## Impact of tide gates on the upstream movement of adult brown trout, *Salmo trutta*

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## Abstract

Tide gates, used to regulate tidal flow as part of land reclamation programmes, temporally block fish movement by closing during the flood tide. Their impact on the upstream movement of brown trout, *Salmo trutta*, and other fish species has received little consideration. The River Stiffkey, UK, discharges into the North Sea via three top-hung tide gates, one counterbalanced (Gate 1), and two not (collectively referred to as Gate 2). Three-hundred adult trout were caught between 0.5 and 6.0 km upstream from the gates on 20 separate days between July and December 2011 (*n* = 15 per day) and implanted with 23 mm half-duplex Passive Integrated Transponder (PIT) tags before being released 15 m downstream from Gate 1 where PIT antennas were located on either side. Overall, gate attraction (percentage of fish released that were detected by at least one antenna) and passage efficiencies (number of fish that passed Gate 1 reported as a proportion of those that approached) were 96.7% and 92.4%, respectively. The operation of an orifice, installed to improve connectivity for adult trout and juvenile eels, did not influence passage efficiency or delay. Of the fish that passed Gate 1 when the orifice was operational, 42.6 - 55.7% approached the orifice entrance and 70.6 - 92.3% of these passed through. Individuals that passed through the orifice were larger than those that did not. Movement past the tide gates (median duration = 6.04 h) took 6 times longer than passage through two unimpeded reaches upstream. Duration of passage through the gates was predominately related to the mean angle of gate opening during the time prior to passage, followed by water temperature. Overall, a counterbalanced top-hung tide gate delayed the upstream movement of brown trout, highlighting a need to assess and potentially mitigate the impact of gates with more restrictive opening apertures and durations.

**Keywords:** sea trout, fish migration, anadromy, fish passage, land reclamation

## 1. Introduction

Impoundments are one of the most prominent stressors to aquatic ecosystems (Heinz Center, 2002; Pielou, 1998). They disrupt natural discharge, sediment transport and temperature regimes, reduce connectivity with floodplains (Poff *et al.*, 1997; Poff and Hart, 2002), and impact water quality, e.g. by increasing nutrient loads and causing algal blooms (Kondolf, 1997). Habitat fragmentation can reduce native species richness and abundance, including for diadromous fish that migrate between marine and freshwater to complete their lifecycles (Pess *et al.*, 2008; Pringle *et al.*, 2000). Compared to large infrastructure, the impacts of low-head dams and other intermittent barriers to migration, such as tide gated culverts in dikes and levees used to help prevent tidal inundation as part of efforts to reclaim land, have received little attention (Garcia de Leaniz, 2008; Lucas *et al.*, 2009).

Tide gates open when hydraulic head differential is sufficient during the ebb tide, and close when minimised during the flood. As a result they temporally impede migrating fish, particularly those that utilise selective tidal stream transport to minimise energetic costs during river entry on the flood tide (adult Atlantic salmon, *Salmo salar*: Potter, 1988; Priede *et al.*, 1988; Russell *et al.*, 1998, juvenile American eels, *Anguilla rostrata*: McCleave and Kleckner, 1982). Further, when tide gates are open, migration may be restricted if apertures of entry are small, and by high velocities (Haro *et al.*, 2004), turbulence (Hinch and Rand, 1998), rapid changes in salinity (Leray *et al.*, 1981; Niu *et al*., 2008), abrupt temperature gradients (van der Vyver *et al*., 2013), and/or the presence of overhead cover (Kemp *et al.*, 2005).

Dikes and levees decrease floodplain productivity and overall system yield by limiting fluvial connectivity (Welcomme, 1995), with tide gates inhibiting fish species abundance, richness (Boys *et al.*, 2012; Pollard and Hannan, 1994) and movement (Doehring *et al.*, 2011). Interestingly, previous studies often fail to assess the effects of tide gates on diadromous species, including economically important salmonids (but see Wright *et al*., 2014 for an exception). Impacts may include delayed migration and congregation of fish at structures which can increase risk of predation (Schilt, 2007), disease transfer (Garcia de Leaniz, 2008) and energy expenditure (Congleton *et al.*, 2002), thus influencing gonad production (Bernatchez and Dodson, 1987), egg viability (de Gaudemar and Beall, 1998), and decreasing the ability to reach spawning grounds (Bernatchez and Dodson, 1987).

Barrier removal is the most effective and efficient way to improve fish dispersal and production in rivers (Roni *et al.*, 2002). However, this is an unlikely option when considering schemes required to protect valuable land from tidal inundation. Instead, more affordable mitigation options have been developed, including the replacement of top-hung gates with side-hung doors or self-regulating valves that allow the structure to remain open wider for longer. Modification of existing gates with counterbalances, retarders or orifices that extend the period of connectivity is even more economical and thus attractive to river managers. The effectiveness of alternative mitigation options for improving upstream migration has yet to be quantified.

In Europe, the socio-economically important brown trout, *Salmo trutta*, exhibits a wide spectrum of life history traits, ranging from individuals that remain in freshwater for the duration of their lifecycle to full anadromy (Lucas and Baras, 2001). Stocks of the anadromous form, commonly known as sea trout, have undergone serious declines throughout parts of Europe, including a number of regions in the UK (Harris and Milner, 2006) where the species is listed as threatened under the UK Biodiversity Action Plan (JNCC, 2010).

The present study aimed to identify the impact of top-hung tide gates and an orifice modification on the upstream passage efficiency and duration of adult brown trout. Passive Integrated Transponder (PIT) telemetry was used to determine: 1) the number of fish that passed a top-hung tide gate in the River Stiffkey, UK, as a proportion of those that approached, also known as passage efficiency, when an orifice was either operational or non-operational, and 2) duration, also referred to as delay, taking into account the influence of other environmental factors and video observation of behaviour at the orifice.

## 2. Materials and methods

### 2.1. Study site

The River Stiffkey, North Norfolk, UK (52° 57' N; 0° 57' E; Fig. 1), is situated on a chalk aquifer and fed by a catchment of 141 km2. From 5 July to 10 December 2011 mean (± SD) daily flow measured at Little Walsingham, 12.6 km upstream from the tide gates, was 0.09 (± 0.03) m3 s-1 (equivalent to Q72 from 2009 - 2011). The river flows 33 km north from its source at Swanton Novers and through the Stiffkey Valley Site of Special Scientific Interest (SSSI) prior to discharging into the Blakeney Channel and the North Sea via two tide gates. Tide Gate 1 (Fig. 2) (width = 3.0 m, height = 2.1 m) is top-hung and counterbalanced by a weight allowing it to open wider for longer. The gate opens at the seaward end of a corrugated metal pipe culvert (length = 25.8 m), which is situated at the end of the main river channel, and through which the dominant proportion of river flow is discharged (Fig. 1). Tide Gate 2 (Fig. 3) consists of a pair of non-counterbalanced top-hung gates (width = 1.6 m, height = 1.5 m), each located at the seaward end of a smooth concrete pipe culvert (length = 25.8 m). Gates 1 and 2 opened for a mean (± SD) duration of 7.9 (± 0.8) h each tidal cycle at a median angle of 3.7o (range = 0.7 - 35.8o) and 6.4o (0.7 - 23.4o), which equated to a distance of 13.6 (2.6 - 129.1) cm and 16.8 (1.8 - 60.8) cm at the widest part of the aperture, respectively. Once the water level downstream from the gates started to rise, mean (± SD) duration to gate closure was 10.4 (± 7.0) min. The probability of flooding in the lower river is decreased by a carrier channel that increases storage capacity, ending 2.7 km inland from the tide gates (Fig. 1).

Fig1.tif

**Fig. 1.** The lower reaches of the River Stiffkey, North Norfolk (UK) showing release location (**X**) and direction of water flow (→) through Tide Gates 1 and 2. Four of the PIT loops (PLs, ▬), numbered in sequence from upstream to downstream, define limits of a reach containing Gate 1 and its culvert (A [between PLs 4 and 3; 27.8 m]), and two control reaches containing no structures (B [between PLs 3 and 2; 63.7 m] and C [between PLs 2 and 1; 55.0 m]). Fish that passed Gate 2 (PLs 6 and 5) were excluded from further analysis.



**Fig. 2.** Left: Tide Gate 1 in the River Stiffkey, North Norfolk (UK) a counterbalanced top-hung gate. Right: An orifice fish pass installed in Gate 1.



**Fig. 3.** Tide Gate 2 in the River Stiffkey, North Norfolk (UK) consisting of two top-hung gates (not counterbalanced).

The River Stiffkey maintains a trout population, although anecdotal reports of sea trout capture do not exceed single figures (Pawson, 2008). The tide gates are the only considerable barrier to adult trout migration in the river (Beach, 2009). As part of a programme to enable the free movement of fish through the tide gates and increase sea trout returns to the river the Environment Agency installed an orifice fish pass in Gate 1 (Fig. 2) (width = 0.5 m, height = 0.3 m) in May 2010. The orifice comprised of a bottom hinged door that, under the control of a float, closed at a set tide height. Once Gate 1 had closed, this modification extended the mean (± SD) period of connectivity between the estuary and river by 14.7 (± 8.2) min whilst maintaining flood protection and minimising saline intrusion upstream at high tide.

### 2.2. Fish capture and telemetry

Three-hundred trout were caught on 20 separate days from July to November 2011 (15 trout per day on 5, 6, 21, 22, 29 July; 1, 2, 19 August; 2, 9, 19, 20, 23 September; 4, 5, 13 October; 1, 7, 20, 21 November) by electrofishing in the lower reaches of the River Stiffkey from Buxton Conservation (52° 57' 9.76'' N; 0° 57' 20.85'' E, 1.0 km upstream from the tide gates) to Warham (52° 56' 12.84'' N; 0° 54' 1.40'' E, 6.0 km upstream from the tide gates).

Trout were anaesthetised with MS-222 (80 mg l-1; buffered to pH 7.0 with NaHCO3), measured and weighed (mean fork length [FL] [± SD] = 255.2 [± 64.5] mm [range = 155.0 - 532.0 mm], mean mass [± SD] = 240.1 [± 218.9] g [range = 48.0 - 1495.0 g]), and implanted with a half-duplex PIT tag (Wyre Micro Design, Lancashire, England, UK; 2.0 mm diameter, 23.0 mm length, 0.61 g mass) via a ventral incision. Mean (± SD) tag length was 9.5% (± 2.1%) of FL (range = 4.3 - 14.8%), and mass was 0.4% (± 0.3%) of trout mass (range = 0.04 - 1.3%). Trout recovered from anaesthesia in an aerated water container for a maximum of 1 hour prior to release 15 m downstream from Gate 1 (Fig. 1) when the orifice installed in the gate was set to either ‘operational’ (operating as intended with its door closing only during high tide, trout *n* = 150), or ‘non-operational’ (orifice door clamped shut for the entire duration of the tidal cycle, trout *n* = 150). Status of orifice operation, hereon referred to as orifice status, was alternated after every second tidal cycle.

A separate sample of brown trout (*n* = 13, FL = 178.8 ± 51.7 mm [range = 146.0 - 344.0 mm], mass = 70.9 ± 41.7 g [range = 34.0 - 158.0 g]) were implanted with PIT tags and retained in a perforated plastic in-stream container receiving natural flow for 7 days to quantify tag retention and survival. Trout were fed daily with mealworm. Mean (± SD) PIT tag length was 13.5% (± 2.4%) of FL (range = 6.7 - 15.8%) and mass was 1.1% (± 0.5%) of trout mass (range = 0.4 - 1.8%) with 100% tag retention and survival.

Six half-duplex PIT Loops (PLs) (2.5 mm2 cross sectional area insulated wire consisting of 50 strands of 0.25 mm diameter copper wire) were constructed on wooden frames (height = 1.8 m, width = 2.5 - 4.8 m) and installed in the lower reaches of the River Stiffkey (Fig. 1). Each PL was connected to a dynamic tuning unit (Wyre Micro Design, Model: DTU), PIT reader (Wyre Micro Design) and external data logger (Anticyclone Systems Ltd, Surrey, UK, Model: AntiLog RS232), and powered by a 110ah 12v battery. PLs 3 to 6 (monitoring Gates 1 and 2) operated continuously from 5 July to the end of the study period on 10December 2011, with the exception of PLs 5 and 6 (Gate 2) which did not operate from 23 September to 30 September and 6 October to 10 October 2011 due to logger failure (15 and 0 trout released during these periods, respectively). Logger malfunction also meant that PLs 1 and 2 operated from 27 October and 19 September 2011 to the end of the study, respectively (60 and 150 trout released after these dates, correspondingly).

Throughout the study period, tag detection range and efficiency was tested at different stages of the tidal cycle for each PL. Range (maximum distance of detection) was measured by individually passing three tags oriented at 90o and 45o to each PL, towards its centre, left, and right and recording the distance between the PL and the furthest position detection occurred. Range extended from 10 to 50 cm. Detection efficiency (percentage of tags detected within range of the PL) was quantified by passing three tags, each oriented at 90o and 45o to each PL, vertically and horizontally, through each PL at 20 cm intervals to cover its area. PIT tags were passed through PLs at speeds of 0.6 to 2.9 m s-1 to replicate the optimal and burst swimming speeds of trout at a range of water velocities and temperatures (Clough and Turnpenny, 2001). Tags tested at lower (0.6 - 1.6 m s-1) and higher speeds (1.6 - 2.9 m s-1) gave similar PL detection efficiencies of 100% (90o), and 86.5% and 85.7% (45o), respectively (Table 1). When the tide gates were open, efficiency for 90o oriented tags was 98 - 100%. For 45o oriented tags, efficiency was predominately 100% whilst the gates were open, decreasing to 71 - 93% immediately after the gates opened when water conductivity was high, before rapidly returning to 100%.  Detection efficiency of trout released in this study was calculated as the number of fish recorded at a downstream PL as a percentage of those detected upstream. All PLs displayed 100% trout detection efficiency with the exception of PL4 (96%) (Table 1). Tagged fish re-caught upstream by electrofishing where used to establish detection efficiency of PL1.

**Table 1.** Detection range and efficiency for 6 PIT loops (PLs) in the lower River Stiffkey, UK, of trout (*n* = 2 - 251) and from manual testing with tags (*n* = 3) oriented at 90o and 45o to each PL across their area and at speeds 1 (0.6 - 1.6 m s-1) and 2 (1.6 - 2.9 m s-1). Ranges are reported in parentheses.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| PL Number | Fish Detection Efficiency (%) | Tag Orientation (o) | Range (cm) | Manual Detection Efficiency (%) | | | |
| Area | | Speed 1 | Speed 2 |
| 1 | 100 | 90 | 50 | 98 | (93 - 100) | 100 | 100 |
|  |  | 45 | 45 | 100 |  | 100 | 100 |
| 2 | 100 | 90 | 50 | 100 |  | 100 | 100 |
|  |  | 45 | 45 | 100 |  | 100 | 100 |
| 3 | 100 | 90 | 35 | 100 |  | 100 | 100 |
|  |  | 45 | 30 | 86 | (71 - 100) | 83 | 73 |
| 4 | 96 | 90 | 35 | 100 |  | 100 | 100 |
|  |  | 45 | 10 | 90 | (76 - 100) | 78 | 85 |
| 5 | 100 | 90 | 40 | 100 |  | 100 | 100 |
|  |  | 45 | 40 | 100 |  | 100 | 100 |
| 6 | 100 | 90 | 45 | 100 |  | 100 | 100 |
|  |  | 45 | 45 | 100 |  | 100 | 100 |

### 2.3. Video data

When operational, the orifice was monitored by two infrared (IR) submersible cameras with integrated IR LEDs (Sony, Model: IR 37CSHR-IR 25m) from 19 September 2011 to the end of the study period. By fixing cameras at either side of the orifice, perpendicular to the flow, the entire area of entry was captured. The camera configuration provided an IR light source so that fish passage through the orifice could be recorded at night. Footage was captured on a digital video recorder powered by a 110ah 12v battery and downloaded at weekly intervals.

### 2.4. Environmental variables

Water conductivity, temperature, pressure and barometric pressure (Solinst, Georgetown, Ontario, Canada; Model: LTC Levelogger Junior 3001 and Barologger Gold 3001) were logged at 5 minute intervals either side of Gate 1 from 5 July to 12 December 2011. From these measurements, water depth (measured from the water surface to the riverbed and not to an identical vertical datum point) and salinity were calculated (Fofonoff and Millard, 1983). Tri-axial static acceleration loggers recorded the opening angles of Gates 1 and 2 at 2 minute intervals over the same period (Onset, Bourne, Massachusetts, USA; Model: UA-004-64), and were calibrated weekly using a tape measure. River discharge was recorded every 15 minutes at the Environment Agency gauging station at Little Walsingham. Dissolved oxygen (DO) was logged upstream from the gates every hour (YSI, Yellow Springs, Ohio, USA; Model: 6600 V2-4) from 16 September to 10 November 2011. Velocities through the centre of the widest part of the opening aperture of Gate 1, the centre of its culvert at 60% water depth, and the centre of the orifice were sampled at low water fortnightly from July to October using an electromagnetic flow meter (Valeport, Totness, UK; Model: 801).

### 2.5. Data analyses

#### 2.5.1. Attraction and passage efficiency

Overall attraction efficiency of the gates was calculated as the percentage of fish released that were detected by at least one PL. As this study aimed to assess the influence of orifice installation (in Gate 1 only) on passage efficiency and delay, fish that successfully passed through Gate 2 (*n* = 2) were excluded from further analysis. Passage efficiency at Gate 1 was calculated as the number of fish detected at PL3 (upstream) as a percentage of those detected at PL4 (downstream).

The number of approaches to Gate 1 were defined as the number of individual detections at PL4 > 5 min apart. Mann-Whitney (*U*) tests (including effect size, *r*) were used to assess variation in number of approaches with orifice status.

Video footage recorded when the orifice was operational was manually reviewed between the times that trout were first detected at PLs 4 and 3 to discover any passage events. Where the times between detection at PLs 4 and 3 overlapped for more than one fish it was not always possible to visually identify individuals. Therefore, the percentage of fish approaching the orifice was reported as a range, where the minimum value (*n* = 26) indicates the confirmed number of individuals identified, and the maximum (*n* = 34) includes fish (*n* = 8) that could not be proven to be either individuals or the same fish making recurrent approaches. Where passage times did not overlap *and* individuals could be observed (*n* = 20), fish behaviour was categorised and quantified. Behaviour was defined as either: (1) an *attempt*, when a fish displayed propulsion towards, and then movement away from, the orifice entrance whilst maintaining positive rheotaxis and remaining in the field of view; (2) a *rejection*, when a fish exhibited an attempt to pass the orifice but subsequently retreated away from the entrance and out of the field of view without returning for > 20 s. *Passage* (3) was deemed to have occurred when a fish moved upstream though the orifice after last detection at PL4 and was not seen again for the remaining duration of the video. It was possible to visually identify individuals that passed through the orifice, thus the number of fish that passed and their unique PIT tag code could be successfully identified. A Mann-Whitney test was used to compare the length of fish that passed through the orifice with those that did not.

#### 2.5.2. Delay

The study site was divided into three reaches for analysis: (1) treatment reach A (between PLs 4 and 3), which included Gate 1, and (2) control reaches B (from 19 September 2011 when PL2 was operational) (PLs 3 and 2) and (3) C (from 27 October 2011 when PL1 was operational) (PLs 2 and 1) in which water control structures were absent (Fig. 1). The speed of migration (net ground speed) was calculated for each reach as the quotient of the distance (m) separating upstream and downstream PLs, and duration (s) between first detection at each. Mean angle of opening (Anglefish), discharge (Qfish), water temperature (Tempfish) and percentage of time it was night (N%; defined as the proportion of time between sunrise and sunset), during passage through each reach (i.e. between first detection at the downstream and upstream PLs comprising each reach) were calculated for individual fish. Kolmogorov-Smirnov tests indicated that data were not normally distributed. Therefore, Wilcoxon signed-rank (*T*) and Friedman’s ANOVA (*X2*) were used to test for differences in speed of migration, Qfish, and Tempfish between reach (treatment: A; controls: B and C). Bonferroni correction was applied when pairwise comparisons between multiple groups were made.

Time-to-event analysis was used to assess the influence of orifice status (operational or non-operational) and environmental variables (Anglefish, Qfish, Tempfish, N%) on delay in reach A. Fish that were known to have passed the gates (detection at PLs 3, 2 or 1) but were not detected at either PL4 or PL3 (*n* = 16) were excluded from further analysis. A log-minus-log plot displaying duration of migration for each orifice status (operational or non-operational) with independent baseline hazard functions indicated that orifice status violated the assumption of proportional hazards. Therefore, an extended Cox regression model (Ata and Sozer, 2007) was developed to include orifice status as a time dependent covariate in the form:

*h*(*t*) = [*h*0(*t*)] exp[*B*1\*status + *B*2\*status\**t\_cov* + *B*3*X*3 + *B*4*X*4 + *B*5*X*5 + *B*6*X*6]

where *h* is the probability or ‘hazard‘ of passage at time *t* given that an individual had not passed prior to time *t*, *h*0(*t*) is the baseline hazard function, *B* is the regression coefficient, *X* is the covariate value, and *t\_cov* is time, used to generate orifice status as a time dependent covariate. Time to gate closure after release and FL had no independent relationship with speed of migration and were thus omitted from further analysis. Time from release to darkness was excluded from further analysis due to multicoliniarity with other covariates. Separate Cox regression models were created for each orifice status (operational and non-operational) in the same form as the extended model but excluding the orifice status variable and time dependent covariate. Cox regression analyses were reported as unstandardized *B* coefficients and 95% confidence intervals (*CI*).

Mann-Whitney tests were used to assess variation in Anglefish and Qfish with orifice status, and to compare the duration of passage through reach A between trout that used the orifice with those that did not, but passed the gate when the orifice was operational (detection at PLs 3 and 4). The relationships between duration of passage through reach A and downstream and upstream temperature and discharge at the time of release, and number of approaches, were explored using Spearman’s rho (*rs*).

#### 2.5.3. Environmental data

Environmental data for the full duration of the study period (5 July to 30 November 2011) could not be transformed to meet the assumption of normality (Kolmogorov-Smirnov tests: *P* < 0.05) and sample sizes were not equal. Therefore, independent samples Mann-Whitney tests were used to compare median and difference (Δ) in temperature, salinity, depth and DO upstream and downstream of the gates when open and closed.

When the gates were closed, Mann-Whitney tests were used to compare median and difference (Δ) in water temperature, salinity and depth between either side of the gates over the entire study period for each orifice status. Mann-Whitney tests were also used to compare DO upstream between each orifice status when the gates were closed, and gate angle and ΔDepth when open.

## 3. Results

### 3.1. Attraction and passage efficiency

Of the 300 PIT tagged trout released downstream from Gate 1, 290 were detected by at least one of the PLs, giving an attraction efficiency of 96.7% (orifice operational: 94.7% [*n* = 142]; non-operational: 98.7% [*n* = 148]). Of these, 276 trout were detected at PLs 4 and 6 immediately downstream from the gates, two of which successfully passed through Gate 2 (without approaching Gate 1). Of the fish detected at PL4 (*n* = 274), 251 passed through Gate 1 (detection at PL3), giving a passage efficiency of 91.6% (orifice operational: 90.9% [*n* = 120]; non-operational: 92.3% [*n* = 131]). Four fish detected upstream of the gates (PLs 1 - 3) but not at PLs 4 or 6 were released between 23 - 30 September when PLs 5 and 6 (Gate 2) were not operational. Of the 11 fish detected at PL4 during this period, only one was not detected at any upstream PLs. Three of 30 fish released 3 and 4 days prior to 6 - 10 October when PLs 5 and 6 were not operational were not detected at any upstream PLs.

Fish passed the gate a median of 5.00 (0.02 - 9.02) h prior to gate closure, showing no distinct preference for passing during the flood or ebb tide. Trout made a median of 8 (1 - 154) approaches to the gate, which did not vary with orifice status (operational: 9 [1 - 60]; non-operational: 8 [1 - 154]; *U* = 7125.00, *r* = -0.08, *P* > 0.05). More fish passed at night (66.7%), and no individuals returned downstream after passing the gate. Twenty-one fish were detected at PL3 for the first time when the gates were closed, a median of 1.03 (0.12 - 4.08) h after closure.

Of 61 fish that passed Gate 1 (detection at PLs 4 and 3) when the orifice was operational and video cameras functional, 26 - 34 (42.6 - 55.7%) approached the orifice entrance and 24 successfully passed through (passage efficiency = 70.6 - 92.3%). Of the individual fish identified (*n* = 20), half made more than 1 attempt to pass the orifice (*n* = 10, median number of attempts = 2 [range = 1 - 15]) and almost one third made a rejection (*n* = 6, median number of rejections = 1 [1 - 9]). Trout that passed through the orifice were larger (median = 298.5 mm, range = 201.0 - 487.0 mm) than those that passed Gate 1 when the orifice was open but did not use it (median = 249.0 mm, range = 190.0 - 325.0 mm) (*U* = 255.50, *r* = -0.36, *P* < 0.01). Fish used the orifice a median of 3.54 (0.94 - 7.77) h prior to gate closure, when the gate was at a median angle of 2.2o (0.7 - 10.8o) which equated to a median distance of 8.1 (2.6 - 39.5) cm at the widest part of the aperture. Fish did not use the orifice when Gate 1 was closed.

### 3.2. Delay

Median duration from release to detection at PL4 was 1.05 (0.03 - 460.41) h. Median duration of passage through reach A containing the tide gates was 6.04 (0.03 - 197.75) h, with 31.1% and 13.9% of the fish taking more than 12 h and 24 h, respectively, comparable to when excluding fish that passed Gate 1 when PLs 5 and 6 were not operational (5.65 [0.03 - 197.75] h). Speed of migration through reach A was slower than for the two unimpeded reaches (B and C) immediately upstream (Fig. 4, Table 2). Median Qfish was marginally lower in reach A than B (Table 2) when PL2 was functional (*n* = 125) but not PL1 (*n* = 43) (Table 2). Median Tempfish was higher in reach A than B (Table 2) when PL2 was functional (*n* = 125) but marginally lower when PL1 was operating (*n* = 43).

Fig4.tif

**Fig. 4.** Speed of migration of 43 brown trout through a reach with a tide gate (A) and two reaches with no obstructions (B and C) in the lower River Stiffkey, UK, in November 2011. The box plots illustrate the median (horizontal line), interquartile range (boxes), overall range up to (whiskers), and outliers greater than (o), 1.5 times the interquartile range.

**Table 2.** Results of Wilcoxon signed-rank (T) with effect size (r) and Friedman’s ANOVA (X2) statistical analyses of median speed of migration, duration of migration (per 27.8 m of each reach), Qfish and Tempfish for PIT tagged brown trout moving upstream in the River Stiffkey, UK, through a reach with a tide gate (A [PL4 - PL3]) and two reaches with no structures present (B [PL3 - PL2] and C [PL2 - PL1]) during July - December 2011. Ranges are reported in parentheses.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | *n* |  |  | | Reach | |  | |  | | Statistical analysis | | *P* | |
|  | A | B | | C | |  | |  | |  | |
| Speed (m s-1) | 251 |  | 0.001 (0.00004 - 0.27) |  | |  | |  | |  | |  | |
| 125 |  | 0.002 (0.00007 - 0.09) | 0.011 (0.00003 - 0.37) | |  | |  | | *T* = 1452.00, *r* = -0.55 | | 0.000\*\* | |
| 43 |  | 0.005 (0.00009 - 0.09) | 0.029 (0.00015 - 0.29) | | 0.020 (0.00004 - 0.21) | |  | | *X22* = 19.02 | | 0.000\*\* | |
| Duration (h) | 251 |  | 6.04 (0.03 - 197.75) |  | |  | |  | |  | |  | |
|  | 125 |  | 4.16 (0.08 - 117.40) | 0.70 (0.02 - 278.35) | |  | |  | | *T* = 2368.00, *r* = -0.35 | | 0.000\*\* | |
|  | 43 |  | 1.71 (0.08 - 97.99) | 0.27 (0.03 - 52.81) | | 0.39 (0.04 - 183.40) | |  | | *X22* = 19.02 | | 0.000\*\* | |
| Qfish (m3 s-1) | 251 |  | 0.08 (0.07 - 0.13) |  | |  | |  | |  | |  | |
| 125 |  | 0.09 (0.07 - 0.12) | 0.09 (0.07 - 0.13) | |  | |  | | *T* = 1652.50, *r* = -0.30 | | 0.001\* | |
| 43 |  | 0.09 (0.09 - 0.10) | 0.09 (0.09 - 0.10) | | 0.09 (0.09 - 0.10) | |  | | *X22* = 0.91 | | 0.634 | |
| Tempfish (oC) | 251 |  | 15.04 (7.43 - 18.79) |  | |  | |  | |  | |  | |
| 125 |  | 13.24 (7.43 - 15.56) | 12.00 (7.24 - 15.77) | |  | |  | | *T* = 1943.00, *r* = -0.44 | | 0.000\*\* | |
| 43 |  | 7.75 (7.43 - 11.38) | 7.99 (7.24 - 11.05) | | 7.72 (5.10 - 11.35) | |  | | *X22* = 25.72 | | 0.000\*\* | |

\* *P* < 0.01

\*\* *P* < 0.001

Orifice status did not influence median duration of passage (operational: 4.20 [0.17 - 197.75] h; non-operational: 7.27 [0.03 - 155.44] h) through Gate 1 (Fig. 5, Table 3). Median time from fish release to gate closure did not vary between the orifice being operational (4.83 [range = 2.68 - 7.03] h) or non-operational (6.23 [0.47 - 7.53] h) (Mann Whitney *U* = 9189.00, *r* = -0.02, *P* > 0.05). Anglefish had the most significant relationship with duration of passage followed by Tempfish. Separate Cox regressions for each orifice status revealed that Anglefish was the sole influential parameter on duration when the orifice was non-operational, and Tempfish was the most significant covariate when operational. Median Anglefish and Qfish were marginally higher for fish that were released when the orifice was non-operational (Anglefish = 4.0 [0.8 - 25.1]; Qfish = 0.09 [0.07 - 0.13]) compared to operational (Anglefish = 3.0 [0.6 - 17.3]; Qfish = 0.08 [0.07 - 0.11]) (*U* = 3432.50, *r* = -0.49, *P* < 0.001; *U* = 3095.00, *r* = -0.52, *P* < 0.001, respectively). Duration of passage through reach A did not differ between individuals that used the orifice (*n* = 24, 3.76 [0.38 - 40.30] h) and those that did not pass through (*n* = 37, 10.00 [0.17 - 87.99] h) (*U* = 393.00, *r* = -0.10, *P* > 0.05).

Fig5.tif

**Fig. 5.** Cumulative passage of upstream moving brown trout past Tide Gate 1 when an orifice was either operational (▬) or non-operational (▬) at release.

**Table 3.** Results of an extended Cox proportional hazards regression that assessed the influence of orifice status (operational or non-operational) combined with time (*t\_cov*) to create a time dependent covariate, on duration of passage past the tide gate in reach A and Cox regressions on environmental covariates for orifice status for fish that passed, or were detected downstream of Gate 1 (PL4) but not upstream (censored).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | *n* | | Variable | *B* | 95% CI | | Mean | *P* |
|  | Passed | Censored | Lower | Upper |
| Combined Data | 251 | 23 | Orifice Status | 0.241 | 0.918 | 1.763 | 0.46 | 0.147 |
|  |  |  | Orifice Status \* *t\_cov* | -0.008 | 0.981 | 1.003 | 2.86 | 0.172 |
|  |  |  | Anglefish (o) | 0.163 | 1.116 | 1.242 | 3.66 | 0.000\*\* |
|  |  |  | Tempfish (oC) | 0.074 | 1.016 | 1.141 | 13.96 | 0.013\* |
|  |  |  | Qfish (m3 s-1) | -2.052 | 0.000 | 9441.996 | 0.09 | 0.720 |
|  |  |  | N% | -0.001 | 0.993 | 1.006 | 52.46 | 0.826 |
| Non-operational | 131 | 11 | Anglefish (o) | 0.174 | 1.125 | 1.259 | 4.80 | 0.000\*\* |
|  |  |  | Tempfish (oC) | 0.082 | 0.999 | 1.179 | 13.69 | 0.054 |
|  |  |  | Qfish (m3 s-1) | 2.172 | 0.000 | 2683094.317 | 0.09 | 0.736 |
|  |  |  | N% (%) | -0.002 | 0.989 | 1.007 | 52.71 | 0.639 |
| Operational | 120 | 12 | Anglefish (o) | -0.421 | 0.429 | 1.005 | 3.23 | 0.052 |
|  |  |  | Tempfish (oC) | 0.105 | 1.010 | 1.221 | 14.15 | 0.030\* |
|  |  |  | Qfish (m3 s-1) | 3.401 | 0.000 | 3.750E+12 | 0.08 | 0.794 |
|  |  |  | N% | -0.004 | 0.987 | 1.005 | 50.25 | 0.353 |

\* *P* < 0.05

\*\* *P* < 0.001

Of the 274 fish included in the extended Cox regression models, 3 (1.1 %) were first detected at PL4 during a different orifice status from when they were released. Of the fish that passed Gate 1 during the study period (*n* = 251), 36 (14.3 %) were detected upstream at PL3 under a different orifice status compared to release.

Number of approaches to Gate 1 was positively correlated with duration of passage through reach A (*rs* = 0.58, *P* < 0.001) and negatively related to Anglefish (*rs* = -0.14, *P* < 0.05). Duration of passage through reach A was negatively related to downstream temperature (*rs* = 0.17, *P* = 0.01), upstream temperature (*rs* = 0.16, *P* < 0.05) and discharge (*rs* = -0.15, *P* < 0.05) at the time of release.

### 3.3. Environmental data

Upstream and downstream median water temperatures were slightly higher when the gates were closed than when open (Table 4, Table 5, Fig. 6b). The difference in water temperature upstream and downstream from the gates was marginal when open, but greater when closed. Downstream temperature changed by a median of -0.59oC (-2.62 - 1.08oC) within the first hour of gate opening, followed by ≤ 0.05oC h-1 thereafter.

**Table 4.** Upstream median dissolved oxygen (DO) saturation from 16 September to 10 November 2011 and median and difference (Δ) in water temperature, salinity and depth (upstream and downstream measured to the riverbed and not the same vertical datum point) upstream and downstream from Tide Gate 1 in the River Stiffkey, UK, when open and closed, or during periods of gate closure when the orifice was operational and non-operational, from 5 July to 30 November 2011, with ranges in parentheses.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Location | Status | Temperature (oC) | Salinity (PSU) | Depth (cm) | DO Sat (%) |
| Gate | Upstream | Open | 14.06 (6.28 - 20.01) | 0.49 (0.32 - 15.68) | 99.60 (94.78 - 164.38) | 68.22 (45.73 - 132.20) |
|  |  | Closed | 14.31 (6.49 - 19.94) | 7.32 (0.32 - 16.32) | 129.69 (96.36 - 164.71) | 67.20 (49.43 - 131.77) |
|  | Downstream | Open | 14.10 (5.96 - 22.79) | 0.83 (0.30 - 32.64) | 100.00 (95.80 - 167.81) |  |
|  |  | Closed | 14.91 (5.92 - 22.89) | 27.40 (0.36 - 34.70) | 208.57 (97.01 - 444.86) |  |
|  | Δ | Open | 0.00 (-2.87 - 1.23) | 0.33 (0.00 - 29.23) | -0.11 (-4.55 - 36.38) |  |
|  |  | Closed | -0.63 (- 4.37 - 1.59) | 19.86 (0.00 - 31.52) | 78.69 (-2.59 - 306.92) |  |
| Orifice  (Gate Closed) | Upstream | Operational | 14.77 (7.02 - 19.94) | 7.19 (0.32 - 16.32) | 130.44 (96.58 - 164.71) | 67.33 (51.40 - 131.77) |
|  | Non-operational | 13.17 (6.49 - 19.72) | 7.44 (0.33 - 14.68) | 128.80 (96.36 - 159.63) | 67.20 (49.43 - 119.60) |
|  | Downstream | Operational | 15.52 (6.99 - 22.89) | 26.31 (0.41 - 34.70) | 212.48 (97.01 - 372.48) |  |
|  |  | Non-operational | 13.40 (5.92 - 20.72) | 28.59 (0.36 - 34.08) | 204.38 (97.33 - 444.86) |  |
|  | Δ | Operational | -0.71 (-4.37 - 1.59) | 19.08 (0.00 - 31.52) | 82.12 (-2.59 - 244.56) |  |
|  |  | Non-operational | -0.55 (-3.72 - 1.13) | 20.63 (0.00 - 30.73) | 75.46 (-0.79 - 306.92) |  |

**Table 5.** Mann-Whitney statistical comparisons of upstream dissolved oxygen (DO) saturation from 16 September to 10 November 2011 and median and difference (Δ) in water temperature, salinity and depth recorded over the full duration of the study (5 July to 30 November 2011) upstream and downstream of Tide Gate 1 in the River Stiffkey, UK, when open and closed, or during periods of gate closure when the orifice was operational and non-operational.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Comparison | Location | Temperature | | | Salinity | | | Depth | | | DO Sat (%) | | |
| *U* | *r* | *P* | *U* | *r* | *P* | *U* | *r* | *P* | *U* | *r* | *P* |
| Gate | Open vs Closed | Upstream | 172679155.00 | -0.04 | 0.000\*\* | 73239258.50 | -0.50 | 0.000\*\* | 27564932.00 | -0.71 | 0.000\*\* | 187042.00 | -0.06 | 0.038\* |
| Downstream | 149743417.00 | -0.15 | 0.000\*\* | 35670239.00 | -0.67 | 0.000\*\* | 4367915.50 | -0.81 | 0.000\*\* |  |  |  |
| Δ | 60764602.00 | -0.56 | 0.000\*\* | 33576144.50 | -0.68 | 0.000\*\* | 2160224.00 | -0.82 | 0.000\*\* |  |  |  |
| Orifice  (Gate Closed) | Operational vs Non-operational | Upstream | 17482997.00 | -0.29 | 0.000\*\* | 25950667.00 | -0.01 | 0.396 | 24243630.00 | -0.06 | 0.000\*\* | 26165.00 | -0.05 | 0.250 |
| Downstream | 17303089.50 | -0.29 | 0.000\*\* | 22261547.00 | -0.13 | 0.000\*\* | 24123350.00 | -0.07 | 0.000\*\* |  |  |  |
| Δ | 22843118.50 | -0.11 | 0.000\*\* | 22251847.50 | -0.13 | 0.000\*\* | 24641490.00 | -0.05 | 0.000\*\* |  |  |  |

\**P* < 0.05

\*\**P* < 0.001

Fig6.tif

**Fig. 6.** An example of tidal and diel variation in gate angle (▬) and (a) depth, (b) temperature, (c) salinity and (d) dissolved oxygen (DO) upstream (- - -) and downstream (▬) of Tide Gate 1 in the River Stiffkey from 19 - 21 September 2011. Triangles indicate time that adult brown trout (*n* = 15) were released downstream (▲) and passage of individuals upstream (detection at PL3) (Δ) of Gate 1 during this time.

Upstream and downstream median salinity was higher when the gates were closed than when open (Table 4, Table 5, Fig. 6c). The difference in salinity upstream and downstream was minor when gates were open. Salinity upstream from the gates was considerably lower than downstream when they were closed. Within the first 30 min after Gate 1 opened, downstream salinity decreased by a median of 21.50 (4.30 - 28.46) PSU, followed by 3.46 PSU over the next hour and ≤ 1.13 PSU h-1 thereafter.

Upstream DO was higher when the gates were open than closed (Table 4, Table 5, Fig. 6d). Median velocities measured at the bottom of the water column under Gate 1 through the centre of the widest part of its opening aperture and through the gate’s culvert at low water were 0.36 (0.18 - 1.41) and 0.19 (0.12 - 0.64) m s-1, respectively.

Orifice status did not influence upstream median salinity when the gates were closed, but was associated with variation in median difference in depth either side of the gates, downstream salinity, and upstream and downstream temperature (Table 4, Table 5).

When the gates were open, Gate 1 angle and ΔDepth (Table 6) were greater when the orifice was non-operational. Median velocity through the orifice at low water was 0.51 (0.29 - 1.30) m s-1.

**Table 6.** Results of Mann-Whitney statistical comparisons for Gate 1 angle and difference in depth (ΔDepth) between upstream and downstream in the River Stiffkey, UK, over the entire period of the study (5 July to 30 November 2011) when Gate 1 was open and the orifice was either operational or non-operational.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Variable | Status | Median (Range) | *U* | *r* | *P* |
| Orifice  (Gate Open) | Gate Angle (o) | Operational | 3.5 (0.7 - 35.8) | 60748486.50 | -0.19 | 0.000\* |
|  | Non-operational | 4.3(0.7 - 29.4) |  |  |  |
| ΔDepth (cm) | Operational | -0.36 (-4.55 - 17.65) | 53631075.50 | -0.27 | 0.000\* |
|  | Non-operational | 1.51 (-4.85 - 36.38) |  |  |  |

## 4. Discussion

Despite being commonly installed to prevent tidal inundation of low-lying land in many regions of the world, the impact of tide gates on the movement of fish has received little attention. Although the present study observed high attraction (96.7%) and passage efficiency (91.6%) in a small UK stream, a tide gate delayed the upstream movement of adult brown trout by 6 times when compared to unimpeded reaches. Operational failure of PLs had little effect. Installation of an orifice to increase the period of longitudinal connectivity during each tidal cycle did not improve attraction and passage efficiency, or reduce delay.

Information on how estuarine structures impact upstream movement of fish is scarce. Where evidence exists, attraction and passage tends to be considerably lower than that reported in the present study. For example, an average of 49% of acoustic tagged adult Chinook salmon, *Oncorhynchus tshawytscha*, passed tidal gates at an intertidal structure when other routes were blocked in the Sacramento Delta, USA, having been released 2.4 km downstream (Vincik, 2013). In the Wadden Sea, The Netherlands, 49% of radio tagged adult sea trout migrated upstream through sluices at an intertidal barrage (Bij de Vaate *et al.*, 2003). The same study found that fewer sea trout (14%) released along the south-west coast of The Netherlands chose to pass via sluices in another barrage when presented with a choice to migrate through a man-made canal (20%). Unfortunately, these studies fail to separate attraction and passage efficiency, and hence the impacts of the tidal structures themselves are not determined. In the UK, 73% of adult sea trout and Atlantic salmon tagged with combined acoustic and radio transmitters approached an intertidal barrage on the River Tawe, Wales, of which 42% successfully passed, predominately over tidally inundated weirs (Mee *et al.*, 1996). For downstream migrants, high passage efficiency at top-hung tide gates has been observed (sea trout smolts: Wright *et al*., 2014; adult European eel: Wright *et al*., 2015).

Delayed migration can increase risk of predation (Schilt, 2007), energy expenditure (Jonsson *et al.*, 1997), and susceptibility to (Schreck *et al.*, 1993), and transfer of (Garcia de Leaniz, 2008), disease where fish congregate. Although passage in this study was blocked at high tide when the gates were closed, fish did not initiate upstream movements immediately after opening on the ebb as might have been expected. A number of factors may have contributed to this.

First, discharge through the gates would have been highest on opening, creating velocities that may have exceeded the swimming capabilities of the tagged fish (Clough and Turnpenny, 2001). For example, maximum recorded velocity through the underside of Gate 1 at low water was 1.41 m s-1, marginally less than the projected burst swimming speed of a 255 mm brown trout at 14oC (1.66 m s-1) (Clough and Turnpenny, 2001). Velocities at the time of gate opening would have exceeded these values.

Second, a chaotic hydrodynamic environment immediately downstream from the gate on opening may have caused behavioural avoidance. Turbulence is known to negatively impact fish swimming by increasing the energetic costs (Enders *et al.*, 2005) and reducing stability (Tritico and Cotel, 2010).

Third, the trout may have avoided stark transitions in environmental parameters when the gates opened. In unimpeded estuaries of similar depth and geomorphology to the Stiffkey, mixing at the tidal and freshwater interface creates gradual temperature, salinity and DO gradients (Kaiser *et al*., 2005) which can be interrupted by impoundments (Quinn *et al*., 1997; Rulifson and Wall, 2006). In the present study, temperature upstream of Gate 1 varied from downstream at the time of opening by -2.87 to 1.23oC. Sudden alterations in temperature can elicit physiological stress responses in fish (reviewed in Donaldson *et al*., 2008; Iwama *et al*., 1998) which can impair physical ability (Griffith, 1978; Steinhausen *et al*., 2008) and induce behavioural avoidance (van der Vyver *et al*., 2013). In Pacific salmonids, a sudden increase of 2oC at temperatures ≥17oC can decrease swimming performance by impacting cardiac output and arterial oxygen delivery resulting in increased blood lactate (Steinhausen *et al*., 2008). Trout in the present study also experienced abrupt differences in salinity upon gate opening, with upstream waters up to 29.23 PSU lower than downstream and a sharp decrease occurring downstream during the first 1.5 h. Osmotic stress has previously been observed in salmonids transferred from fresh to saline (32 - 36 ppt) water, elevating plasma osmolarity, plasma chloride and muscle dehydration (Handeland *et al*., 1996; Leray *et al.*, 1981; Niu *et al*., 2008), impairing ability to swim (Brauner *et al*., 1992; Brauner *et al*., 1994) and evade predators (Handeland *et al*., 1996).

Even after the initial release of flow through the gate had subsided and water velocities and opening aperture were sufficient for passage, trout did not tend to move through. Instead, they passed on average approximately 5 hours prior to gate closure (i.e. mid tidal cycle), after repeatedly approaching Gate 1 and exhibiting searching and milling behaviour as reported for salmonids at other structures (Croze *et al.*, 2008; Gowans *et al.*, 1999; Mee *et al.*, 1996). This recurrent avoidance behaviour was related to lower mean gate angles and led to longer passage times. Other studies suggest that the presence of overhead cover at culverts (Greenberg *et al.*, 2012; Kemp *et al.*, 2005), and prevention of selective tidal transport caused by the gates (Aprahamian *et al.*, 1998; Potter, 1988), could contribute to the behavioural avoidance observed.

Delayed entry and ascent of rivers by adult salmonids has been associated with increased water temperature (Jonsson and Jonsson, 2002 for sea trout; Solomon and Sambrook, 2004, for Atlantic salmon). Similarly, duration of passage through the tide gate in this study was positively related to temperature. Longer durations of passage past structures at high water temperatures could negatively affect fish by increasing the presence and transfer of disease and parasites in salmonids (Garcia de Leaniz, 2008) and the energetic costs of swimming (Enders *et al.*, 2005). High temperatures may also decrease DO concentration (Ozaki *et al.*, 2003) and thus increase fish avoidance (Richardson *et al*., 2001; Whitmore *et al.*, 1960), although this seems unlikely in the present study as minimum DO saturation was 46%.

Previous studies have shown high passage efficiencies through orifices for adult salmonids. In an experimental flume, 95% of mature male brown trout (average length = 27.3 cm) chose to pass upstream through a submerged orifice (0.2 x 0.1 m) rather than over a weir with the same maximum water velocity (1 m s-1) and turbulence (Guiny *et al.*, 2003). Further, 100% of radio tagged adult Atlantic salmon that approached a pool and submerged orifice fish ladder (orifice diameter = 0.84 m, velocity = 2.4 m s-1) at the Pitlochry Dam, Scotland, successfully passed upstream, although fish were delayed for an average of 14.8 days (Gowans *et al.*, 1999). In the present study, 70.6 - 92.3% of fish that located the orifice subsequently passed, which is high when compared to the efficiency of mitigation measures employed at other water infrastructure (Noonan *et al.*, 2012). However, the orifice was ineffective at improving passage efficiency or decreasing delay at Gate 1, a result of the low number of fish that approached it (42.6 - 55.7% of those released when the cameras and orifice were operational) and the number of attempts (50% made a median of 2 attempts) and rejections (30% rejected at least once) exhibited. To successfully attract upstream moving fish, discharge emanating from fishways must be discernible from competing flows (Armstrong *et al.*, 2010), yet the dominant discharge at Gate 1 would have been associated with its aperture rather than the orifice. The complex hydraulic environment and high velocities created by the orifice and float configuration may have induced behavioural avoidance similar to that which may have occurred around the gate aperture. This is supported by larger fish on average using the orifice, which discharged a maximum recorded velocity at low water of 1.30 m s-1. Velocities at other states of tide and flows that precluded measurements with a handheld flow meter would have often exceeded this.

Adult salmonids often use selective tidal stream transport to migrate through unimpeded estuaries (Aprahamian *et al.*, 1998; Potter, 1988), yet trout in this study used the orifice on average approximately 3.5 h prior to gate closure (i.e. mid tidal cycle), and no fish passed during the flood tide when Gate 1 was closed.

### 4.1. Conclusion

High passage efficiency was observed for adult brown trout at a top-hung tide gate in a small UK stream. However, migration past the gate was slower than for subsequent progression upstream through unimpeded reaches, and this was not mitigated by installation of an orifice that extended the period of connectivity. Under the configuration described, competing flows through the gate aperture likely limited the number of fish attracted to the entrance of the orifice, suggesting it is not a suitable mitigation option for adult salmonids. Trout did not use the orifice when the tide gate was closed, however the effect of extending the period of longitudinal connectivity during this time by increasing orifice door float arm length and/or ballast requires assessment. The effect of the orifice on other species and life stages (e.g. targets: salmonid smolts, juvenile eels; non-targets: adult European eel [Wright *et al*., 2015]) and at sites with different tidal regimes should also be considered. Gate angle was the most significant correlate with delay. Sea level rise (Nicholls *et al*., 1999), changes in flow regimes (Arnell, 2004) and increasing abstraction demands (Weatherhead and Knox, 2000; Wilby *et al*., 2006) could decrease gate opening angles and extend the duration of gate closure in the future (Walsh and Miskewitz, 2013). Consequently, modifications or replacements that enable gates to remain open wider and over a longer proportion of the tidal cycle, such as retarders, lightweight gates and self-regulating designs would likely be more beneficial to the effective passage of adult salmonids.

## Acknowledgements

This project was funded by Engineering and Physical Sciences Research Council, the University of Southampton, the Environment Agency and the Interreg IVB Living North Sea Project. The authors thank Cefas, Wild Trout Trust, Buxton Conservation, Holkham Estate and Fishing Syndicate, Aquatic Control Engineering, the EA Norfolk Fisheries Team, Lady Kay Buxton, Rosie Edgington, Tom Harrison, Sam Sykes, Simon Karlsson, Tom Worthington, Adam Piper, Peter Marchant, Ben Kerley, Josh Nightingale, Emma Dyson, Freddie Wells, Ralph Wright, Silvana Wright, Toby Diggens, Lee Corsi and Nick Stokes. All data supporting this study are openly available from the University of Southampton repository at <http://dx.doi.org/10.5258/SOTON/390304>.

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## Highlights

* Diadromous fish passage at tide gates has received little consideration
* Upstream adult brown trout, *Salmo trutta*, passage at a tide gate was high
* Adult trout moved 6 times slower past the gate than through unimpeded river reaches
* An orifice modification did not improve passage or decrease duration
* Smaller gate apertures and higher temperatures were related to longer passage times

## Glossary

Anadromous: a lifecycle where fish spawn, hatch and rear in freshwater and mature in salt water

Connectivity: the water-facilitated transfer of energy, materials and organisms across a hydrologic environment

Delay: the time taken to pass an aquatic structure after first approach

Detection range: the maximum distance from a PIT Loop (PL) that a PIT tag can be detected

Detection efficiency: the proportion of PIT tags within range of a PL that can be detected

Diadromous: a life history that involves migrating between marine and freshwater

Discharge: the volume rate of water flow (m3 s-1)

Fork length: the length of a fish measured from the snout tip to where the central caudal fin rays end

Passage efficiency: the number of fish that pass a structure as a proportion of those that approach

Q72: a flow rate that is equalled or exceeded for 72% of the specified period

Smolt: an anadromous salmonid life stage where juveniles adapt for the marine environment by undergoing a series of physiological and behavioural changes, including migration downstream to sea

Species abundance: the number of individuals within a species in a habitat

Species richness: the number of species in a habitat

Speed of migration: the duration of fish movement between two points divided by the distance

Tide gate: a water control structure that discharges river flow during the ebb tide and closes during the flood, predominately for flood protection and land reclamation