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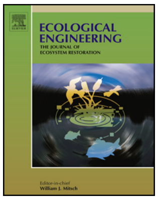

Efficacy of a side-mounted vertically oriented bristle pass for improving upstream passage of European eel (*Anguilla anguilla*) and river lamprey (*Lampetra fluviatilis*) at an experimental Crump weir

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ABSTRACT

Globally, populations of diadromous anguilliform morphotype fish, such as eel and lamprey, have experienced substantial declines, partly as a result of habitat fragmentation caused by river infrastructure. In the UK, a new configuration of hydraulically unobtrusive bristle pass (side-mounted and vertically oriented) has been developed to help upstream moving European eel (*Anguilla anguilla*) negotiate gauging weirs. The efficacy of vertically oriented bristle passes remains untested, despite their potential as a low-cost low-maintenance solution to improve habitat connectivity at low-head structural barriers worldwide. This study assessed the ability of small (82–320 mm) and large (322–660 mm) European eel and adult (291–401 mm) river lamprey (*Lampetra fluviatilis*) to pass upstream over an experimental Crump weir installed in a large open-channel flume with (treatment) and without (control) side-mounted vertically oriented bristle passes under three different hydraulic regimes. Both species were highly motivated to explore their surroundings and move upstream during the trials. Under flooded control conditions, passage efficiency (the total number of times fish passed the structure as a percentage of total attempts) and passage success (the number of fish that passed the structure as a percentage of those that attempted) were high, delay was short, and number of failed attempts before passage was low for both species. When difference in head was at its greatest (230 mm) and velocity and its variation downstream were high (maximum u and σ: 2.43 ms^{-1} and 0.66 ms^{-1}, respectively), the upstream movement of small eel and lamprey was blocked, and passage efficiency and success for large eel low (4.6% and 17.2%, respectively). For large eel that successfully passed, delay was long, and number of failed attempts before upstream passage was high. When bristle passes were installed, passage efficiency for small (91.5%) and large eel (56.7%), and passage success for large eel (76.5%) and lamprey (36.7%) was higher, while delay and the number of attempts before passage was lower for both species. Bristle passes helped European eel and river lamprey pass a small experimental Crump weir, although interspecific variation in efficacy was evident.

1. Introduction

Impacts of infrastructure, such as dams, weirs and barrages, on the physical and chemical processes of rivers are well established (Petts, 1980). Impoundments alter flow and sediment regimes (Nilsson et al., 2005; Xu and Milliman, 2009), channel morphology (Gordon and Meentemeyer, 2006), and nutrient and oxygen availability (Bellanger et al., 2004; Gresh et al., 2000). Ecological impacts include changes in invertebrate communities (Boon, 1988), and for fish the loss of, or reduced access to, critical habitat (Pess et al., 2008), delayed migration (Caudill et al., 2007), population isolation (Morita and Yamamoto, 2002), and reduced productivity and diversity (Agostinho et al., 2008; Matzinger et al., 2007). As a consequence, populations of riverine fish have declined worldwide (Aparicio et al., 2000; Dekker et al., 2007; Kruk, 2004; Nelson et al., 2002). For diadromous species these declines are often due to impeded migration between essential habitats (Feunteun, 2002; Lucas and Baras, 2001; Ojutkangas et al., 1995; Yoshiyama et al., 1998).

In an effort to re-establish fluvial connectivity and reverse population declines a range of mitigation strategies have been developed, including the installation of fish passes at structural

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barriers to migration (Beach, 1984; Clay, 1995; Larinier and Marmulla, 2004). Unfortunately, fish passes, such as those developed for upstream migrating salmonids, often perform poorly for weaker-swimming non-salmonid species (Bunt et al., 1999, 2000, 2001; Cooke et al., 2005; Noonan et al., 2012; Slatick and Basham, 1985). For example, anguilliform morphotype fish, such as eel (*Anguilla* spp.) and lamprey (e.g. *Lampetra* spp. and *Petromyzon marinus*), exhibit distinctly different forms of locomotion (Sfakiotakis et al., 1999) and behaviour (Russon and Kemp, 2011a), compared to those with a subcarangiform morphology. Although anguilliform morphotypes have good acceleration and are highly manoeuvrable (Muller et al., 2001; Sfakiotakis et al., 1999), they do not leap at barriers and their burst swimming speeds are relatively low (Beamish, 1978; Clough et al., 2004; Russon and Kemp, 2011b; Keefer et al., 2012). Instead, if required, eel and lamprey adopt alternative strategies to ascend obstacles; juvenile eel climb wetted slopes using substrate surface irregularities (Legault, 1988; Tesch, 2003), while lamprey use their oral disc to attach to structures to rest between intermittent bouts of activity (Kemp et al., 2009; Quintella et al., 2004; Russon et al., 2011). In recognition of these adaptations, and in response to environmental legislation (e.g. The Eels [England and Wales] Regulations 2009; CITES; European Habitats Directive [92/43/EEC]; EU Water Framework Directive [2000/60/EC]; Bern convention [COE, 1979]) enacted in an attempt to reverse population declines (Dekker, 2003; Dekker et al., 2007; ICES, 2012; Kelly and King, 2001; Moriarty and Tesch, 1996; Renaud, 1997), specialist fish passes have been developed and employed for several anguilliform morphotype fishes (Moser et al., 2011; Solomon and Beach, 2004).

For upstream migrating juvenile eel, specialist fish passes predominantly rely on their ability to climb (Legault, 1988; Tesch, 2003). A variety of substrates have been developed to facilitate climbing (Environment Agency, 2011; Porcher, 2002), including those that incorporate clusters of bristles (usually synthetic), set at regular intervals, protruding from a solid surface (see Environment Agency, 2011). This ‘bristled substrate’, when used in a traditional configuration (where the base is oriented horizontally, or slightly off horizontal, with water flowing through the bristles), has proved effective at facilitating the upstream passage of a large number (hundreds of thousands per year) (Briand et al., 2005; Jellyman and Ryan, 1983; Moriarty, 1986) and a broad size range (60–500 mm) (Moriarty, 1986; Robinet et al., 2003) of eel worldwide. Further, there is some evidence that lamprey passage can also be enhanced by the judicial use of a bristled substrate (Laine et al., 1998). Bristled substrate is now being used as a cost effective and hydraulically unobtrusive (Environment Agency, 2010) addition to low-head gauging structures, such as Crump weirs (common in the UK), to facilitate the upstream passage of eel (Environment Agency, 2011) and possibly other anguilliform morphotype species. However, to minimise flow interference and negate the need for a separate water source (i.e. as required for ‘up and over’ installations – see: Environment Agency, 2011), the bristled substrate is oriented vertically and attached with the bristles protruding perpendicularly towards the wing wall of a gauging structure. The efficacy of this configuration of bristle pass is currently untested, despite regional implementation and the recommendation of nationwide deployment in England and Wales (Environment Agency, 2011).

This study investigated the behaviour of European eel (*Anguilla anguilla*) and European river lamprey (*Lampetra fluviatilis*) as they attempted to pass an unmodified (control), or modified (treatment – with bristle passes installed) Crump weir, under experimental conditions. The experiment was repeated under three hydraulic regimes (low, medium and high velocity) that represent flow conditions similar to those encountered at Crump weirs in the field (see: National River Flow Archive). Passage and delay were quantified and the influence of hydraulic regime and treatment assessed.

2. Methodology

2.1. Experimental setup

A model Crump weir (2.38 m long, 1.38 m wide and 0.34 m high) (Fig. 1a) was installed midway along an indoor recirculating flume (21.40 m long, 1.38 m wide, and 0.60 m deep) at the International Centre for Ecohydraulics Research (ICER) facility, University of Southampton, UK (50°57′42.6″ N, 1°25′26.9″ W). A 14 m long experimental area, sectioned off from the rest of the channel by flow straightening devices (100 mm thick polycarbonate screens with elongated tubular porosity – 7 mm diameter), extended 7 m either side of the weir crest. Under treatment conditions, vertically oriented bristle passes (10 mm thick polypropylene board covered with 30 mm spaced orthogonally oriented clusters of ca. 24 synthetic fibres [70 mm long × 1.5 mm diameter]) were attached with bristles protruding towards the flume wall on each side of the channel (Fig. 1b and c). The bristled substrate was installed in accordance with Environment Agency guidelines to maintain a 70 mm cavity (equal to bristle length) between the bristle board and flume wall (see: Environment Agency, 2011).

Experiments were conducted under three hydraulic regimes: high (HV), medium (MV) and low velocity (LV) (Fig. 2), created by altering the downstream water level (depth: 220, 330 and 450 mm, respectively) by adjusting an overshot weir (located at the downstream end of the channel), under a constant discharge ($0.09\ \mathrm{m^3\ s^{-1}}$). The HV and MV regimes were within the modular limits of the experimental weir with upstream water level (depth: 450 mm) independent of that downstream. The LV regime was outside the modular limits of the weir (flooded conditions – upstream water depth: 455 mm). As such, head difference under the HV, MV and LV regime was 230, 120, and 5 mm, respectively. Velocities were measured using an Acoustic Doppler Velocimeter (ADV) (Vectrino, Nortek-AS, Norway – frequency 50 Hz, sample volume $0.05\ \mathrm{cm^3}$, record length 60 s), and mean velocity ($V = \sqrt{\bar{u}^2+\bar{v}^2+\bar{w}^2}$) and standard deviation ($S.D. = \sqrt{\sigma_u^2+\sigma_v^2+\sigma_w^2}$) calculated. Where u, v and w are the instantaneous velocity values corresponding to the x, y and z spatial coordinates, overbar denotes time-average, and σ is the standard deviation of its subscript. *S.D.* was used as a proxy for the intensity of turbulence. In conditions that precluded using the ADV, i.e. when depth was <60 mm or air entrainment was high, an electromagnetic flow meter (Model 801 Flat, Valeport, UK – frequency 1 Hz, record length 30 s) was used to measure *V* and *S.D.* Spatial maps of the hydraulics associated with the Crump weir were generated in ArcMap v10 (Esri, USA) using a spline interpolation.

The velocity at the crest of the weir was similar under each regime (ca. $0.83\ \mathrm{ms^{-1}}$) (Fig. 2). Maximum velocity (2.43, 1.91, and $0.80\ \mathrm{ms^{-1}}$ under the HV, MV, and LV regimes, respectively) was inversely related to head difference (Fig. 2) and occurred at the weir crest under the LV and just upstream of the hydraulic jump under the MV and HV regime (Fig. 2). The hydraulic jump consisted of a standing wave generated as the super-critical flow along the face of the weir rapidly decelerated on reaching the downstream water level. Despite flooded conditions under the LV regime, a small hydraulic jump occurred ca. 100–150 mm downstream of the weir crest (Fig. 2). Downstream of the hydraulic jump, under all regimes, velocity gradually decreased as the channel deepened (Fig. 2).

Upstream of the weir the intensity of turbulence was low and similar under each regime ($S.D.$ = ca. $0.05\ \mathrm{ms^{-1}}$). High intensities of turbulence, relative to maximum velocity, were generated