Movement patterns of seaward migrating European eel (*Anguilla anguilla*) at a complex of riverine barriers: implications for conservation

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Running headline: Downstream migration patterns in European eel

ABSTRACT

River infrastructure such as weirs and hydropower stations commonly present migrating fish with multiple potential passage routes. Knowledge of the cues fish use to navigate such environments is required to protect migrants from hazardous areas and guide them towards safe passage, however, this is currently lacking for many species. Employing high-resolution positioning telemetry, this study examined movements of downstream migrating adult European eel, *Anguilla anguilla*, as they encountered a complex of water control structures in one location on the River Stour, southern England. The distribution of eels across five potential routes of passage differed from that predicted based on proportion of discharge alone. Certain routes were consistently avoided, even when the majority of flow passed through them. Passage distribution was partially explained by avoidance in the vicinity of a floating debris boom. Movement paths were non-randomly distributed across the forebay and eels moved predominantly within a zone 2-4 m from the channel walls. Understanding of avoidance and structure-orientation exhibited by eels will help advance effective guidance and downstream passage solutions for adults.

Keywords: fish passage; bypass; fishway; hydropower; migratory barriers.

INTRODUCTION

Many populations of diadromous fish are threatened by anthropogenic activities, such as overfishing and the construction of river infrastructure that impedes or blocks access to essential habitat (Limburg & Waldman 2009; McCauley et al. 2015). The catadromous European eel (*Anguilla anguilla*, Linnaeus, 1758) exhibits a semelparous life history that includes an initial journey as larvae (leptocephali) across the Atlantic Ocean to the coasts of Europe and North Africa followed by an inland migration to estuaries, rivers and streams, where they may remain resident for between 2 and 20+ years. As adults, the eels will embark on an outward final 5000–6000 km migration to spawning grounds in the Sargasso Sea (Aarestrup et al. 2009; Bruijs & Durif 2009). Compared to the 1980s, juvenile eel recruitment has reduced by 88 to 96% in many rivers (Dekker 2003; ICES 2014). As a result, the species is considered critically endangered (Jacoby & Gollock 2014) and listed under Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES). Accordingly, the European Union implemented the Eel Recovery Plan (2007) to establish management strategies to restore stocks (Council Regulation No. 1100/2007/EC), and the International Council for the Exploitation of the Sea recommended that mortality during the adult eel migration as a result of human induced stressors should be reduced to zero whenever possible (ICES 2014).

Several contributory factors have been attributed to the decline of European eel. These include loss of habitat and reduced habitat quality (Feunteun 2002), bioaccumulation of toxins (Belpaire et al. 2009), impacts of parasites (Kirk 2003; Palstra et al. 2007) and disease (van Beurden et al. 2012; Van Ginneken et al. 2005), overharvest (Briand et al. 2003), and oceanic climate changes such as shallowing of the mixed layer depth and reduced primary productivity near the spawning grounds which may impair the survival and transport of leptocephali (Friedland et al. 2007; Kettle et al. 2008; Knights 2003). Loss of hydrological continuity due to the presence of river infrastructure, such as weirs and dams, limits both juvenile upstream migration and adult spawner escapement (Bruijs & Durif 2009; Jansen et al. 2007; Verbiest et al. 2012; White & Knights 1997). Estimates of the proportion of downstream migrating eels that reach the marine environment range between 15 and 96% in regulated rivers (Aarestrup et al. 2010; Breteler et al. 2007; Breukelaar et al. 2009; Feunteun et al. 2000; Verbiest et al. 2012; Winter et al. 2006).

River infrastructure may delay or prevent downstream migration (Acou et al. 2008; Behrmann-Godel & Eckmann 2003), while hydropower and pumping stations cause direct mortality through blade strike, cavitation and pressure differences (Bruijs & Durif 2009; Schilt 2007; Turnpenny et al. 1998). Mortality of adult eels at these facilities may range between 10 and 100% (Calles et al. 2010; Carr & Whoriskey 2008; Larinier 2008). Physical screens may be installed to prevent adult eels from entering intakes to pumps and turbines, but can be expensive and cause injury and mortality through collision and impingement (Calles et al. 2010; Hadderingh & Jager 2002). Screens may also guide fish to alternative downstream passage routes. Guiding screens should create an attractive, or at least not an unattractive, environment (e.g. structural, hydrodynamic, acoustic) that does not induce avoidance and delay. Effective guidance for eel is considered lacking (Boubée 2014; Bruijs & Durif 2009; Haro 2014), and for those designs tested so far, efficiencies are highly variable and generally lower than expected (Calles et al. 2012; Gosset et al. 2005; Marohn et al. 2014). Development of effective guidance requires improved understanding of fish response to environmental parameters associated with structures at realistic scales (Goodwin et al. 2006; Kemp et al. 2012).

Downstream eel migration has previously been considered to be predominantly semi-passive, with elements of both active swimming and drifting with the currents (Porcher 2002; Tesch 2003), and a tendency to follow bulk flow (Breteler et al. 2007; Bultel et al. 2014; Jansen et al. 2007). Similarly, downstream migration of juvenile salmonids was historically thought to reflect obligate passive displacement with flow (Flagg et al. 1983; Smith 1982 for *Oncorhynchus* sp.; Thorpe & Morgan 1978; Tytler et al. 1978 for *Salmo salar*). This is now known not to be the case, as juvenile salmonids are capable of relatively strong swimming (e.g. Peake & McKinley 1998), actively seek high velocity zones (Svendsen et al. 2007), and avoid rapid accelerations of flow (Enders et al. 2009; Kemp et al. 2005; Svendsen et al. 2011). Indeed, diadromous fish are likely to exhibit a complex repertoire of migratory behaviours to accommodate the diversity of physical and hydrodynamic cues they encounter as they move through freshwater and marine environments (Goodwin et al. 2014; Kemp et al. 2012; Smith et al. 2014).

As predicted under assumptions of semi-passive downstream migration, the distribution of migratory adult eels at river bifurcations and flow diversion structures may be proportional to the flow passing each route (Breukelaar et al. 2009; Bruijs & Durif 2009; Calles et al. 2013; Jansen et al. 2007; Piper et al. 2013). Recent studies cast doubt on the simplistic semi-passive drift assumption, however, and describe a wide variety of behaviours displayed by eels when approaching structures. These include active hesitation before passing trash racks (Bruijs & Durif 2009), and altering of position in the water column and recurrent or searching behaviours on encountering rapid velocity gradients (Piper et al., 2015) and debris screens (Brown et al. 2009 for *A. rostrata*; Keeken et al. 2011 for *A. anguilla*). In flumes, eels associate closely with channel walls and structure (Adam et al. 1999; Russon et al. 2010) and may react to turbulent flow features (Russon et al. 2010; Silva et al. in press) and reject velocity acceleration (Newbold et al., 2015).

This study aimed to enhance understanding of the migratory behaviour of eels by exploring fine-scale movement and route choice of actively downstream moving adults in a field setting when presented with a variety of passage routes at one location. Using high resolution positioning acoustic telemetry, European eel were tracked through the forebay of a complex of water control structures, including both overshot and undershot sluices at a redundant hydropower site. Movement patterns were analysed and compared to those predicted based on the assumption of proportional passage with the flow through five available routes. Spatial distribution of eels across the forebay was examined to determine the influence of structural boundaries.

MATERIALS AND METHODS

STUDY SITE

The study was conducted on the River Stour, Southern England, in the forebay of a complex of water level control structures (50˚46'31.98"N, 1˚54'41.08"W) located 19 km upstream of the estuary. The complex comprises of two broad-crested Crump weirs (15.2 m width, A; 14.8 m width, C, Fig. 1); a pool and weir fish pass (1.8 m width, B, Fig 1); an adjustable overshot radial weir (7.5 m width, D, Fig. 1); and a set of 6 undershot sluice gates on the downstream side of an intake channel (7.6 m width) that formerly led to two hydropower turbines that were removed in the 1970s (Redundant Hydropower – RHP, E, Fig. 1). At the intake, a vertical bar rack (7.6 m width, 55˚angle, 58 mm bar spacing), extends the full width and depth of the channel (Fig. 1). Floating debris is diverted via the radial drop weir by a rubber floating boom that spans the width of the channel upstream of the RHP (Fig. 1). The forebay channel ranges from 15 to 35 m wide, with vertical banks bounded by steel revetments.

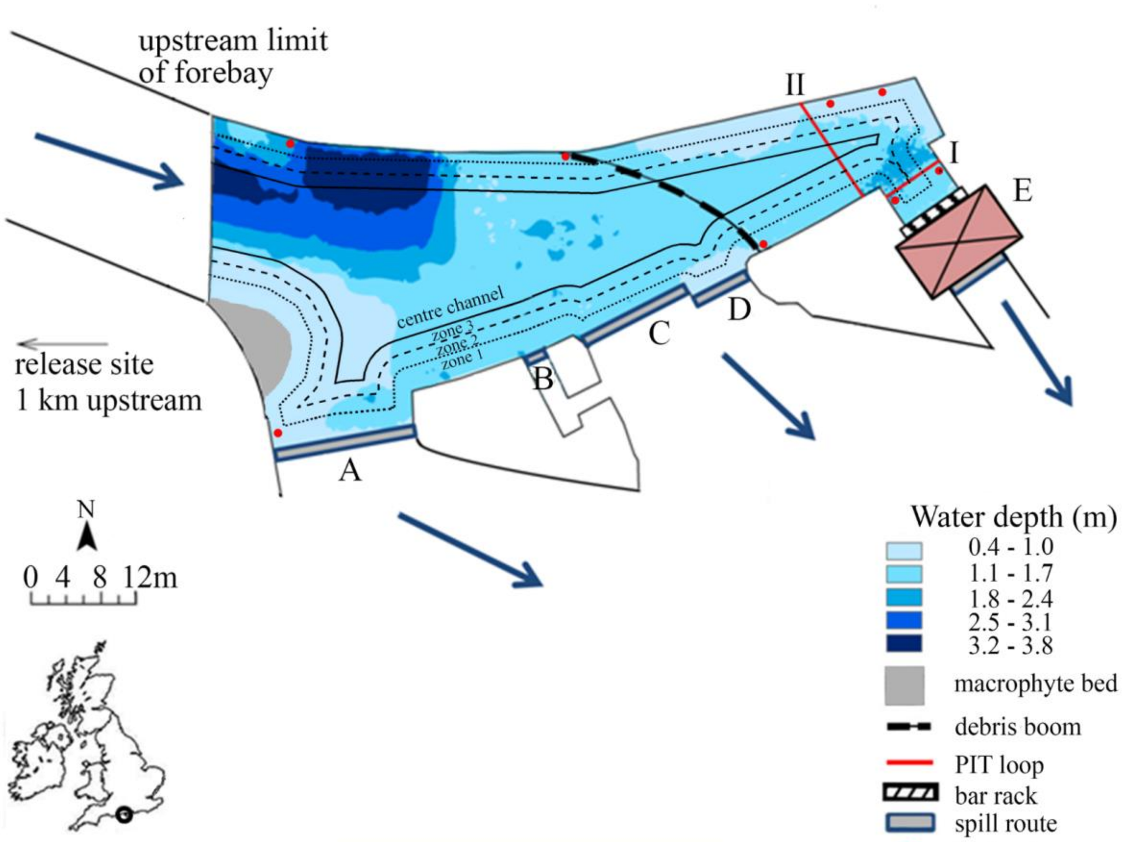

Fig. 1. Forebay bathymetry and location of structures (A and C - broadcrest weirs; B - pool and weir fish pass; D - radial weir, and E - an intake to a redundant hydropower (RHP) facility at Longham water works, River Stour, Dorset, UK. Red lines show PIT antennas I and II. Structures A to D are overshot discharge routes, whereas E (RHP intake) is undershot. Red dots denote the positions of hydrophones. For spatial analysis, the site was divided into four zones at increasing distances from the channel walls: Zone 1 (0 to 2 m, small dashes); Zone 2 (2 to 4 m, large dashes); Zone 3 (4 to 6 m, solid line), and centre channel (the remainder of the site)

Adjustable water control structures were maintained at fixed positions throughout the study with RHP sluice gates 50% open. An automatic flood control gate upstream of the forebay diverted excess flow down an alternate channel and thereby regulated the total channel discharge passing the study site.

A downward focused raft-mounted Acoustic Doppler Current Profiler with onboard GPS (ADCP, Sontek M9 River Surveyor®; www.sontek.com) was used to map site bathymetry and quantify discharge flowing into the study site and through each water control structure (Fig. 1). For bathymetry, the ADCP measured distance to channel bed using a vertical acoustic beam (0.5 MHz), and was pulled from bank-to-bank along a zig-zag transect to sample the entire forebay (see Dinehart & Burau 2005 for detailed description). For discharge, daily ADCP transect measurements in which the raft was pulled bank to bank perpendicular to flow were conducted across the inlet channel of the forebay, 4 m downstream of the debris boom, and 2 m upstream of structures A to D. Discharge was calculated within processing software RiverSurveyor Live v3.01 (Sontek; www.sontek.com) using established methods (Simpson 2001; SonTek 2010). Water level (cm) and temperature (˚C) were recorded every 15 minutes throughout the study period by fixed loggers located near the debris boom (HOBO® U20, OnsetComp; www.onsetcomp.com). Temperature ranged from 7.9 to 8.6 (mean 8.1 ± 1.3 S.D.) over the study period. Flow patterns were generated through linear interpolation based on ADCP discrete transect measurements and continuously logged changes in water level.

TELEMETRY CONFIGURATION AND VALIDATION

Acoustic telemetry (Hydroacoustic Technology Inc.; www.htisonar.com) was employed to track 2-dimensional movements (x and y) of tagged eels within the study site. Eight hydrophones (300 kHz) were positioned around the perimeter of the study area (Fig. 1) and detections were logged by a receiver (HTI, Model 290). As it was not possible to accurately determine the position of the fish in the shallow water column from acoustic detections alone, Passive Integrated Transponder (PIT) telemetry (Model LF-HDX-RFID, Oregon RFID; www.oregonrfid.com) was employed to indicate eel depth. A pass-over antenna was positioned across the full width of the intake channel (7.6 m length, 0.5 m width) (I, Fig 1), with a second antenna positioned across the channel 6.0 m upstream (14 m length, 0.5 m width) (II, Fig 1,).

The detection range of the acoustic tags was assessed at various positions throughout the study site. This enabled optimal positioning of the hydrophones and quantification of detection efficiency. Known tag locations demonstrated a minimum accuracy of < 1m which is comparable to other studies (Brown et al. 2009; Svendsen et al. 2011). Similarly, PIT antenna range testing indicated consistent detection (> 99 %) for depths < 0.2 m across both antennas. Both telemetry systems logged continually throughout the study period.

FISH CAPTURE AND TAGGING PROCEDURE

Actively migrating adult eels (n = 25) were trapped downstream of the RHP on five consecutive nights in November 2009, within the typical migration period for this river (Roger Castle, pers. comm.). Fish were transferred to in-river perforated holding barrels and held for a maximum of 8 h before being individually anesthetised (Benzocaine 0.2 g l^{-1}). Morphometric measurements were collected: wet mass (M, g); total length (L_T), mm); left pectoral fin length from insertion to the tip (mm), and maximum vertical and horizontal left eye diameter (mm). All individuals captured exceeded 450 mm (L_T) and were therefore presumed to be female (Durif et al. 2005). Degree of sexual maturation was quantified prior to tagging using two metrics; the Ocular index (I_O), according to Pankhurst (1982), and Fin Index (I_F), according to Durif *et al*. (2009). European eel with $I_O \geq 6.5$, and $I_F \geq 4.3$ (females only) were considered to be at the migratory silver stage. The first five eels fulfilling these criteria were selected for tagging each night. Tagged eels ranged from 635 to 827 mm L_T, 596-1049 g M, with median I_O 8.9 (range 6.8-12.3) and median I_F 4.6 (range 4.4 to 5.0).

An acoustic tag (HTI model 795G, 11mm diameter, 25mm length, 4.5 g mass in air, 300kHs, 0.7 − 1.3 s transmission interval), and Passive Integrated Transponder (PIT) tag (HDX, 3.65 mm diameter, 32 mm length, 0.8 g mass in air, Texas Instruments; www.ti.com) were surgically implanted into the peritoneal cavity of each eel following methods similar to Baras and Jeandrain (1998) under UK Home Office licence. No individual surgical procedure exceeded 3 minutes.

After tagging, eels were transported to the release location (1 km upstream of the study site) and held for 10-12 hours in a barrel to allow post-operative recovery and acclimation before release. No mortality was observed. To reduce bias in route choice, the holding barrel was tethered in the centre of the channel following previous studies (Piper et al. 2013; Svendsen et al. 2010). On each study night in darkness (20:00 h), the barrel lid was removed remotely with rope and pulley to minimise disturbance and allow individuals to leave volitionally.

DATA ANALYSIS

Acoustic tag detections were manually marked to remove background noise, then processed and corrected for speed of sound using MarkTag v5 and AcousticTag v5 software (Hydroacoustic Technology Inc., www.htisonar.com). Only detections within the perimeter of the hydrophone array were used (Ehrenberg & Steig 2003; Svendsen et al. 2011). Time-stamped Universal Transverse Mercator (UTM) designated detections (eel tracks) were imported into ArcMap v10 (ESRI; www.esri.com). Fish were deemed to have entered the study domain when tracks crossed a hypothetical cross-channel line between the two most upstream hydrophones at the upstream entrance to the forebay (Fig. 1). Passage was deemed to have occurred at the last detection point before an individual passed downstream of one of the five structures (A to E, Fig. 1). Residence time was calculated as the duration between first and last detection in the study domain before downstream passage. PIT records were examined for detections at the times when acoustic tracks intersected antenna locations. Positive detection provided a surrogate measure of near-bed (≤ 20 cm) movement.

Randomization tests of goodness of fit (200 replicates) (McDonald 2009) were used to assess whether: 1) the number of fish that passed varied between nights, and 2) passage through the five available routes was proportional to flow. Where assumptions of normality and homogeneity of variance were met. one-way ANOVAs were used to test for differences in the body length, ocular index and fin index of eels that passed the five available downstream routes. Buffer analysis was conducted on mapped tracks in ArcMap to explore spatial patterns of eel movement across the forebay. Three edge zones (buffers) of 2 m width (to encompass the maximum possible error in fish positioning i.e. ± 1 m) were imposed inside the structural site perimeter (zone 1: 0 – 2, zone 2: 2 – 4, and zone 3: 4 – 6 m from channel walls) and a fourth zone (centre channel) encompassed the remainder of the site (Fig. 1.). For each eel, the length of track falling within each of the four zones was calculated and weighted to account for the difference in area covered by each zone (20.9, 18.9, 17.2 and 43.0% of total site area, respectively). Weighted lengths were compared between zones using a one-way repeated measures ANOVA with pairwise comparisons and Tukeys post-hoc test. The Greenhouse-Geisser correction was applied where data violated the assumption of sphericity. Values are quoted as mean ± S.E. The significance level was 0.05. Statistical analyses were carried out using IBM SPSS v21 (IBM; www-01.ibm.com/software/uk/analytics/spss).

RESULTS

Of the 25 fish released, 19 passed downstream via the five available routes (Fig. 2). Three individuals remained undetected, and a further three were detected briefly in the forebay entrance, but returned upstream and were thus excluded from further analysis. The number of fish that passed did not vary between nights (randomisation test, $p = 0.82$). Fish took between 1.67 and 53 h to enter the forebay after release, and mean residence time was 8.2 min ± 1.35 min (Fig. 3). Passage always occurred during the hours of darkness.

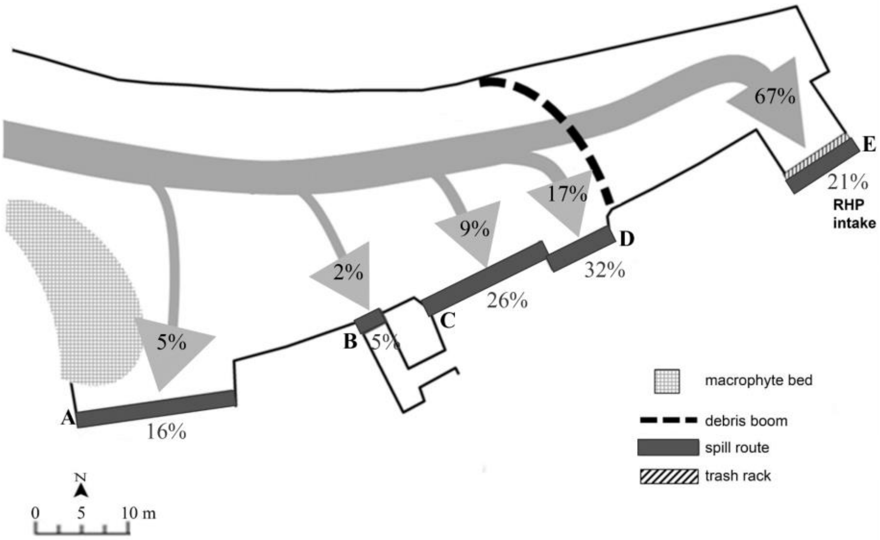

Fig. 2. Passage routes of downstream migrating adult eel (Anguilla anguilla) (n = 19) (%) via two broad crested weirs (A,C), a pool and weir fish pass (B), a drop weir (D) and a redundant hydropower (RHP) intake (E) at Longham Water Works, river Stour, UK. Arrows indicate water discharge routes, with percentages (in arrow heads) indicating total mean channel flow through each route. The proportion of eels that passed the routes differed ($p < 0.01$) from that predicted based on the distribution of flow through the routes.

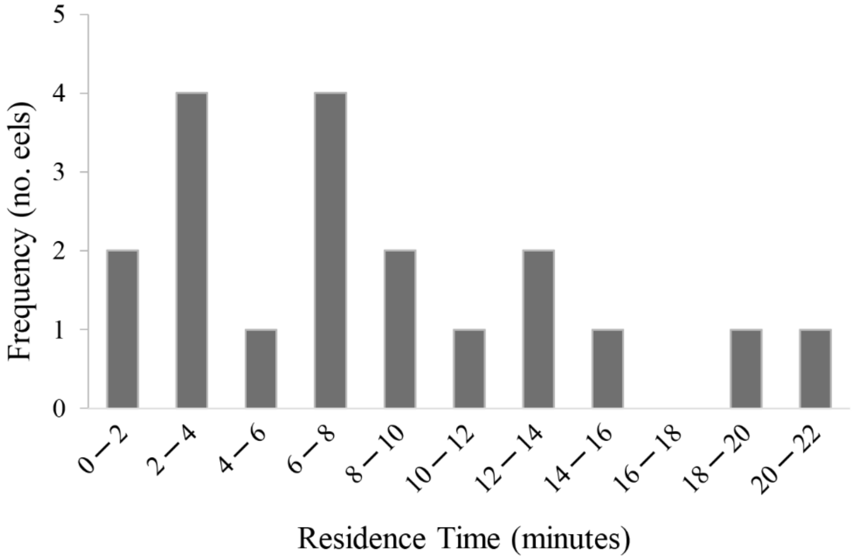

Fig. 3. Residence time of downstream migrating adult eel (*Anguilla anguilla*) (n = 19) within the forebay of a complex of water control structures at Longham, UK, prior to passage downstream via one of five flow spill routes.

Mean total flow into the forebay was 12.88 ± 0.2 $m^3 s^{-1}$. The proportion of flow spilling via each passage route remained reasonably consistent throughout the study period, irrespective of minor fluctuations in total discharge entering the study site. Eels passed the structures in proportions that differed from the division of flow through the five routes (randomisation test, $p = 0.01$). The majority of individuals (63%) (n = 12) initially swam downstream with a relatively direct path towards the debris boom, although most (8 individuals) trajectories diverted on encountering it. Although 67% of river flow passed through the RHP intake, only 21% of fish descended via this route (Fig. 2). There was no relationship between eel body length, ocular index and fin index and the passage route used by downstream migrants ($F_{4,14} = 0.356$, $p = 0.836$; $F_{4,14} = 0.316$, $p = 0.862$; $F_{4,14} = 0.292$, $p = 0.878$, respectively).

Sixteen percent of individuals showed comparatively direct paths to the point of passage. The remaining eels either explored, making lateral movements transverse to the direction of flow with a non-direct path, or initially rejected a structure, i.e. abrupt switch from downstream to upstream swimming (>90° turn angle) before subsequently passage. The highest depth averaged velocity (derived from ADCP measurements) directly upstream of any structure was 0.62 m s^{-1} (radial drop weir) and within the burst swim speed capability of adult migrating eel (≥450 mm L_T) (1.30 – 1.75 m s^{-1}) (Russon & Kemp 2011; Solomon & Beach 2004), indicating that movements were volitional.

Rejection behaviour was exhibited by five individuals in the vicinity of the debris boom. Eels rejected either at a point directly upstream (< 2.5 m) of the boom (Fig. 4a), or shortly after passing underneath it (Fig. 4b). Several individuals showed less abrupt changes in direction and followed along the upstream edge of the boom (Fig. 4c). Only four individuals passed downstream of the boom, of which three exhibited an initial rejection between 0.9 and 2.8 m upstream of RHP bar rack, although all ultimately passed through the intake. Four eels recaptured at a trap downstream were alive and had no sign of external damage.

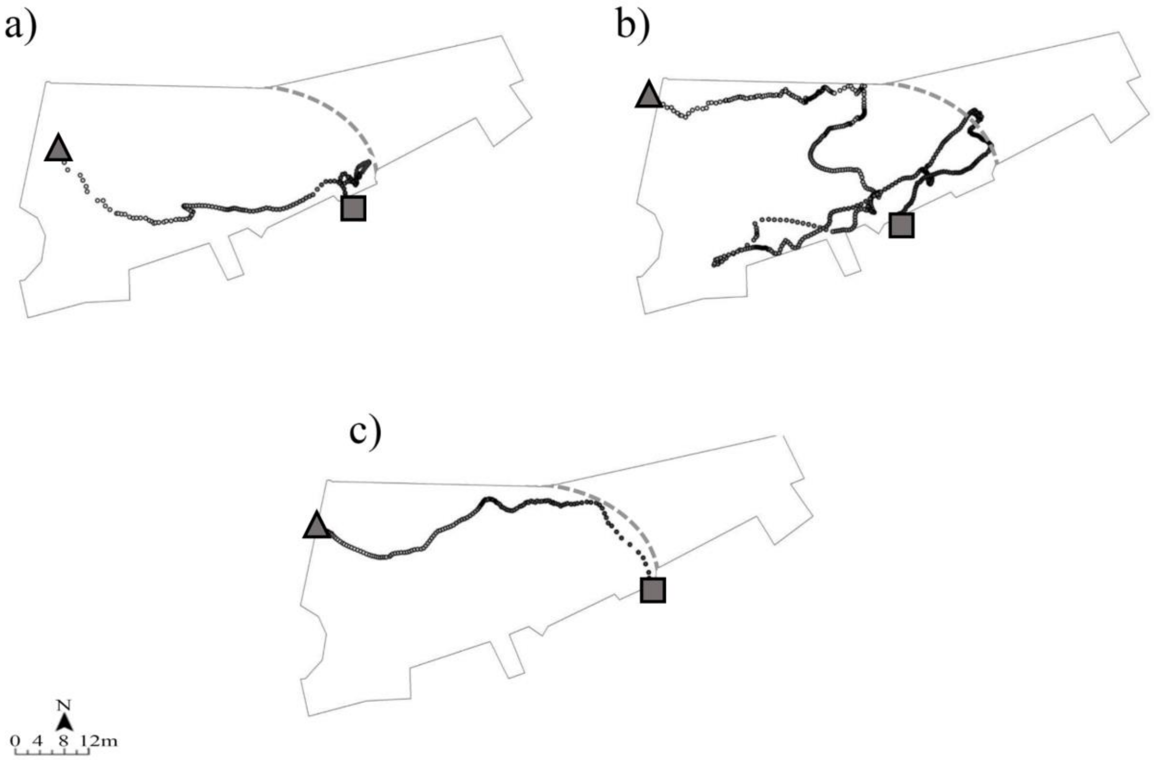

Fig. 4. Examples of tracks of three downstream migrating adult eels (*Anguilla anguilla*) that a) rejected immediately upstream of a debris boom (dashed line), b) rejected immediately downstream of the boom, and c) changed direction at the boom and swam parallel to it before passing the radial weir. Grey triangle and square denote the start and end of tracks, respectively.

Track length ranged from 36 to 267 m and tracks were not randomly distributed within the site ($F_{1.53,\ 27.47} = 10.02$, $p < 0.01$). Instead, eels predominantly moved within a zone extending 2 to 4 m inside of the channel walls (Fig. 5). Less than 19% of total track lengths (unweighted) were potentially in contact with structures (< 2 m).

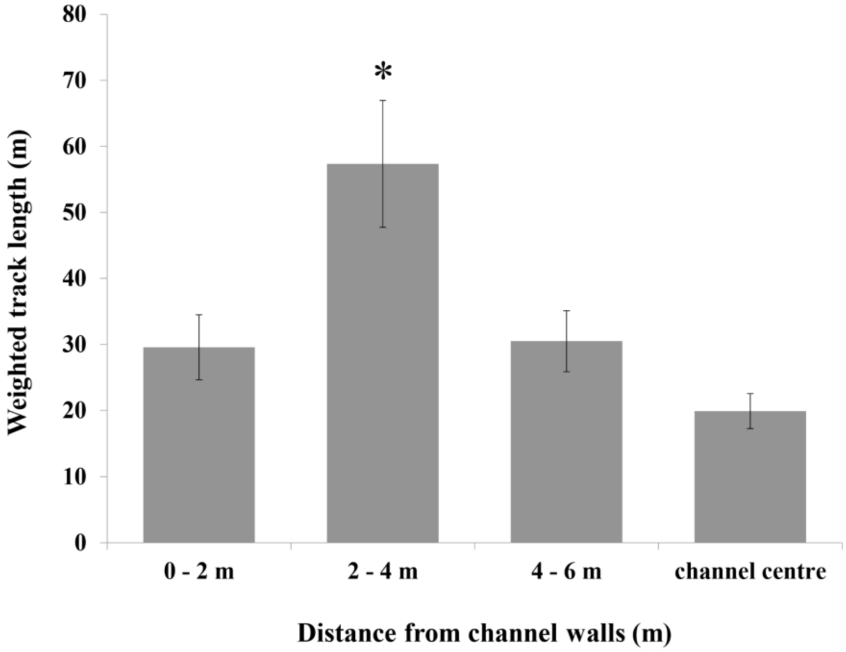

Fig. 5. Mean weighted track length of tagged eels (*Anguilla anguilla*) within 2 m wide zones extending between 0 and 6 m inside the site boundary, and a fourth zone which encompassed the channel centre (grey bars) ± 1 standard error. * denotes significant difference from all other groups ($p<0.05$).

Eel swim depth determined by PIT telemetry on the approach to, and within, the RHP intake channel was within 0.2 m of the channel bed for all individuals that descended via this route (n = 4). Water depth in the vicinity of the antennas ranged from 0.4 to 1.7 m, indicating that eel movements were within the lower 12 – 50% of the water column.

DISCUSSION

Facilitating effective protection, guidance and passage of seaward migrating adult eel at river infrastructure is an important component of their conservation and management (Feunteun 2002; Han et al. 2008; Haro et al. 2000; Jellyman et al. 2002). The distribution of European eel passing five water control structures did not coincide with the predominant flow direction, demonstrating that individuals were not passively transported downstream with the current. The principal spill route (RHP) passed only 21% of eels, with many showing avoidance behaviour at a cross-channel debris boom upstream. Further, swim paths were not evenly distributed across the study site; eels predominantly moved within a zone 2-4 m from the channel walls. The highly variable movement patterns revealed by fine-scale telemetry demonstrated a strong behavioural component to eel descent at riverine structures.

Eel movements in the forebay upstream of the debris boom initially coincided with the route of bulk flow, as predicted (Breukelaar et al. 2009; Bruijs & Durif 2009; Calles et al. 2013; Jansen et al. 2007; Piper et al. 2013); however, final downstream passage routes did not reflect this pattern. Studies that report proportion of discharge as the main determinant of eel route selection were typically conducted in large, relatively uniform approach channels with limited variation in passage route (Gosset et al. 2005; Jansen et al. 2007; Travade et al. 2010). In the current study site, which encompassed multiple passage routes including undershot and overshot spill structures in close proximity, movement patterns were highly variable. The debris boom influenced eel distribution across passage routes, apparently modifying behaviour in the upstream vicinity with clear rejection observed in five individuals and less abrupt changes in direction in three others. Mark and recapture studies conducted at the same location by the Environment Agency in 2010 and 2011 in which a sample of downstream migrating adult eels were floy tagged and released upstream of the study site (n = 87 & 194, ranging from 356 to 815 & 480 to 790 mm in 2010 and 2011, respectively) indicated a recapture rate of 29 and 17 % of tagged individuals in the RHP trap in 2010 and 2011, respectively. This is broadly comparable with the 21% which descended via this route in the current acoustic telemetry study suggesting that the observed migration patterns are typical for this site. The debris boom effectively diverted eels towards the two structures immediately upstream (C and D) which spilled only 26% of flow, but passed 58% of fish.

The boom projected 40 cm down from the water surface (total water depth: 1 to 1.6 m), while the eels tended to be benthic–oriented, in common with previous studies (Brown et al. 2009; Gosset et al. 2005). Rejection at the debris boom was, therefore, unlikely to be a consequence of physical contact with the structure. It was not possible to decouple the physical influence of the debris boom from other environmental factors within this area. Eels have been shown to react to hydrodynamic features independent of physical contact with structures. In a recent flume study, 46% of eels switched from downstream to upstream swimming as they encountered an accelerating velocity gradient created by a flow constriction (Newbold et al. 2015). In a manipulated flow experiment at the RHP intake, Piper et al. (2015) observed that downstream migrating tagged eel predominantly rejected rapid water velocity gradients created by flow constriction, yet showed slower, exploratory movements on encountering low gradients. The boom likely induced a downstream sweeping flow parallel to the upstream face (Odeh & Orvis 1998) and flow distortion with turbulent upwelling in the area immediately downstream (Toniolo 2014). Such hydrodynamic conditions may have deterred some eels, causing them to return upstream, and guided others towards structures C and D.

Surface guidance devices such as floating booms, louvers and guide walls have been used with some success for diverting downstream migrating juvenile salmonids (smolts) towards safe passage routes (Adams et al. 2001; Hanson 1999; Odeh & Orvis 1998; Scruton et al. 2008). For example, a floating louver installed at a hydroelectric facility on the Exploits

River, Canada, achieved a fish guidance efficacy of 54 to 73.3% (Scruton et al. 2003) and an angled surface wall at Bellows Falls power station, Connecticut River, US, guided 84% of smolts to a sluice gate (Odeh & Orvis 1998). In contrast to eels, smolts typically travel higher in the water column when migrating downstream (Ruggles 1980). Nevertheless, observed rejection by eels at the debris boom suggests that surface structures may also have application for eel guidance in shallow water sites.

Eels predominantly followed paths that aligned with the structural perimeter of the study site, maintaining a distance of on average 2-4 m from the channel walls or water control structures. It is unclear how eels navigated along this route without making contact with the channel wall. There was little reduction of water depth near the vertical engineered perimeter walls with no distinctive topographic feature (e.g. trench or ridge) that would explain the bias in the distribution. Although the dark and highly turbid conditions in the forebay likely limited the visual field, it is recognised that eels, like other fish, derive navigational cues from flow field distortion created by fixed structures, detected through the mechanosensory system (Kalmijn 1989; Montgomery et al. 2000; Montgomery et al. 1995; Nestler et al. 2000).

Fine scale observations in the current study revealed that downstream migrating eels do not necessarily ‘go with the flow’. Avoidance and structure-oriented behaviours provide optimism for the development of eel passage solutions in situations where demands for hydroelectric generation and water abstraction dictate that only a relatively small amount of flow is available to pass down alternate routes (e.g. bypasses). Effective guidance measures to divert eels away from the bulk flow passing deleterious routes (e.g. turbines and pumps) and towards safe passage is urgently needed to aid their conservation. As the mechanisms that underpin the behaviours observed in this study remain unclear, further investigation is needed to examine the fine scale response of eel to specific and well defined cues (Anderson, 1988; Schilt, 2007; Williams *et al.*, 2012), especially to relatively simple structures like surface booms in shallow water. Given the results presented and other recent advances (e.g. Newbold et al., 2015, Piper et al., 2015, Russon et al., 2010), further investigation of eel reponse to hydrodynamic features synonymous with water control structures is likely to prove valuable in the development of guidance devices.

ACKNOWLEDGEMENTS

This study was joint-funded by the University of Southampton and the Environment Agency, UK. This research was supported by a grant (SFRH/BPD/89473/2012) from the Foundation for Science and Technology (FCT) in Portugal to JCS. The authors would like to thank Sembcorp Bournemouth Water for making the study facilities available and staff assistance during set-up. Thanks are also due to Paula Rosewarne Alan Piper, Roger Castle and Jim Davis for assistance in the field.

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