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Can navigation locks be used to help migratory fishes with poor swimming performance pass tidal barrages? A test with lampreys

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ABSTRACT

Worldwide, tidal barrages reduce aquatic habitat connectivity and limit fish movements, especially for diadromous migrating species. Providing fish passage at these structures is crucial but technically and economically challenging. We measured the performance of a navigation lock, employed as a single-chamber vertical-slot fish pass, at a tidal barrage by the mouth of a tributary of the River Ouse, NE England. In autumn 2015, 265 European river lamprey *Lampetra fluviatilis* were tagged with Passive Integrated Transponders (PITs) and released in 11 replicate trials ($n = 157$ in lock, $n = 108$ immediately below lock). Fifty nine lamprey were double tagged with PIT and acoustic tags and released in the Ouse, 350 m downstream of the barrage. The percentage of lamprey attempting to pass the upstream gates during PIT trials was moderate to high (55 and 93% for lamprey released below, and in the lock, respectively). Passage efficiency, for lamprey attempting to pass the upstream gates, was also high (average of 66% for releases in lock, 78% for releases below lock). Ninety percent of lamprey, released below the lock and attempting to migrate upstream passed the entire lock in <128 min following release. However, acoustic-tagged lamprey displayed poor attraction to the lock under prevailing high river-discharge conditions. Overall, 36% of acoustic-tagged lamprey attempted to pass the barrage, mostly comprising lamprey released at low tide (cf. high tide), generating a high passage efficiency of 76% (16/21). However, 15 individuals passed through the sluices and only one used the lock. Nevertheless, using navigation locks as fishways has the potential to provide increased access between estuarine and river habitats for a range of biota, including those with poor swimming performance, but effectiveness is dependent on managing water discharge routes. Future studies using different operating protocols, especially to improve fish attraction under different environmental conditions and for a range of species, are encouraged.

1. Introduction

Habitat loss is the greatest threat to global biodiversity (Pimm and Raven, 2000) and estuaries provide key migration routes for a range of diadromous and euryhaline fish species (Baras and Lucas, 2001; Buysse et al., 2008). However, rivers and estuaries have been altered worldwide by the construction of anthropogenic structures (Nilsson et al., 2005), which dramatically reduce their longitudinal connectivity and hinder movement of these species between key habitats (Baras and Lucas, 2001). This has caused severe fish population declines and even population extinctions (Limburg and Waldman, 2009; Lucas and Baras, 2001).

River channel obstacles close to the river mouth or in the estuarine area have the greatest impact on diadromous biota (Kemp and O'Hanley, 2010; Nunn and Cowx, 2012), as they obstruct passage to and from a large part of or the entire basin. Barrages and lock-and-dam structures occur in estuaries and tidal rivers around the world (Beelen, 2012; McCartney et al., 1998). Tidal barrages, which are intended to prevent or limit tidal influence and intrusion of brackish water, provide new agricultural areas, freshwater supply and suitable navigation or recreational conditions (Larinier, 2002a). They also impact the migration of fishes and other animals (Larinier, 2002a; Lucas et al., 2009; Gough et al., 2012; Piper et al., 2012). Nonetheless, the impacts of engineered structures in tidal waters on fish migration are considered much less frequently than

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for freshwater dams and weirs (Giannico and Souder, 2005; Gough et al., 2012; Wright et al., 2014).

Due to their location and the highly variable water levels and discharges associated with these sites, providing traditional engineering solutions for fish passage (i.e. conventional fish passes) at tidal barrages is economically and technically demanding (Guillard and Colon, 2000; Larinier, 2002a). Furthermore, provision of conventional fishways of standard design, including at tidal-water sites, does not ensure good passage performance for targeted species (Moser et al., 2000; Nichols and Louder, 1970; Roscoe and Hinch, 2010; Smith and Hightower, 2012; Stuart and Mallen-Cooper, 1999). In fact, when navigation lock operation is managed to improve fish passage, the performance of those structures can be even better than existing fish passes (Moser et al., 2000). In addition, navigation locks can be the only available option at low-head dams (whether tidal or freshwater) for fish to pass an obstacle (Buysse et al., 2008; Johnson et al., 2005). Thus, although variable results have been obtained, previous studies suggest that, when their operation is adjusted to favour fish passage, navigation locks have the potential to be used as a cost-effective alternative for fish migration where they are present (Garrone-Neto et al., 2014; Lin et al., 2013; Lucas and Baras, 2001; Moser et al., 2000; Travade, 2002). However, information concerning the potential of navigation locks for fish passage is scarce (Garrone-Neto et al., 2014; Lin et al., 2013; Young et al., 2012) and is mainly focused on shads (Bailey et al., 2004; Ely, 2007; Guillard and Colon, 2000; Moser et al., 2000; Nichols and Louder, 1970; Smith and Hightower, 2012; Young et al., 2012).

Navigation locks in tidal and non-tidal waters have been employed as migration routes for fish using an operation protocol similar to a fish lift (i.e. Bailey et al., 2004; Guillard and Colon, 1998; Moser et al., 2000; Nichols and Louder, 1970; Young et al., 2012), but rarely if ever as a vertical slot fish pass. Those 'fish lift' protocols comprised a series of lockage cycles in which the upstream and downstream gates and valves open at different times to attract to and retain fish in the lock and subsequently to allow upstream movement. Usually the upstream gates are kept closed at the start, only opening the accessory valves to provide attraction flow. Both or one of the downstream gates are open during that period to allow fish entrance to the lock. Thereafter the downstream gates close and the upstream ones open to allow upstream migration. The availability of passage is reduced (upstream or downstream gates close) in this operation and some individuals entering the lock can leave the structure downstream before the upstream gates open to allow upstream passage (Moser et al., 2000). Thus, new approaches to operation of navigation locks, such as their use as vertical slot fish passes (partially opening the lock gates), should be evaluated to improve the use of locks as fish passage routes.

Diadromous species, which rely on migrations between fresh and marine water for lifecycle completion, are among those taxa most affected by losses in habitat connectivity (Baras and Lucas, 2001; Hall et al., 2011; Limburg and Waldman, 2009; McDowall, 1992). Indeed, as a result of habitat fragmentation and other factors such as pollution and overfishing, most diadromous species of the North Atlantic have declined dramatically in the last century (Lassalle et al., 2009; Limburg and Waldman, 2009). As a response, and with the aim of conserving socially, economically and ecologically important species (Close et al., 2002; Helfman, 2007; Limburg and Waldman, 2009), legislation requiring free passage for diadromous species migration is increasing (Brown et al., 2013; WFD, 2000). Nonetheless, the majority of remedial effort historically has focused on salmonids, and to a lesser degree on clupeids, with much less attention being given to other taxa (Noonan et al., 2012; Roscoe and Hinch 2010), especially to poor swimmers such as lampreys (Foulds and Lucas, 2013; Keefer et al., 2011; Tummers et al., 2016). Accordingly, the aim of this study was to investigate passage of European river lamprey *Lampetra fluviatilis* (hereafter referred to as river lamprey) at a tidal barrage through measuring 1) the performance of a navigation lock used as a vertical slot fish pass to facilitate attraction and passage, 2) the attraction and passage through alternative routes (sluices).

2. Methods

2.1. Site description

The study was carried out in autumn 2015 on the lower River Derwent, at its confluence with the tidal River Ouse, at Barmby barrage, NE England (Fig. 1). The Humber river basin, of which the Ouse is one of two major catchments, is the largest drainage basin in Britain and its estuary is highly turbid (Uncles et al., 2006). Typical Secchi depths for the Ouse and Derwent rivers in the study locality are ∼0.05 m and ∼0.5 m respectively (M. Lucas, unpublished data). The Ouse is macrotidal (its tidal range greater than 4 m) in its lower reaches, and is weakly brackish around Barmby (Uncles et al., 2006). A variety of strictly diadromous, euryhaline and freshwater fishes exhibit seasonal movements within the tidal Ouse but are limited in their access to tributaries (Lucas et al., 1998). Parts of the Humber estuary and River Derwent are Special Areas of Conservation (EU Natura 2000 sites), for which sea lamprey *Petromyzon marinus* and river lamprey are conservation-listed features (Foulds and Lucas, 2014). Barmby barrage, which is the first obstruction for upstream-migrating fishes in the Derwent, has been shown to be a major obstacle for river lamprey migration (Lucas et al., 2009), and is presumed to significantly affect other diadromous species (Nunn and Cowx, 2012). Barmby barrage is a tidal barrage with two undershot sluice gates (7 m wide × 5 m high, with a fixed width and variable aperture height of up to 5 m) and a navigation lock (20 m long and 5 m wide, ∼4 m deep at high tide; one lock chamber with steel gates) on the west side of the river (Fig. S1). The purpose of the barrage is to prevent the penetration of tidal water from the Ouse to the Derwent and to maintain suitable water levels upstream of the barrage, principally for potable water abstraction purposes.

2.2. Sluice operation

The sluice opening procedures comprise several phases, which are dependent on water levels upstream (Derwent) and downstream (Ouse) of the barrage (JBA, 2004; Fig. S2). During the Tide Lock Phase the sluices remain closed while the Ouse water level is higher than the Derwent level (most of the flooding tide and usually the first 1.5 h of the ebbing tide). The subsequent Free Flow Phase starts during the ebbing tide when the Derwent level is higher than in the Ouse. During this phase the water level in the Derwent tracks that in the Ouse and therefore is the phase that provides lower heads (difference between upstream and downstream water levels) at the barrage. The Retention Phase is activated if the water level necessary for abstraction and navigation upstream is compromised. During this phase the sluice openings are reduced, releasing a lower flow, to maintain a constant water level upstream of the barrage, instead of tracking the downstream level (moving with the tide). Retention phases are usually activated only with Derwent flows lower than 25 m s^{-3} (JBA, 2004; representing approximately an annual flow exceedance value of Q_{20}). The cycle starts again at the flooding tide when the Ouse level reaches the Derwent level, which activates the lock phase.

The tidal cycle was completed at Barmby in an average (±*SE*) of 12.4 ± 0.1 h (range: 11.5–13.7 h) during the study period (24 November to 21 December 2015). The flooding and ebbing tides comprised an average of 2.8 ± 0.1 h and 9.6 ± 0.1 h per tide respectively. The tidal range was (mean ± *SE*) 2.8 ± 0.1 m (range: 0.8–4.4 m).