Escapement, route choice, barrier passage and entrainment of seaward migrating European eel, *Anguilla anguilla*, within a highly regulated lowland river

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ABSTRACT

Fluvial disconnectivity can have important impacts on fish populations, including hindering movement between habitats required for different ontogenic stages. Recruitment of the European eel (*Anguilla anguilla)* has reduced by over 90% since the early 1980's, in part due to the effect of riverine barriers on its catadromous migration. There is a legislative requirement to restore free passage, increase habitat availability, and limit anthropogenic losses at intakes to aid eel recovery and good ecological status; necessitating an improved understanding of underlying processes. Escapement, route choice, delay at structures, and entrainment at water abstraction points of downstream migrating silver eels were examined using acoustic and Passive Integrated Transponder (PIT) telemetry in the heavily regulated lower river Stour, UK. Downstream migrating adult eel (n=69) were trapped approximately 10 km upstream of the tidal limit, surgically implanted with an acoustic transducer and PIT transponder, and released between October and December in 2009 and 2010. Movements of tagged individuals were monitored by a linear array of 19 fixed acoustic receivers extending from the release site, through the last 9.2 km of the freshwater catchment. Three groups of water control structures, two water abstraction intakes and several possible routes of migration are present in the reach.

Seventy six and 65% of tagged eels escaped from the study reach in 2009 and 2010, respectively. Entrainment at a single intake was the principal cause of loss and positively related to rapid increases in abstraction whilst eels were in the vicinity of the intake. Route choice into the estuary was dependent on discharge over a large intertidal weir; opening regimes of a tidal gate at the termination of the alternative channel; and abstraction rate at a nearby water intake. Long delays (up to 68.5 days) and recurrent behaviour were associated with several structures in the study reach; high variability between individuals reflected the management of spill at weirs. Potential scenarios for minimising entrainment and delay through integrated management of water level control structures and abstraction rates are discussed.

1. Introduction

Fluvial ecosystems have been impacted globally by the construction of in-channel structures such as weirs and dams for water regulation and flood defence; abstraction for consumptive water; hydropower generation, and navigation (Jungwirth, 1998; Nilsson *et al.*, 2005). The consequences, including disrupted flow regimes, changes to water chemistry, and altered geomorphology are widely documented (Opperman *et al.*, 2010; Poff *et al.*, 1997; Ward and Stanford, 1995). The impact of in-channel structures on fish communities can be considerable. Obstructions hinder movement between the habitats required for different ontogenic stages (Lucas and Baras, 2001; Northcote, 1998; Werner and Gilliam, 1984), which has been directly linked to loss of populations and occasionally entire species of fish (Nilsson *et al.*, 2005). Furthermore, while the impact of certain structures such as dams are well studied, the implications of smaller features such as weirs, ramps, culverts and road bridges on fish populations are rarely considered by catchment managers, although they are likely to be 2-4 orders of magnitude more numerous than large structures (Lucas *et al.*, 2009).

The perceived high abundance of the European eel (*Anguilla anguilla*) prior to the early 1980's, coupled with highly variable life-history traits and habitat use (Daverat *et al.*, 2006), has meant the impact of barriers on the species is poorly understood and has, until recently, received little attention. Recruitment in some parts of Europe has reduced by greater than 90% since the early 1980's (Dekker, 2003; ICES 2011a; Moriarty, 2000), and the stock is now considered outside safe biological limits (ICES 2011b). Exact causes of the decline remain unclear; however, riverine barriers to both inward migrating juvenile lifestages and seaward migrating adult eels (silver eels hereafter) are considered a key factor (Bruijs and Durif, 2009; Feunteun, 2002).

In-channel structures, hydropower facilities and water abstraction intakes for irrigation, domestic, and industrial supply can delay downstream movement of silver eels resulting in cessation of migration (Behrmann-Godel and Eckmann, 2003; Durif *et al.*, 2005; Durif and Elie, 2009); damage (Bruijs and Durif, 2009); and direct mortality (Calles *et al.*, 2010). Eels are particularly vulnerable at intake screens, pumps and turbines due to their elongated morphology and poor burst swimming capabilities (Boubee and Williams, 2006; Calles *et al.*, 2010; Russon *et al.*, 2010). Typical hydropower mortality has been estimated at between 15 and 38% per turbine encountered (Hadderingh and Bakker, 1998; ICES 2007; Winter *et al.*, 2007), though may be as high as 100% in some cases (Carr and Whoriskey, 2008). Delay of fish at barriers also exacerbates pressures such as predation and disease (Garcia De Leaniz, 2008; Lucas and Baras, 2001). There are potential population level consequences if silver eel escapement is impaired and fewer individuals reach the spawning grounds; however, the reproductive viability of escaped spawners is also important. Energy reserves (vital for successful oocyte production and an oceanic migration of 5000 to 6000 km) may be depleted due to milling and searching while delayed at barriers (Behrmann-Godel and Eckmann, 2003; Brown *et al.*, 2009; Haro and Castro-Santos, 2000; Travade *et al.*, 2010).

Silver eel migration typically occurs over short periods or ‘runs’ induced by environmental cues including increased river discharge, a fall in water temperature and lunar phase (Haro, 2003; Tesch, 2003). Barrier mitigation, for example opening spill gates during these key periods, can effectively increase escapement. In New Zealand, the release of spill for 2.5 hours enabled 70% of longfin eels (*A. dieffenbachii*) released upstream of a hydropower facility to pass without damage (Watene and Boubee, 2005). The same principal may be applied for systems without hydropower but with major water regulation structures. There is strong evidence that eels make route selection choices based on those localities with highest flow (Breteler *et al.*, 2007; Jansen *et al.*, 2007). The operation of sluices can influence route choice and the rate of eel migration in some systems (e.g. Breukelaar *et al.*, 2009); although few studies have investigated this.

To reverse the decline in European eel populations, the European Union has adopted the Eel Recovery Plan (2007) (Council Regulation No 1100/2007/EC). This requires all Member States to produce Eel Management Plans (EMPs) detailing actions to meet the target to permit with high probability the escapement to sea of at least 40 % of the silver eel biomass relative to the best estimate of escapement that would have existed if no anthropogenic influences had impacted the stock. Mitigation for the effects of riverine barriers and improvements to upstream and downstream passage has been highlighted as a key means of achieving escapement targets across Europe (e.g. U.K., Denmark, Greece EMPs). Furthermore, under the EU Water Framework Directive (WFD) (2000/60/EC) member states are obliged to ensure fish passage at all artificial structures (Kemp *et al.*, 2008).

To meet legislative escapement targets it is important to identify key locations of silver eel loss and delay during freshwater migration (Breukelaar *et al.*, 2009). Current knowledge gaps concerning the physical and environmental conditions at structures that prevent or delay eel passage hinder attempts to identify and remediate such restrictions (Acou *et al.*, 2008; Defra, 2010a). In particular, the individual and cumulative effect of low-head, and often only temporally restrictive structures, on eel migration is poorly understood. Such knowledge is urgently required to provide effective mitigation measures.

The aim of this study was to assess the impact of low-head structural barriers, flow regime management, and environmental variables on the seaward migration of adult silver phase eels. To achieve this, six key objectives were addressed. Acoustic and

PIT telemetry were used to quantify 1) escapement, which in the context of this study refers to escapement of tagged individuals from the study reach to sea, 2) escapement duration, 3) barrier delay, 4) migration velocity, 5) entrainment loss, and 6) route choice of eels as they migrated through a highly regulated section of the river Stour, UK. The information gained will provide valuable guidance for optimising escapement of adult eels in line with EU requirements.

2. Materials and Methods

2.1 Study area

The river Stour is a lowland river in Southeast England flowing eastwards for approximately 98 km from its source north of Haverhill to its tidal limit at Manningtree (51°57'10.78"N, 1° 3'14.21"E) where it enters the estuary and ultimately the North Sea. Land-use within the 85.8 km^2 catchment is predominantly agricultural, although the wider region is one of the most densely populated areas of the UK placing great demands on freshwater systems. Downstream migrating silver eels have several options of route to sea and may encounter up to 52 cross-channel structures before reaching the tidal limit.

The lower Stour is typically 10 to 15 m wide and has a 10 year mean daily flow of 3.37 m^3 s^{-1}. The present study was conducted in the lower 9.2 km of the freshwater river which encompasses 12 cross-channel structures for water level management and navigation; two water abstraction intakes, and several points where the main channel bifurcates. Moving downstream from Stratford St Mary the river passes Stratford intake (Fig. 1) where water is abstracted to augment potable water storage at Abberton reservoir (0.29 m^3 s^{-1}, 10 year mean). The 6.12 m wide intake oriented perpendicular to flow is fitted with a vertical bar trashrack (14 cm spacing), with further debris screening provided by a travelling band screen (8 mm mesh opening) set back (4 m) from the river. The main river channel flows relatively unobstructed to Dedham mill, only diverting down, a small side channel, Stratford Brook (A, Fig. 1). At Dedham the main channel divides briefly into: 1) a mill channel intersected by 6 undershot penstock sluice gates (B, Fig. 1) , and 2) a channel forming a navigation lock with manual side hung lock gates that operate under low flows, and an automatic level controlled overshot radial gate to control high flows (C, Fig. 1). The channels rejoin immediately downstream. A similar configuration exists at the next downstream structure, Flatford Mill, with a navigation lock within the right-hand channel (D, Fig. 1) and 6 undershot sluice gates on the left (E, Fig. 1). Additionally, fish may migrate down the old mill channel over a stopper-board weir adjacent to the sluices (F, Fig.1).

Downstream from Flatford (0.68 km) the main channel is intersected by Judas Gap (G, Fig. 1), a broad-crested weir (20.8m wide, 1.8m AODN height) (for description see Piper *et al.*, 2012). Principally constructed for water level management, this intertidal weir contains a pool and weir fishway at its southern end that has failed to function effectively since its construction in 1972 due to disparity between its design spill height and maintained river levels. An additional structure, Cattawade Barrage (Fig. 1), located at the end of the intertidal South Channel controls the height of tidal ingress to provide flood protection through a combination of undershot lifting gates and top-hung tidal flaps (50 m total width). This structure operates to maintain tide cycles up to Judas Gap weir, while preventing saline water inundating the freshwater catchment.

Directly upstream of Judas Gap the river bifurcates, flowing down a historic navigation channel which terminates at the Cattawade North Channel (CNC) sluice. This second intertidal barrier comprises an overshot sluice gate on the freshwater side and top-hung tidal flap on the estuary side (Fig. 1). Brantham intake (3.2 m wide), located 185 m upstream of the sluice, abstracts at a maximum pumping rate of 0.64 $m^3 s^{-1}$, dependent on requirements. Screening facilities are similar to those at Stratford intake, although after the trashrack, water is drawn approximately 0.5 km through a pipe (107 cm diameter) before reaching the travelling band screen and pumps.

No commercial fishing for eels is licensed within the freshwater catchment, although low level fishing (<10 fyke nets) is conducted within the estuary.

2.2 Fish capture and telemetry

Actively migrating silver eels were captured in small batches (6 to 11 individuals) from October to November in 2009 (year 1) and from October to December in 2010 (year 2) using fyke nets set nightly upstream of the study area and checked each morning. Captured individuals were visually assessed for signs of external damage or disease and only selected for tagging if undamaged (approximate 2% rejection rate in both years). Eels selected for tagging were transferred to in-river perforated holding barrels and held for a maximum of 2 h, before being anaesthetised

(Benzocaine 0.2 g L^{-1}), weighed (wet mass , WM, g), and measured (total body length, mm). The length of the left pectoral fin (FL, mm) from insertion to the tip, and maximum vertical and horizontal left eye diameter (mm) were also measured. Degree of sexual maturation or “silvering” was quantified prior to tagging using two metrics: the Ocular Index (OI), according to Pankhurst (1982), and Fin Index (FI), according to Durif *et al.* (2009). All eels captured within the study exceeded 450 mm and were thus considered female (Tesch, 2003). European eel with OI ≥ 6.5, and FI ≥ 4.3 (females only), are considered to be at the migratory silver stage (Durif *et al.*, 2009; Pankhurst, 1982). Only eels fulfilling these criteria were selected for tagging (87% and 92% in year 1 and 2 respectively).

Selected individuals ranged in size from 581 - 921 mm TL, 434 - 1398 g WM in Year 1, and 569 - 853 mm TL, 357 - 1211 g WM in Year 2. Mean OI was 8.3 (range 7.1 - 11.9) and 9.4 (range 8.5 - 14.6) in year 1 and 2, respectively. Mean FI was 4.8 (range 4.4 - 5.5) and 5.1 (range 4.3 - 6.0) in year 1 and 2 respectively. An acoustic tag (model V92L, tag interval 15 - 25 s, 29 mm x 9 mm, 2.9 g in water or V72L, tag interval 15 - 25 s, 20 x 7 mm, 0.75 g in water VEMCO, Nova Scotia, Canada; dependent on eel size) and Passive Integrated Transponder (PIT) tag (23 x 4 mm, 0.6 g, Wyre Micro Design, Poulton-Le-Fylde, Lancashire) were surgically implanted into the peritoneal cavity of each eel following methods similar to Baras and Jeandrain (1998), and the incision closed with two separate dissolvable sutures (Vicryl Rapide[R]; Ethicon Inc., Cornelia, GA, U.S.A.).

After tagging, eels were transferred into a perforated holding barrel for 10 - 12 h to allow post-operative recovery and acclimation before release. No eels died or showed signs of sustained damage during recovery. Tagged eels were released directly downstream of the capture sites; at Stratford St Mary (Fig. 1) (12th October to 22nd November) in year 1, and 1.3 km further upstream in year 2 (5th October to 19th December) to include the Stratford St Mary abstraction point (Fig. 1). Releases took place in darkness (2000 - 2100 h) from a holding barrel tethered in the channel centre to eliminate bias in route choice. The lid was removed allowing individuals to leave volitionally.

Movements of tagged individuals were monitored through the study reach from October to March in both years using a linear array of 19 fixed acoustic receivers (VEMCO, model VR2W) extending from 0.6 km upstream of the Stratford St Mary release site, to a point 1.6 km into the estuary. Receivers were strategically placed immediately up and downstream of each structure and at mid points between barriers. Receiver locations were selected to provide high detection efficiency, yet distinctly separate detection zones, i.e. preventing simultaneous detection on multiple receivers; as determined by tag detection tests. Weekly tag detection and range testing was conducted throughout the study period, and demonstrated consistency in both range and precision of detection. Efficiency of logging tags was high (>96% based on tests and sequential records of tagged fish by multiple loggers). In addition, manual tracking (VEMCO, VR100) using canoe and bank walking was conducted to locate individuals “lost” between fixed receivers. Detection loss may occur for a number of reasons including large amounts of background noise, shielding of a receiver e.g. by macrophytes and debris, or if a tagged fish passes a receiver detection zone quicker than the delay time between tag transmissions. PIT telemetry comprising a single channel half duplex reader (DEC-HDX_ATU, 134.2 kHz, 100 ms scan cycle, Wyre Micro Design), and data logger (AntiLog RS232, Anticyclone Systems Ltd, Surrey, UK) with single loop swim-through antennae was used to confirm passage at the entrance of Brantham intake (antenna dimensions 3.2 m width x 1.2 m depth, in 'figure of eight' configuration) (Fig. 1), and within the mill channel at Flatford (antenna dimensions 0.6 m width x 1 m depth) (F, Fig. 1). Manual testing indicated that the detection efficiency at each antenna was >99%. System settings were employed to detect and log a tag only once (until cleared by detection of subsequent tag). This reduced the likelihood of missed detections due to 'blocking' effects or tag collision which may occur when multiple tags are within the field of detection simultaneously.

2.3 Hydrometry, barrier operation and environmental variables

The operation of sluices and intakes varied during the study period in response to abstraction requirements and water level management. Barrier position setting, river level, and water temperature were recorded at 15 minute intervals throughout the study period. Data were obtained from operational records and the Environment Agency's fixed monitoring sites at Stratford St Mary, Dedham, Flatford, Judas Gap and Cattawade North and South Channels using an ultrasonic level measuring device (Pulsar Blackbox, Pulsar Process Measurements, Malvern, UK). Total river discharge (River Q) ($m^3 s^{-1}$) was calculated immediately upstream of Dedham, Flatford and Judas Gap structures using 15 minute gauging data recorded at

Langham flow gauging station, 1.2 km upstream of the study site upper limit, and adjusted for additional inputs and abstractions throughout the study reach accordingly. At the Judas Gap bifurcation, the proportion of discharge passing down either channel was attained by calculating Q over Judas Gap weir (Judas Q) using the discharge equation for a British standard rectangular broad-crested weir (BSI, 1990):

$$Q = \left(\frac{2}{3}\right)^{3/2} g^{1/2} b C {h_1}^{3/2}$$

Where *g* is the acceleration due to gravity, *b* is the width of the weir perpendicular to the direction of flow, *C* is the gauged head discharge coefficient and h_1 is the upstream gauged head relative to the crest elevation. The discharge coefficient *C* was obtained from ISO data for rectangular broad-crested weirs (BSI, 1990). Where data were below recommended limits (h_1 values <0.07 in this study), a conservative value of $C = 0.8$ was used (3% of dataset). Judas Q was deducted from river Q to provide a Q value for CNC.

Judas Gap was not constructed to conform to BSI standards, so to assess the accuracy of calculated Q, empirical point sampling was conducted under a range of flow conditions using an Acoustic Current Doppler Profiler (ADCP) (M9, SonTek/YSI, San Diego, USA). The ADCP was mounted on a raft (Hydroboard) and manually pulled across the channel in a series of moving transects perpendicular to flow immediately upstream of Judas Gap, and 100m downstream in CNC. Mean river Q was calculated from 4 repeated transects conducted at each sampling location on each occasion (8 non-consecutive sampling days). Calculated and empirical discharge values were similar (varied by < 11%). Water abstraction rates ($m^3 s^{-1}$) were obtained at 15 minute resolution for Brantham and Stratford St Mary intakes from Essex and Suffolk Water company.

Mean daily water temperatures (˚C) were calculated from hourly data recorded using fixed data-loggers (Tinytag Aquatic T-2100, Gemini Data Loggers, Chichester, UK) located upstream of each set of structures. Mean water temperature ranged from 3.2 to 16.4 ˚C and from 3.5 to 13.6 ˚C over the two study periods (Oct - Mar, both years). Maximum tide heights and lunar phase for each day were obtained from the UK Hydrographic Office. River flow measured immediately upstream of the study site (Langham flow gauging station, Environment Agency) ranged from 0.5 to 25.7 $m^3 s^{-1}$ 0.81 to 29.3 $m^3 s^{-1}$, with mean daily flow of 5.2 ± 5.0 $m^3 s^{-1}$ (S.D.) and. 3.5 ± 3.9 $m^3 s^{-1}$ (S.D.), in year 1 and 2 respectively.

2.4 Fish movement, behaviour and data analysis

Detection data were downloaded monthly from receiver stations then combined and filtered to provide chronological records for each fish as they migrated downstream. The data were used to address the six objectives of the study:

Escapement was deemed to have occurred when an individual was first detected at the receiver immediately downstream of either of the intertidal barriers (Judas Gap or Cattawade sluice).

Escapement duration was calculated as time (h) between release and escapement.

Barrier delay was defined as the duration (mins) between first detection of an individual at the receiver immediately upstream of a structure, and the last detection on the same receiver prior to confirmed barrier passage (*passage event*). A *passage event* was confirmed by detection on the receiver immediately downstream of the structure. At both abstraction points, delay for each individual was defined as the duration (mins) from first to last detection at the receiver positioned immediately within the intake entrance.

On occasion, individuals passed a receiver without being detected. Detection on subsequent downstream receivers enabled interpolation to determine route choice, but interpolated data were excluded from delay time and passage event analyses.

Mean migration velocity (MMV) (m s^{-1}) was calculated for individuals that passed through both an unobstructed reach (immediately downstream of Dedham to immediately upstream of Flatford, 2.26 km) and b) an obstructed reach (immediately upstream of Dedham to immediately downstream of Flatford 2.66 km). The calculation used time taken (between detections) to travel the distance between receivers, assuming shortest possible swim path. MMVs within each year were compared using related samples Wilcoxon signed ranks tests.

Entrainment loss was deemed to have occurred when an individual was detected at the acoustic receiver located within a water abstraction intake, with no subsequent detection at the receiver immediately outside the intake entrance, or those further upstream or downstream (monitored for 3 months beyond study termination). At Brantham, this was corroborated by detection at a PIT antenna set 1 m into the intake. It was not feasible to install PIT telemetry at Stratford due to the steel construction of the intake which made the detection range unreliable. To assess detection efficiency within Stratford and Brantham intakes, a beacon tag transmitting approximately every 120 s was secured within the intake sump and was detected consistently throughout the study.

Eels that selected the CNC either travelled into Brantham intake and became entrained, or moved downstream and out to the estuary via the CNC sluice gate. Generalised linear models (GLM) with binomial error distributions and a logarithmic link function were used to investigate the effect of a number of factors on entrainment (a binary response of either entrained or not entrained i.e. passed out of CNC sluice), for both years combined. Variables within the maximum model were: River Q; mean temperature; position of CNC sluice gate (% open), and abstraction rate at Brantham intake (all at the time of entrainment or gate passage); total time fish spent in the immediate vicinity of intake and sluice gate, and relative difference between mean abstraction rate for 0.5 h leading up to, and including, entrainment or passage vs. the mean abstraction rate for the 1 h prior to this. These time periods were decided on using data mining techniques. A model with 1st order interaction terms was fitted and stepwise deletions were performed using chi-square tests to identify non-significant terms. The minimum adequate model (MAM) was arrived at as the most parsimonious model with lowest AIC value (Akaike, 1973).

Suitability of the binomial error structure was evaluated using plots of standardised residuals against square root of the fitted values.

Route choice – was defined using receivers positioned strategically at locations where routes diverged. The '*time of route choice'* was defined as the last detection by a receiver upstream of the divergence.

Where quoted, percentage values refer to the proportion of eels approaching each bifurcation point, rather than as a proportion of total eels released.

Eels approaching both the Dedham and Flatford structures could pass downstream via either of two principal routes: 1) the sluice or 2) lock/radial gate. Eels moving towards Dedham could alternatively pass down Stratford Brook, but as the entrance to this channel is 830 m upstream of the lock and sluice complex these eels were excluded from route choice analyses for Dedham. At Flatford the mill channel also presented an additional route option, but this was excluded from analyses due to the small number of eels (4) that passed this route. Eels approaching Judas Gap could either continue downstream within the CNC or pass over Judas Gap weir into the South Channel. Generalised linear models (GLM) with binomial error distributions and a logarithmic link function were used to investigate route choice for the 3 locations: Dedham, Flatford (both binary response, sluice or lock), and Judas Gap (binary response, Judas or CNC). In all cases, a model with 1st order interaction terms was initially fitted, and then stepwise deletions were performed to obtain the MAM using previously described methods. For route choice at Dedham and

Flatford, independent variables included in the maximal models were: River Q, upstream water level, radial gate position (% open), sluice gate position (% open), water temperature, and lunar phase (all at time of passage), study year, and duration of delay (time of arrival to time of passage, mins). For Judas Gap, variables in the maximal model were: River Q; Judas Q; position of CNC gate (% open); rate of abstraction at Brantham intake; temperature; lunar phase, and year.

All statistical analyses were carried out in R v2.14 (R development core team, 2011).

3 Results

3.1 Escapement

Downstream eel migration predominantly took place from the start of November to the end of Jan with 96% of escapement occurring within this period. Overall escapement from the study reach was 76% in year 1 (n = 29), and 65% in year 2 (n = 40) (Fig. 2).

3.2 Escapement Duration

Escapement duration was highly variable between individuals within both years. In year 1 the time taken to reach the estuary ranged from 188 h (8 days), to 2722 hours (113 days), with median escapement duration of 700 h (29 days). In year 2, escapement duration (for eels released 1.3 km further upstream than in year 1), ranged from 122 h (5 days) to 2402 h (100 days), with a median duration of 915 h (38 days).

3.3 Barrier Delay

Some eels were delayed upstream of structures or in the vicinity of intakes for substantial periods before continuation of downstream migration. Longest delays were associated with two structures in year 1: Dedham, where 15% of fish experienced delay in excess of 350 h; and Brantham intake, with median delay of 147.8 h. In year 2, Stratford Intake and Flatford Lock were associated with longest delays. At Stratford Intake 45% (year 2 only) of eels experienced delay, with 28% delayed longer than 50 h, with a maximum of 947 h. At Flatford, 25% of fish took longer than 15 h to pass the structure.

Substantial delays were observed at both water abstraction intakes for some fish. At Stratford St. Mary individuals spent between 4 minutes and 947 h within the intake sump. Of the eels that moved through the CNC (Fig. 2), all were detected within the entrance, or immediately upstream of Brantham intake, and spent between 8 min and 787 h, and 5 min and 192 h in the area, during year 1 and 2 respectively. Abstraction pumps were in operation at Brantham intake for 93% and 87% of the year 1 and 2 study periods. Abstraction pumps were in operation at Stratford St Mary intake for 89% of the year 2 study period.

3.4 Mean Migration Velocity

Eels travelled more rapidly through an unobstructed (MMV ranged 0.16 to 2.55, median= 1.89 m s^{-1}, in year 1; and ranged 0.01 to 5.76, median = 1.97 m s^{-1}, in year 2) than through an obstructed (2 structures) (MMV ranged 0.006 to 2.54, median = 1.04 in year 1; and ranged 0.003 to 5.26, median = 1.50 in year 2) reach during both year 1 (W = 16, p = 0.02, 13 d.f.) and year 2 (W = 66, p = 0.02, 23 d.f.).

3.5 Entrainment Loss

Stratford St Mary abstraction point was only included in the study reach in year 2, during which no eels were entrained at this intake.

There were two main outcomes for eels that reached the lower section of the CNC. First, to enter Brantham intake, or second, to pass into the estuary via Cattawade intertidal sluice. Entrainment loss of 12% and 26% in year 1 and 2 respectively, occurred at Brantham intake (Fig. 2). Two significant predictors of entrainment loss were identified: difference in mean abstraction rate between passage event and delay (44.6% of residual deviance, p = 0.02, 28 d.f.), and gate position at Cattawade sluice (% open) (12.9% of residual deviance, p = 0.03, 27 d.f.). Entrainment loss principally occurred when abstraction levels increased abruptly (i.e. pumps rapidly switched between low and high abstraction), combined with reduced opening of Cattawade sluice gate.

3.6. Route Choice

Two principal downstream route options were available at each of the 3 main structure locations (Dedham, Flatford and Judas Gap) (Fig. 1). Although Flatford and Dedham comprise similar structure types, route choice differed between the two locations. Eels that did not move downstream via Stratford Brook subsequently approached the main Dedham structures, at which point 71% (36 of 51 fish) passed downstream via the undershot sluices, and the remainder passed via the lock route (containing overshot radial gate). In contrast, at Flatford, 74% of individuals (45 of 61 fish) passed via the Lock route (overshot radial gate), and 20% (12 of 61 fish) via the undershot sluices, the remainder passing via the mill channel (Fig. 2).

The MAM describing route choice at Dedham for both years identified the position of the radial gate and an interaction between gate position and upstream water level as significant predictors. Increased passage via the lock channel was strongly associated with greater opening of the radial gate (31% of residual deviance, $p < 0.001$, 42 d.f.), and a combination of high water level upstream and gate opening (18%, $p < 0.001$, 40 d.f.). The MAM describing route choice at Flatford for both years identified sluice gate position, radial gate position and delay time as significant predictors. Sluice gate and radial gate positions explained 20.5% and 29% of deviance, respectively ($p < 0.01$, 45 d.f.; $p < 0.01$, 44 d.f.), delay time explained 15.1% of deviance ($p = 0.03$, 43 d.f.). Obviously, eels were unable to pass via the sluice when it was in the full closed position, and passed via the lock at these times. Opening of the sluice increased the probability of fish passing via this route.

Extended delay upstream of the structures resulted in more fish passing downstream via the sluice when open.

Of the eels that approached Judas Gap, 40% passed over this broad-crested weir in year 1 and 60% in year 2 (Fig. 2). Discharge over this structure was the only significant predictor of route choice, explaining 64% of residual deviance ($p < 0.01$, 55 d.f.). Selection of Judas Gap occurred during periods of highest discharge, and no eels passed via this route until the spill level exceeded 0.18 m.

5 Discussion

This study highlights the negative impacts of low-head river infrastructure on the migration and escapement of adult European eel to an estuary in the UK. Structures such as sluices, locks, water intakes, and weirs, are abundant across European catchments, but seldom considered as impediments to fish migration (Lucas *et al.*, 2009). Migration speed was lower in obstructed reaches; long delays were apparent at some barriers; and escapement of eels from the freshwater catchment was impacted, principally through entrainment loss. Management regimes of sluice gate position, abstraction rate and weir spill strongly affected probability of entrainment at intakes and the route choice of eels.

Riverine fish may encounter a range of engineered features which can delay movement (e.g. at impoundments such as weirs), and result in impingement and entrainment (e.g. at hydropower and water abstraction intakes, and pumping stations). In heavily impacted rivers, the cumulative effect of multiple structures may reduce overall escapement to low levels. For example, previous studies on the rivers Meuse and Rhine, estimated silver eel escapement at 15% (Verbiest *et al.*, 2012), and 15 – 32% (Breteler *et al.*, 2007; Breukelaar *et al.*, 2009), respectively, which in both cases was influenced by entrainment at hydropower facilities. The current study focused on the most downstream 10% (9.5 km) of the freshwater river. Nevertheless, more than one quarter of emigrating eels were prevented from escaping; and with additional water abstraction points present upstream of the study reach, values for the total catchment are likely to be higher.

Estimates of potential escapement of silver eel from a catchment in the presence and absence of anthropogenic pressures are required to determine compliance, or lack of, with EU eel management targets. Due to a lack of quantitative data describing current escapement for many European catchments, several countries have adopted modelling approaches to estimate eel densities and escapement under scenarios with and without human induced stress (e.g. the Probability Model; Scenario-based Management of Eel Populations, SMEP) (Aprahamian *et al.*, 2007). Impacts of fishing and the operation of hydropower plants and pumping stations are however currently underrepresented in many models due to insufficient empirical data (Aprahamian *et al.*, 2007; ICES, 2011a). In this study, telemetry enabled location and magnitude of entrainment loss and delay within the lower river Stour to be identified and quantified, providing information required on which to base management decisions.

The SMEP II model used to assess compliance with 40% escapement targets in England and Wales (Aprahamian *et al.*, 2007; Defra, 2012), identified the river Stour as failing to comply. The modelled potential silver eel escapement values for the entire catchment in 2009 and 2010 were 262 and 204 kg, equating to 0.68 and 0.53 kg ha^{-1}. If the losses calculated in this study (which provide a conservative estimate of barrier and abstraction impact) are considered when predicting escapement for the catchment, then values for 2009 and 2010 are estimated to be 0.51 and 0.34 kg ha^{-1} (converted to biomass using mean mass of predicted escaping eels). When compared to the 40% escapement (biomass) target of 6.5 kg ha^{-1} (Defra, 2010b), the river Stour falls far below the level required for compliance even before adjustment for entrainment loss. Clearly, preventing entrainment at the critical point identified in this study would be insufficient to achieve compliance alone, but would provide an important first step.

Interestingly, all entrainment loss occurred at only one of two water intakes. Although delay was associated with both intakes, behaviour differed notably between sites. Eels made excursions into both, but returned to the main river at Stratford St Mary, while 12 individuals did not reappear at Brantham. This may have been due to the relative positions of the travelling band screens. At Stratford St Mary, eels encountered the screen 4 m behind the trashrack. In contrast, at Brantham a 0.5 km pipe exists between the intake and the screen, so eels that navigated the length of this pipe may have been more susceptible to disorientation, damage, and predation (ICES, 2011a). Abstraction rate also differed between the two intakes with the mean at Brantham being 1.4 times greater than at Stratford St Mary. Entrainment was associated with rapid increases in abstraction rate, i.e. rapid start-up of pumps, although eels likely entered the intake volitionally as maximum velocities at the trashracks were always below burst swimming speed capabilities of large adult eels (≥450 mm TL) (1.30 – 1.75 m s^{-1}) (Russon and Kemp, 2011a; Solomon and Beach, 2004). When closure of the intertidal sluice coincided with low flows, abstraction volumes represented a significant proportion of, or at times, the entire river flow in the vicinity of Brantham intake, which may provide an explanation, at least in part, for these findings.

This study demonstrated that relatively small low head structures can delay seaward migration and reduce overall migration velocity in impounded reaches. Further, individual barrier delay was calculated from the point of first detection above a barrier; hence this may be considered to represent a minimum delay as individuals may have been deterred from entering the area upstream of barriers at a range that exceeded this detection range. Delay at critical structures in the river Stour was influenced by flow management and atypical operation. For example, malfunction of the radial weir within Dedham lock caused it to remain closed for the majority of the autumn migration in year 1, during which the sluices in the adjacent channel were also shut. Eels approaching these structures either settled for extended periods immediately upstream or showed milling behaviour, consistent with other studies (Brown *et al.*, 2009; Haro and Castro-Santos, 2000; Travade *et al.*, 2010).

The structures at Flatford were similarly associated with long delays. In year 2 a large piece of woody debris became lodged upstream of the undershot sluices and although the gates remained partially open for much of the time, eels were delayed for long periods and few ultimately passed. Silver eels have been observed to exhibit predominantly benthic-oriented movement at barriers during their migration downstream, and prefer undershot routes at structures (Behrmann-Godel and Eckmann, 2003; Gosset *et al.*, 2005; Russon and Kemp, 2011a; Russon and Kemp, 2011b). Although benthic oriented passage was possible for eels at Flatford despite the debris, the abrupt velocity gradients near the constricted openings may have induced the avoidance behaviour observed (Coutant and Whitney, 2000).

The relationship between eel migration velocity and delay on energetic expense, depletion of fat reserves, general health, and subsequent migration and reproductive success is unclear. Degeneration of the alimentary tract during silvering (Pankhurst and Sorensen, 1984) causes eels to stop feeding, which continues to the end of their lifecycle (Dufour and Van den Thillart, 2009; Van Ginneken, 2006). Oceanic migration and gonad production therefore relies on energy provided by body fat reserves (Van den Thillart and Dufour, 2009). Delay at barriers is undoubtedly associated with energy expenditure which may be high, particularly as eels do not remain sedentary (Behrmann-Godel and Eckmann, 2003; Brown *et al.*, 2009; Haro and Castro-Santos, 2000; Travade *et al.*, 2010). There has long been concern that insufficient adults may be reaching the spawning grounds (Righton *et al*, 2012, and references therein). However, the implications of increased energetic costs on the overall success of the spawning migration remains an important, and as yet, largely unaddressed subject.

5.1 Management Recommendations

Mitigation for fish damage and loss at abstraction and hydropower intakes is increasingly important as the global demands placed on water resources for consumption and power generation grow (Nilsson *et al.*, 2005). In Europe, the protection of eels at intakes is being driven by legislative targets (e.g. WFD, EU Eel Regulations), and is most commonly provided by physical exclusion screens. Screening methods can be highly effective at protecting fish (Environment Agency, 2011); however, costs of screen installation, maintenance, and cleaning can be substantial, while abstraction or power generation may be consequently reduced. Screens primarily protect fish from harmful pump and turbine blades through physical exclusion, though to provide effective mitigation, an alternative safe route of passage is also required (Clay, 1995). Where a screened intake is flush with the river bank, natural sweeping river flows may be sufficient to guide eels to safe passage (Environment Agency, 2011). However in many locations main river flow may be insufficient to do this (as is the case at Brantham), or intakes are positioned perpendicular to flow (e.g. commonly the case at hydropower installations). In these situations additional physical or behavioural methods may be required to guide fish.

In many regulated systems, adapting management regimes may offer a cost effective alternative to installing fish passage facilities. Distinct peaks in eel migration are typically observed and strategic non-pumping during these short periods can be highly effective at improving escapement (Haro *et al.*, 2003). Abstraction rate was found to be a key determinant of entrainment loss in the current study; hence cessation of abstraction during migration periods, combined with opening of intertidal sluices is likely to reduce eel loss. Complete cessation of pumping for long periods may not be economically viable; however findings suggested that a slow start up of pumps and provision of alternate route of passage is likely to reduce entrainment loss at intakes where eel entrance is volitional.

It is important to highlight that only large female silver eels were tagged due to their dominance within the emigrating stock for this catchment; evident in both fyke net catches and previous monitoring (Environment Agency, unpubl.). The low eel density within this catchment is believed to be the cause of the population bias towards large females at the silver eel lifestage (Defra, 2010b). Nevertheless, many systems comprise a significant proportion of small males; therefore further work should determine if findings are comparable for this component of the population.

Telemetry enables quantification of entrainment loss from catchments, but also highlights the locations of key entrainment points and barriers associated with long delays during downstream migration. In light of our findings that anthropogenic catchment management is an important factor in delay and entrainment losses, there exists an opportunity to work with catchment managers in many heavily regulated rivers to manipulate current regimes and optimise escapement of silver eels to the estuary.

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Figures

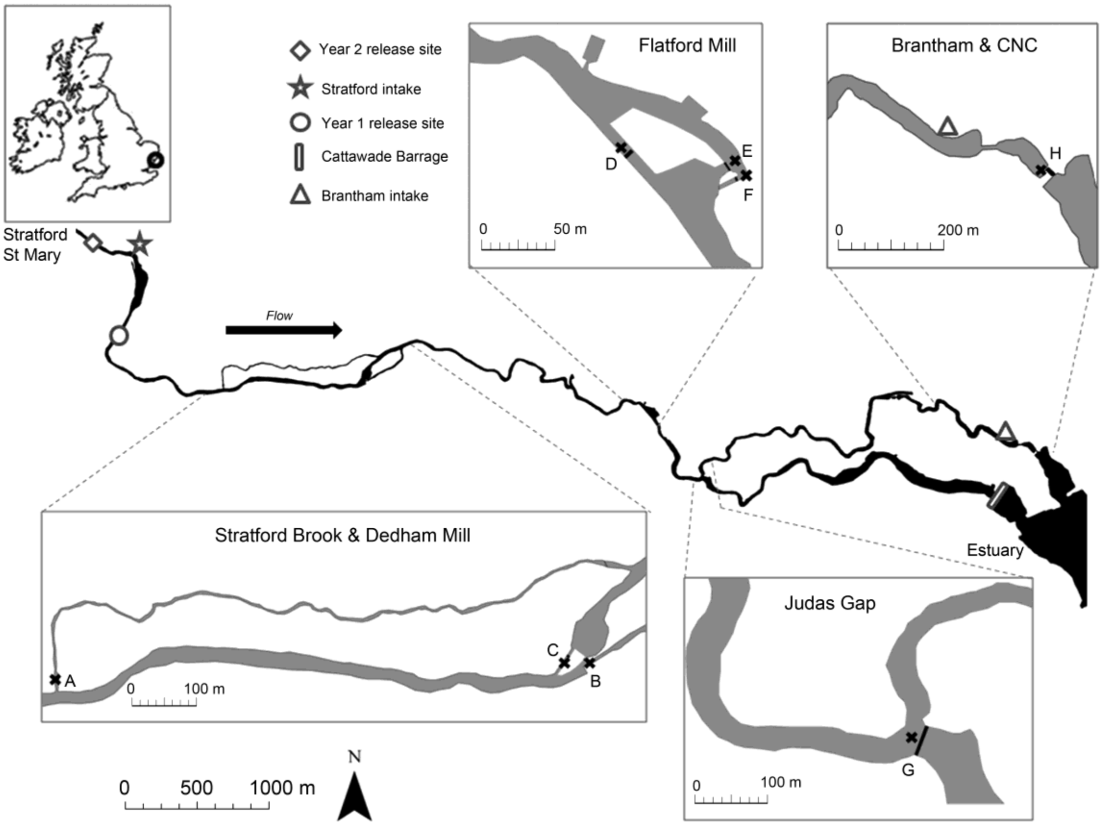

Fig. 1 Lower Stour catchment indicating river structures at A - Stratford brook, B - Dedham Sluice, C - Dedham Lock, D - Flatford Lock, E - Flatford Sluice, F - Flatford mill channel, G -Judas Gap intertidal weir, H - Cattawade North Channel (CNC) intertidal sluice.

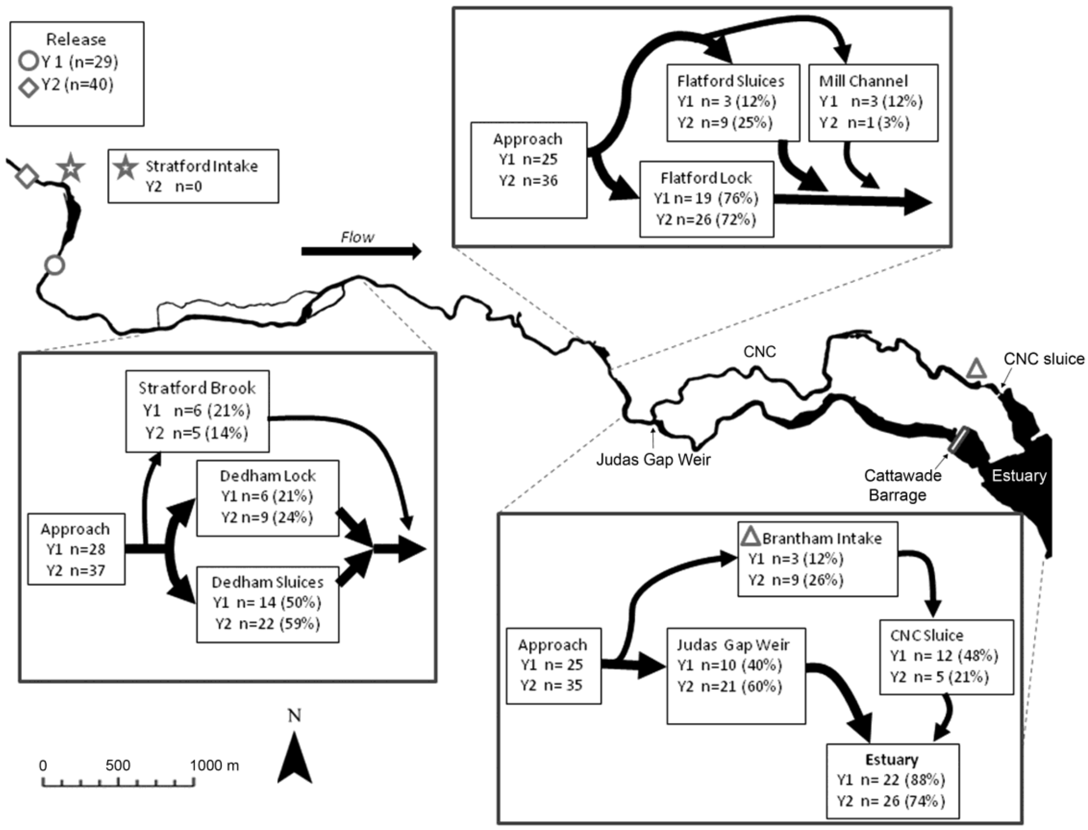

Fig. 2 Route choice of combined acoustic and PIT-tagged silver eels at structures and entrainment at water abstraction intakes during seaward migration through lower Stour catchment to the estuary in year 1, 2009 (n = 29) and year 2, 2010 (n = 40). Percentages denote proportion of eels that approached the structure.