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The impact of an Archimedes screw hydropower turbine on fish migration in a lowland river

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ABSTRACT

There has been an increase in the abundance of small hydropower (< 10 MW) installations. These tend to be 'run-of-river', thereby reducing or averting the need for impoundment and water storage, and so are considered to have lower environmental impact. The Archimedes screw turbine (AST) has been described as 'fish friendly' based on magnitude of observed first order impacts, i.e. low rates of direct damage and mortality due to blade strike. However, potential second order effects, such as altered fish behaviour prior to or after passage, and consequences for long-term survival and fitness, have been largely ignored. This two-year study employed acoustic and Passive Integrated Transponder (PIT) telemetry and dual frequency imaging sonar to investigate the influence of an AST and associated fish passes (Larinier super-active baffle pass and upstream eel ladders) on the movement patterns and behaviour of five species of potadromous fish and European eel (*Anguilla anguilla*). Seaward-migrating adult (silver) eels successfully descended the AST, but under high flows most individuals took an alternative route via an overshot weir which resulted in faster passage rates. There was no immediate silver eel mortality as a result of passage through the turbine and no effect on subsequent migration behaviour through the lower freshwater catchment and estuary. Some eels were delayed at the complex and exhibited frequent rejection and milling on their approach to the AST and fish passes. Upstream passage rate (%) at the Larinier pass varied among species with highest for dace (81%) and the lowest for roach (10%). Fish that aggregated up- and downstream of the AST rapidly dispersed on turbine start-up. Although ASTs can be considered a potential downstream passage route for both eels and potadromous species, adult eels milled and rejected at the upstream entrance, while other fish exhibited startle response on turbine start-up. Potential delay to seaward migration of silver eel and the energetic costs of observed behaviours should be considered during future impact assessments, particularly where there is no alternative migration route or there are multiple such facilities in a watercourse.

1. Introduction

Hydropower is the largest renewable energy resource globally, accounting for one sixth of all generation in 2016, and currently supplies 16.5% of Europe's primary energy production from renewable sources (EU, 2016; World Energy Council, 2017). It is often considered a more reliable resource than solar or wind (Kosnik, 2008) and its importance is due to increase as economies reduce dependence on fossil fuels, driven by legislation such as the European Renewable Energy Directive. Most hydropower is produced by large-scale facilities, often defined as generating greater than 10 MW (Paish, 2002), that necessitate construction of dams to produce sufficiently large head difference and water storage for controlled release through the turbines (Bratrich et al., 2004). In Europe, exploitation of small-scale (≤10 MW) opportunities is the principal means by which hydropower production may be increased; most large-scale opportunities have already been exploited and those remaining are deemed environmentally unacceptable (Manzano-Agugliaro et al., 2016; Paish, 2002). Europe is now the second biggest utiliser of small hydropower after Asia, with 13,000 MW of installed capacity (Doukas et al., 2009). Such facilities are generally designed to operate as 'run-of-river' installations, i.e. use river flow without water storage, often with limited head difference of a few metres or less (Cheng et al., 2015; Okot, 2013). The UK is committed to increasing renewable generation to 15% by 2020, and subsidies (feed-in

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tariffs) for facilities generating 5 MW or less have fuelled recent growth in small hydropower (Nolden, 2015). Between 2010 and 2015, 644 new hydropower installations with a cumulative capacity of 70.5 MW came online in the UK, most of which were of the smallest size category (≤15 kW) (Nolden, 2015).

The environmental impacts of large hydropower (dam) schemes are substantial and well-documented, including modifying flow regimes, hindering or preventing the movement of aquatic biota, and causing damage and mortality to fish through direct contact with the turbines or indirectly by cavitation (Kemp, 2015). Small hydropower schemes have not always been subjected to the same scrutiny by regulatory authorities as larger ones (Shaw, 2011) and their potential adverse effects have frequently been assumed absent or so minor as to be inconsequential or easily mitigated (Abbasi and Abbasi, 2011 and references therein; International Energy Agency, 1998; Bratrich et al., 2004). However, there is a growing number of case-studies globally that highlight the negative environmental impacts and increasing social conflict associated with small hydropower (Kelly-Richards et al., 2017). Indeed, some authors claim that per kilowatt generated, the environmental impacts of small hydropower are comparable to, or even greater than, those of large schemes (Abbasi and Abbasi, 2011; Hennig et al., 2013). Robson et al. (2011) argue that with regard to fish populations, many of the issues surrounding large scale hydropower are equally relevant to small schemes. Fish may become disoriented during passage through the turbine, and the impounding structures, though small (typically < 5 m head difference), may hinder or block their longitudinal movements and thereby reduce access to habitats required for spawning, feeding/rearing and refuge (Kubecka et al., 1997). Delay at structures is linked to lower success in reaching spawning areas (Caudill et al., 2007), depletes energy reserves, causes fish to congregate in areas where they may become more susceptible to predators and exploitation (Garcia De Leaniz, 2008; Lucas et al., 2009) and may lead to loss of migratory motivation and reduced feeding opportunities (Nyqvist et al., 2017). Indirect effects may be caused by wider habitat modification, such as the creation of a depleted reach (Kibler and Alipour, 2017) with reduced fish biomass and changes to community and age structure (Ovidio et al., 2008), as well as altered sediment dynamics and physicochemical conditions (Ligon et al., 1995). Even if the impacts of a single installation are considered acceptable, the cumulative effects of multiple facilities in a watercourse can be substantial (Anderson et al., 2015; Robson et al., 2011).

The Archimedes screw turbine (AST), which comprises 2–5 spiral blades around a central shaft connected to a gear box and generator, is employed at over 400 facilities worldwide, mostly in low-head (< 2.5 m) situations (Lashofer et al., 2012). ASTs are generally perceived as 'fish friendly' due to their slow rotational speed, low shear force and small pressure changes, when compared to conventional Francis and Kaplan turbines (Kibel et al., 2009; Spah, 2001). A study on the UK's first AST installation on the River Dart monitored downstream passage of European eels (*Anguilla anguilla*) captured and introduced to the turbine 1 m upstream of the leading edge. No eels were killed during turbine transit and although camera footage revealed that 28% of individuals were struck by the moving parts, damage rate as assessed by visual inspection of external injury was < 1%. No immediate damage or mortality was recorded for the 11 Atlantic salmon (*Salmo salar*) kelts that naturally passed through (Kibel, 2008). In a study of river lamprey (*Lampetra fluviatilis*) on the River Derwent, UK, damage rate among 66 juveniles that were released immediately upstream and subsequently passed an AST was 1.5% (Bracken and Lucas, 2013). Reported damage rates among juvenile salmonids as assessed by scale loss after turbine passage were either low or negligible (Brackley et al., 2015; Kibel, 2007), and zero for non-salmonids (Merkx and Vriese, 2007).

Based on these low damage and mortality rates, screening of the intake and tail race of an AST is not typically recommended. However, even if fish pass through a hydro facility apparently unharmed, other effects may render ASTs less benign than inferred. For example, two studies noted that some fish were hesitant to enter the turbine, with delays recorded for kelts and larger eel (Kibel, 2008; Merkx and Vriese, 2007). To date, assessment of AST impacts on fish has relied heavily on 'injection studies' that use wild-caught or hatchery-reared fish and release them close to the turbine. Little attention has been given to the behavioural response of fish at such structures and to the implications of delay and sub-lethal effects of turbine passage on subsequent fitness.

Previous studies on the impacts of small hydropower on fish populations have predominantly focussed on diadromous species, principally salmonids (Brackley et al., 2015; Kibel, 2007, 2008; Thorstad et al., 2017), but also lamprey (Bracken and Lucas, 2013) and eel (Kibel, 2008; Vowles et al. 2014). While the often long migrations between freshwater and marine environments necessary for completion of a diadromous lifecycle frequently bring these species into contact with hydropower facilities, potadromous fish also make significant migrations within freshwater for the purposes of feeding, refuge and reproduction, and unlike long distance migrants, may pass structures multiple times (Katopodis, 2005; Lucas and Frear, 1997). Cyprinids are most abundant in the lowland systems that are the current focus of many small low-head hydropower development efforts in Europe, yet few studies have assessed impacts for this important component of fish communities (but see Kubecka et al., 1997; Ovidio and Philippart 2002; Santos et al., 2006). Greater information on the potential impacts of small hydropower on a wide range of fish species is required to help policy makers and water managers make appropriate risk-based decisions and balance the drive to increase renewable energy generation with legislative demands to maintain and improve connectivity for fish.

The aim of this study was to assess the impact of a new AST installation on the movement and behaviour of eel and several potadromous fish (cyprinids, percids and esocids) in an English lowland river. Conducted over two years to encompass seasonal variability, and employing PIT and acoustic telemetry and dual frequency imaging sonar to track fish movements, the four objectives of the study were to determine: 1) passage rates for upstream and downstream migrating fish at the AST and associated fish passes; 2) the influence of operation on fish attraction to passage facilities; 3) fish response to turbine start-up, and 4) the effect of operation on route choice, delay and subsequent migration success of seaward-migrating adult European eel. Comparison of adult eel movement data with those from a two-year study on the same river conducted prior to installation of the AST enabled before and after quantification of impacts.

2. Materials and methods

2.1. Study site

The study was conducted on the River Stour and its estuary in southeast England. This lowland river flows eastwards from it source at Haverhill for approximately 98 km to the tidal limit at Manningtree (51°56′43.47″N, 1° 3′43.51″E) where it enters the estuary and ultimately the North Sea. The lower river Stour is typically 10–15 m wide and has a mean daily flow of 2.99 ± 3.99 $m^3 s^{-1}$ (± S.D.) (1962–2015). The fish population is dominated by cyprinids, mainly roach (*Rutilus rutilus*), dace (*Leuciscus leuciscus*) and chub (*Squalius cephalus*). Salmonids are rarely recorded. Flow is heavily regulated and the catchment contains circa 52 cross-channel structures. The study focussed on Flatford Mill (51°57′31.73″N, 1° 1′17.06″E), a former watermill, where an AST, Larinier super-active baffle pass and upstream eel ladder were installed in 2012 (Fig. 1).

The river bifurcates approximately 100 m upstream of the old Flatford mill complex. The southern channel comprises a navigation lock with a pair of lock gates at each end which operate during the summer months. During winter when flows are higher, the lock gates are fixed open and water level managed using an automatically controlled bottom-hinged tilting gate (2.96 m width) (Fig. 1). The northern

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