Habitat Micromeasures for Fish Migration

Final Report

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Executive summary

The tidal Thames is an important habitat for fish which utilise the estuary as a nursery area and migration corridor. Urban development has narrowed the channel leading to an increase in turbulence and flow velocity particularly through the central London section. These changes in turbulence and velocity have the potential to impact upon fish populations by exceeding their swimming abilities and leading to displacement or wash out from the estuary. Other potential effects include increased energy expenditure and migratory delay. Although previous research has concluded that the Thames Tideway Tunnel project would not have significant adverse effects on fish passage through the estuary, a commitment was made by the Habitat Compensation Working Group to study artificial habitat structures, which might, if deployed, enable fish to move more freely through the estuary.

The present study assesses the effectiveness of baffle type structures selected from laboratory flume research and preliminary field trials, also known as habitat micromeasures, deployed in the Thames Tideway. The investigation aimed to determine whether: (i) habitat micromeasures deployed on the foreshore were more likely to be used by fish during the ebb tide when compared to similar natural habitat where no structures were present, and; (2) fish at the micromeasures were more likely to maintain their position in flowing water, also referred to as holding station, than fish using similar natural habitat where structures were absent.

Sixty habitat micromeasures were deployed at an experimental site covering 60 m^2 of foreshore on the Chiswick Eyot, a site selected for its well sorted and oxygenated gravel habitat and upper Tideway location which, in spring and early summer, is likely to support the numbers of fish required for assessment. A reference site without any structures present but displaying similar topographic features to the experimental site was selected upstream of the micromeasures site for comparison during the study period. To assess fish usage, both sites were monitored using ARIS, a sonar imaging device, during the mid-ebb tide on 10 alternate days between 30 June to 13 July 2016. Seine netting was also conducted towards the end of the ebb tide simultaneously at both sites on each day. A control period of monitoring based on the same protocol over 6 alternate days followed from 15th to 25th July 2016 where there were no structures present at either site.

Sonar imaging footage revealed that there was no difference in the number of fish that passed through the experimental and reference sites during the treatment and control periods. However, fish passing through the experimental site when the micromeasures were deployed were significantly more likely to hold station. Holding station demonstrates that fish can withstand flow velocities, likely a result of advantageous hydraulic conditions created by the habitat micromeasures such as low velocity areas for refuge. Fish that held station at the micromeasures ranged from 53 to 566 mm, demonstrating application of the structures to a number of fish species and life stages.

Seine netting revealed that small juveniles were capable of withstanding velocities along the intertidal foreshore towards the end of the ebb tide with no difference in species diversity, number of fish or length of those caught with or without the micromeasures in place. This finding reiterates the advantages of the habitat micromeasures during the higher velocities that occur mid-tidal cycle.

Overall, the habitat micromeasures were used by a greater proportion of fish to hold station during the ebb tide when compared with a reference site with no micromeasures present. Fish appeared to utilise areas of advantageous hydraulic conditions around the structures that minimised the energetic costs of maintaining position in high velocity flows.

Project design principle IRVR.01, which guides the development of the in-river structures, states that "…features integral or adjacent to the foreshore structure that can provide refuge to migrating fish shall be included where practicable". This study demonstrates that artificial habitat micro-measures could, if installed, provide refuge for migrating fish. It is therefore recommended that consideration is given to including these measures in accordance with design principle IRVR.01, where it is practicable to do so.

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Glossary

Anadromous: a lifecycle where fish spawn, hatch and rear in freshwater and mature in salt water (e.g. salmon, sea trout).
ARIS (Adaptive Resolution Imaging Sonar): a sonar imaging system that creates digital pictures by transmitting sound pulses.
Benthic: the lowest portion of the water column; benthic organisms utilise habitat near, or within, the ocean or riverbed substrate.
Control: a period of the study where no habitat micromeasures were present at the experimental or reference sites used as a comparison with the Treatment period.
Cyprinid: Family of freshwater fish which include the carps and true minnows.
Diadromous: a life history that involves migrating between marine and freshwater environments.
Experimental site: location where 60 habitat micromeasures structures were laid out in six rows of ten structures covering an area of 60 m^2 during the treatment period.
Flow: the volume rate of water flow (m3 s-1).
Flow velocity: the speed of water flow over a set distance (m s-1).
Habitat micromeasures: pre-constructed concrete beams, square in cross section (100 mm x 100 mm) and shaped in a zigzag formation.
Holding station: fish maintenance of lateral and longitudinal position in flowing water, defined in the present study as a fish maintaining position for ≥ 5 s at a time.
Hydraulics: the study of the conveyance of liquids through channels and pipes.
Hydrodynamics: the study of fluid motion, specifically concerning the forces acting on, or exerted by, fluids.
Migration: to move from one location to another, e.g. for the purposes of spawning or feeding.
Piscivorous: Fish eating (usually referring to birds or other fish)
Reference site: location where conditions such as substrate type, shoreline profile and wave exposure replicated those at the experimental site as closely as possible, without the deployment of habitat micromeasures during the treatment or control periods.
Salmonid: a fish belonging to the family *Salmonidae* e.g. Atlantic salmon, brown trout.
Seine: a long net rigged with floats along the top and weights along the bottom enabling it to hang vertically in the water column. The ends are drawn together to encircle fish.
Species diversity: the measure of diversity within a community by combining species richness and evenness of species abundances.
Tidal limit: the limit of tidal influence at the mouth of a river.
Treatment: a period of the study where habitat micromeasures were present at the experimental site.
Turbidity: a measure of suspended particulate matter in the water.
Turbulence: a flow regime characterised by chaotic changes in property.

1 Introduction

The tidal Thames is an important habitat for fish which use the shallow intertidal margins to make migrations through the estuary to reach preferred habitats near the upper tidal limit. Progressive encroachment by urban development has narrowed the channel leading to an increase in turbulence and flow velocity particularly through the central London section. Increases in flow velocity coupled with the loss of intertidal habitat present a challenge for small, and weak swimming juvenile fish and enhance the risk that individuals will be unable to successfully complete their migrations.

This report presents the findings of a study undertaken in June and July 2016 to test prototypes of a fish habitat refuge structure, known as habitat micromeasures. The structures have been developed on behalf of the project by fish specialists and tested through a series of laboratory and field based trials. The context for the study in terms of fish migration in the Tideway and the habitat features required to enable migration is presented in 1.1 and Error! Reference source not found.. The overall objective of the study and a summary of previous phases are presented in 1.2 and 1.3.

1.1 Fish migration in the Thames Tideway

The Thames Tideway is an important habitat for a range of marine, estuarine and freshwater fish species. It supports commercially important species such as sole, *Solea solea*, thicklip grey mullet, *Chelon labrosus*, thinlip grey mullet, *Liza ramada,* bass, *Dicentrarchus labrax*, sprat, *Sprattus*, dab, *Limanda limanda*, herring, *Clupea harengus,* and whiting *Merlangius merlangus* (Colclough *et al*., 2002). Estuarine habitat is highly productive, providing valuable feeding opportunities and refuge from predation by piscivorous fish and mammals (Able, 2005). Rapid growth is promoted by greater temperatures when compared to marine environments, minimising vulnerability to smaller predators (Bergman *et al*., 1988).

Juveniles of marine species such as bass migrate to the upper reaches of the estuary in the spring to access feeding and nursery habitat in the shallow intertidal margins before moving back into the outer estuary in the autumn. Freshwater fish such as dace, *Leuciscus leuciscus*, and bream, *Abramis brama*, which are spawned upstream in the main River Thames or its tributaries move downstream as fry (Turnpenny *et al*., 2008) and colonise habitat within the Tideway where the salinity is suitable. Species that are resident in the estuary such as flounder, *Platichthys flesus*, and common goby, *Pomatoschistus microps*, also make migrations through the Tideway to reach feeding and nursery habitat.

Water currents in the estuary may exceed the swimming ability of juvenile life stages or small species and therefore migration or dispersal relies upon a number of behavioural strategies. For example, smelt are spawned in the upper estuary and then move downstream by passive drift with the current. Displacement from feeding areas is prevented by moving to the upper layers of the water column during the flood tide (Moller and Dieckwisch, 1991; Elliott and Hemingway, 2002). The juveniles of cyprinid species such as dace occupy marginal or benthic habitat such as reed beds, and periodically move up into the water column or laterally into faster flows, causing downstream distribution

(Pavlov,1994; Pavlov *et al*.,1996; Reichard *et al.* 2004; Sonny *et al.,* 2006). These life stages therefore depend upon sufficient marginal habitat in the form of vegetation or bed roughness to create low velocities.

Many fish including migratory species, such as Atlantic salmon, *Salmo salar*, and sea trout, *Salmo trutta*, take advantage of tidal currents which assist movement in their preferred direction (i.e. upstream or downstream) (e.g. Potter, 1988). As the tide turns, fish may attempt to take refuge from the current and maintain their position until the end of the adverse tidal cycle. This mechanism is known as selective tidal stream transport (STST).

For successful migrations to occur, uninterrupted passage should be maintained along the tidal foreshore. While this issue has been recognised in the scientific literature (e.g. Colclough *et al*., 2002), there appears to have been no research into preferred shoreline conditions for juvenile and small fish migrations and therefore the subject is poorly understood. It may be surmised from observations of such migrations that a gradually sloping intertidal foreshore is the preferred condition. This allows juvenile fish to remain in shallow, slower-moving water, away and protected from adult fish, throughout the tidal cycle. Under this hypothesis, if young fish were forced by obstructions to move out into deeper water, this could reduce their ability to hold station or make progress in a flow, and increase their susceptibility to predation by adult fish.

1.2 Fish habitat micromeasures study

A commitment was made by the Habitat Compensation Working Group to study artificial habitat structures, which might, if deployed, enable fish to move more freely through the estuary. The concept of a refuge or easement structure, hereon referred to as habitat micromeasures, was developed by the Thames Habitats Working Group, an expert panel set up following submission of the Development Consent Order application in 2014 to identify and agree the appropriate type and number of schemes required to compensate for the agreed permanent loss of 1.2 ha of estuarine habitat (Tideway, 2014). The purpose of the structures was to provide refuge where fish can rest with minimum energy expenditure during the reverse tidal phase. It was envisaged that these easement structures would be integrated into Thames Tideway Tunnel foreshore sites such as Putney Embankment Foreshore, King Edward Memorial Park, Chambers Wharf and Victoria Embankment Foreshore.

As well as providing refuge for fish, the Thames Habitats Working Group identified a number of other important requirements for the structures. Most critically, members of the Working Group, particularly the Port of London Authority required that the structures should not project vertically into the water column by more than approximately 0.3 m to avoid limitation or hazard to small vessel navigation. For the purposes of the Thames Tunnel Project, it was also desirable that the design could, where practicable, be incorporated into, for example, new scour protection measures.

The design of the above ground Thames Tideway Tunnel structures is underpinned by a series of design principles which form part of the development consent. Incorporation of features such as habitat micromeasure structures into the design of the foreshore sites is given effect through Design Principle IR0101 which states:
'*Features integral to or adjacent to the foreshore structures that can provide refuge to migrating juvenile fish shall be included where practicable*.'[1]

1.3 Phases of the study

Phase one of the habitat micromeasures study aimed to identify a design for the fish refuge structures using a small-scale laboratory flume investigation (URS and THA, 2014a). Whilst cylindrical structures provided the most favourable wakes for fish shelter at low current velocities, chevron shapes were more effective at high velocities. Of the chevron designs tested, those with a 60^{o} angle were most utilised with fish holding station both in front and behind.

The second phase of the study aimed to test the structures under field conditions. A chevron shaped concrete baffle (1.0 m x 0.5 m footprint) was designed, fabricated and trialled in the River Test, Hampshire, (URS and THA, 2014b). The River Test was selected due to the clarity of the water for observing fish behaviour and the presence of a suitable testing facility at Romsey. Video camera monitoring revealed that these pre-fabricated structures were stable in strong riverine currents and immediately attracted fish. The habitat micromeasures were subsequently trialled in the Thames Tideway between Blackfriars Bridge and Millennium Bridge (URS and THA, 2014b). Few fish were recorded during the study, considered to be due in part to the late summer timing of the study when juvenile fish may have moved into deeper water, and to the sampling methods used. The results of this phase were inconclusive in relation to the effectiveness of the micromeasures, given the low number of fish recorded overall. It was determined that netting alone was not an effective method and future experimentation should use hydroacoustic detectors earlier in the year.

The third phase of the study investigated possible locations in the Tideway where there may be a requirement for the refuge structures. The Individual Based Model (IBM) from the Environmental Impact Assessment stage of the Thames Tideway Tunnel project was modified to highlight areas of the river channel where 'model fish' would take refuge during ebbing tides (URS and THA, 2015). Field observations were compared with the outputs from the IBM to determine key holding zones that might be impacted by the permanent works of the Thames Tideway Tunnel project. This study provided useful recommendations for the location of mitigation and monitoring of juvenile fish migration, in particular for the reaches at Albert Embankment and Putney Bridge which are close to proposed works.

The present study forms the fourth phase of the micromeasures project, and aimed to assess whether a deployment of 60 habitat micromeasures on the foreshore of the Thames Tideway would be

[1] https://www.tideway.london/media/1791/app20601-design-principles.pdf

successfully utilised by fish during periods of high velocity flows. In 2015, a site immediately upstream of Putney Bridge was selected based on habitat suitability and access although agreement was not reached with the Port of London Authority (PLA) over the site and the trial did not proceed. It was agreed that the trial would be re-scheduled for spring/summer 2016, when juvenile fish numbers in the upper and middle Tideway are at a maximum, and that it would be located at an alternative site, adjacent to the Chiswick Eyot in the London Borough of Hounslow. This report presents the findings of this trial undertaken in 2016. The aims and objectives of the study are presented in section 2. Further details of the site selection process and the Chiswick Eyot site are provided in section 3.1.

2 Aims and objectives

The study aimed to determine whether:

i) habitat micromeasures deployed on the foreshore were more likely to be used by fish when compared to similar natural habitat during the ebb tide;

ii) fish in the experimental site were more likely to 'hold station' than fish using the reference site

The term 'holding station' refers to fish maintaining their position in flowing water.

3 Materials and methods

3.1 Study Site

The River Thames is the second longest river in the UK, rising in the Cotswolds hills and flowing 346 km west though the Chilterns and Berkshire Downs, Oxford, Abingdon and Reading before discharging into the North Sea at London (Environment Agency, 2014). The Upper Thames estuary, as defined by the Water Framework Directive (WFD), is a Heavily Modified Water Body with transitional water.

Thirty-four potential sites were reviewed between Chiswick and Blackfriars to assess accessibility, safety considerations and habitat suitability. Lying 14.2 river km downstream from the tidal limit at Teddington Lock, Chiswick Eyot (51° 29' 15.0000" N; 0° 14' 44.9988" W) (Figure 1) was selected for its well sorted and oxygenated gravel habitat and upper Tideway location. Juveniles of a number of marine species, such as bass, and freshwater species, such as dace and bream, reach a peak in abundance in the upper Tideway in the spring (Section 1.1), hence the site was considered likely to support the numbers of fish required to assess effectiveness of the micromeasures. The site was discussed and agreed with the Port of London Authority prior to development of the detailed design of the trial.

Figure 1: Thames Tideway, London, UK, showing location of experimental (micromeasures present during treatment phase) and reference (no micromeasures present) sites.

3.2 Micromeasures habitat structures

The habitat micromeasures structures consist of pre-constructed concrete beams, square in cross section (100 mm x 100 mm) and shaped in a zigzag formation (Salix, Thetford, Norfolk, UK) (Figure 2). The footprint of each individual micromeasure is 1.0 m x 0.5 m.

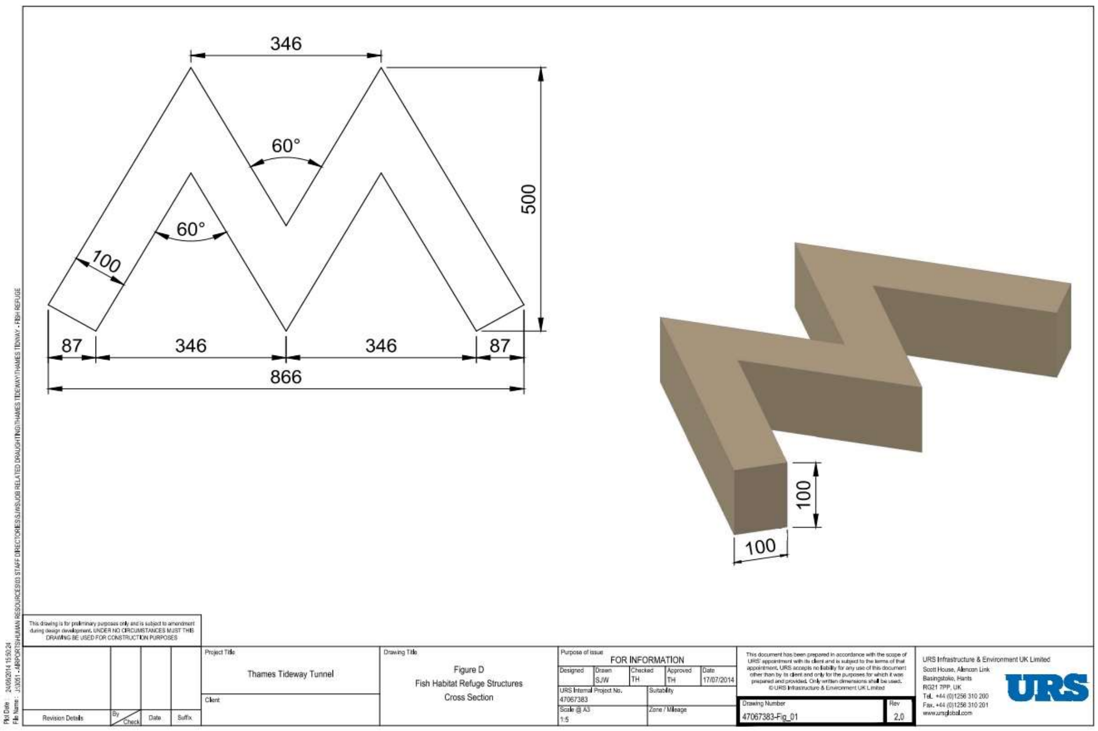

Figure 2: Habitat micromeasure structure.

3.1 Site set up and programme

Sixty micromeasures structures were laid out in six rows of ten structures covering an area of 60 m^2 (Figure 3). This was referred to as the experimental site. The rows of structures were laid on the intertidal foreshore, perpendicular to the tidal stream with the lowest point approximately 2 m above lowest astronomical tide (LAT). An independent reference site where no structures would be deployed was identified approximately 30 m upstream of the experimental site.

Sampling at the reference site mirrored the experimental site with the aim of ensuring that any differences in observations of fish behaviour between the two sites were a result of the micromeasures structures and not due to other environmental conditions at the site. It was therefore important that conditions at the reference site replicated those at the experimental site as closely as possible, including substrate type, shoreline profile and wave exposure.

Figure 3: Sixty micromeasures structures laid out at the experimental site on the foreshore of Chiswick Eyot, River Thames.

Sampling was undertaken during ebbing tides on alternate days at the experimental and reference sites over a period of 10 days (5 days at the experimental site; 5 days at the reference site) from 30 June to 13 July 2016. This was known as the treatment period. The micromeasures were removed on the 14th July and the foreshore substrate raked by hand to remove any undulations created by the structures. Monitoring continued at the experimental and reference sites (3 days at the experimental site; 3 days at the reference site) from 15th to 25th July, referred to as the control period. The control period enabled data to be collected from exactly the same location that the micromeasures were deployed to identify if any significant findings were a result of variations between the experimental and reference sites.

3.2 Materials and methods

3.2.1 Sonar imaging

The experimental and reference sites were monitored during mid ebb tide on alternate sampling days using Adaptive Resolution Imaging Sonar (ARIS) (Sound Metrics, Bellevue, Washington, USA; Model: 1800) for a total of 10 days during the treatment period (5 days per site) and 6 days during the control period (3 days per site) (Figure 4). Operated at high frequency (1.8 MHz: 14^{o} x 29^{o} field of view created by 96 beams of 0.3° width), the ARIS had a 5.7 m field of view, which began 2.5 m from the ARIS transponder. The ARIS was deployed 1 m above lowest astronomical tide from a 0.5 m high bed mounted aluminium frame at low water prior to onset of the flood tide. Monitoring commenced as soon as water levels decreased sufficiently during the ebb tide to allow access to Chiswick Eyot via boat. A 115 ah 12 v deep cycle battery powered the ARIS, a pan and tilt unit and a laptop on which the footage was captured. Monitoring ceased as soon as water level fell below the transponder of the ARIS.

Figure 4: ARIS set up ready to monitor the reference site once submerged by the tide during the treatment period. The experimental site is pictured to the right (30 m downstream).

3.2.2 Seine netting

Upon completion of ARIS recording towards the end of the ebbing tide, seine nets (25.0 m x 2.7 m with 3 mm knotless mesh; Collins Nets, Bridport, Dorset, UK) were deployed simultaneously around both the experimental and reference sites on 10 and 8 days during the treatment and control periods, respectively (Figure 5). All fish captured were identified to species level, counted and total length measured (L_T). Where fish counts were high, L_T was measured for only the first 50 individuals.

Figure 5: Seine netting simultaneously around the experimental and reference sites once water depth becomes too low for observations with ARIS.

3.3 Environmental data

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 at Chiswick Pier, 500 m upstream from the study site, from 30 June to 26 July 2016. From these measurements, water depth and salinity were calculated (Fofonoff and Millard, 1983). Replicates at the experimental and reference sites during the treatment and control periods were evenly distributed around spring tides.

3.4 Data analysis

3.4.1 Sonar imaging

Monitoring commenced as soon as water levels decreased sufficiently during the ebb tide to allow access to Chiswick Eyot via boat. During each replicate or sampling period footage was viewed by the sampling team in real time on the laptop stationed on the Eyot for a period of two hours ending 10 minutes prior to exposure of the ARIS by the ebbing tide.

Fish use of the experimental and reference sites was quantified using two metrics:

- total number of fish observation events; and
- percentage of fish holding station.

Each observation event was defined by a fish moving into view and out again. Adverse conditions such as extreme weather occasionally caused temporary cessation of monitoring. Therefore, all observation events were calculated as number of fish observation events per hour (f h^{-1}).

For the purpose of data analysis, holding station was defined in the present study as a fish maintaining lateral and longitudinal position for ≥ 5 s at a time. Other metrics assessed included fish net ground speed of travel from one side of the viewing area to the other (based on the shortest possible route), direction of movement and orientation. These metrics were also compared across the first and second half of the tidal cycle. Highest velocities are anticipated during the first half of the ebb tide, and so differences between observations of fish behaviour during these periods may be important in understanding the role of the micromeasures in maintaining position against velocity.

Fish were measured using ARISFish (SoundMetrics). Fish lengths recorded through sonar imaging processing software have previously been demonstrated to provide relatively accurate estimates of fish lengths when compared to manually measured fish (Burwen *et al*., 2010).

Independent *t* tests were used to compare total number of fish observation events per hour, percentage of fish holding station, net ground speed, direction of movement, orientation and length between experimental and reference sites for the treatment and control periods. Shapiro-Wilk and Levene's tests revealed that all data met the assumptions of normal distribution and homogeneity of variance, respectively ($p > 0.05$).

3.4.2 Seine netting

Independent *t* tests were used to compare species diversity, total number and length by species between experimental and reference sites for the treatment and control periods. Shapiro-Wilk and Levene's tests revealed that all data met the assumptions of normal distribution and homogeneity of variance, respectively ($p > 0.05$). Species diversity was calculated according to the Simpson's Diversity Index.

3.4.3 Environmental data

Shapiro-Wilk and Levene's tests identified that all data met the assumptions of normal distribution and homogeneity of variance, respectively ($p > 0.05$). Independent *t* tests were used to compare mean water temperature, depth and salinity recorded over each 2 hour ARIS sampling period. Salinity was reported in Practical Salinity Units (PSU).

4 Results

The results from the sonar imaging analysis and seine netting are considered separately below in sections 4.1 and 4.2, respectively.

4.1 Sonar imaging

Thirty-two hours of ARIS footage were viewed, identifying a total of 693 fish observation events at the experimental and reference sites during treatment and control periods. Fish length ranged from 36 to 773 mm (mean [± standard deviation, SD] = 24.0 [± 15.2]).

During the treatment period, mean (± SD) total number of fish detected per hour did not differ significantly between sites (experimental = 17.4 [± 7.4] f h^{-1}; reference = 33.8 [± 21.7] f h^{-1}, independent *t* test: $t_{4.92} = -1.5987$, $p > 0.05$) (Figure 6). However, a greater mean percentage of fish held station at the experimental site (26.5 [± 5.9] %) compared to the reference site (9.0 [± 4.4] %) ($t_{7.3} = 5.3281$, $p < 0.001$) (Figure 7).

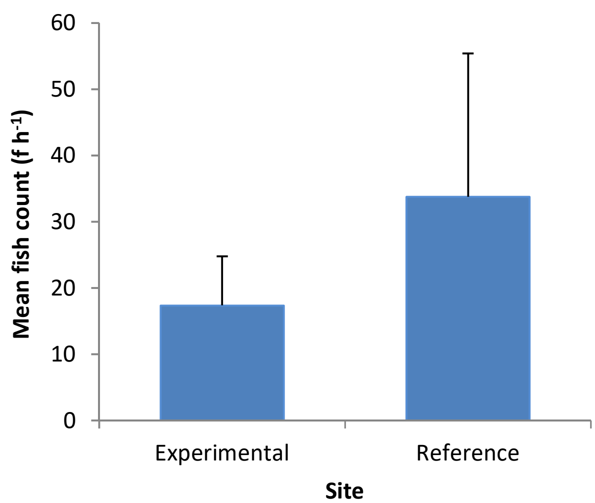

Figure 6: Mean (± SD) total number of fish per hour recorded at the experimental (micromeasures present) and reference (no micromeasures) sites during the treatment period.

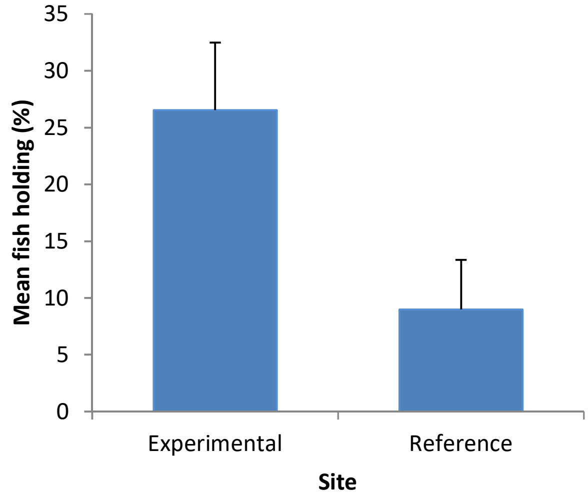

Figure 7: Mean (± SD) % of fish holding station recorded at the experimental (micromeasures present) and reference (no micromeasures) sites during the treatment period.

The mean (± SD) total number of fish detected per hour did not differ between the experimental and reference sites during the control period (experimental = 18.6 [± 10.7] f h^{-1}; reference = 21.7 [± 10.9] f h^{-1}, $t_{4.0} = -0.3466$, $p > 0.05$) (Figure 8). Similarly, there was no difference between mean percentage of fish that held station at the experimental site (2.8 [± 2.5] %) compared to the reference site (5.1 [± 4.6] %) during the control period ($t_{3.13} = -0.7731$, $p > 0.05$) (Figure 9).

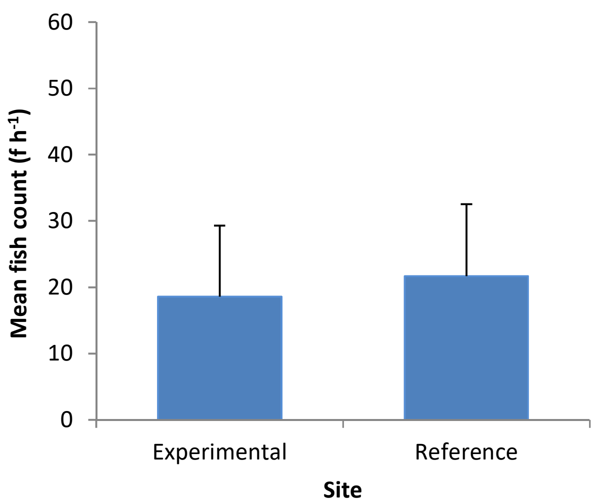

Figure 8: Mean (± SD) total number of fish recorded per hour at the experimental and reference sites during the control period.

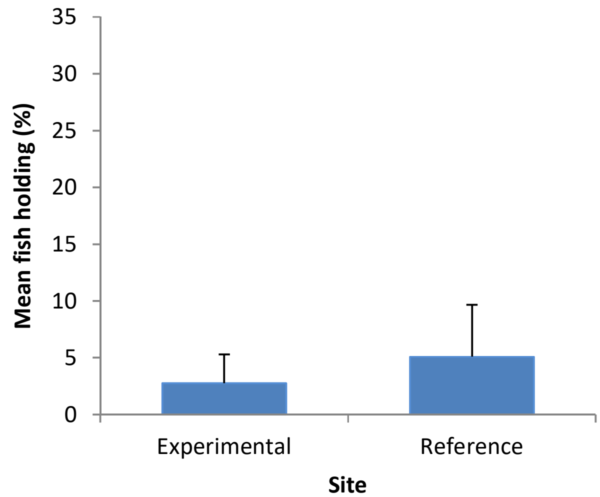

Figure 9: Mean (± SD) % of fish holding station recorded at the experimental and Reference sites during the control period.

Mean (± SD) fish length was similar between sites for treatment (experimental = 209 [± 54] mm; reference = 227 [± 30] mm; $t_{6.3}$ = -0.5056, $p > 0.05$) and control (experimental = 31.7 [± 6.0] mm; reference = 27.3 [± 6.1] mm; $t_{4.0}$ = 0.8890, $p > 0.05$) periods.

An example of a fish holding station around the micromeasures is presented in Figure 10. Mean (± SD) number of these holding events at the experimental site was 4.7 (± 2.6) f h^{-1}. Length of fish using the micromeasures ranged from 53 to 566 mm. There was no difference in mean (± SD) length of fish at the experimental site that displayed holding behaviour (153 [± 49] mm) compared to those that did not (229 [± 59] mm) ($t_{7.7}$ = -2.2189, $p > 0.05$).

Fish predominately held station immediately downstream of the micromeasure structures (48.5 [± 23.5] %), although this behaviour was also displayed immediately upstream (24.7 [± 16.4] %) and equidistant to both up and downstream of the structures (26.7 [± 19.2] %). There was no evidence of schooling or burst and glide behaviours whilst fish held station. A small number of individuals demonstrated low stress behaviours including forward run or dart type movements to utilise the structures to assist passage upstream, and explorative activity where fish passed over the structures a number of times.

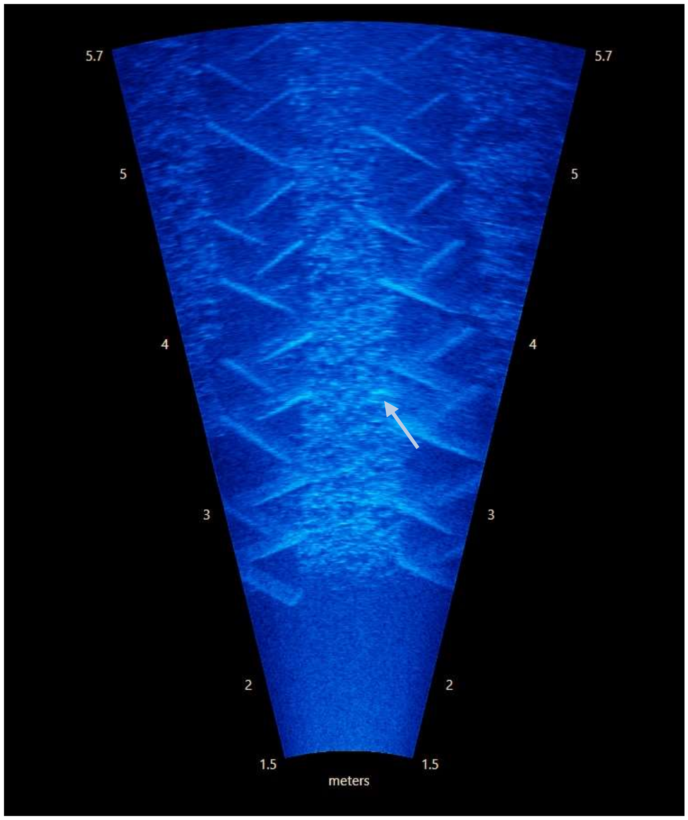

Figure 10: Still image extracted from ARIS footage depicting fish holding station immediately upstream of the habitat micromeasures, approximately 3.6 m distant from the ARIS transducer on 6 July 2016. Direction of flow = left to right.

There was no significant variation in the net speed, direction of movement or orientation between the experimental and reference sites during the treatment and control periods ($p > 0.05$). Similarly, the mean total number of fish observation events, percentage of fish holding station, net speed, direction or movement or orientation did not differ between the first and second half of the ebb tide at the experimental and reference sites during the treatment and control periods ($p > 0.05$).

4.2 Seine netting

Mean (± SD) total number of fish caught during seine netting did not differ between experimental and reference sites during treatment (experimental: 63.2 [± 47.9]; reference: 60.4 [± 77.3]; $t_{15.0} = 0.0973$, $p > 0.05$) or control (experimental: 272.9 [± 167.9]; reference: 143.3 [± 132.3]; $t_{13.3} = 1.7151$, $p > 0.05$) periods.

Mean (± SD) species diversity of fish caught during seine netting did not differ between experimental and reference sites during treatment (experimental: 0.2 [± 0.2]; reference: 0.4 [± 0.3]; $t_{15.8} = -1.9331$, $p > 0.05$) or control (experimental: 0.3 [± 0.2]; reference: 0.5 [± 0.1]; $t_{12.9} = -1.5520$, $p > 0.05$) periods.

A total of eleven species were caught (Table 1). Of these, chub (*Squalius cephalus*, *n* = 2) were only caught at the experimental site. Perch, (*Perca fluviatilis*, *n* = 1), stone loach (*Barbatula*, *n* = 2) (Figure 11) and zander (*Sander lucioperca*, *n* = 1) were only caught at the reference site. Number of fish caught and mean length per species for each replicate are reported in Appendix I.

Table 1: Mean (± SD) number of fish and length of species caught by seine netting simultaneously at the experimental and reference sites during the treatment and control periods.

Species	Mean (± SD) Number of Fish (*n*)				Mean (± SD) Length (mm)			
	Treatment		Control		Treatment		Control	
	Experimental	Reference	Experimental	Reference	Experimental	Reference	Experimental	Reference
Stickleback	1.0 (± 1.8)	0.8 (± 1.0)	0.0	0.3 (± 0.5)	224 (± 23)	214 (± 64)		290 (± 85)
Bass	0.0	0.0	0.8 (± 1.2)	0.9 (± 1.5)			263 (± 33)	254 (± 22)
Chub	0.2 (± 0.6)	0.0	0.0	0.0	192			
Goby	5.0 (± 8.6)	3.7 (± 8.3)	223.9 (± 168.9)	81.1 (± 84.1)	228 (± 40)	222 (± 45)	210 (± 12)	213 (± 9)
Dace	4.8 (± 6.0)	8.4 (± 17.3)	3.6 (± 5.2)	9.4 (± 14.9)	265 (± 98)	340 (± 145)	333 (± 153)	389 (± 119)
Eel	0.6 (± 1.1)	0.4 (± 1.3)	0.4 (± 0.7)	0.0	894 (± 118)		738 (± 4)	
Flounder	51.6 (± 39.4)	46.9 (± 73.9)	43.9 (± 27.3)	51.3 (± 58.4)	274 (± 30)	287 (± 26)	344 (± 35)	349 (± 50)
Perch	0.0	0.1 (± 0.3)	0.0	0.0		610		
Stone Loach	0.0	0.1 (± 0.3)	0.0	0.1 (± 0.4)		220		450
Zander	0.0	0.0	0.0	0.1 (± 0.4)				650
Bullhead	0.0	0.0	0.4 (± 0.7)	0.1 (± 0.4)		160	355 (± 78)	
Species Diversity	0.22 (± 0.21)	0.45 (± 0.31)	0.34 (± 0.17)	0.46 ± 0.13				

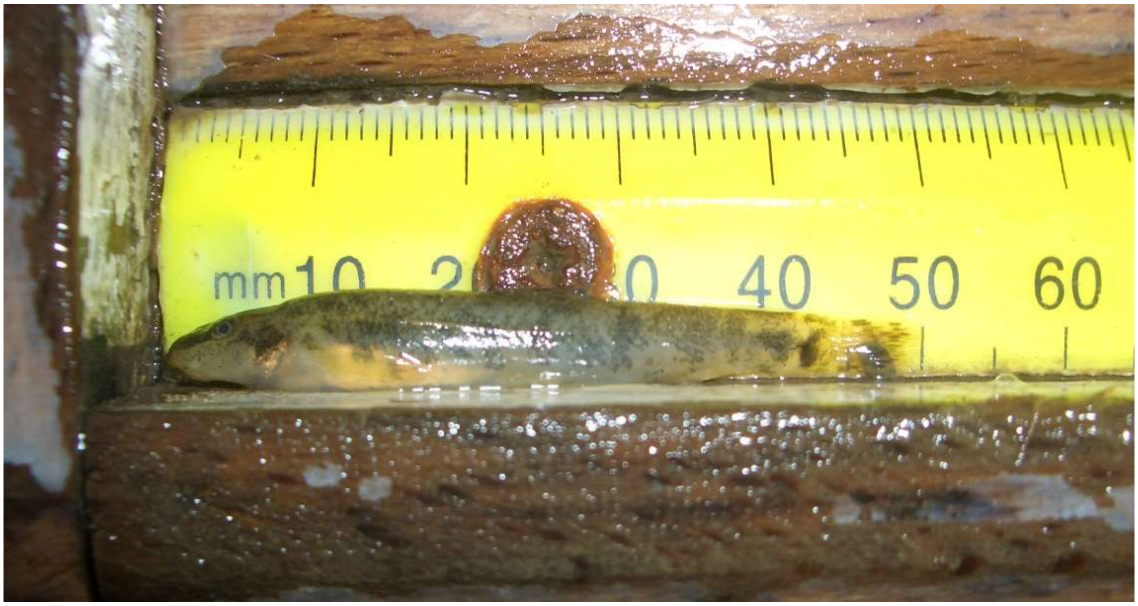

Figure 11: Stone loach, Barbatula barbatula, caught at the reference site on 25 July 2016.

Seven species were caught at both the experimental and reference sites (Table 1). Flounder(Figure 12) were most abundant during the treatment period, followed by dace(Figure 13) and common goby (Figure 14). Three-spined stickleback, *Gasterosteus aculeatus*, (Figure 15) and European eel, *Anguilla anguilla*, (Figure 16) were also caught. During the control period, bass and bullhead, *Cottus gobio*, (Figure 17) were also caught. There was no difference between mean total number of fish or length between the experimental and reference sites during the treatment or control period for any species caught ($p > 0.05$).

Figure 12: Flounder, Platichthys flesus, caught at the experimental site on`11 July 2016.

Figure 13: Dace, Leuciscus leuciscus, caught at the reference site on 22 July 2016.

Figure 14: Common goby, Pomatoschistus microps, caught at the reference site on 19 July 2016.

Figure 15: Three-spined stickleback, Gasterosteus aculeatus, caught at the reference site on 8 July 2016.

Figure 16: European eel, Anguilla anguilla, caught at the experimental site on 7 July 2016.

Figure 17: Bullhead, Cottus gobio, caught at the reference site on 19 July 2016.

4.3 Environmental data

There was no difference between mean temperature and salinity recorded at the experimental and reference sites during ARIS monitoring on the ebb tide throughout both treatment and control periods. Depth was found to be 0.26 m higher at the reference compared to the experimental site during the control period (Table 2). However, depth during the control period at reference site is not relevant to the aim of the study to assess holding at the micromeasures, for which key comparison conditions are depth during treatment period between experimental and control sites and experimental site during treatment and control periods. It was found that none of these varied significantly.

Table 2: Temperature, depth and salinity recorded during each 2 h ARIS monitoring period on 16 days between 30 June and 25 July 2016.

Period	Site	Temperature (°C)				Depth (m)				Salinity			
		Mean (± SD)	t	df	p	Mean (± SD)	t	df	p	Mean (± SD)	t	df	p
Treatment	Experimental	17.92 (± 0.77)	0.0557	8.0	0.957	2.12 (± 0.07)	-2.2995	7.6	0.469	0.32 (± 0.02)	-0.0317	7.4	0.052
	Reference	17.90 (± 0.76)				2.24 (± 0.09)				0.32 (± 0.01)			
Control	Experimental	21.20 (± 0.86)	0.8018	2.7	0.487	2.06 (± 0.02)	-4.0667	2.2	0.048*	0.28 (± 0.08)	0.2113	3.5	0.844
	Reference	20.19 (± 2.01)				2.32 (± 0.11)				0.27 (± 0.06)			

* $p < 0.05$

5 Discussion

5.1 Summary of results

Habitat micromeasures were utilised by fish for holding station during the ebb tide when deployed on the intertidal foreshore of the Thames Tideway. At a reference site and during a control period where there were no micromeasures present, a significantly lower proportion of fish were observed holding station. Fish predominately held station immediately downstream of the structures, although one quarter selected to maintain position immediately upstream with no evidence of schooling. There was no difference in the number of fish recorded in the vicinity of the micromeasures compared to the reference site. Similarly, there was no difference in the mean species diversity between the experimental and references sites during the treatment and control periods.

5.2 Fish utilisation of the Thames Tideway

The Thames Tideway forms crucial habitat for several environmentally and socio-economically important fish species that occupy a number of ecological guilds (Elliott and Taylor, 1989). Guilds describe the mechanisms by which fish utilise estuaries and include marine juveniles, estuarine residents, adventitious freshwater species and diadromous species.

The Thames Tideway is an important nursery ground for marine juveniles including commercially important species such as sole, thicklip grey mullet, thinlip grey mullet, bass, sprat, dab, herring and whiting (Colclough et al., 2002). Estuarine habitat is highly productive, providing valuable feeding opportunities, refuge from predation (Able, 2005) and rapid growth when compared to marine environments (Bergman et al., 1988). Estuarine residents such as flounder (Wheeler, 1988; Jager, 1999; Skerrit, 2010) and common goby (Turnpenny *et al.*, 2004) spawn in outer estuaries prior to migrating upstream as juveniles. Adventitious freshwater species such as dace may occupy estuaries as juveniles and migrate to freshwater to spawn in the spring (Lucas *et al*., 1998). The small size of such inhabitants puts them at high risk of displacement downstream in locations of increased velocity (particularly where there is little benthic roughness), and may also prevent movement back upstream.

Successful passage upstream through the Tideway is also critical to diadromous species such as adult Atlantic salmon, sea trout, and European smelt, *Osmerus eperlanus,* which travel from the sea upstream through the estuary to reach freshwater spawning grounds. Having undergone serious declines throughout parts of Europe, including a number of regions in the UK when compared to historic catches (Environment Agency, 2009; Harris and Milner, 2006), Atlantic salmon are listed as a protected species under Annex II of the Habitats Directive (EC, 1992) and sea trout are regarded as threatened under the UK Post-2010 Biodiversity Framework (2012), which replaced the UK Biodiversity Action Plan (JNCC, 2010). European eel are also diadromous, often migrating as juveniles upstream to freshwater where they mature. European eel are designated as critically endangered (Freyhof and Kottelat, 2008) with recruitment having diminished by more than 90% since the early 1980s (Dekker, 2003; ICES, 2012) resulting in populations lower than sustainable conservation limits (Bult and Dekker, 2007).

For the aforementioned fish populations that depend on inhabiting the Tideway, excessive velocities can have a number of negative impacts. Many species, including juvenile eels (White and Knights, 1997a), adult salmonids (Aprahamian *et al*., 1998; Potter, 1988), flounder (Jager, 1999; Wheeler, 1988), bass (Jennings and Pawson, 1992) and European smelt utilise Selective Tidal Stream Transport (STST) to transition through estuaries. Selective Tidal Stream Transport is an energy preserving behavioural mechanism whereby individuals travel upstream with the flood tide and retire to the estuary bed during the ebb to maintain longitudinal position along a watercourse. Other species such as post larval sole make diurnal vertical movements, rising into the water column at night (Marchand and Masson, 1988).

Increased velocities resulting from encroachment combined with the absence of suitable substrate may adversely impact fish attempting to hold position during the ebb tide, or fish that make diurnal migrations into the water column, by (1) exceeding swimming capabilities and displacing fish from the estuary and (2) delaying migrations and increasing energy expenditure. Where fish swimming ability is sufficient to withstand high velocities, adverse effects may still arise from delayed migrations and increased energy expenditure to avoid displacement downstream during ebb tides. Augmented energy reserve depletion can increase susceptibility to disease (Schreck *et al.*, 2006), probability of spawning in suboptimal habitats (Caudill *et al.*, 2007; Naughton *et al.*, 2005), and pre and post spawning mortality (Budy *et al.*, 2002; Geist *et al.*, 2003; Gerlier and Roche, 1998). Other impacts include decreased predator evasion (Ryan *et al*., 2003), gonad production (Bernatchez and Dodson, 1987), ova viability (de Gaudemar and Beall, 1998), capability to reach spawning grounds (Bernatchez and Dodson, 1987) and overall reproductive success (Geen, 1975).

Potential effects of increased velocities such as delayed migration and increased energy expenditure will be cumulative for fish that must pass through a number of encroached sites (Jackson and Moser, 2012; Naughton *et al*., 2005). These collective impacts may be critical for species that cease feeding during migrations such as juvenile European eel (Bardonnet and Riera, 2005) and adult salmonids (Jonsson *et al*., 1997).

5.3 Observations of fish use of the micromeasures structures

Over a quarter of fish observed at the site of the habitat micromeasures deployed in the Thames Tideway used the structures to hold station. This was significantly more than the proportion holding station at the reference site, and during the control period where there were no structures present. Fish preferentialy identify hydrodynamic areas where energetic expenditure can be reduced by selecting low drag locales or adopting specialised behaviours. Baffle structures similar to those used in Larinier super-active baffle fish passes create areas of decreased velocity enabling fish to hold station whilst minimising energy expenditure (Wilson *et al.*, 1990; THA 2014a). In a laboratory flume, trials using habitat micromeasures prototypes indicated that 30 - 40 mm sand smelt, *Atherina presbyter*, and 40 - 80 mm roach, *Rutilus rutilus*, tended to reside in residual turbulent eddies in the wake of high turbulent flow at input current velocities ranging from 0.1 to 0.7 m s^{-1} (THA 2014a). This has also been demonstrated in other studies where fish exploit areas of turbulent flow with uniform vortices (Liao *et al*., 2003; Taguchi and Liao, 2011) and where turbulent length scales do not approach body length (Webb and Cotel, 2010). In the field, fish can be observed holding position in similar hydraulic conditions created by spoiler baffles in culverts (MacDonald and Davies, 2007), coarse benthic substrates such as cobbles and boulders (Rinóon and Lobón-Cerviá, 1993) and woody debris (Crook and Robertson, 1999).

In the present study fish predominately held station immediately downstream of the micromeasures (48.5 %). During prototype flume trials, fish that sheltered downstream would retain a distance of 5 - 10 body lengths, thought to be a result of retaining the capacity for forwards escape via burst swimming (THA 2014a). A quarter of fish in the present study exhibited this behaviour, holding station equidistant to both up and downstream structures. A high proportion of fish also maintained position immediately upstream of structures in laboratory tests, as displayed by a quarter of fish at the experimental site.

In addition to the structures' effectiveness for creating habitat where fish can hold station, other behaviours relating to hydraulic conditions can be indicative of the deployment's success. For example, burst and glide behaviours that can be symptomatic of stress during high flows (THA 2014a) were not observed at the experimental site. Conversely, a number of fish demonstrated unperturbed behaviours (THA 2014a) including forward run or dart type movements to utilise the structures to assist passage upstream, and explorative activity where fish passed over the structures a number of times. Schooling behaviour, which is also believed to provide energetic benefits to fish whilst reducing stress for some species (THA 2014a), was not evident at the micromeasures or the reference site in the present study, although it was observed in the earlier flume studies.

Optical video monitoring of the micromeasures undertaken during the second phase of the micromeasures study in the clear waters of the River Test chalk stream, Hampshire, revealed that fish were immediately attracted to the structures (THA 2014b). The present study detected no difference in the number of fish observed at the experimental site when the micromeasures were present compared to the reference site without any structures. In the macrotidal and turbid Thames Tideway, fish are unlikely to detect the micromeasures' presence until moving through the site. However, those fish that encountered the site were more likely to attempt to avoid displacement away to potentially less energetically favourable locations by holding station. Although higher proportions of fish were holding station at the experimental site it would not necessarily be expected that absolute numbers of fish at the experimental site would be higher. Fish numbers in the Thames are relatively high during the spring, meaning that a comparable number of fish could be moving through the reference site, as holding station on the experimental site, at any given moment. Furthermore, holding behaviour for any one individual fish may last from 5 seconds to 2 hours meaning that fish could come and go over the period of the trial and thus may not hold station at the same time.

5.4 Observations from seine netting surveys

Seine catches were dominated by juvenile flounder, common goby and dace. Number of fish caught, species diversity and species length did not vary between experimental and reference sites, suggesting that at the stage of the tidal cycle seine netting was carried out, weak swimmers such as small species and juveniles were able to successfully occupy the submerged margins of the intertidal zone irrespective of presence of the micromeasures.

An absence of larger fish in seine catches suggests that adult fish were not using the intertidal margins during the latter part of the ebb tide cycle. In contrast, larger fish (up to 566 mm) were observed in the ARIS footage of the micromeasures structures. This suggests that the habitat micromeasures provided habitat for a wider range of fish sizes when velocities were at their highest during mid-tidal cycle. At high and low water, these fish conceivably move to deeper waters whilst velocities in such locations are lower.

6 Conclusions

The study aimed to determine whether:

i) habitat micromeasures deployed on the foreshore were more likely to be used by fish when compared to similar natural habitat during the ebb tide;

ii) fish in the experimental site were more likely to 'hold station' than fish using the reference site

Specifically in relation to the aims of the study, no difference was observed in the number of fish recorded in the vicinity of the micromeasures compared to the reference site, and therefore habitat micromeasures were not more likely to be used by juvenile fish than similar natural habitat without structures (Aim i). In the highly dynamic and turbid environment of the Thames Tideway, fish may be unable to identify the fine scale hydraulic features created by the micromeasures until encountering the site of the structures. Where micromeasures are deployed in high velocity applications, fish adopt searching behaviour to identify the most suitable areas of refuge or passage.

A significantly greater mean percentage of fish held station at the experimental site compared when the micromeasures were installed to the reference site (Aim ii). The structures provided a range of hydraulic conditions such as low velocity areas benefitting a variety of fish sizes, encompassing both juveniles and adults. This is important because many of the fish species and life stages that inhabit the Tideway must hold station during ebb tides, thereby minimising energy expenditure and avoiding displacement from the estuary. Seine netting results suggested that current velocities in the intertidal zone towards the end of the ebb tide at the study site were sufficiently low that weak swimmers and juveniles were able to successfully occupy this habitat irrespective of presence of the micromeasures. There were few larger fish and no variation in species diversity, numbers, or species lengths caught. This highlighted the advantageous application of micromeasures for fish of a wide range of fish sizes during mid tidal cycle when velocities were highest.

Overall, the habitat micromeasures were successful in providing habitat for fish to hold station during the ebb tide. Results demonstrate that fish utilise areas of advantageous hydraulic conditions around the structures that likely minimised the energetic costs of maintaining position in high velocity flows.

Project design principle IRVR.01, which guides the development of the in-river structures, states that "…features integral or adjacent to the foreshore structure that can provide refuge to migrating fish shall be included where practicable". This study demonstrates that artificial habitat micro-measures could, if installed, provide refuge for migrating fish. It is therefore recommended that consideration is given to including these measures in accordance with design principle IRVR.01, where it is practicable to do so.

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Appendix 1– Fish mean length data from seine netting surveys

Table 3: Total number (n) of fish caught by seine netting at the experimental (E) and reference (R) sites during the treatment and control periods.

Date	Period	Site	Replicate	Species (*n*)											Species Diversity
				Stickleback	Bass	Chub	Goby	Dace	Eel	Flounder	Perch	Loach	Zander	Bullhead	
30/06/2016	Treatment	E	1					1		14					0.13
		R	1	1						2					0.67
01/07/2016		E	2							10					0.00
		R	2												0.00
04/07/2016		E	3							9					0.00
		R	3					1		1		1			1.00
05/07/2016		E	4					1		78					0.03
		R	4				2	10		242					0.09
06/07/2016		E	5				1	14		128					0.19
		R	5	1				3		4					0.68
07/07/2016		E	6	3			9	16	2	39					0.62
		R	6	1			1	4		92					0.12
08/07/2016		E	7	2		2	6	9	3	77					0.39
		R	7	2			5	4		34					0.42
11/07/2016		E	8				3	2		43					0.20
		R	8				2	57		35					0.50
12/07/2016		E	9	5			28	4	1	86					0.47
		R	9	3				3	4	26	1				0.49
13/07/2016		E	10				3	1		32					0.21
		R	10				27	2		33					0.53
15/07/2016	Control	E	1				21	1		40					0.48
		R	1				85	3		114			1		0.51
18/07/2016		E	2		2		184			80					0.43
		R	2		1		14	44		7					0.51
19/07/2016		E	3		1		33	1		19					0.51
		R	3		2		280	2		159				1	0.48
20/07/2016		E	4				229	3		65					0.36
		R	4				37			6					0.25
21/07/2016		E	5		3		439	4							0.03
		R	5				58	7		74					0.54
22/07/2016		E	6				344	16	2	26				2	0.22
		R	6	1	4		34	16		9					0.64
23/07/2016		E	7				104	1		65				1	0.49
		R	7	1			86	3		29					0.42
25/07/2016		E	8				437	3	1	56					0.21
		R	8				55			12		1			0.32
			TOTAL	20	13	2	2527	236	13	1746	1	2	1	4	

Table 4: Mean length of fish species caught by seine netting at the experimental (E) and reference (R) sites during the treatment and control periods.

Date	Period	Site	Replicate	Mean Length (mm)										
				Stickleback	Bass	Chub	Goby	Dace	Eel	Flounder	Perch	Loach	Zander	Bullhead
30/06/2016	Treatment	E	1					19.0		22.1				
		R	1	15.0						26.5				16.0
01/07/2016		E	2							25.6				
		R	2											
04/07/2016		E	3							27.8				
		R	3					18.0		28.0		22.0		
05/07/2016		E	4					25.0		27.6				
		R	4				20.5	28.1		26.4				
06/07/2016		E	5				22.0	21.7		24.6				
		R	5	22.0				22.7		27.0				
07/07/2016		E	6	20.7			19.8	27.5	91.5	24.9				
		R	6	15.0			31.0	31.5		26.2				
08/07/2016		E	7	25.0		192.5	18.8	23.4	76.7	30.0				
		R	7	25.5			18.8	25.5		30.2				
11/07/2016		E	8				22.0	25.5		29.9				
		R	8				22.5	46.6		32.1				
12/07/2016		E	9	21.4			30.0	49.8	100.0	30.8				
		R	9	29.3			21.5	62.3		32.0	61.0			
13/07/2016		E	10				24.0	20.0		31.1				
		R	10				19.2	37.0		31.3				
15/07/2016	Control	E	1				18.6	25.0		28.8				
		R	1				19.9	30.3		30.1			65.0	
18/07/2016		E	2				22.3	23.5		31.8				
		R	2		28.0		21.5	53.3		30.3				
19/07/2016		E	3		24.0		20.9	35.0		33.7				
		R	3		24.0		20.4	24.5		30.3				
20/07/2016		E	4				21.1	25.3		34.3				
		R	4				21.0			40.3				
21/07/2016		E	5		28.7		21.1	28.3						
		R	5				22.9	49.9		34.4				
22/07/2016		E	6				22.6	31.4	73.5	37.0				41.0
		R	6	23.0	24.3		21.3	45.0		43.7				
23/07/2016		E	7				20.8	28.0		35.9				30.0
		R	7	35.0			22.0	30.7		34.1				
25/07/2016		E	8				20.5	70.0	74.0	39.4				
		R	8				21.2			36.0		45.0		
			MEAN	23.2	25.8	192.5	21.7	32.8	83.1	31.0	61.0	33.5	65.0	29.0
			SD	6.1	2.3		2.8	13.2	12.0	4.8		16.3		12.5

Appendix 2 Report: 522R0701 Flume Experiments for Structures Aiding Migration

Flume Experiments for Aiding Migration on Juvenile Fish

Prepared by: Jay Willis

Document No. 522R0701

Date: 12/03/14

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Report Reference:		**Revision Date:**	
Prepared by:	Jay Willis	**Position:**	Principal Scientist
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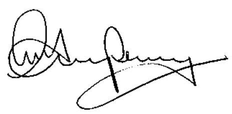
Approved by:	Richard Horsfield	**Position:**	Director
Approver's signature:		**Date:**	19 March 2014

SUMMARY

The work described here aimed to investigate the potential for use of man-made structures that will act as easements for fish passage within the ecological corridor of the Thames Tideway. The need for such interventions stems from the progressive long-term urban encroachment which has narrowed the channel over a period of centuries. One of the effects of encroachment has been to accelerate fluvial and tidal flows within the hydraulic channel, particularly within the central London area, which creates challenging conditions for small, weaker-swimming juvenile fish that have to negotiate water currents during their migration and dispersal phases. During migration, fish take advantage of tidal currents during the phase when they will move fish in the preferred direction (upstream or downstream) and the tidal excursion of up to 12 km can carry fish a considerable distance on a single tide. The purpose of the easement structures is to provide shelter where they can rest with minimum energy expenditure during the reverse tidal phase. It is envisaged that easement structures would be located at critical 'staging posts' where fish could hold station during their migratory passage.

The present study reviewed literature on easement structures used in other fish passage applications and identified concepts that could be considered for the Thames Tideway. As well as performing as fish passage easements, the Thames Habitats Working Group identified a number of other important requirements. The most critical one was that any structures would not project vertically into the water column by more than, say, 0.3 m, as they would otherwise present a limitation or hazard to small vessel navigation. Secondly, it was preferred that any structures could fabricated from timber, providing a more natural aesthetic and presenting less of a threat of damage to vessels grounding on them. For the purposes of the Thames Tunnel Project, it was also desirable that any designs could be incorporated into the scour-protection aprons that will be installed at each CSO point.

After consideration of various study methods, including computational fluid dynamics (CFD) modelling, physical modelling in a laboratory flume and direct experimentation in the field, the flume option was chosen as the most cost-effective, using THA's small annular flume at our Ashurst laboratory.

Key findings

- Fish use structures by sheltering in front as well as behind. When in front they shelter much closer to the structure (often with tail touching) than when behind when they are 5-10 body lengths off.
- Fish are less stressed in flow, in schools, than in still water alone.
- Their behaviours seem moderated by the need to maintain a forward burst capacity, i.e. clear water, or other school members, immediately in front; allowing a school escape route.

- Fish schools can be assessed as if they were super-individual units in faster streams. There is a history of this type of analysis with the smallest school of obligate schooling fish being known as an 'atomic unit' in modelling terms.
- Structures which are sharp edged and produce high turbulence are most effective
- Structures which form sheets of high speed laminar flow are to be avoided
- Fish do not shelter in the areas of highest turbulence but stand-off a structure, it seems they sense the residual turbulent eddies of a highly turbulent area and are comfortable behind in flow which has been slowed but which does not have a strong vertical component
- Schooling behaviour reduces individual stress and all schoolers benefit from school hydrodynamics. Loners use the structures differently (which is likely to be species dependent behaviour)
- The best structures tested are chevron shapes, which produce intense turbulence with short mixing scales close to the structure.
- Zigzag structures of timber beams (square in cross section around 50 mm to 100 mm), similar to ribs used to aid fish passage on weirs, with a 60 ^{o} angle on the zigzags (similar to Larinier fish passes) should be tested in the field. In particular, the optimal distance between ribs of various cross-sectional heights, and frequency of zigzags, are appropriate targets for field trials.

Contents

INTRODUCTION

Background

The work described here aims to investigate the potential for use of man-made structures that will act as easements for fish passage within the ecological corridor of the Thames Tideway. The need for such interventions stems from the progressive long-term urban encroachment which has narrowed the channel over a period of centuries. One of the effects of encroachment has been to accelerate fluvial and tidal flows within the hydraulic channel, particularly within the central London area, which creates challenging conditions for small, weaker-swimming juvenile fish that have to negotiate water currents during their migration and dispersal phases. During migration, fish take advantage of tidal currents during the phase when they will move fish in the preferred direction (upstream or downstream) and the tidal excursion of up to 12 km can carry fish a considerable distance on a single tide. The purpose of the easement structures is to provide shelter where they can rest with minimum energy expenditure during the reverse tidal phase. It is envisaged that easement structures would be located at critical 'staging posts' where fish could hold station during their migratory passage.

The study initially reviewed literature on easement structures used in other fish passage applications and identified concepts that could be considered for the Thames Tideway. As well as performing as fish passage easements, the Thames Habitats Working Group identified a number of other important requirements. The most critical one was that any structures would not project vertically into the water column by more than, say, 0.3 m, as they would otherwise present a limitation or hazard to small vessel navigation. Secondly, it was preferred that any structures could fabricated from timber, providing a more natural aesthetic and presenting less of a threat of damage to vessels grounding on them. For the purposes of the Thames Tunnel Project, it was also desirable that any designs could be incorporated into the scour-protection aprons that will be installed at each CSO point.

After consideration of various study methods, including computational fluid dynamics (CFD) modelling, physical modelling in a laboratory flume and direct experimentation in the field, the flume option was chosen as the most cost-effective, using THA's small annular flume at our Ashurst laboratory.

Study aims

The aim is to identify through observation types of small structures that will allow fish to shelter from strong currents during selective tidal stream transport and to use these observations to recommend structures for trial in the river. As far as we are aware there has been no scientific work on these types of structures, although the design of some fish passes is potentially closely related. Our approach has two phases; 1. A rapid assessment of a wide range of shapes and a qualitative observation of the way fish react with these, in various current speeds in turbulent flow. 2. A quantitative assessment of the behaviour of fish in respect of the most promising basic shapes.

In general the trials were focused on sustained swimming behaviour of fish as opposed to burst swimming. Fish can burst swim extremely quickly (8-10 body lengths a second) for a few seconds but sustained swimming (1-2 body lengths a second) is usually tested over a period of 200 minutes. The standard method of testing the limits of sustained swimming is to run individual fish in smooth laminar flow for 200 minutes, or until they stop swimming and are impinged at down flow screen. However, in the real situation fish swim in schools which can impact their hydrodynamics and their behaviour; river flow is rarely smooth and often turbulent. Furthermore, such tests may be used to discover the physiological limits of fish, which in a natural situation they may be reluctant to reach, as it is usually associated with death through pursuit predation. Since we are assessing the value of structures that fish may choose to use to aid migration, rather than ones they are compelled to use, performance under physiological limits may not be appropriate. Therefore we have focused on identifying behaviour which indicates the instantaneous state of schooling fish in flow situations and ways in which we can quantify that in terms of likelihood of fish maintaining that position indefinitely. The results have been positive, in that we have learned unexpected behaviours of fish, and identified basic structures that work well as shelter. We have also started to develop a methodology to quantifiably measure the effectiveness of such structures and put it into use to contrast structures of different types and against controls.

METHODS

Summary of apparatus

- First test subjects, sand smelt (*Atherina presbyter*)
    - Hardy, common
    - Easy to catch and keep healthy
    - Convenient size 30-40 cm
    - Not strong swimmers, surf zone fish that exhibit rheotaxis but weakly
- Second test subjects, roach (*Rutilus rutilus*)
    - Hardy, common, similar to observed fish in Thames
    - Size: 40-80 cm (similar size to fish in Thames)
    - Freshwater fish, very strong swimmers
    - Strong rheotaxis (obligate)
    - Schoolers
- Annular flume (**Figure 18**)
    - Range of current speed 0.1-1 m/s

- Turbulent flow
- Convenient size
- Immediate availability

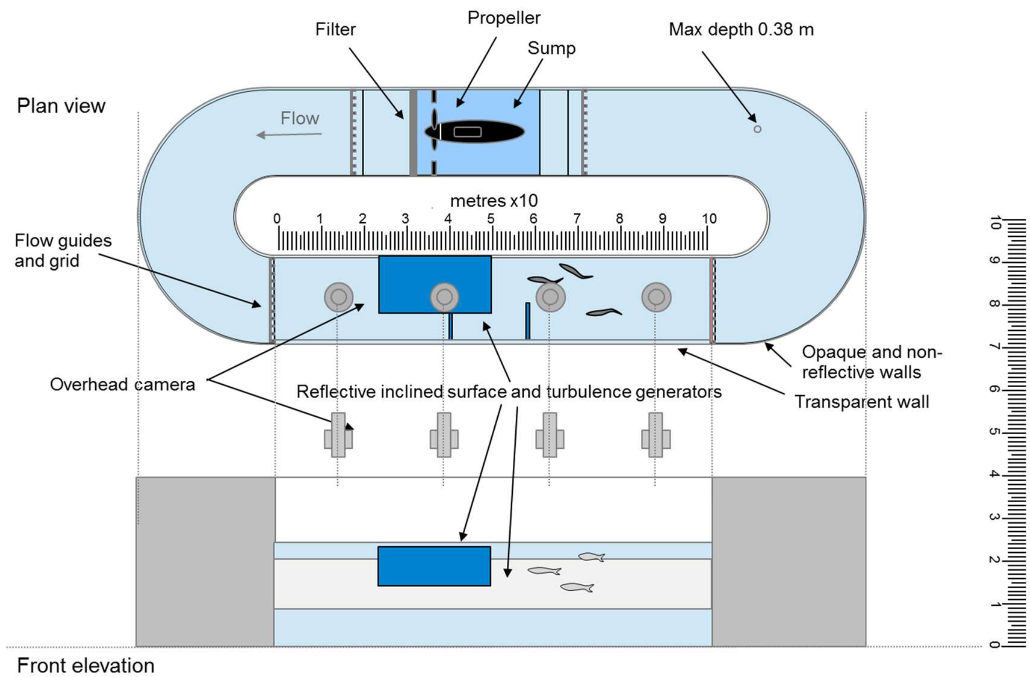


Figure 18 **Annular flume. The flume produces a turbulent flow**

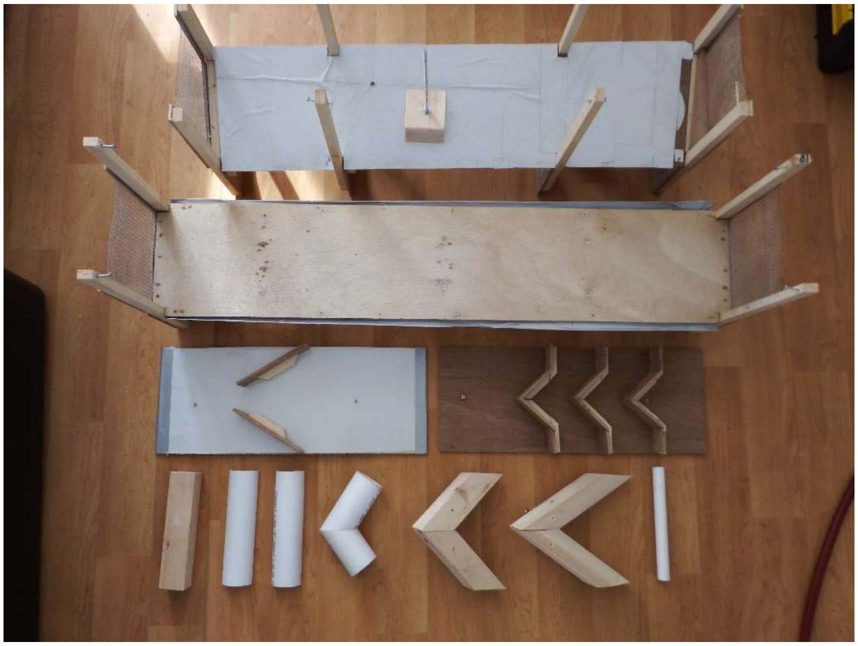


Figure 19 Some examples of the experimental equipment. This collection includes level and inclined planes, turbulence generators, basic shapes, and fish pass type structures

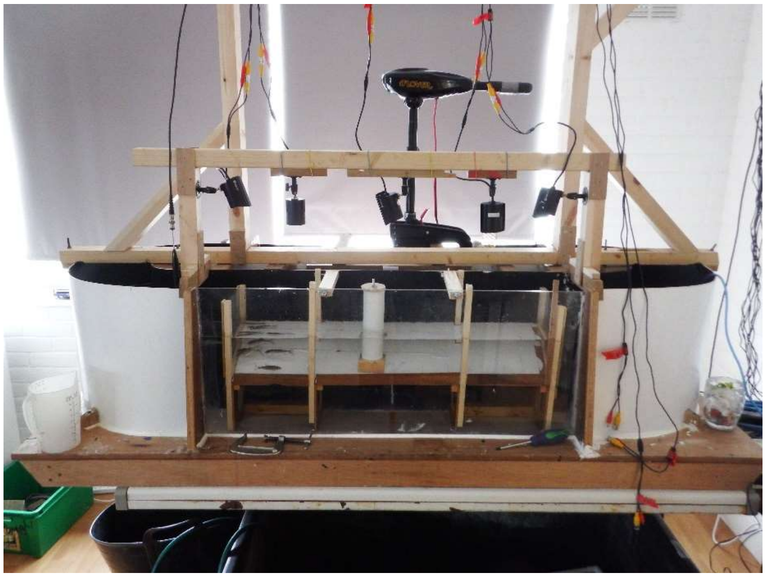


Figure 20 Photograph of small flume used for experiments with schools of juvenile fish. The impeller is visible at the back. There are 5 infrared video cameras set up above the experimental zone. Fish are contained in the experimental zone, in this case with an inclined plane and a cylindrical object.

General Methods

Fish were kept in holding tanks close to the test apparatus. Fish had been in captivity for several weeks in the case of sand smelt, and for several months in the case of the roach. Flume water was held in large holding tank under the flume and aerated. The water was introduced into the flume holding tank and left for 24 hours before the fish were introduced and was changed on a weekly basis. A fraction of the water in the holding tank was pumped into the flume for each set of trials and aerated while in the flume. The flume water was filtered in the flume, using the flume flow, the filters were removed before each trial.

Temperature was recorded before each trial and fish were introduced if the temperature difference between holding tank and flume was less than 0.5 ^{o}C. Fish were not handled (for instance measured on a measuring board) before being introduced into the flume and were transferred by 2 litre water jug. Fish were habituated for 15 minutes with zero flow initially, although it was discovered that a minimum flow of less than 0.1 ms^{-1} appeared to habituate the fish in a less stressed state than still water and this regime was adopted after the first few trials. Fish held in still water were sensitive to the slightest movement visible through the transparent flume wall, whereas fish in a slight flow were not. Water in the flume was turbulent and therefore accurate instantaneous measurements of water speed were not sufficiently precise to be of use. Bulk measurement of the movement of neutrally buoyant objects run through the flume 20 times were used to specify the bulk flume speed between 0.1 and 0.7 ms^{-1}, where instantaneous speeds were up to maximum of about 1.5 $m\ s^{-1}$ depending on the shape of obstacles and depth of water in the experimental zone. These bulk speed measurements led to the use, in experimental trials, of 4 general bulk speed levels specified dependent on impeller settings and used throughout: slow ~0.1 ms^{-1}, medium 0.1-0.2 ms^{-1}, fast 0.2-0.4 ms^{-1}, fastest ~0.5 ms^{-1}. Fish were used in up to 8 trials in one session in the flume, each trial lasted 15 minutes, with a rest period of 10 minutes in between trials. During the rest period the flow was set at slow. Sometimes the fish in the flume were fed, in slow flow and still water. It was part of the trials to watch the behaviour of schooling fish in relation to buoyant food released in the flow. Fish in the flume in general fed very well in low flows. Before subsequent trials, after feeding, flume water was filtered in-situ using temporary filters introduced into the flume near the impeller.

RAPID ASSESSMENT

Rapid assessment introduction and methods

The initial assumption is that fish will sit more comfortably behind objects which produce smooth and predictable turbulent streams which are predominantly orientated side to side. Fish movement is constrained by the orientation of the backbone and fish move sinuously and change direction quickly from left to right but are not so flexible in a vertical orientation and thus are unable to change direction so quickly and smoothly in an up and down direction. Their eyes and other senses, especially the lateral line, are orientated side to side, rather than top to bottom, and so their perception is matched in this orientation. Therefore the initial trials were made with objects that were vertically orientated such as cylinders, rods, and blocks. We used marine fish (sand smelt (*Atherina presbyter*)) in sea water.

These fish are hardy as they live in the surf zone and used to dealing with turbulent water. These fish were tested with various simple shapes on an inclined bed at bulk water speeds from 0.1 to 0.7 ms^{-1}.

It was clear that the sand smelt performed in exactly the way as had been suspected. They were most comfortable standing off vertically inclined structures that produced smooth predictable turbulence. However, these fish did not form cohesive schools in the test apparatus, and so it was concluded that they were not obligate schoolers in the test situations. Furthermore the sand smelt were relatively weak swimmers, and became impinged at bulk current speeds in excess of 0. 5 ms^{-1}. We therefore extended the rapid assessment phase to include river fish that we suspected were better adapted to maintaining station in strong turbulent flows. Roach (*Rutilus rutilus*) were used for the remainder of the rapid assessment phase and the whole quantitative phase of the study.

Rapid assessment results

The results included the observation that individual fish acted differently from schools. Schools can be treated as super-individuals with a set of school behaviours which are quantifiable at the level of the school rather than the individual. School behaviours such as taking up a more dense, affine (cigar shaped) shape when the current is increased are not evident from the movements of individual fish. The general results in terms of school shape, orientation and churning are described in **Figure 21** and **Figure 22**. **Figure 23** shows an example of fish in the predictable turbulent flow behind a cylindrical object. **Figure 24** shows schooling behaviour in fast flowing water.

See table of video objects for related video based results. The video objects; circular01.mp4, rectIncline01.mp4, rectIncline02.mp4 and roachSchoolFast.mp4, demonstrate some of the key typical behaviours observed in the rapid assessment phase. These video objects are explained and summarised in the appropriate following section.

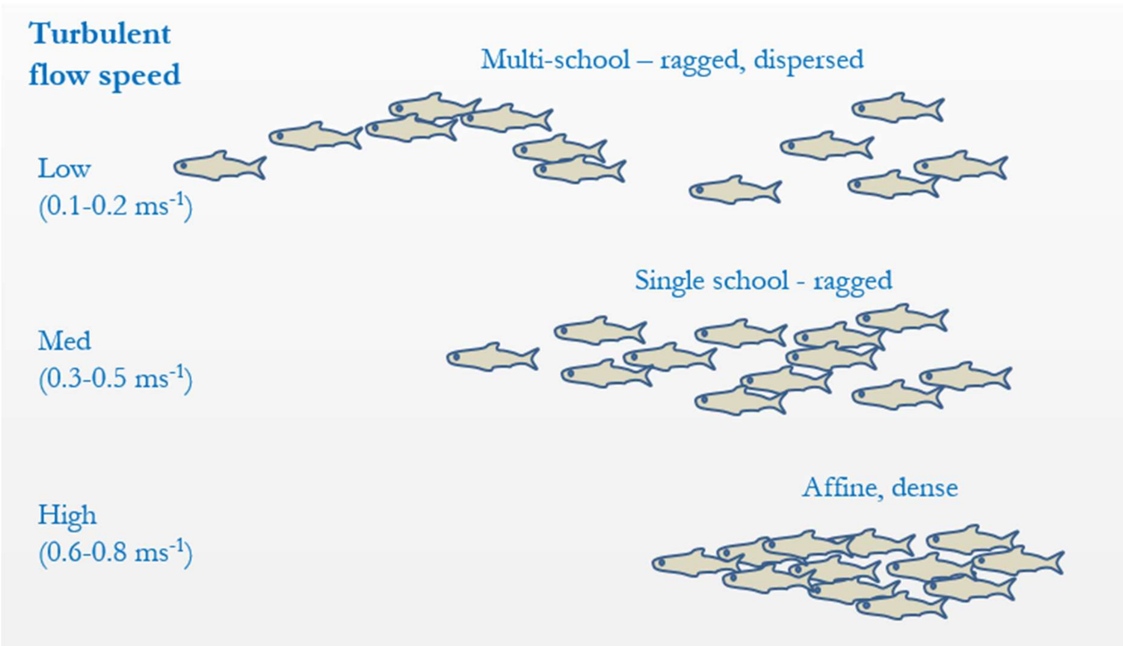


Figure 21 **Typical shapes of fish schools (roach (Rutilus rutilus)) in the test apparatus in various flow conditions. In higher flows the fish formed more dense affine schools closer to the bed with all fish roughly in the same plane, whereas at lower the speeds the group dispersed vertically and horizontally. The linkage in behaviour between the individual fish thus increased with flow.**

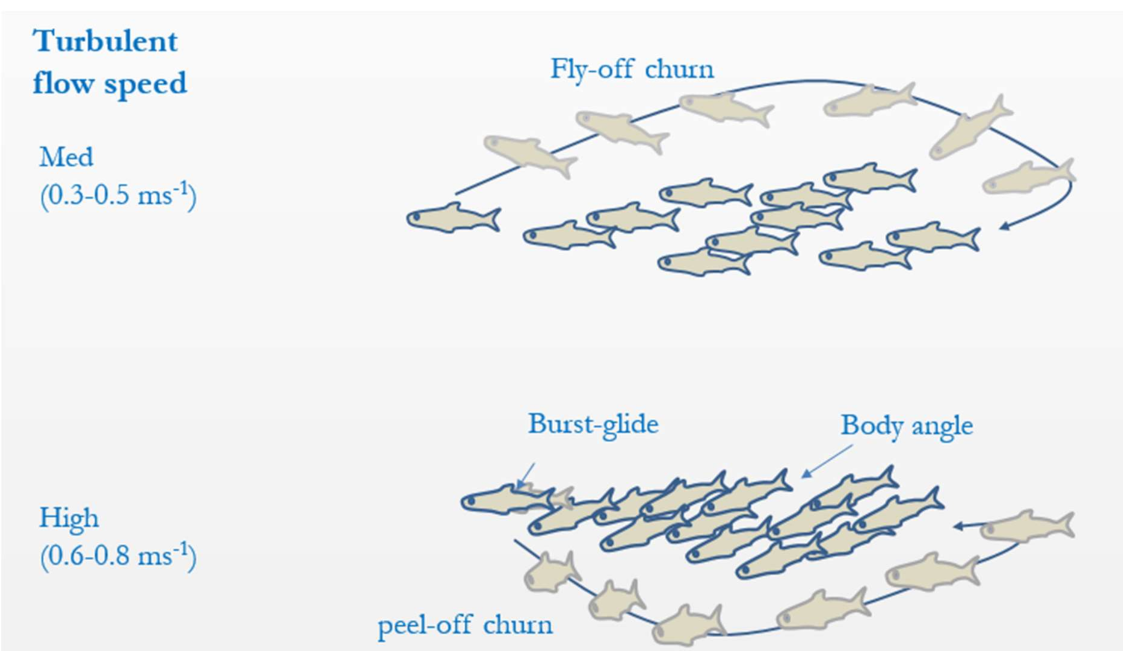


Figure 22 **Behaviours associated with schooling fish (roach (*Rutilus rutilus*)) in turbulent flows. Churning relates to the movement of a fish from the front to the back in a single smooth movement. At lower speeds churns are performed in a vertical orientation while at high speeds the fish 'peel off' in the plane of the school and maintain a position close to the bed. At higher speeds, burst glide is also evident, and is considered an**

indication of high stress and discomfort. The nose down body angle is another sign of increasing work rate against the flow and is either an involuntary effect of hydrodynamic lift through pressure gradients in velocity or behaviour to mitigate the effects of lift.

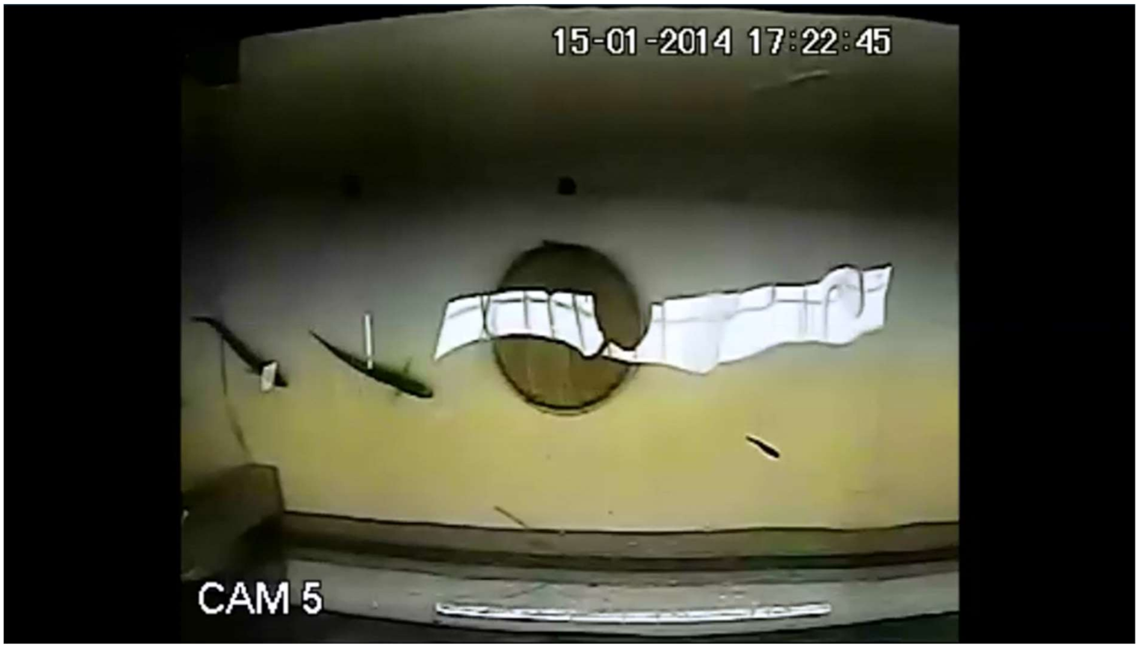


Figure 23 Still picture from a video showing sand smelt (*Atherina presbyter*) taking up comfortable positions in a slow turbulent, but predictable, pattern which forms behind a cylindrical object. The floor is inclined at about 20 º from the horizontal which leads to an asymmetric street of vortices behind the cylinder; the fish prefer the deeper side. Flow is from right to left in this picture.

Figure 24 Photograph of a school of 20 roach behind a chevron shaped object in fast turbulent flow. The standing wave behind the object is visible on the side wall of the flume. The fish are in a tight school, in a single plane close to the bed and are angled slightly head down in the flow.

Other types of equipment and shapes used in the trials are shown in **Figure 19**.

Quantitative indicators of suitability of shelter

Quantifiable behaviours were identified that indicate that a school of fish, holding position in a turbulent flow with constant speed, is becoming more stressed by the increasing flow. The usefulness of a shelter depends on its capacity to provide areas where schools of fish can swim in a relatively unstressed state. The indicators that we have identified are indicators of stress for a school of 10-20 fish in a turbulent flow are as follows:

1. School shape – density increases with flow, school becomes more affine and shorter,
2. Individual angle in water, steeper in higher flow, overall closer to bed in higher flows
3. Burst and glide – behaviour increases at highest flows, indicative of stress (known from other experiments)
4. Churning – fish at the front of school move to back – increases in frequency with flow speed
5. Fly-off – fish churn by lifting off from the front vertically and drifting back – increases with flow but stops at higher speeds.
6. Peel-off – fish churn by angling their bodies at right angles to the flow and drifting back close to the bed. Churning method at high speed
7. Forward run or dart – type of movement to get past obstacle in front, fish move like they are connected by a rubber band, not getting too far in front. Only happens in comfortable flow conditions.
8. Crossing and re-crossing structure. This type of exploration was indicative of the most comfortable behaviours in all flow conditions. Structures were most clearly differentiated in the fastest conditions by this activity.

Quantitative assessment of chevron

Quantitative assessment of chevron methods

The assessment of chevron shapes was performed using four shapes: 90° block chevron, 60° block chevron, undercut 60° chevron, aerodynamic 60° chevron (**Figure 25** and **Figure 26**). The angular dimensions refer to the inner angle of a 45 mm square section block construction. Examples are shown in **Figure 19**. At the highest speed and turbulence, the number of crossing of the structure, in both directions, was the primary statistic related to comfort of the fish in the experimental set-up. The more comfortable the fish were with the structure the more often they were prepared to cross and re-cross. There were no structures tested where fish were content at high and highest speed and turbulence which allowed them to remain in a single area of the test apparatus indefinitely. The most comfortable position in this case was just in front of the structures. Therefore the structure crossing behaviours under higher flows were the foci, as these provided the clearest differentiation between the test structures. Passes in high flow (speed 3) were measured over 15 minute intervals, and highest flow (speed 4) over a 2 minute period.

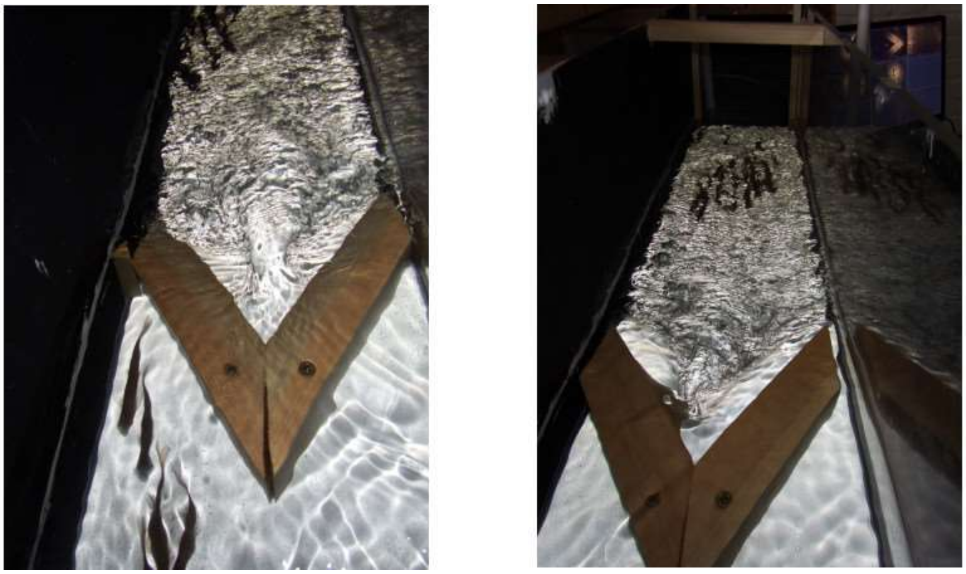


Figure 25 Difference in turbulent wakes of two chevron shaped objects. The object on the left has aerodynamic chamfered downstream edges whereas on the right all the edges are square. The wake of the left hand shape is appreciably more concentrated in the centre. The surface appearance of the water is enhanced through the use of standard flash photography.

Figure 26 Aerodynamically chamfered object in fast flow. This object was relatively uncomfortable for fish to pass apparently due to the sheet of high speed laminar flow over the object and the centrally concentrated turbulent wake. The laminar layer should be viewed in contrast to the wedge shaped flow pattern produced by the square edged object in Figure 7.

Quantitative assessment of chevron results

Table 5 **Summary results of chevron trials, means +/- 1 standard error of 3 replicates**

Treatment	Temperature °C	First passage (minutes)	Upstream pass (speed 3)	Downstream pass (speed 3)	Pass (speed 4)
Wedge 60	18.1	8	17 +/- 3	11 +/- 3	2
Wedge 60 (aero)	18	5	13 +/- 2	4 +/- 2	0
Wedge 60 (under)	18.1	8	2 +/- 1	2 +/- 3	0
Wedge 90	18.1	8	11 +/- 3	1 +/- 1	1

The video objects which are attached to this report show how the fish approached and passed the chevron shaped objects (attemptedPass90.mp4). The summary of the behaviour is that fish approached the object from downstream in a tight school until with about 20 cm of the downstream face of the object when individual fish, or groups of two or three fish, burst forward to explore the face of the object. The exploration of the face of the object took the form of a lateral movement in the laminar flow region against the object. Passage was attempted from the central position in the chevron. Fish would pass by turning onto their side (barrel roll) to cross the downstream edge of the object. Fish appeared to work together to provide hydrodynamic support to one another just before the exploration phase and during the passage. The fish also seemed emboldened by seeing others cross. The undercut and aerodynamic sectioned chevrons were not passed so often. The undercut perhaps gave a confused signal with respect to the position of the face, and the aerodynamic had a fast moving sheet of water which presented a difficult challenge to passage.

VIDEOS ATTACHED TO THIS REPORT

Name	Explanation
circular01.mp4	This clip demonstrates how sand smelt in slow moving water are most comfortable in the predictable turbulent wake of cylindrical object (**Figure 21**). This is the standard type of trial for fish in turbulent wakes and is shown to be predictable but not appropriate for our purposes as the flow is too slow and the fish are not in school formation.

rectIncline01.mp4	This clip shows how fish shelter predictably in the wake of a rectangular object. This confirms the type of results we derived from modelling flows in the Thames with fish objects that were modelled to be attracted to flow speeds and depths in predefined limits. Again the flows are too slow for our purposes (the objects were very much smaller than those in the Thames model but the results are consistent and can be scaled if necessary through having an approximately similar Reynolds number which contrasts hydrodynamic situations with different length scales and velocities).
rectIncline02.mp4	This clip shows loose schooling of sand smelt and shows how these schools use the small vertical rectangular blocks attached to the side of the flume for shelter. This effect was not maintained for high speed water.
roachSchoolFast.mp4	This clip shows school activities in fast water flow. Fish at the rear of the school maintain position in the school for 20-30 seconds before moving forward in the school. This process is called churning. All fish are swimming continually, generally in a single horizontal layer near the bed. There are no burst glide type movements. There is the occasional fountain effect type of startle response to unknown stimulus which demonstrates that fish can move substantially faster than the current for very short bursts.
attemptedPass90.mp4	This clip shows some typical behaviour of fish approaching and passing a chevron shaped object. The fish often approach and move along the face of the object. This exploration is terminated by a peel off or direct attempt at passage. The more acute angled object was easier to pass as the fish spent less time exploring and attempted passage more often. This video clip also shows the relative comfort of fish sheltering in front of the object.
modelFish.mp4	This is a clip from a model of fish in turbulent flow. They behaviour in two ways: speed is changed to roughly maintain position from left to right and swimming direction is based on reactions to 3 nearest neighbours with a slight bias to swim upstream. The model fish behave in many ways similar to the experimental fish which

	indicates that the underlying rules are similar to the actual situation.

Discussion

This rapid assessment was successful in that new information was gained which was unexpected. It was initially assumed that cylindrical objects vertically inclined would provide the most comfortable turbulent wakes for fish to shelter. This was the case for slow flows with predictable turbulent patterns and weak swimming fish. For turbulent high speed flows, chevron shapes made of blocks square section were superior. The apparatus used in this experiment was unusual in fish swimming behavioural experiments due to the high speeds and turbulence. The experimental design was unusual in that schools of fish were used rather than singletons. Usually singletons and slow moving water in predictable patterns is appropriate to isolate the components of fish movements and the physiological limits of individual fish. However, the experimental set up used in this study is much closer to the natural circumstances in which the proposed structures are to be installed. The way schools act as super individuals and moderate fish behaviour is an important factor in the way these structures work for both passage and for sheltering. A list of school-based behaviours was developed that can be used to quantitatively assess the response of schools to structures. This work is potentially of value to fish pass design. The design of the most effective structure closely follows the design of the standard Larinier type 'super-active baffle' fish pass. Nevertheless this study was a rapid assessment experiment and much improvement could be made in the apparatus, methods and experimental design in the future. Longer trials with more species in a larger, more naturalistic, flume or in-river would prove useful. Different surfaces for the bed and structures may be an interesting factor, we found that fish were less likely to make contact with rough bed surfaces, whereas the smooth surfaces were more attractive in this respect. Surfaces of a similar composition to natural structures may be more appropriate, with algae or other vegetative mats being potentially important micro-scale features.

Further work – River trials

The next phase of this project is to test designs in the river. We are reasonably confident that a chevron design of angle around 60 degrees is most effective in fast flowing turbulent shallow water. This is similar to the design of structures used to aid fish passage over flat weirs (**Figure 27** and **Figure 28**). The study suggests that the most important places to attract fish to shelter are immediately in front of these structures with respect to the river flow, and at very fast flows, some distance behind the structures well in the turbulent wake. Thus that the structures should be reasonable distant from each other (**Error! Reference source not found.**). A zigzag design would be bi-directional and potentially self-maintaining to certain extent due to the sedimentary scour patterns being similar on both sides and being spatially variable, which would lead to a relatively high level of scour variance and thus the maintenance of various depths useful for shelter during shallow water periods. The unknown factors are size and separation of structures, and so a wide variety of each should be tested.

Figure 27 **River Uck gauging station weir showing the use of square section block structures to aid fish passage. The spacing is approximately 40 cm and the section approximately 50mm**

Figure 28 **Isfield gauging station with structures designed to aid fish passage**

Appendix 3 – Report: River Trials for Structures Aiding Juvenile Fish Migration

Thames Tideway Tunnel River Trials for Structures Aiding Juvenile Fish Migration

Thames Tunnel

Creating a cleaner, healthier River Thames

Contents amendment record

This document has been issued and amended as follows:

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Tessa Harding 21/04/2015

Name – Title Date

Name – Title Date

Thames TidewayTunnel

River Trials for Structures Aiding Juvenile Fish Migration

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Executive Summary

This report summarises the trial of microhabitat structures in the Thames Tideway. The aim of the structures is to provide shelter to fish which are attempting to migrate along the Thames Tideway using selective tidal stream transport. Using this mode of swimming small fish can be pushed back by the outgoing tide and structures behind which they could shelter throughout the ebbing tide are assumed to be a potential aid to their migration. The fish have particular depth preferences and so the performance of these structures should remain constant throughout the ebbing tide while the depth decreases and the foreshore becomes progressively more exposed. The structures were initially tested in the River Test in Hampshire for hydrodynamic stability, sampling efficiency and for general acceptability to fish. The structures were then installed in the Thames Tideway between Blackfriars Bridge and the Millennium Bridge. Visibility in the water was very low (under 5 cm). Two types of sampling were employed; hand nets to collect from areas around the structures (at an appropriate scale to the volumes impacted by the structure), and seine nets to sample fish from a large area around the experimental site to characterise the species and likely density of fish in the local area.

The results were not conclusive with respect to the efficacy of the structures. The seine sampling demonstrated that there were very few juvenile fish in the target area at any time throughout the experiment. The density of fish within the study reach was too low for there to be any reasonable expectation of catching any with the hand nets which swept a much smaller volume. Nevertheless, healthy fish of all the main representative species were caught, which indicated that there was no systemic reason for the low density. The experiment, which was undertaken in August 2014, may have been more effective if performed earlier in the year, or in an area where the water clarity was more appropriate for video sampling (e.g. Putney). Another option may be to use hydroacoustic detectors (such as a Didson 'acoustic daylight' camera) to observe fish without net sampling although they have not been used in this application previously.

In summary the work here provided useful insight into the experimental protocol for testing these types of structures and thus will inform planning in the future. The recommendation for future studies is to use a similar methodology, however at times and in areas of higher fish density and water clarity, using either photographic or hydroacoustic monitoring, or more studies over a wider area using a standard protocol developed around the seine net as a sampling tool.

1 Introduction

1.1.1 The Thames Tideway, over hundreds of years, has been affected by progressive encroachment into the tidal corridor, with potential adverse consequences for fish migration. These arise primarily from 'channel squeeze' and consequent acceleration of river flows, making it more difficult for certain species of juvenile fish to ascend the Tideway to access their preferred habitat towards the upper tidal limit (Colclough *et al*., 2002). These small fish, which typically include e.g. elvers (young eel) *Anguilla anguilla*, sea bass *Dicentrarchus labrax*, dace *Leuciscus leuciscus* and flounder *Platichthys flesus*, use an energy efficient transport mechanism known as selective tidal stream transport (STST). STST was first demonstrated by Greer-Walker *et al.* (1978), as a means by which flatfish can save energy by 'hitching a ride' on the tide when it is flowing in the desired direction, while sitting out the reverse tide on the bed. The process in these species is therefore one of vertical modulation of movement between slow moving water at the bed and faster moving water above or to one side. STST has since been demonstrated for other species, including elvers (Naismith and Knights, 1988), and some pelagic fishes and crustaceans (Miller, 1988; Schultz *et al*., 2000). In recognition of such potential effects, the Environment Agency's Tidal Thames Encroachment Policy presumes against developments riverward of existing flood defences where these would, individually or cumulatively, change flows so that fisheries could be affected or there could be loss or damage to habitat.

1.1.2 The Thames Tideway Tunnel Project will involve the construction of foreshore-sited facilities including temporary coffer dams, jetties and campsheds, and permanent structures such as pumping stations and outfalls. The need to protect fish migration through the affected reaches both during construction and operation has been fully recognised by the Project and extensive modelling to assess the potential impacts of these structures on fish migration has been undertaken[ii]. These highlighted the need to provide habitat complexity and hydraulic heterogeneity along the river margins, so that small fish would have the opportunity to take refuge from excessive water velocities when attempting to hold station during the STST resting phase.

1.1.3 The aquatic ecology assessment included within the EIA for the Thames Tideway Tunnel concluded that the scheme would not have significant adverse effects on migratory fish. However, significant effects were anticipated due to the permanent loss of intertidal habitat resulting from the interception structures located on the foreshore. The package of measures agreed with the Examining Authority to offset this loss include the development of structures which would act as fish refuges and improve the hydraulic heterogeneity of the channel margins.

1.1.4 During an initial literature review of the subject, it became clear that there was no established design practice for the provision of appropriate artificial habitats and refuge on in channel structures. This

[ii] Thames Tunnel Project, Environmental Assessment

finding has led Thames Tideway Tunnel Project to commission the present programme of laboratory and field studies to develop suitable designs for in-river refuge structures. An initial laboratory flume study (Thames Tideway Tunnel, 2014) evaluated various structures on a small scale and the present trials moved into river trials where a more realistic scale could be evaluated. The basic aim is to develop structures that are simple to make, can be easily deployed in the conditions of the Thames Tideway, have high resilience and a low vertical profile so as not to impede navigation. A later stage of the study will be to identify locations in the Tideway where refuge structures can be deployed for maximum effect.

2 Methodology

2.1 River Test Trial

2.1.1 The structures were installed in the river Test in Hampshire on the 29th July 2014. The purpose of this trial was to ensure that the structures were stable in strong currents, on various substrates in an artificial channel and on the natural river bed. This test provided an opportunity to test transport and installation methods in a benign environment. The sampling strategy was tested (albeit in visibility conditions which were crystal clear and very different from the Thames) and the general attractiveness of the structure to any fish that were present.

2.2 River Thames trial

2.2.1 The trial entailed introducing three small scale structures on to the bed of River Thames at one location and to identify through observation how fish use them to shelter from strong currents during ebb tide in daylight. The results of the trial will be used inform the final design of the structures that will be used to fulfil the requirements of design principal control.

2.2.2 Earlier flume and riverine (Appendix B, River Test trials) trials demonstrated that a chevron baffle design, angled around 60 degrees provided effective hydraulic refuge conditions in the lee of the structure in fast flowing turbulent, shallow water for both juvenile and small species of fish. The chevron baffles were pre-constructed concrete beams shaped in a zigzag formation (Figure 1; Figure 2). The beams were square in cross section with a width of 100 mm and height of 100 mm. The maximum footprint of the zigzag shape was 1 m x 0.5 m. Together the three concrete shapes used a maximum area of 6 m2.

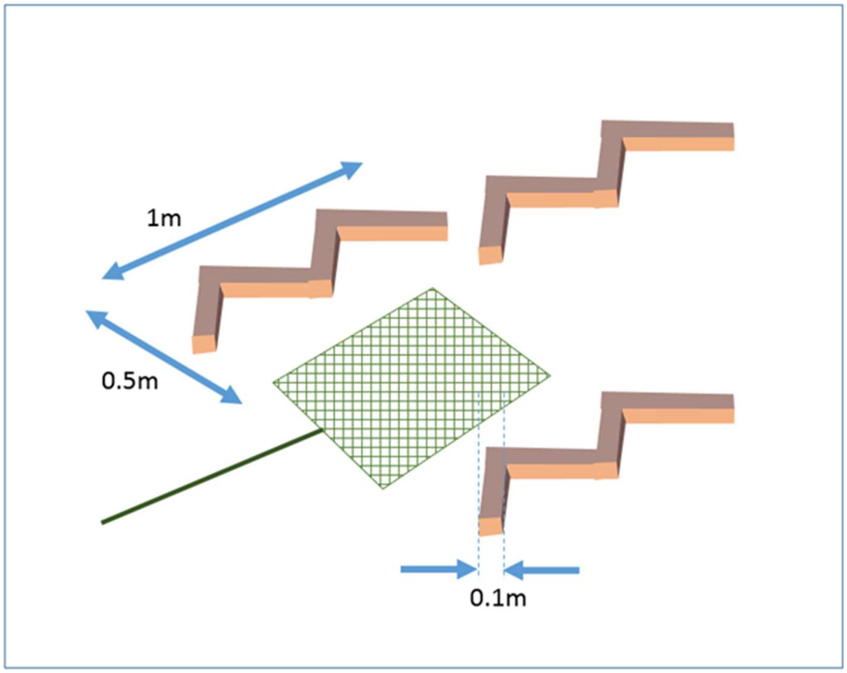

Figure 1Concrete beams laid in water to increase turbulence in area where fish are likely to hold position in strong tidal currents. Hand net were used to sample fish associating with the structures.

Figure 2A concrete refuge structure element

2.3 Location

2.3.1 The trial was undertaken on the River Thames intertidal foreshore between Blackfriars Road Bridge and Bankside Pier (Figure 3) on the 19th and 20th of August 2014. The site was accessed via steps onto the foreshore immediately east of the Founders Arms on Hopton Street (Figure 3).

2.3.2 Observations were undertaken from the foreshore using hand held sampling nets (0.7 m2 – 6 mm mesh). The trial was undertaken over a two day period in order to obtain observations across at least two full ebbing tidal cycles. Four operatives were present during the trial. The important sampling time was on the maximum outgoing tide and thus the depth around the structures at this time was decreasing.

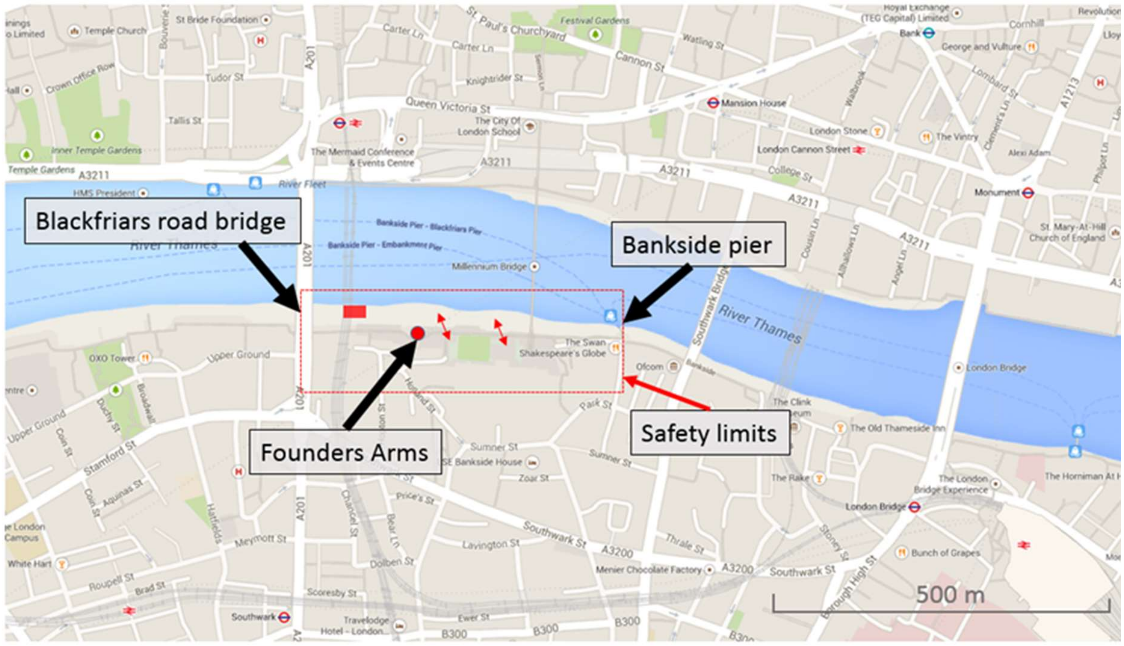

Figure 3Thames trial site location

2.4 Permits and Licences

2.4.1 The following permissions and licenses were obtained:

- PLA Consent for temporary works. 1500N00/hpg
- Environment Agency Authorisation No B/SL/31072014/C3.

2.5 Trial set-up

2.5.1 Concrete baffles were placed, end to end in a line perpendicular to the shoreline, and as the water depth decreased the uppermost structure was exposed (Figure 4). When nearly exposed the uppermost structure was lifted and placed at the deepest end of the line. Thus the line of structures was stepped down the foreshore during the ebbing tide.

The position of the line of concrete baffles was switched between two sites, one control and one experimental site, on alternate days to reduce sampling bias from e.g. site/habitat fidelity. The two sites were separated by approximately 50 m along the shore line.

Figure 4Concrete structure being placed in the Thames, at the end of a line of 3 similar structures placed perpendicular to the foreshore.

2.6 Sampling strategy

2.6.1 Two sampling method were employed, hand netting (Figure 5) and seine netting (Figure 6). The hand nets were deployed simultaneously around the structures and in a similar area 20 m upstream of the structures as a control. The nets were laid flat against the bed, held in position for between 2 and 5 minutes and quickly lifted (in an upwards and upstream sweep that had been shown to be effective in earlier trials of equipment). The hand nets were also used as ‘kick nets’ where they are held vertically with the edge of the net touching the bed and drawn upstream by the operator making small exaggerated steps toe-kicking the bed lightly. This standard sampling method is effective for observing fish that habitually make contact with the bed (flat fish such as flounder). The hand net lifts were synchronised and recorded by the recorder who stood back from the water in between the treatment and control sample.

Figure 5Hand net sampling

2.6.2 The second method of sampling was by 25 m long seine net, used to characterise the area in terms of density and species of fish and to check whether the experimental zone was typical or otherwise of this stretch of foreshore during the ebbing tide. The seine net was pulled out from the shore by one operative, starting several metres upstream of the structures. One other team member fed the net out from the shore to ensure it remained un-twisted. Once the first operative reached waist depth, he/she would turn and continue pulling the net downstream, parallel to the shore. After the whole net had been pulled out from the shore, it would be held parallel with the shore for several minutes, with the third team member standing at waist depth holding the upstream end of the net. When ready, the net would be enclosed into a semi-circle on the shore with the fish trapped in the middle to be collected.

The seine net was used around the position of the structures and used 30 m upstream and downstream of the structures at regular intervals through the ebbing time.

Figure 6Seine net sampling with a structure in the foreground just about to be exposed by the ebbing tide.

2.6.3 The fish were counted, identified, measured (standard length) and returned to the river without being removed from the water for any period longer than required to identify and measure. Additional sites were sampled using the same methodology at distances up and downstream of between 20 to 50 m from the experimental site to provide background density and distributional data of fish fauna along the foreshore.

3 Results

3.1 River Test trial

3.2 Sample Data

3.2.1 A full list of sampling and results are provided in Appendix A.

3.3 Summary

3.3.1 The seine net with an effective area of capture of about 50 m^2 caught a maximum of 5 fish per repeat (range 0 - 5, N=13, mean = 2). The hand nets had an effective capture area of less than 1 m^2 so the expectation is that they would catch a single fish after 25 pulls if the fish were evenly distributed in the volume of water. In fact no fish were caught in the hand nets after 50 (25 x 2) pulls and this is well within the expected range. This neither supports nor falsifies the hypothesis that these sampling methods are adequate in this environment to discern if the structures had an impact on fish positioning.

3.3.2 The fish that were caught in the seine nets included: elver (*Anguilla anguilla)*, roach (*Rutilus rutilus*), bass (*Dicentrarchus labrax*), goby (*Gobio sp*.), flounder (*Platichthys flesus*), bream (*Abramis brama*), bream x roach hybrid and dace (*Leuciscus leuciscus*). Shrimp (*Crangon crangon)* were also common in the catches. These fish and Crustacea were all in good condition and so were suggestive that the river was in good environmental condition and so the reason for the low numbers of fish was most likely due to the time of year. However, there were too few fish caught to observe any effects of the structures.

4 Conclusions and further work

4.1.1 The work described here was not conclusive in either supporting or falsifying a hypothesis that the structures tested provided enhanced shelter in the ebb tide. The primary reason for this was determined as a general low density of fish in this area which was most likely a result of the seasonal timing of the work and the rainfall patterns which may have restricted movements of some species. In the future there are several potential options to improve the experimental methods, including relocation to an area with improved water clarity, and trials at different times of year. It is proposed that in future trials other sampling techniques are considered for observing fish association with the structures. These are likely to include underwater video photography (water clarity allowing), hydroacoustic methods such as the Didson ‘acoustic daylight’ camera (which can be used irrespective of water clarity) or electric fishing apparatus.

The installation of habitat enhancement measures are best focussed in areas where fish are likely to seek refuge from the current and it is proposed to identify appropriate locations for enhancement from analysis of existing hydraulic and fish behaviour models. By re-tasking outputs from the existing fish model it is possible to determine fish dwell time in areas within both construction phase and post-development flow scenarios throughout the study reach. This can be combined with GIS based ecological mapping of fish habitat to enable broad scale analysis of overlap, similarity and correlation of existing habitat availability. This approach would enable targeting and prioritisation for future habitat enhancement.

5 References

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6 Appendix A Detailed Results

Date 19/8/2014.			
Time	Action	Detail	Results
10:35	Arrive at site	Waterline 3 m from walk way	
12:00	Oxygen, Temp., salinity		DO 7.68 mg/l Temp: 18.1 °C Salinity 1889 µS (1.11 ‰)
12:05	Structures in water		
12:22	Hand net pull	synchronised with upstream control	zero fish caught
12:24	Hand net pull	synchronised control	zero fish caught
12:27	Hand net pull	synchronised control	zero fish caught
12:35	seine net	around structures	elver (eel) x1 ~70 mm roach x1 45 mm bass x1 15 mm gobi x1 25 mm Crustacea (shrimp) x5 ~50 mm
12:45	Hand net pull	synchronised control	zero fish caught
12:48	Hand net pull	synchronised control	zero fish caught
12:53	Hand net pull	synchronised control	zero fish caught
13:00	seine net	around structures	flounder x1 25 mm
13:05	seine net	control 25 m down stream	flounder x1 25 mm
13:07	seine net	around structures	gobi x1 25 mm elver (eel) x1 70 mm Crustacea (shrimp) x7 ~50 mm
13:10	seine net	control 25 m down stream	smelt x1 75 mm gobi x1 25 mm flounder x1 25 mm bream/roach hybrid x1 30 mm Crustacea (shrimp) x7 ~50 mm
13:27	Hand net pull	synchronised control	zero fish caught
13:32	Hand net pull	synchronised control	zero fish caught
13:35	Hand net pull	synchronised control	zero fish caught
13:40	seine net	control 50 m upstream	gobi x1 45 mm
13:50	Hand net pull	synchronised control	zero fish caught
13:54	Hand net pull	synchronised control	zero fish caught
14:00	Hand net pull	synchronised control	zero fish caught
14:05	Kick net samples	20-30 m kick net	zero fish caught
14:17	Hand net pull	synchronised control	zero fish caught
14:21	Hand net pull	synchronised control	zero fish caught
14:25	Hand net pull	synchronised control	zero fish caught

14:30	Structures out		
14:31	Oxygen, Temp., salinity		DO 7.74 mg/l Temp: 18.0 °C Salinity 1229 µS (0.61 ‰)
15:00	Low tide		

Date 20/8/2014.			
Time	Action	Detail	Results
11:30	Arrive on site		
11:54	Oxygen, Temp., salinity		DO 7.35 mg/l Temp: 18.6 °C Salinity 1911 µS (1.12 ‰)
12:00	seine net	over sandy bed above previous area	zero
12:10	seine net	parallel to midway of last set (19/8)	bream x1 110 mm FL
12:25	Hand net pull	synchronised control	zero fish caught
12:33	Hand net pull	synchronised control	zero fish caught
12:38	Hand net pull	synchronised control	zero fish caught
12:40	Kick net samples	20-30 m kick net	zero fish caught
12:50	seine net	around structures	stickleback x2 15 mm gobi x2 25 mm flounder x1 25 mm Crustacea (shrimp) x5 50 mm
13:00	seine net	around structures	dace x1 ~20 mm
13:15	Hand net pull	synchronised control	zero fish caught
13:20	Oxygen, Temp., salinity		DO 7.93 mg/l Temp: 18.0 °C Salinity 1440 µS (0.84 ‰)
13:21	Hand net pull	synchronised control	zero fish caught
13:24	Hand net pull	synchronised control	zero fish caught
13:30	Kick net samples	20-30 m kick net	zero fish caught
13:32	seine net	around structures	stickleback x1 15 mm Crustacea x1 50 mm
13:35	seine net	control 25 m down stream	smelt 150 mm bass x2 15 mm
13:45	Hand net pull	synchronised control	zero fish caught
13:53	Hand net pull	synchronised control	zero fish caught
13:58	Hand net pull	synchronised control	zero fish caught
14:05	Kick net samples	20-30 m kick net	zero fish caught
14:35	seine net	around structures	dace x1 75 mm

			Crustacea x3 50 mm
16:23	Low tide	Leave site	

7 Appendix B River Test Trials

7.1.1 The structures were installed in the river Test in Hampshire on the 29th July 2014. The purpose of this trial was to ensure that the structures were stable in strong currents, on various substrates in an artificial channel and on the natural river bed. This test provided an opportunity to test transport and installation methods in a benign environment. The sampling strategy was tested (albeit in visibility conditions which were crystal clear and very different from the Thames) and the general attractiveness of the structure to any fish that were present. The results were encouraging. The structures were very simple to install and were stable under strong shallow currents. The structures immediately attracted fish in the downstream sheltering areas as expected in the areas in which fish could be caught using the hand nets as planned. This part of the River Test has exceptional clarity when compared to the tidal Thames and thus these trials were the only opportunity in which the structures and their turbulent impact could be visually inspected. Since fish that used the structures avoid nets primarily through vision, it was determined that the hand net technique was likely to have a reasonable chance of success in more turbid water.

Figure 7Structures on the natural bed of the River Test.

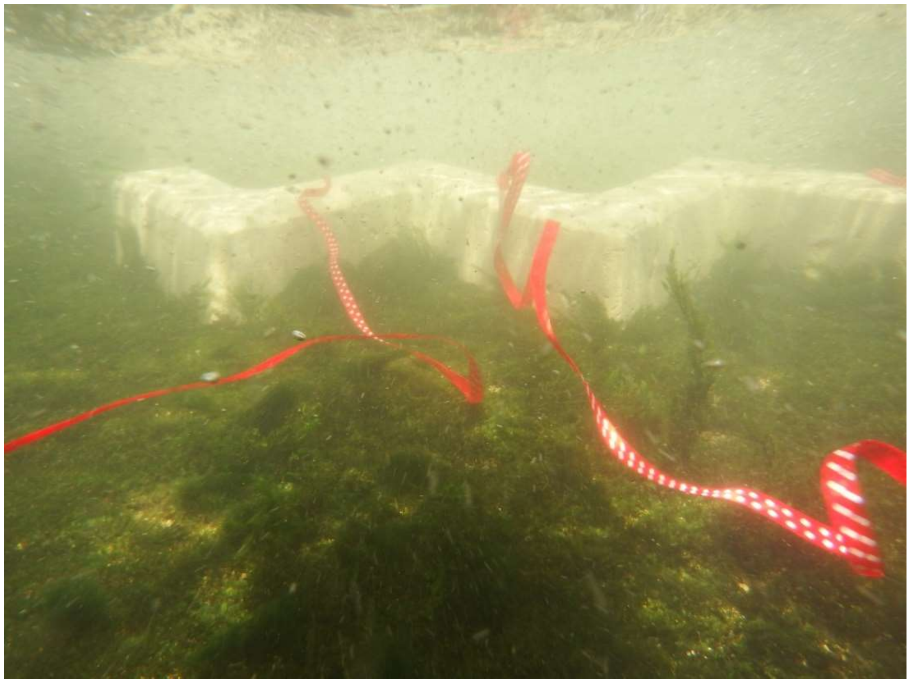

Figure 29 Structure placed on artificial hard substrate in River Test with ribbons used to visualise turbulent wakes of structures

Figure 30 Two structures installed in an artificial channel in the River Test. In this channel the water velocity could be increased to levels above what is likely to prevail in the Tidal Thames

Appendix 4: Report: Optimal Fish Refuge Locations

Thames Tideway Tunnel Optimal Fish Refuge Locations

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Tessa Harding (Associate Director) March 2015

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Thames TidewayTunnel

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Executive Summary

The aim of this study is to identify optimal fish refuge habitats which can be enhanced and potentially expanded through the introduction of the fish refuge structures developed in earlier trials and laboratory studies. The results from the Individual Based Model (IBM) used in the assessment process have been re-tasked specifically to highlight areas where model fish take refuge against the ebbing tide.

These places are thought to be the ‘rungs’ of the ladder that juvenile fish use to climb the tidal Thames and are herein correlated to foreshore physical characteristics observed in an independent study. The results demonstrate that, where the model and observations overlap, that there is statistically significant correlation to a number of physical foreshore characteristics for each of the three species of modelled fish. The model results are considered meaningful for each of the species and provide incidentally a method of rapid assessment of areas yet to be covered in the observational field study. The key holding zones predicted by the model are analysed throughout the extent of the river that will be impacted by the permanent works of the Thames Tideway Tunnels project.

It is outlined where mitigation and monitoring would be most effectively focused to aid and observe juvenile fish migration. The hot spot analysis shows that there are several locations near the proposed permanent works which may be good targets for mitigation and monitoring of fish behaviour and abundance. In particular, hot spots for juvenile bass were noted immediately up and downstream of the Victoria Embankment Foreshore permanent structure, and upstream of the Albert Embankment foreshore, and Putney Embankment Foreshore structures.

8 Introduction

The Thames Tideway Tunnel will involve the construction of permanent foreshore structures. The need to protect fish migration through the affected reaches both during construction and operation is recognised and extensive modelling to assess the potential impacts of these structures on fish migration has been undertaken[3]. Individual Based Models (IBMs) were used to assess the impact of the foreshore structures on migrating fish as part of the EIA process. These highlighted the importance of habitat complexity and hydraulic heterogeneity along the river margins, so that small fish would have the opportunity to take refuge from excessive water velocities.

Following completion of the EIA, two studies were undertaken to develop small scale structures which could be easily introduced into the Thames Tideway and would act as refuges for juvenile fish. From an initial literature review of the subject, it became clear that there was no established design practice for the provision of appropriate artificial habitats and refuge on in channel structures. An initial laboratory flume study evaluated various structures on a small scale before progressing onto river trials where a more realistic scale could be evaluated. The basic aim is to develop structures that are simple to make, can be easily deployed in the conditions of the Thames Tideway, have high resilience and a low vertical profile so as not to impede navigation. The structures were initially tested in the River Test in Hampshire and then in the Thames Tideway between Blackfriars Bridge and the Millennium Bridge.

The River Test study undertaken in July 2014 found that fish were immediately attracted to the structures, and due to the clarity of the water, the effects of turbulence around the structures on fish behaviour could be observed directly. The trial in the Thames Tideway at Blackfriars (August 2014) was not conclusive in either supporting or falsifying a hypothesis that the structures tested provided enhanced shelter in the ebb tide. The primary reason for this was determined as a general low density of fish in the study area which was most likely a result of the seasonal timing of the work and the rainfall patterns which may have restricted movements of some species. However, sufficient evidence was gathered from both studies to demonstrate that small scale structures located in areas where fish are likely to seek refuge from the current may offer benefits to fish migration and allow prioritisation for future habitat enhancement.

The aim of this study is to identify existing optimal fish refuge habitats which can be enhanced and potentially expanded through the introduction of the fish refuge structures developed in the above trials. The study re-examines the Individual Based Models (IBMs) used to assess the impact of the foreshore structures on the currents in the Thames to discover if the fish refuge patterns that can be derived from the model are related to the physical conditions on the foreshore.

[3] Thames Tideway Tunnel Environmental Statement January 2013 and ES Update Report March 2014 http://infrastructure.planningportal.gov.uk/projects/london/thames-tideway-tunnel/?ipcsection=docs&stage=app&filter=Environmental+Statement

Outputs from the IBM are compared with existing GIS based ecological mapping of foreshore habitats in order identify locations for enhancement. Observations of the foreshore were undertaken by Turnpenny Horsfield Associates Ltd (THA), for the Lower Thames Operating Agreement (LTOA), in 2011 and used to classify the Thames foreshore from Chelsea Road Bridge to Teddington Lock according to its suitability for fish. The two studies (IBM and the LTOA) overlap between Chelsea Road Bridge and Hammersmith Bridge and also includes several sites of the proposed above ground works of the Thames Tideway Tunnels project which encroach on the river.

Juvenile marine fish attempt to get as high upstream in the tidal Thames as they are able. The opportunities for feeding for very small fish are better the further upriver they go and, so long as they remain in a tidal estuary, the chances of predation are reduced the further upstream they live. However, as they grow larger they tend to move back down toward the sea. They are spawned and emerge from the egg in the most downstream areas of the estuary and therefore are strongly motivated to move upstream when very small (about the size of postage stamps). This is challenging for them because, being small, they can't swim very fast. In fact they cannot swim as fast as the tidal currents in the river. To avoid being flushed out of the river on the ebb tide they must shelter in a low flow area. Rivers flow slower nearer the banks, near the bed and behind obstructions such as bridge piers. These areas all hold potential dangers for very small fish, for example, they may generate turbulence which fish are unable to escape from.Different species hold themselves against the ebbing current in different ways. When the current is going upstream on a flood tide however, these fish take advantage of the current and tend to swim up from the bottom, in from the sides, and out from behind obstructions. This type of behaviour is called selective tidal stream transport (STST) and is very common among fish that live in tidal zones and has been observed since the 1950's.

Conceptually, STST can be seen as like a series of rungs in a ladder that juvenile fish use to 'climb' the Thames. Each rung is a place where a juvenile fish can shelter from the tide. The rungs will be in different places for different species; some like to touch the bed for instance and others don't. In a natural river there may be an enormous density of places for fish to shelter and complex banks leaving back eddies and pools. In the Thames however, these places are restricted due to the channelization and bank restriction particularly in the central stretch of the Tidal Thames.

The Individual Based Model (IBM) simulates STST behaviour. Juvenile fish migration is limited by water depth, swimming speed, sensory perception, holding ability and so forth, which were derived from flume studies and observations in the scientific literature. Crucially the IBM model demonstrates that fish could get to a sequence of these rungs by modelling entire journeys through a complex circuitous river and strong tides. The question of this present study is then: where are these 'rungs' and thus where would mitigation be most advantageously placed?

9 Materials and methods

9.1 Study area and site locations

The River Thames flows for 346 km through southern England from its source in Gloucestershire to its mouth at Southend-on-Sea. The Thames Estuary begins at Teddington Lock, and runs for 112 km. The mean tidal range of the river at London Bridge during neap tides is 4.6 m, while on spring tides, this rises to 6.6 m.

Figure 31 shows the study area which is limited to the zone in which the IBM modelling and the LTOA environmental data overlap (roughly between Hammersmith Bridge and Chelsea Road Bridge). Within this zone the predicted movements of the modelled fish can be overlain on the habitat information to show the most suitable areas for habitat enhancement.

The IBM has been extended upstream past Putney Bridge (the most upstream point in the earlier modelling study) to beyond Hammersmith Bridge in order to maximise the overlap with the LTOA data. Although it could be extended all the way through the LTOA, it was not originally calibrated for this area and the river gets progressively narrower and more circuitous, furthermore there are no further work proposed above Putney. Figure 31).

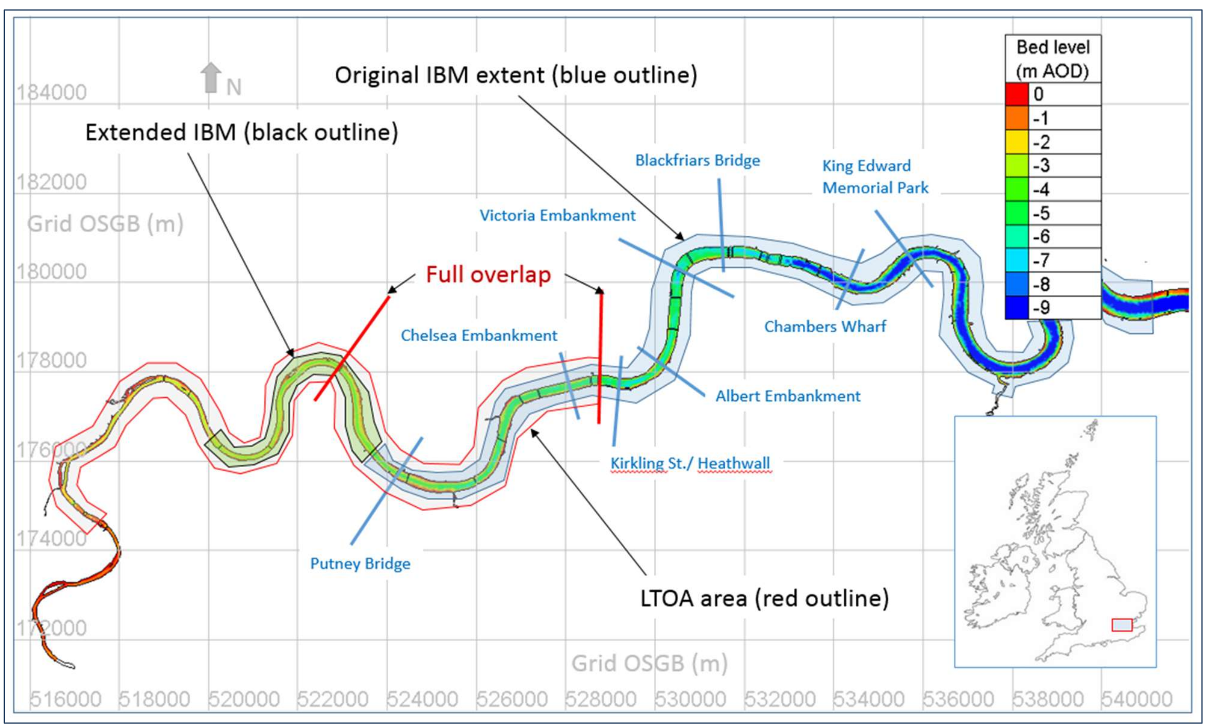

Figure 31: The two study areas and their overlap.

9.2 LTOA study, general methods and data capture

The Lower Thames Operating Agreement (LTOA) describes a set of protocols agreed between Thames Water plc and the Environment Agency that determines (in combination with abstraction licences) the volume of water that can be abstracted from the Lower Thames. In 2011 Thames Water plc undertook a review of the LTOA which involved a series of ecological surveys to identify the potential impact of the abstractions on the ecology of the lower river and Tideway and to ensure appropriate mitigation.

The surveys included an assessment of potential fish spawning habitat, as well as macrophytes (large plants) and sediment sampling. Whilst the study did not focus on fish migration, the shallow, well oxygenated marginal habitats considered to be suitable for spawning, are also those that are used primarily by juvenile fish for migration, and therefore it was considered to be relevant to the current study. The aim of the fish surveys was to provide in GIS compatible format an overview of currently available spawning habitats for species with different substrate preferences within the Tideway from Teddington to Battersea. This study area was used since it represents the section of the Thames Tideway that may be influenced by abstractions which may be affected by the upstream abstractions. Video and photographic surveys were undertaken from a boat moving upstream on the ebbing tide between Battersea and Richmond. The survey recorded substrate type and distribution as well as the size and frequency of macrophyte stands.

The substrate and macrophyte spatial data was used to form the basis of a GIS map identifying potential and known spawning sites for a range of fish species. Georeferenced photographs taken on the spawning substrate survey were overlaid on a base map of the Tideway. Each photo was used to estimate the distribution of sediment types, representing the nearby surrounding foreshore; each area equalled one “sediment cell”. Overall, there were 404 photos of the intertidal area, producing 404 sediment cells (split equally between the north and south banks). This study used 205 areas defined down stream of Teddington Lock, roughly between Hammersmith Bridge and Chelsea Road Bridge, as these overlapped with the IBM and the proposed works.

The key substrates for spawning within the Tideway were identified as:

- Clean hard revetments (e.g. for smelt, *Osmerus eperlanus*);
- Clean gravel and rock (e.g. bleak, *Alburnus alburnus*, and bullhead, *Cottus gobio*),
- Mud/fines (e.g. gudgeon, *Gobio gobio*, and three-spined stickleback, *Gasterosteus aculeatus*);
- Algae (e.g. roach, *Rutilus rutilus*, and ten-spined stickleback, *Pungitius pungitius*);
- Emergent macrophytes (e.g. bream, *Abramis brama*, and sand smelt, *Atherina presbyter*);
- Submerged macrophytes (e.g. roach, zander, *Sander leucioperca*, smelt);

- Ruderal (seasonal) vegetation (e.g. bream and carp, *Cyprinus carpio*);
- Large woody debris (perch, *Perca fluviatilis*).

A DARFOR scale was used to estimate coverage of each substrate type in each sediment cell along the Tideway:

- Dominant (5): >75% coverage
- Abundant (4): 51 – 75% coverage
- Frequent (3): 26 – 50% coverage
- Occasional (2): 6-25% coverage
- Rare (1): 1-5% coverage
- Not present (0): 0% coverage

These scores had been input into the GIS base layer to form an array of maps split into 2 km reaches displaying each sediment type (clean revetments, two types of clean coarse material (gravel and rock), mud/fines and algae) as well as separate maps displaying availability of submergent and emergent macrophytes, any additional seasonal vegetation, and any large woody debris. In this present study vegetation data was not used as they were not sufficiently diverse enough to make any meaningful correlation (i.e. they were mostly zero in the reach within which we were interested, and only became an important factor higher in the catchment and especially upstream of Richmond Lock where the tide is restricted by Richmond Half-Tide Weir.

9.3 Individual based models (IBMs) for assessment of juvenile fish migration

The IBM was constructed as part of the assessment process to model the behavioural responses of the fish to stimulants which exist in the hydrodynamic models of the various flow conditions in the Thames (Willis 2011, Willis & Teague 2014). Individual fish objects introduced into the hydrodynamic models exhibit swimming and movement behaviour related to depth, currents and tidal state, which is derived at their location from the hydrodynamic model.

The IBM was designed to test a wide variety of starting conditions and a wide variation in the population of fish by using a large number of model fish, all with slightly different parameters and starting conditions. Thus the IBM is used to model the variation in the real population as well as uncertainty about the capabilities or behaviour of individual fish. This approach is extended in this study where the positions of 2500 model fish are recorded every 10 minutes (or timestep) to develop a virtual 'surface' or map showing the probability that fish will be in a particular position at any one time. This surface is derived from several million positions where individual fish were recorded at every 10 minute timestep. The probability surface or map can be used to determine the likelihood that any particular model fish will successfully through the Tideway and to highlight the places where they are likely to spend the most time holding station against the current.

9.4 Difference between fish species in the IBM

- The study used the three species originally chosen for the IBM model used in the assessment:

juvenile bass (*Dicentrarchus labrax),*

flounder (*Platichthys flesus*) and;

European eel (*Anguilla anguilla*)

- The species were chosen as they are common in the Thames Tideway and are archetypical examples of a round fish (bass - which stays away from contact with the bed or banks and is averse to being touched – thixophobic), a flat fish (flounder – which rests on the bed and is shaped accordingly) and an eel like fish (eel – which positively likes to touch the bed and bank, uses touch for navigation sometimes, and behaves differently in night and day – thixophilic).
- Differences between real fish and model fish were incorporated in the model in differences in capability and behaviour which had been studied and calibrated in the earlier flume experiments. Model bass remained in the water column, avoided too deep or too shallow water and avoided being swept away on the ebb tide by moving toward slower moving water. Flounder were able to get close to the bed in the ebb tide (into the boundary layer where friction between the water and the bed results in lower current velocity), and were thus protected from the current.
- A 'peel off' function was incorporated when water speed was too high to allow this behaviour. Eel were similar to flounder in this respect but had different swimming and turning capabilities and different depth preferences. All modelled fish species strongly avoided becoming beached as this is rarely (but sometimes) seen in real rivers, and thus remained in wet areas at all times in the model run.

9.5 Methods of modelling and data analysis

The following section provides a summary of the modelling and data analysis that were undertaken.

The IBM model was run for a period of seven days to allow all 2500 fish to pass through the modelled area between Chelsea Road Bridge and Hammersmith Bridge (Figure 1). The positions of each fish (n = 2500) was saved at ten minute intervals during the seven day model run resulting in a total of 2.5 million positions.

The positions of the fish at each time step were saved on a regular square (10 m x 10 m) grid overlain on model domain. This was a measure of residence times for individual fish recorded within each grid square. The distribution of these points on this 10 m x 10 m square grid was thus used to make a residency surface (paragraph 2.3.2) with the value in each grid square being the number of residency points within it throughout the entire length of the model run.

Residency time within each of the LTOA zones was then calculated for each species.

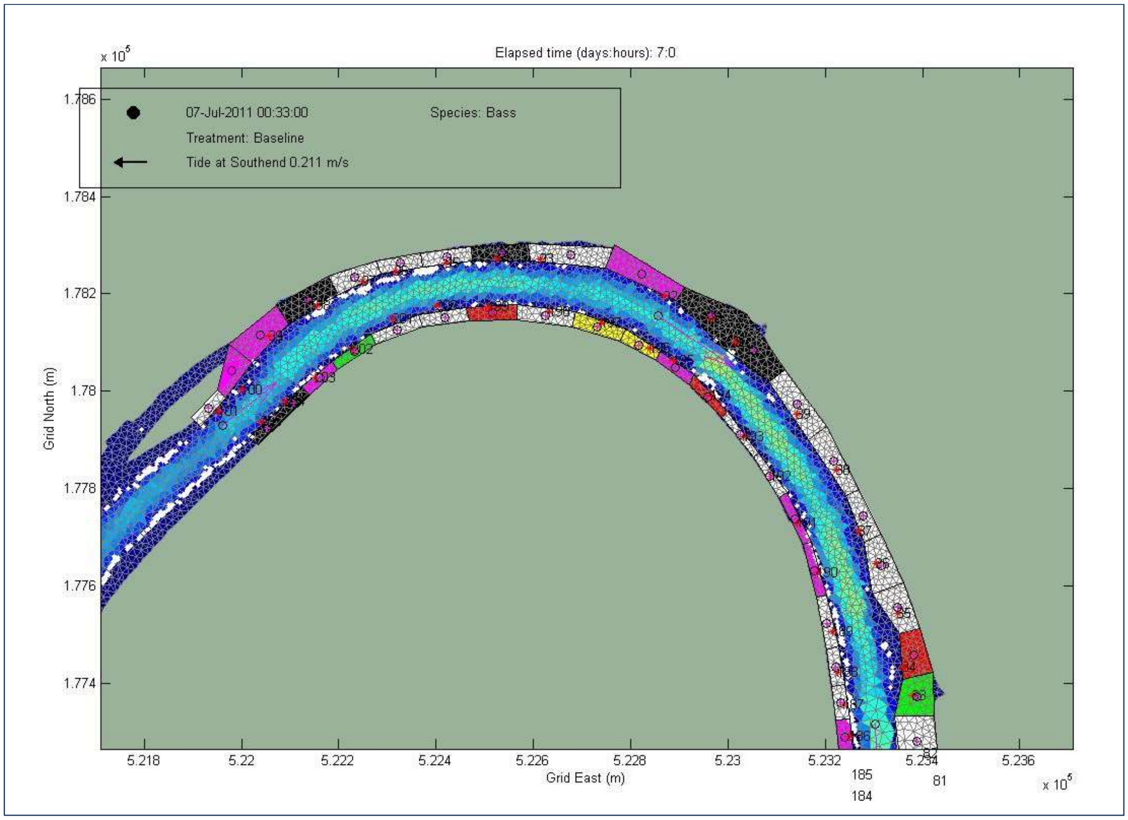

Figure 32: Various components of the analysis are plotted together as the IBM model was running.

The white dots are model fish, the colour scale on the small triangular elements show current speed over the triangular irregular network (TIN) grid of the water model, the flat coloured zones are the LTOA areas, with their GPS reference marks shown as red stars and their centres shown as black circles (and magenta crosses), the magenta arrows show current direction. The axis tick marks are the OSGB grid (m), the sub-axis shows that this was a model of bass, in the baseline treatment (present conditions) on the 7th July 2011, at 12:33 in the morning, and while the tide was beginning to come in at Southend it was still going out at this stretch of the river (around Hammersmith and Barnes).

The residency times were weighted according to the length of shoreline of each zone. This relates to the fact that each of the zones was a different length of river bank. It was decided to account for this by dividing the number of residency points per zone by the lengths of the zones. This leaves a "residency per unit length of zone type". The alternative might mean that types of zones which were on average longer would appear to have great residency potential, as a result of having more bank length to catch residency points (the model fish were compelled to go past all the zones). Correlation to zone area was also assessed (but there was no correlation.) This provided a cross check to ascertain if there was any correlation to zone area or foreshore extent (as this varied considerably between LTOA zones and may well have been differentiated between zone types, for instance revetments may cause or maintain diminished foreshore relative to say gravel areas which might increase foreshore area, it may also just be a proxy variable to bank steepness which is likewise important. Nevertheless, there were no correlations here as reported in the results section.)

Simple linear correlation coefficients were calculated between variables of LTOA classifications and above derived residence times. It was decided to use simple statistical tests to ensure that the results could be easily understood by the widest audience. Since the sources of data (i.e. the IBM and the LTOA ecological mapping) were collected independently of each other and for studies that were not designed for a different purpose, any correlations are likely to be more difficult to identify. For instance the DARFOR scale for each sediment type was qualitatively assessed along only 6 possible values and one must expect some subjective personal bias in the results. However, since this was assessed entirely independently it remains a very robust statistical measurement when used for the purpose of this study, and was adequate for the original purpose.

10 Results

The results are split into two sections. The first are simple linear correlations between the various DARFOR scale values used for sediment types on the photographic survey and the residency times from the IBM fish model. The aim here is to determine any relationships between fish use of the various substrate types. These simple linear correlations were made for each of the three species (bass, flounder and eel) in the baseline model. That is the model of the present situation with no permanent works.

The second section of the results relates to the pattern of residency in the baseline model and in the model of permanent works. Analysis of the second section highlights the general pattern of residency predicted by the IBM in the river outside and inside of the overlap area between the fish model and the LTOA classifications of foreshore. It also highlights the differences between the residency patterns between the baseline and the permanent works.

10.1 Simple linear correlation bass

•	• Pearson's r	• p-value	• R-lo	• R-hi	• Significant
• Revetments	• -0.21	• 0.0023	• -0.34	• -0.08	• *
• Coarse clean material - Rocks	• 0.02	• 0.8107	• -0.12	• 0.15	•
• Coarse clean material – Gravel	• -0.02	• 0.8231	• -0.15	• 0.12	•

• Mud and fine material	• 0.29	• 2.81E-05	• 0.16	• 0.41	• ***
• Algae	• -0.30	• 1.72E-05	• -0.42	• -0.16	• ***
• Area of zone (Foreshore)	• 0.14	• 0.0515	• 0.00	• 0.27	•
• Index up river position	• 0.41	• 8.79E-10	• 0.29	• 0.52	• ***

Table 6: Simple linear least squares correlation between juvenile bass IBM residency time and zonal classification of the LTOA study between Hammersmith and Chelsea Road Bridge.

Pearson product-moment correlation coefficient, also known as Pearson's r, varies between 1 (perfect correlation) through 0 (no correlation) to -1 (perfect negative correlation. The statistically significant relationships are coloured light red, and the marginally significant light green. Statistical significance is defined at a p-value less than 0.001. N=205 sample sites. This table therefore shows that the residency time for juvenile bass is weakly positively correlated with the proportion of mud and fine material, and that this relationship is highly unlikely to be due to chance. R-lo and R-hi are the 95% confidence intervals in the value of the correlation coefficient (r), if these encompass zero it diminishes the confidence that there is any real signal in the data.

10.2 Simple linear correlation flounder

•	• Pearson's r	• p-value	• R-lo	• R-hi	• Significant
• Revetments	• -0.28	• 6.36E-05	• -0.40	• -0.14	• ***
• Coarse clean material - Rocks	• 0.07	• 0.3406	• -0.07	• 0.20	•
• Coarse clean material – Gravel	• 0.01	• 0.8886	• -0.13	• 0.15	•
• Mud and fine material	• 0.39	• 1.00E-08	• 0.26	• 0.50	• ***
• Algae	• -0.19	• 0.0074	• -0.32	• -0.05	• *
• Area of zone (Foreshore)	• 0.22	• 0.0015	• 0.09	• 0.35	•
• Index up river position	• 0.38	• 2.51E-08	• 0.25	• 0.49	• ***

Table 7: Simple linear least squares correlation between juvenile flounder IBM residency time and zonal classification of the LTOA study between Hammersmith and Chelsea Road Bridge.

Pearson product-moment correlation coefficient, also known as Pearson's r, varies between 1 (perfect correlation) through 0 (no correlation) to -1 (perfect negative correlation. The statistically significant relationships are coloured light red, and the marginally significant light green. Statistical significance is defined at a p-value less than 0.001. N=205 sample sites. R-lo and R-hi are the 95% confidence intervals in the value of the correlation coefficient (r), if these encompass zero it diminishes the confidence that there is any real signal in the data.

10.3 Simple linear correlation eel

	Pearson's r	p-value	R-lo	R-hi	Significant
Revetments	-0.37	5.35E-08	-0.48	-0.24	***
Coarse clean material - Rocks	0.22	0.0015	0.09	0.35	*
Coarse clean material – Gravel	0.22	0.0013	0.09	0.35	*
Mud and fine material	0.17	0.0157	0.03	0.30	
Algae	-0.25	0.0003	-0.37	-0.12	**
Area of zone (Foreshore)	0.20	0.0045	0.06	0.33	
Index up river position	0.52	1.18E-15	0.41	0.61	***

Table 8: Simple linear least squares correlation between juvenile eel IBM residency time and zonal classification of the LTOA study between Hammersmith and Chelsea Road Bridge.

Pearson product-moment correlation coefficient, also known as Pearson's r, varies between 1 (perfect correlation) through 0 (no correlation) to -1 (perfect negative correlation. The statistically significant relationships are coloured light red, and the marginally significant light green. Statistical significance is defined at a p-value less than 0.001. N=205 sample sites. R-lo and R-hi are the 95% confidence intervals in the value of the correlation coefficient (r), if these encompass zero it diminishes the confidence that there is any real signal in the data.

10.4 Patterns of residency in baseline

The log transformed probability density kernels for a representative river reach demonstrate the differences in use of the foreshore by the different species Figure 33, Figure 34 Figure 35).

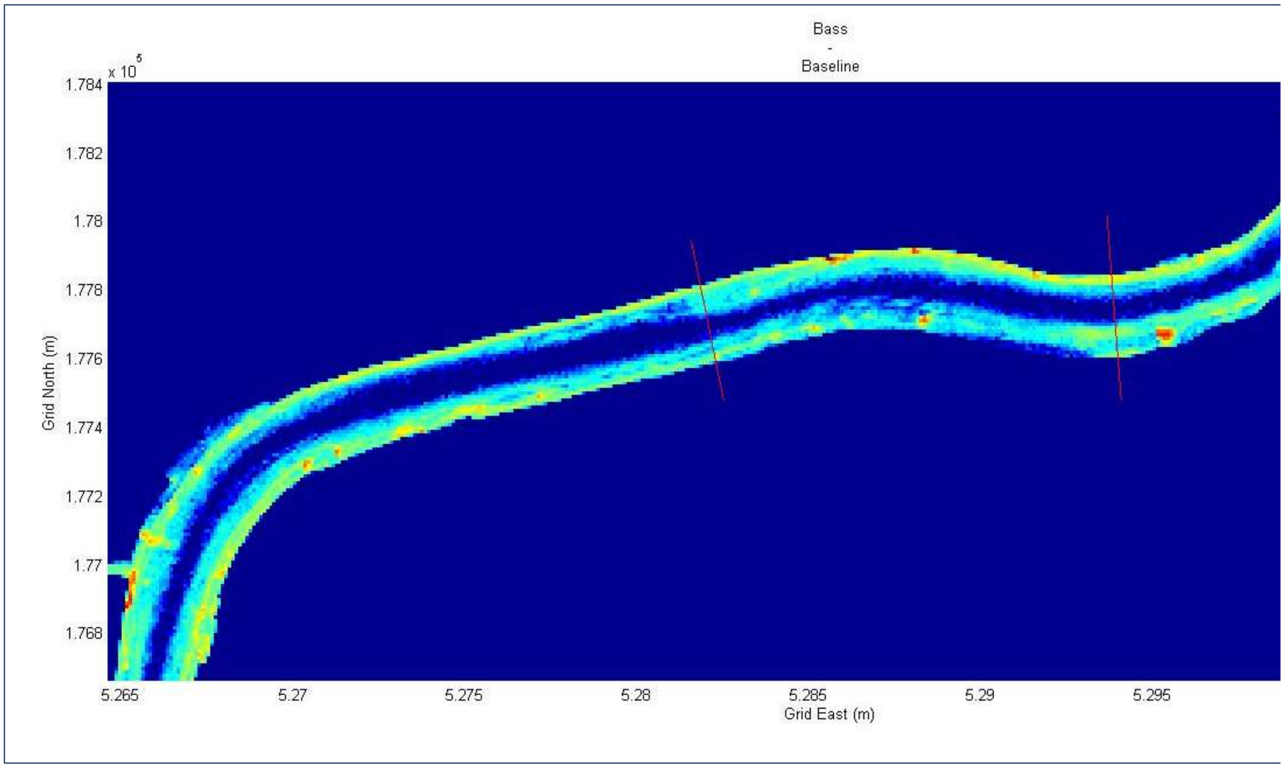

Figure 33: Log transformed probability density kernel for the residency of bass in the baseline model.

All the positions over a seven day run of the model were saved every ten minutes for 2500 model fish. These 2.5 million positions were distributed over a 10 m x 10 m grid that covered the model area, the figure is a colour plot of that distribution. The log transformation tends to enhance the lower values. The colour scale varies between dark blue (no residency) to red (about 400 positions in a 10 m x 10 m grid element). The axis tick marks are the OSGB grid (m) and this figure covers the Chelsea Embankment in the centre of the model area. The comparatively poor residency areas are apparent on the northern bank of the central channelized section and it is evident that the model fish spend little or no time in the thalweg (the central fastest moving centre of the river flow). Hotspots are evident as the 'rungs' on the ladder that the fish use to climb the river and are coloured red.

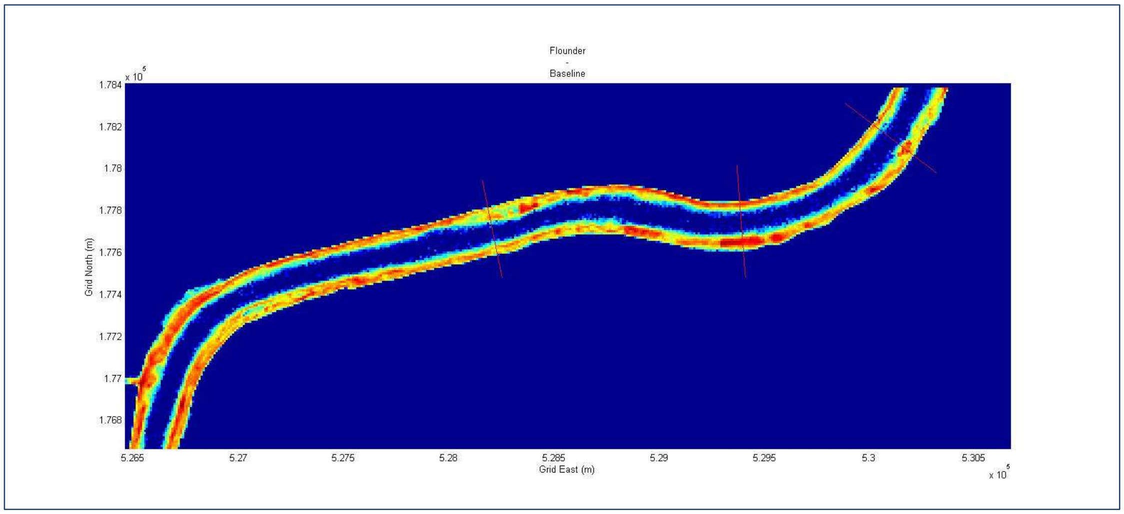

Figure 34: Log transformed probability density kernel for the residency of flounder in the baseline model.

All the positions over a seven day run of the model were saved every ten minutes for 2500 model fish. These 2.5 million positions were distributed over a 10 m x 10 m grid that covered the model area, the figure is a colour plot of that distribution. The log transformation tends to enhance the lower values. The colour scale varies between dark blue (no residency) to red (about 200 positions in a 10 m x 10 m grid element). The axis tick marks are the OSGB grid (m) and this figure covers the Chelsea Embankment in the centre of the model area. In contrast to the bass in the above figure, the flounder are relatively evenly spread along the margins of the river. There are hot spots, in somewhat similar areas to bass but these are much larger for flounder, extending to several 100 m along the bank, and thinning considerably in the areas of least residence.

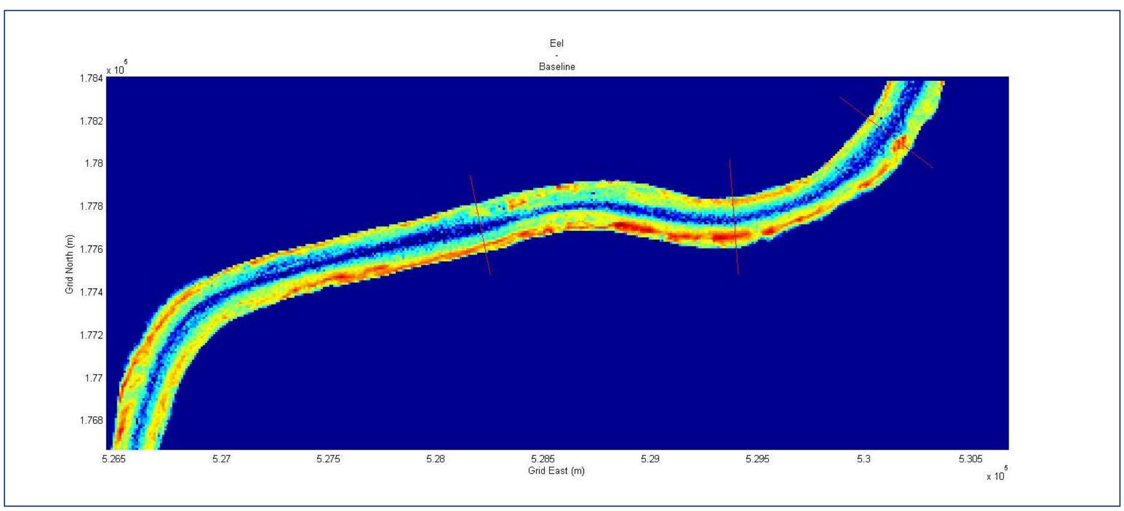

Figure 35: Log transformed probability density kernel for the residency of eel in the baseline model

All the positions over a seven day run of the model were saved every ten minutes for 2500 model fish. These 2.5 million positions were distributed over a 10 m x 10 m grid that covered the model area, the figure is a colour plot of that distribution. The log transformation tends to enhance the lower values. The colour scale varies between dark blue (no residency) to red (about 200 positions in a 10 m x 10 m grid element). The axis tick marks are the OSGB grid (m) and this figure covers the Chelsea Embankment in the centre of the model area. The patterns of distribution share some features with both the flounder and bass figures above. The model fish move more into the centre of the stream, as is observed in the distribution of real eel. The picture may be complicated by lack of movement in daylight. The hotspots are more diffuse than the bass and some coincide with the flounder while others do not.

10.5 Bass hotspots along entire reach

The distribution of residency for bass was more clearly defined than for the other species and the hotpots clearly identifiable. An alternative way to view the log transformed density kernels is as a contour plot, where contour lines are drawn around areas of various height on the probability surface, if these lines are restricted to only one level – a hot spot or not (in this case around 400 residence points in a 10 m x 10 m grid square) the overall pattern of main hotspots can be seen on a single plot (Figure 36).

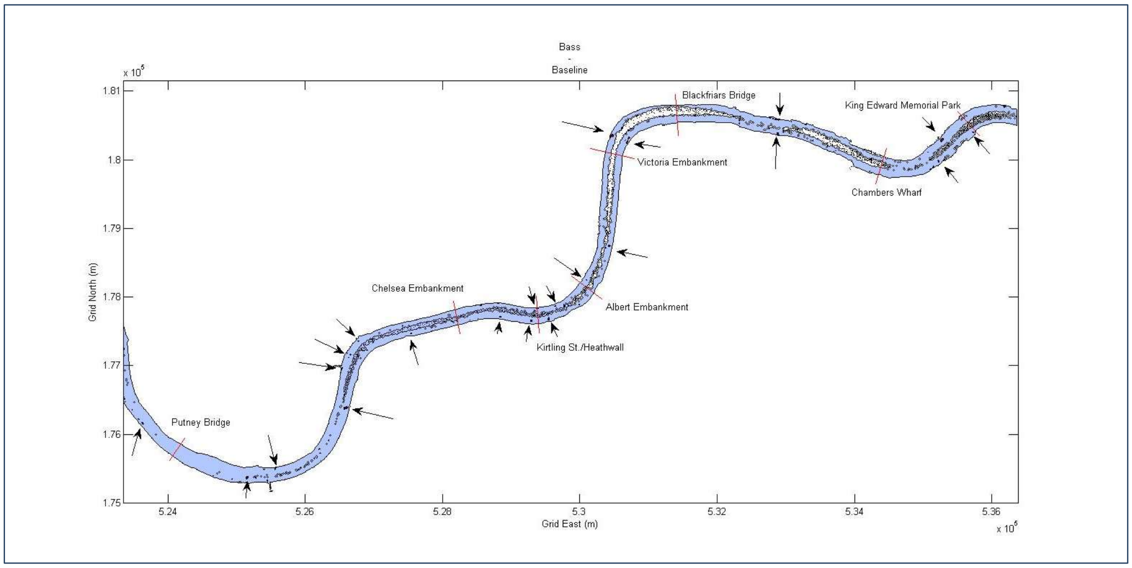

Figure 36: Hotspot patterns along the whole focal reach for bass in the baseline treatment

Figure 7 shows the positions of maximum residency, or 'hotspots' (shown as arrows) for bass in the baseline treatment. A hotspot was defined as an area with over 400 residency points in a 10 m x 10 m area. There is a clear pattern. Moving up river from the eastern side (right hand side) the hot spots are widely spaced and seem to align on north and south banks. There are long clear spaces between these hotspot groups which are correlated to channelized section of the river – the x-axis tick marks are 2 km apart, and the y-axis 1 km apart. The maximum tidal excursion is about 7 km (the distance water moves laterally at each tide). Further up-river the hotspots are clustered around the bends and appear more randomly placed (in the areas around Putney for instance) although there remain long gaps between them.

10.6 Patterns of residency contrasted between permanent works and baseline models

The graphical distribution of the hot spots for bass were more informative than the other species (as is to be expected as they have less opportunity to shelter near the bed and bank than flatfish or eel). Thus the contrast between the treatments (permanent works and baseline) is only shown for bass. Similar patterns were found in the majority of the river in both treatments away from the permanent works. This was to be expected as the permanent works did not influence currents for more than a few hundred meters away and the general patterns of water movements and bed profiles were thus similar. However there were areas with major differences close to several of the permanent works, the more interesting examples are reported here (**Figure 37 Figure 38**, **Figure 39**, **Figure 40**, and **Figure 41**.

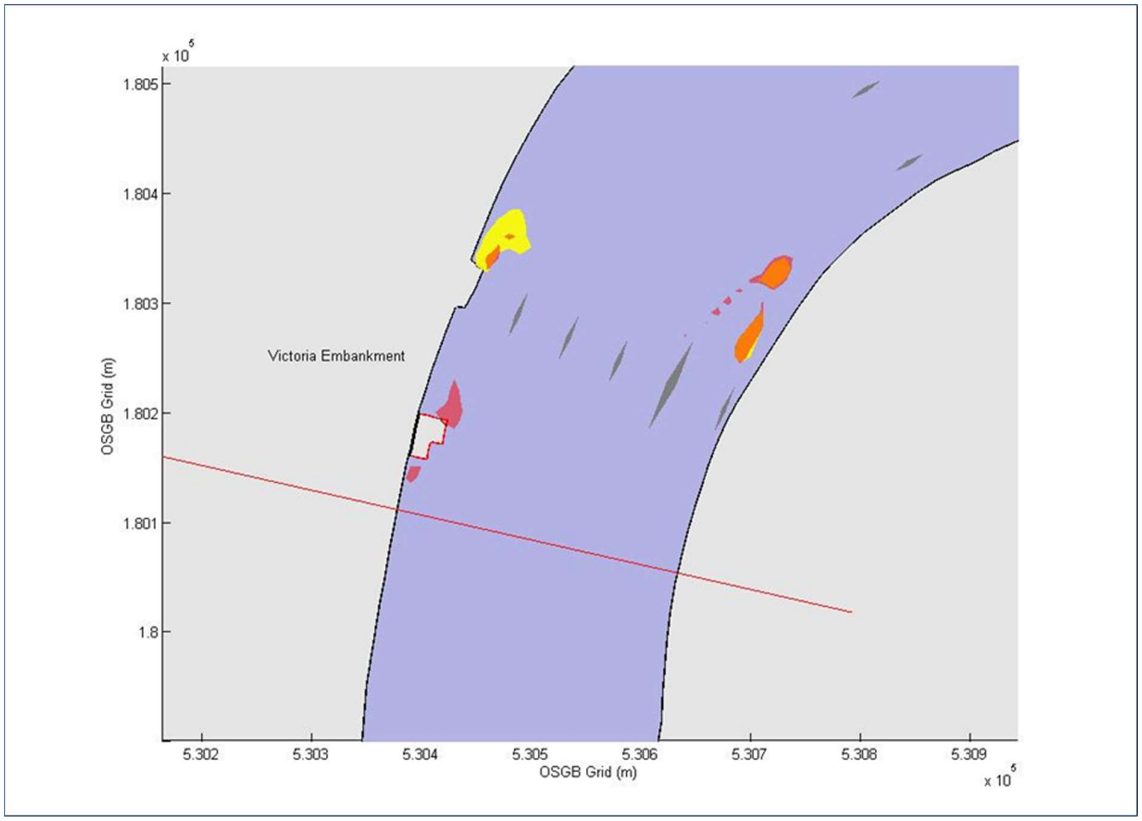

Figure 37: Hotspot patterns for juvenile bass in baseline and permanent works treatments and where they coincide near the Victoria Embankment Foreshore proposed permanent works (TTT permanent works extent shown as a red edged section of bank; bridge piers shown as darker grey filled patches.)

The pattern of hotspots at Victoria Embankment Foreshore (Figure 8) matched on north and south banks is caused by the arrangement of bridge piers, with an interesting multiple pattern on the south bank. This type of behavioural pattern suggests that juvenile round fish actively seek out areas for sheltering or refuges against the ebb tide. The permanent works also create a hot spot, although it appears to have the effect of removing, or reducing the value of an existing one further downstream by the bridge abutment. This appears to suggest that there is a minimum spacing required between refuges (like the rungs or a ladder) in order for them to be of value. are required at regular intervals, rather than clustered together.

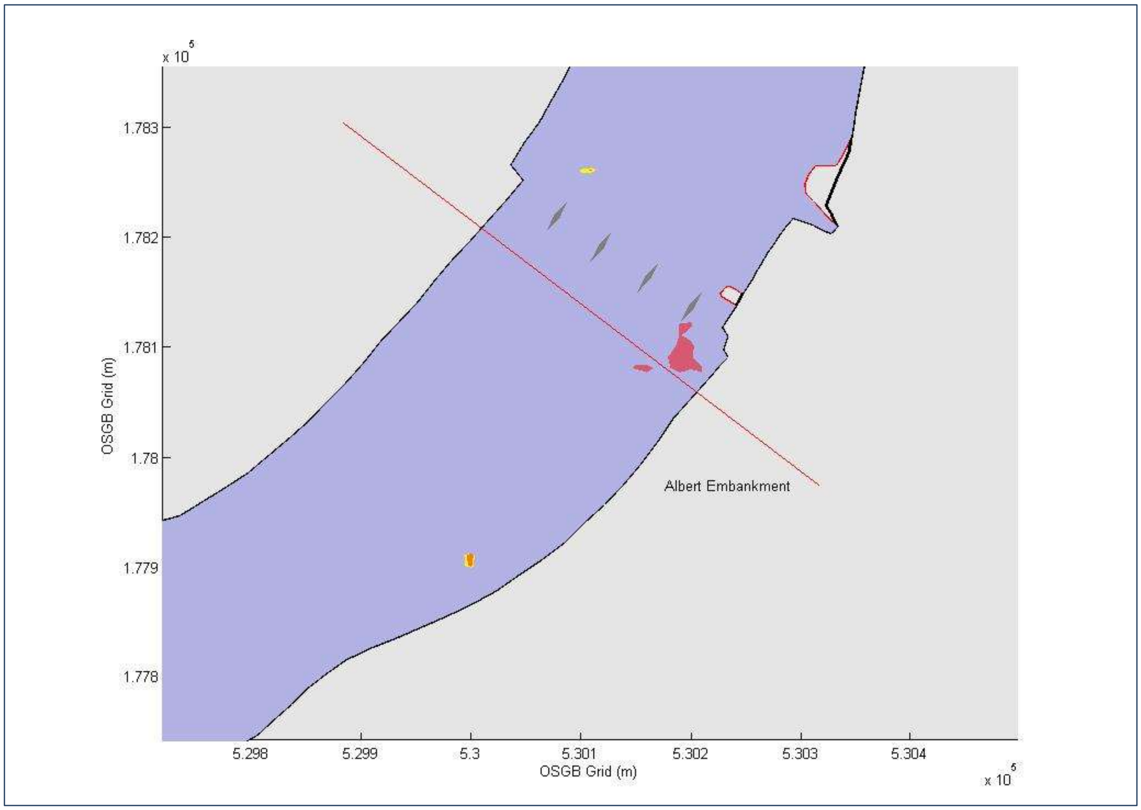

Figure 38: Hotspot patterns for juvenile bass in baseline and permanent works treatments and where they coincide near the Albert Embankment proposed permanent works (TTT permanent works extent shown as a red edged section of bank; bridge piers shown as darker grey filled patches).

The permanent works at Albert Embankment create a hot spot upstream (Figure 9). This hotspot is a potentially valuable rung for fish ascending the river as it is relatively large and exists in an area where comparatively few other hot spots exist.

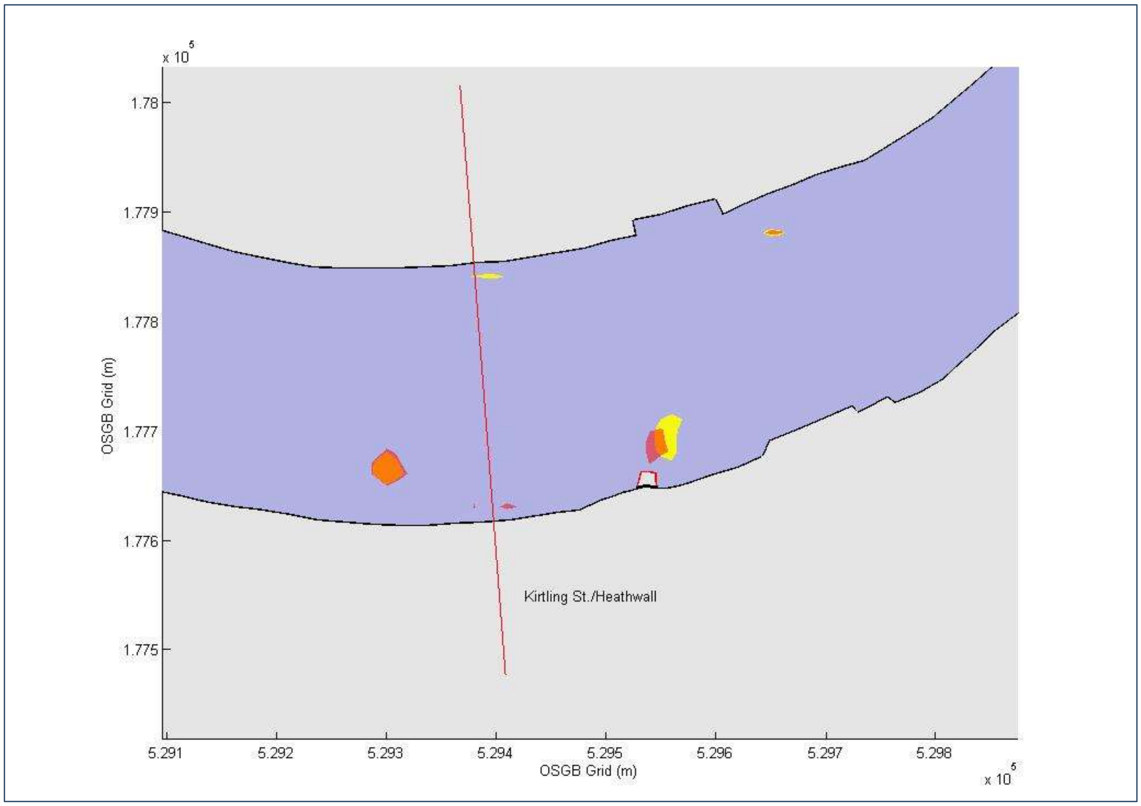

Figure 39: Hotspot patterns for juvenile bass in baseline and permanent works treatments and where they coincide near the Heathwall pumping station proposed permanent works (TTT permanent works extent shown as a red edged section of bank; bridge piers shown as darker grey filled patches).

The pair of hotspots at Heathwall pumping station (Figure 10) is a potentially valuable rung for fish ascending the river as it is relatively large and exists in an area where comparatively few other hot spots exist. The presence of a hotspot here may relate to the location on the outside of a major bend in the river where flow velocities are high, although the precise location of the hotspot may be dictated by a much smaller local feature such as a pier or an undulation in the bed.

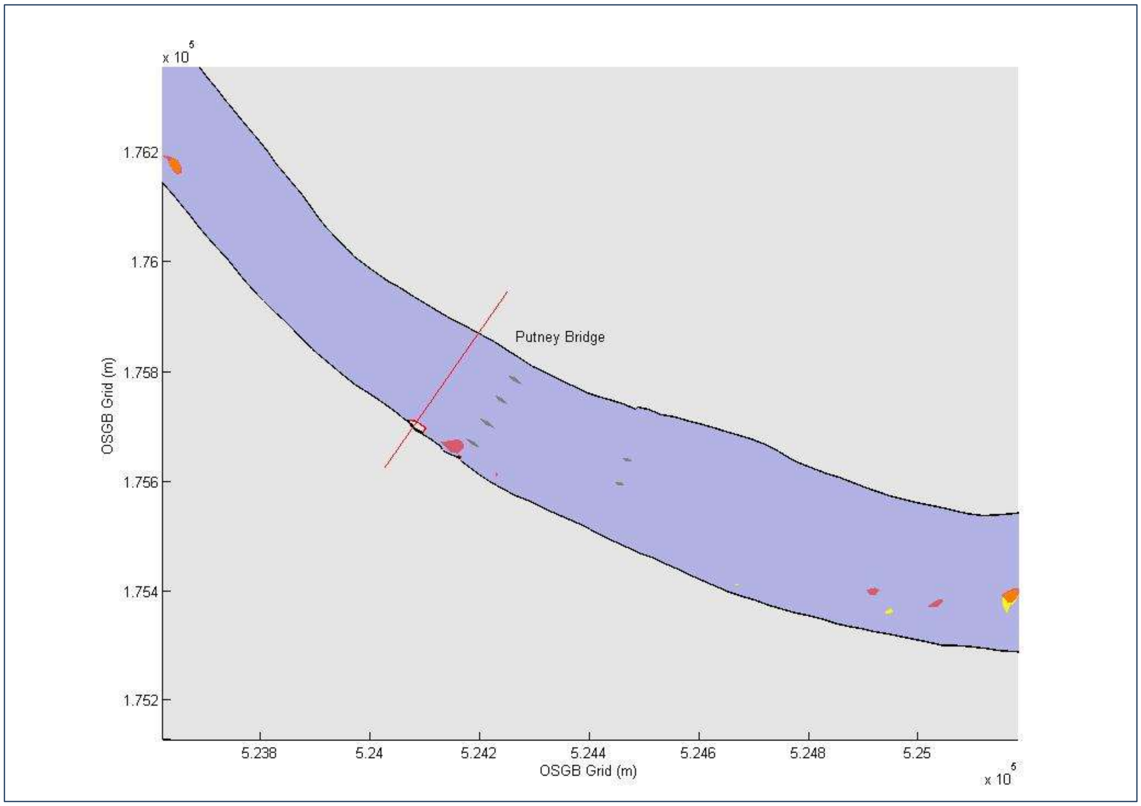

Figure 40: Hotspot patterns for juvenile bass in baseline and permanent works treatments and where they coincide near the Putney Bridge proposed permanent works.

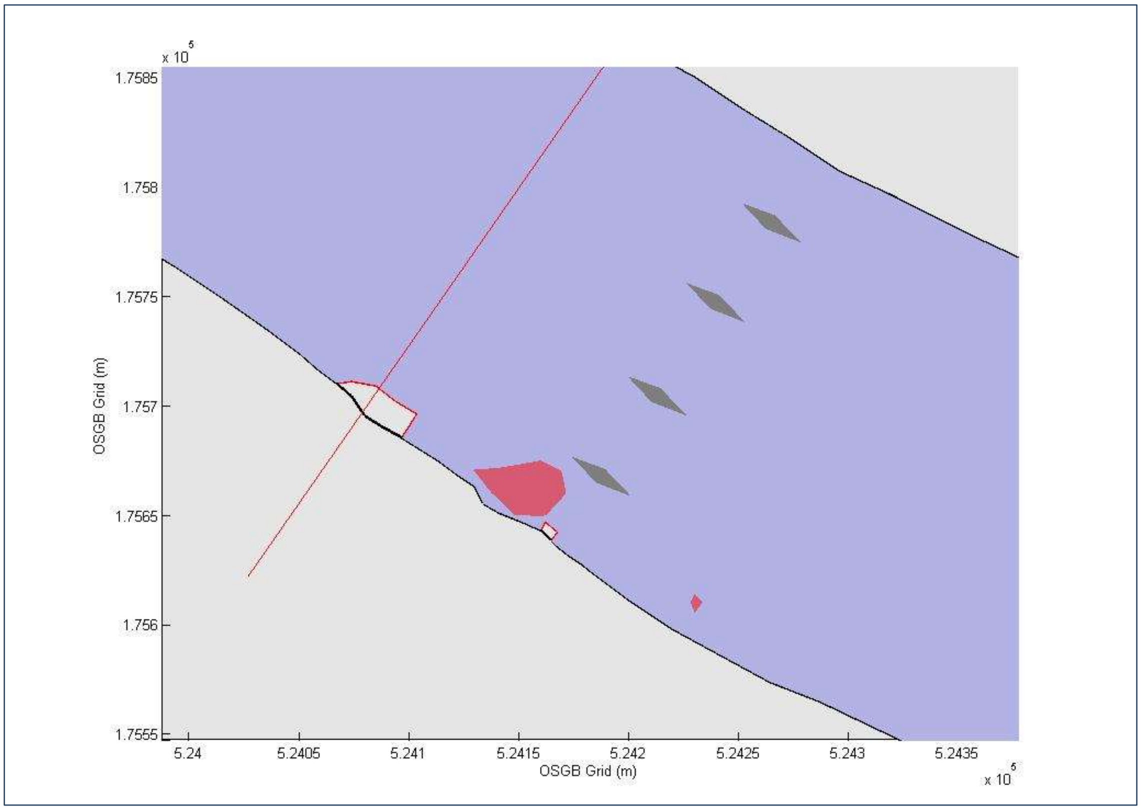

Figure 41: Details of hotspot patterns for juvenile bass in permanent works treatment near the Putney Bridge proposed permanent works.

At Putney Bridge (Figures 11 and 12) the permanent works create a hot spot which is downstream of the major part of the works (Figures 11 and 12). This hotspot is a potentially valuable rung for fish ascending the river as it is relatively large and exists in an area where comparatively few other hot spots exist. The proposed works create minor changes to the hotspot pattern compared with the baseline position at some considerable distance from the works (up to 1 km in this case).

Discussion

10.7 Numerical correlations

The numerical correlations between the distribution of suitable migratory habitat for juvenile fish derived from the LTOA data, and the results of the fish model IBM provides confidence in the model to inform locations of where fish refuge measures would be most effective to aid the upstream migration of juvenile fish within the Thames Tideway.

The correlations whilst weak (Pearson's r values under 0.5) are statistically significant as a result of the large number of replicates (N=201) and therefore the correlations are unlikely to have occurred by pure random chance.

The statistical tests have been used since the effects being investigated need to be obvious and a correlation evident in all tests. More sophisticated tests such as multiple analysis of variance or principal component analysis are available but their complexity is unlikely to increase the true value of the analysis and may obscure the simple relationships.

The correlations make sense, in that it is logical that the opportunities for refuge against the ebbing tide increase as the model fish move up river, since the banks are more evenly graded, more naturalised and not channelized. Furthermore, it is also logical that the fish move more slowly on the flood tide (thus also increasing residency time) as the banks are more gently sloping outside of channelized sections. Thus the correlation to the up-river position of the LTOA zones is relatively strong for all the species, and significant in all cases. The correlation to revetments is negative in all species, although only significant at the least threshold in bass. This means that more revetments correlate to a lower residency time, in all cases.

Revetments range from vertical sheet piling to sloping concrete slabs. They tend to increase water flow speed, restrict natural channel width and thus increase scour on the bank and reduce foreshore lateral extent while increasing foreshore slope. While this may be a major factor for fish that use the bed and foreshore (flounder and eel) it appears to be a minor factor for round fish (which avoid the bed and banks), and other factors may be stronger indicators of residence.

This certainly reflects present understanding of reality in that eels appear much more comfortable on gravel and rock substrates than either of the other species. Flounder are particularly attracted to mud and fine sediment and are able to rest and take refuge in these areas. In the case of bass, the presence of mud may indicate naturally occurring areas of slower moving water or eddies making the water column in these areas suitable for shelter on the ebb tide.

10.8 Patterns of residency and hot-spots

The general patterns of residency for the three species provide an interesting and informative way to view the predictions of the IBM fish model. The hotspots display the positions of greatest probability of finding a model fish over the course of the seven day model. It is interesting that in all three cases the margins of the river are used and relatively infrequently the centre section. The centre section is usually the deepest and fastest moving, but for a small fish may also be a dangerous area (predation).

The patterns are particularly informative for bass. This is to be expected from their behaviour and from the original video based outputs of the IBM. Bass show clear hotspots. The location of the hotspots appear to be influenced by characteristic of the whole river flow over several kilometres (such as changes in velocity caused by large bends) and local river bank shape where small sharper features cause eddies over small distances of several tens of metres.

The effect is evident at the end of a long channelized section such as the Victoria Embankment (**Figure 36**8), where model fish are flushed back in the ebb tide all the way down the main channelized section. Evidently they then form residence hotspots at the first change of flow characteristics, which are caused by small scale complex channel shapes of the bridge piers and abutments on both sides of the river. The effect is clearly shown by how the hotspot created by the permanent proposed works replaces an existing one associated with the nearby bridge pier.

10.9 Areas of optimal refuge and potential foci for mitigation

The hot spot analysis shows that there are several locations near the proposed permanent works which may be good targets for mitigation and monitoring of fish behaviour and abundance. In particular, hot spots for juvenile bass were noted immediately up and downstream of the Victoria Embankment Foreshore permanent structure, and upstream of the Albert Embankment foreshore, and Putney Embankment Foreshore structures.

The hotspots at the Albert Embankment Foreshore site is a potentially valuable rung for fish ascending the river as it is relatively large and exists in an area where comparatively few other hot spots exist. The hot spot also exists close to the proposed works and if it is shown to coincide with fish use it is a potentially excellent monitoring location close to modified banks and permanent works. The Putney site is also of value given the importance of the upper Tideway as a nursery area for juvenile fish.

There are two hotspot sites slightly upstream of the permanent works for Heathwall Pumping Station. This pair of hotspots is a potentially valuable rung for fish ascending the river as it is relatively large and, as for Albert Embankment Foreshore, is in an area where comparatively few other hot spots exist.

10.10 Conclusions and further work

The findings of the study suggest that the factors influencing where fish seek refuge from the current relate to both the shape or morphology of the river at a broad scale (such as the presence of large bends), as well as small scale local features. The analysis of residency hotspots at various Thames Tideway Tunnel sites suggests that the permanent works may offer alternative refuges for juvenile fish and influence the location of existing refuges.

The simple correlation analysis between the LTOA substrate data and the modelled distribution of fish using the IBM showed that habitat or substrate type is a more important factor for species such as flat fish and eel which are more closely associated with the bed, than round fish such as bass.

The next step in the study is to determine whether small scale habitat refuges or micromeasures, developed during the previous stages of the study are effective in providing shelter to small fish from adverse currents. Locations for the study are currently being sought.

Should the habitat micromeasures be found to be effective stakeholders and regulators will be consulted over the potential locations for deployment of the micromeasures within the Tideway.

References

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