al., 2010](#)). All eels impinged during this study were healthy, but they were removed from the screen after ten seconds, and thus further research to quantify the impact of approach velocity during screen contact and impingement duration on eel stress, injury or mortality may be required as studied by [White et al. \(2007\)](#), [Young et al. \(2010\)](#), [Poletto et al. \(2014\)](#), and [Stocks et al. \(2019\)](#). Ultimately, further research at real-world intakes is required to corroborate the findings reported here are representative of natural behaviours.

4.2. Conclusions and management implications

Hazardous intakes, such as for potable and industrial water supply, irrigation, hydroelectric power generation and flood defence, must be screened to prevent eel entrainment, as per EU legislation (EC Regulation No. 1100/2007) and UK Eel Regulations (2009) Statutory Instrument. Given the small size and poor swimming capabilities of juvenile eels, small aperture screens and low approach velocities might be required to prevent impingement and entrainment, which pose operational and financial challenges for site owners. Here, we present the first flume-based quantitative evidence of the influence of passive wedge-wire screen aperture (orientated 90° to the flow) under different hydraulic flow conditions on juvenile eel. Regulators will be able to use eel morphometric data to inform the size of eels that will, in theory, be physically excluded by certain aperture screens. It was then demonstrated that small screen apertures provide physical exclusion of eels, i. e., 1 mm for 60–80 mm and 2 mm for 100–160 mm, but they tended to impinge on the screen. Indeed, impingement occurred when the screen aperture was both narrower and wider than the eels under investigation and during all approach velocities investigated, which may necessitate that effective fish recovery and return systems are also installed at hazardous intakes ([Clough et al., 2014](#); [Turnpenny, 2014](#)). The present research has thus improved our understanding of physical, hydraulic, and biological influences on small eel exclusion at hazardous intakes to inform screening guidance.

CRediT authorship contribution statement

Liam J. Carter: Validation, Investigation, Formal analysis, Writing – original draft. **Stephen J. Collier:** Validation, Investigation, Writing – review & editing. **Robert E. Thomas:** Supervision, Writing – review & editing, Visualization. **Josh Norman:** Data curation, Visualization, Writing – review & editing. **Rosalind M. Wright:** Funding acquisition, Writing – review & editing, Resources. **Jonathan D. Bolland:** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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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References

- Aalto, E., Capoccioli, F., Mas, J.T., Schiavina, M., Leone, C., De Leo, G., Ciccotti, E., 2016. Quantifying 60 years of declining European Eel (*Anguilla anguilla* L., 1758) fishery yields in Mediterranean coastal lagoons. *ICES J. Mar. Sci.* 73 (1), 101–110.
- Acou, A., Laffaille, P., Legault, A., Feunteun, E., 2008. Migration pattern of silver eel (*Anguilla anguilla*, L.) in an obstructed river system. *Ecol. Freshw. Fish* 17 (3), 432–442.
- Barbin, G.P., Krueger, W.H., 1994. Behaviour and swimming performance of elvers of the American eel, *Anguilla rostrata*, in an experimental flume. *J. Fish Biol.* 45, 111–121.
- Belletti, B., Garcia de Leaniz, C., Jones, J., Bizzi, S., Börger, L., Segura, G., Castelletti, A., van de Bund, W., Aarestrup, K., Barry, J., Belka, K., Berkhuisen, A., Birnie-Gauvin, K., Bussetini, M., Carolli, M., Consuegra, S., Dopico, E., Feierfeil, T., Fernández, S., Zalewski, M., 2020. More than one million barriers fragment Europe's rivers. *Nature* 588 (7838), 436–441.
- Bolland, J.D., Murphy, L.A., Stanford, R.J., Angelopoulos, N.V., Baker, N.J., Wright, R.M., Reeds, J.D., Cowx, I.G., 2019. Direct and indirect impacts of pumping station operation on downstream migration of critically endangered European eel. *Fish. Manag. Ecol.* 26 (1), 76–85.
- Boys, C.A., Baumgartner, L.J., Lowry, M., 2013. Entrainment and impingement of juvenile silver perch, *Bidyanus bidyanus*, and golden perch, *Macquaria ambigua*, at a fish screen: effect of velocity and light. *Fish. Manag. Ecol.* 20 (4), 362–373.
- Bromley, R., Coyle, S., Hawley, K., Anderson, K., Turnpenny, A.W.H., 2014. UK best practice fish screening trials study. In: WIT Transactions on State-of-the-art in Science and Engineering, 71.
- Buyse, D., Mouton, A.M., Stevens, M., Van den Neucker, T., Coeck, J., 2014. Mortality of European eel after downstream migration through two types of pumping stations. *Fish. Manag. Ecol.* 21 (1), 13–21.
- Carpenter, S.R., Stanley, E.H., Vander Zanden, M.J., 2011. State of the world's freshwater ecosystems: physical, chemical, and biological changes. *Annu. Rev. Environ. Resour.* 36 (1), 75–99.
- Clough, S.C., Lee-Elliott, I.H., Turnpenny, A.W.H., Holden, S.D.J., Hinks, C., 2003. Swimming Speeds in Fish: Phase 2. Environment Agency. Technical report W2-049/TR1.
- Clough, S.C., Teague, N., Webb, H., 2014. Even fine bar spacing, how low can you go? *Int. Fish Screen. Tech.* 7, 1–10.
- Couto, T.B., Olden, J.D., 2018. Global proliferation of small hydropower plants—science and policy. *Front. Ecol. Environ.* 16 (2), 91–100.
- de Bie, J., Peirson, G., Kemp, P.S., 2021. Evaluation of horizontally and vertically aligned bar racks for guiding downstream moving juvenile chub (*Squalius cephalus*) and barbel (*Barbus barbus*). *Ecol. Eng.* 170, 10.
- Dekker, W., 2003a. Status of the European eel stock and fisheries. In: Aida, K., Tsukamoto, K., Yamauchi, K. (Eds.), *Eel Biology*. Springer, pp. 237–255.
- Dekker, W., 2003b. Did lack of spawners cause the collapse of the European Eel, *Anguilla anguilla*? *Fish. Manag. Ecol.* 10, 365–376.
- Deleau, M.J., White, P.R., Peirson, G., Leighton, T.G., Kemp, P.S., 2019. Use of acoustics to enhance the efficiency of physical screens designed to protect downstream moving European eel (*Anguilla anguilla*). *Fish. Manag. Ecol.* 27, 1–9.
- Edeline, E., Lamber, P., Rigaud, C., Elie, P., 2006. Effects of body condition and water temperature on *Anguilla anguilla* glass eel migratory behaviour. *J. Exp. Mar. Biol. Ecol.* 217–225.
- Egg, L., Mueller, M., Pander, J., Knott, J., Geist, J., 2017. Improving European Silver Eel (*Anguilla anguilla*) downstream migration by undershot sluice gate management at a small-scale hydropower plant. *Ecol. Eng.* 106, 349–357.
- Environment Agency, U.K., 2011. Screening at intakes and outfalls: measures to protect eels. In: *The Eel Manual – GEHO041BTQD-E-E*.
- European Environment Agency, 2022. Water abstraction by source and economic sector in Europe. <https://www.eea.europa.eu/publications/water-resources-across-europe-confronting> [Accessed 26/04/2022].
- Fukuda, N., Aoyama, J., Yokouchi, K., Tsukamoto, K., 2016. Periodicities of inshore migration and selective tidal stream transport of glass eels, *Anguilla japonica*, in Hamana Lake, Japan. *Environ. Biol. Fish* 99, 309–323.
- García, C.M., Jackson, P.R., García, M.H., 2006. Confidence intervals in the determination of turbulence parameters. *Exp. Fluids* 40, 514–522. <https://doi.org/10.1007/s00348-005-0091-8>.
- Geffroy, B., Sadoul, B., Bardonnat, A., 2015. Behavioural syndrome in juvenile eels and its ecological complications. *Behaviour* 147–166.
- Geist, J., 2021. Green or red: challenges for fish and freshwater biodiversity conservation related to hydropower. *Aquat. Conserv. Mar. Freshwat. Ecosyst.* 31 (7), 1551–1558.
- Glova, G.J., Jellyman, D.J., 2003. Size-related differences in diel activity of two species of juvenile eel (*Anguilla*) in a laboratory stream. *Ecol. Freshw. Fish* 9 (4), 210–218.
- Harbicht, A.B., Watz, J., Nyqvist, D., Virmajo, T., Carlsson, N., Aldven, D., Nilsson, P.A., Calles, O., 2022. Guiding migrating salmonid smolts: experimentally assessing the performance of angled and inclined screens with varying gap widths. *Ecol. Eng.* 174, 8.
- Harrison, A.J., Walker, A.M., Pinder, A.C., Briand, C., Aprahamian, M.W., 2014. A review of glass eel migratory behaviour, sampling techniques, and abundance estimates in estuaries: implications for assessing recruitment, local production and exploitation. *Rev. Fish Biol. Fish.* 24, 967–983.
- Imbert, H., Labonne, J., Rigaud, C., Lambert, P., 2010. Resident and migratory tactics in freshwater European eels are size-dependent. *Freshw. Biol.* 55, 1483–1493.
- International Council for Exploration of the Seas (ICES), 2019. Joint EIFAAC/ICES/GFCM working group on eels (WGEEEL). *ICES Sci. Rep.* 1, 177.
- Jacoby, D., Gollock, M., 2014. *Anguilla anguilla*. The IUCN Red List of Threatened Species.
- Jellyman, D.J., 2021. An enigma: how can freshwater eels (*Anguilla* spp.) be such a successful genus yet be universally threatened? *Rev. Fish Biol. Fisheries* 32, 701–718.
- Knights, B., 1982. Body dimensions of farmed eels (*Anguilla anguilla* L.) in relation to condition factor, grading, sex and feeding. *Aquac. Eng.* 1, 297–310.
- Knott, J., Mueller, M., Pander, J., Geist, J., 2023. Bigger than expected: species- and size-specific passage of fish through hydropower screens. *Ecol. Eng.* 188, 106883.
- Laffaille, P., Caraguel, J.M., Legault, A., 2007. Temporal patterns in upstream migration of European glass eels (*Anguilla anguilla*) at the Couesnon estuarine dam. *Estuar. Coast. Shelf Sci.* 73 (1–2), 81–90.
- Langdon, S.A., Collins, A.L., 2000. Quantification of the maximal swimming performance of Australasian glass eels, *Anguilla australis* and *Anguilla reinhardtii* using a hydraulic flume swimming chamber. *N. Z. J. Mar. Freshw. Res.* 34 (4), 629–636.
- Larinier, M., Travade, F., 2002. Downstream migration: problems and facilities. *Bull. Fr. Peche Piscic.* 364, 181–207.
- McCleave, J.D., 1980. Swimming performance of European eel (*Anguilla anguilla* (L.)) elvers. *J. Fish Biol.* 16, 445–452.
- Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and flow regulation of the world's large river systems. *Science* 308 (5720), 405–408.
- O'Keefe, N., Turnpenny, A.W.H., 2005. Screening for Intake and Outfalls: A Best Practice Guide. Environment Agency.
- Parkhurst, J.M., Price, G.J., Sharrock, P.J., Moore, C.J., 2011. Phase unwrapping algorithms for use in a true real-time optical body sensor system for use during radiotherapy. *Appl. Opt.* 50 (35), 6430–6439.
- Peake, S., 2004. Effect of approach velocity on impingement of juvenile northern pike at water intake screens. *N. Am. J. Fish Manag.* 24, 390–396.
- Piper, A.T., Wright, R.M., Kemp, P.S., 2012. The influence of attraction flow on upstream passage of European eel (*Anguilla anguilla*) at intertidal barriers. *Ecol. Eng.* 44, 329–336.
- Podgorniak, T., Blanchet, S., De Oliveira, E., Daverat, F., Pierron, F., 2016. To boldly climb: behavioural and cognitive differences in migrating European glass eels. *R. Soc. Open Sci.* 3 (1).
- Poletto, J.B., Cocherell, D.E., Ho, N., Cech, J.J., Klimley, A.P., Fanguie, N.A., 2014. Juvenile green sturgeon (*Acipenser medirostris*) and white sturgeon (*Acipenser transmontanus*) behavior near water-diversion fish screens: experiments in a laboratory swimming flume. *Can. J. Fish. Aquat. Sci.* 71, 1030–1038.
- Poletto, J.B., Cocherell, D.E., Ho, N., Cech, J.J., Klimley, A.P., Fanguie, N.A., 2018. The effect of size on juvenile green sturgeon (*Acipenser medirostris*) behavior near water-diversion fish screens. *Environ. Biol. Fish* 101, 67–77.
- Pope, S.B., 2000. *Turbulent Flows*. Cambridge University Press, Cambridge.
- Russon, I.J., Kemp, P.S., Calles, O., 2010. Response of downstream migration European eels (*Anguilla anguilla*) to bar racks under experimental conditions. *Ecol. Freshw. Fish* 19, 197–205.
- Sheridan, S., Turnpenny, A., Horsfield, D., Bamford, D., Bayliss, B., Coates, S., Trudgill, N., 2014. Screening at intakes and outfalls: measures to protect eel (*Anguilla anguilla*). *Int. Fish Screen. Tech.* 2011, 17–29.
- Stocks, J.R., Walsh, C.T., Rodgers, M.P., Boys, C.A., 2019. Approach velocity and impingement duration influences the mortality of juvenile Golden Perch (*Macquaria ambigua*) at a fish exclusion screen. *Ecol. Manag. Restor.* 20 (2), 136–141.
- Swanson, C., Young, P.S., Cech, J.J., 2004. Swimming in two-vector flows: performance and behaviour of juvenile Chinook salmon near a simulated screened water diversion. *Trans. Am. Fish. Soc.* 133, 265–278.
- Turnpenny, A., 2014. Trials and tribulations of fish recovery and return. In: WIT Transactions on State-of-the-art in Science and Engineering, 71.
- van Keekstra, O.A., van Hal, R., Winter, H.V., Tulp, I., Griffioen, A.B., 2020. Behavioural responses of eel (*Anguilla anguilla*) approaching a large pumping station with trash rack using an acoustic camera (DIDSON). *Fish. Manag. Ecol.* 0, 1–8.
- Wahl, T.L., 2003. Discussion of “Despiking Acoustic Doppler Velocimeter data” by Derek G. Goring and Vladimir I. Nikora. *J. Hydraul. Eng. ASCE* 129 (6), 484–487.
- White, D.K., Swanson, C., Young, P.S., Cech, J.J., Chen, Z.Q., Kavvas, M.L., 2007. Close encounters with a fish screen II: delta smelt behavior before and during screen contact. *Trans. Am. Fish. Soc.* 136 (2), 528–538.
- Xu, R., Zeng, Z., Pan, M., Ziegler, A.D., Holden, J., Spracklen, D.V., Brown, L.E., He, X., Chen, D., Ye, B., Xu, H., 2023. A global-scale framework for hydropower development incorporating strict environmental constraints. *Nat. Water* 1–10.
- Young, P.S., Swanson, C., Cech, J.J., 2010. Close encounters with a fish screen III: behavior, performance, physiological stress responses, and recovery of adult delta smelt exposed to two-vector flows near a fish screen. *Trans. Am. Fish. Soc.* 139 (3), 713–726.