RIVER RESEARCH AND APPLICATIONS
River Res. Applic. **29**: 1073–1081 (2013)
Published online 13 July 2012 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/rra.2596

POTENTIAL IMPACTS OF SMALL-SCALE HYDROELECTRIC POWER GENERATION ON DOWNSTREAM MOVING LAMPREYS

F. S. A. BRACKEN* AND M. C. LUCAS
School of Biological and Biomedical Sciences, Durham University, Durham, UK

ABSTRACT

Small-scale hydropower is developing rapidly in many countries in response to policies of encouraging renewable energy and reducing reliance on fossil fuels. This rapid increase in the construction of hydroelectric turbines provides a substantial risk to migrating biota, especially fish. Some turbines, such as the Archimedes screw design, are regarded as relatively friendly to fish but have not yet been assessed for their potential impacts on threatened lamprey species. To assess the risk of impingement and the patterns of movement by emigrating river lamprey *Lampetra fluviatilis* transformers and drifting larval ammocoetes at the site of an Archimedes screw turbine in north-east England, drift nets were set over the periods of January to June 2009 and November 2009 to May 2010. Drifting *Lampetra* sp. larvae were recorded in all sampling months, November to June, while emigrating lampreys were recorded in all months but June (93% captured between December and April), reflecting a higher period of impingement risk than expected. Night-time catches were 24- and 8-fold higher for transformers and larvae, respectively, than daytime catches. Catch per unit water volume data in different channel areas suggest that lamprey larvae behaved as passive particles within the river flow but that transformers selected areas of higher flow. Damage rates of lampreys passed through the screw were low (1.5%), suggesting minor impacts on downstream-moving larval and juvenile lampreys. However, the cumulative potential impacts of multiple hydropower sites on downstream fish passage, including lampreys, should be considered by regulatory agencies when planning hydropower development within catchments. Copyright © 2012 John Wiley & Sons, Ltd.

KEY WORDS: migration; hydropower; barrier; lamprey; turbine

Received 7 October 2011; Revised 26 March 2012; Accepted 20 June 2012

INTRODUCTION

Small-scale hydropower is developing rapidly, assisted by policies of encouraging renewable energy and reducing reliance on fossil fuels (Paish, 2002; Kosnik, 2010). Although in Europe most of the large-scale hydropower opportunities have been exploited or are otherwise considered environmentally unacceptable, strong potential remains for small-scale hydropower (Paish, 2002), and the number of such schemes is increasing rapidly. Many developed countries have a rich historic resource of weirs and mills, providing opportunities for installation of run-of-river hydroelectric turbines for small-scale power generation. In England and Wales, the Environment Agency supports the principle of expanding renewable energy through low-head hydropower and has identified nearly 26 000 potential sites, which, if all were developed, could provide 1% of the UK's electricity needs (Entec, 2010). However, there is also a requirement to ensure that such developments do not compromise ecological integrity and biodiversity.

Although hydropower installations are likely to have a wide variety of effects on both the physical and biological constituents within a fluvial system (Čada and Hunsaker, 1990; Robson *et al*., 2011), the biota that are among those at greatest risk of impact are fishes (Lucas and Baras, 2001). In particular, species that rely on regular migrations on a seasonal or lifecycle basis (Baras and Lucas, 2001) will require the longitudinal connectivity of rivers to be upheld. Potential risks include delays to migration, disorientation, increased exposure to predation, and direct mortality and injury (Office of Technology Assessment, 1995; Turnpenny *et al*., 1998; Coutant and Whitney, 2000; Čada, 2001; O'Keefe and Turnpenny, 2005). Thus, considerable efforts have been made to identify species at risk and to minimize impacts of hydroelectric facilities on fish migrating downstream and upstream. Key elements of these processes include appropriate screening, proper siting of facilities relative to flow patterns, provision of efficient upstream and downstream fish passage routes, and minimizing access to dead ends (Office of Technology Assessment, 1995; Turnpenny *et al*., 1998; Coutant and Whitney, 2000).

Lampreys are one group of fishes that are sensitive to the impacts of river barriers and habitat modification, including hydropower generation (Moser *et al*., 2002; Lucas *et al*., 2007, 2009). Anadromous lamprey species, in particular, require free migration to the sea at the macrophthalmia ('transformer') stage and back to spawning areas in rivers as

*Correspondence to: F. S. A. Bracken, School of Biological and Biomedical Sciences, Durham University, South Road, Durham DH1 3LE, UK.
E-mail: fiona.bracken@durham.ac.uk

mature adults. Over half of all lamprey species are considered to be endangered, vulnerable, or extinct in at least a portion of their range (Renaud, 1997), and marked declines in the abundance of anadromous lampreys have been attributed to human activities (McDowall, 1992; Renaud, 1997; Kelly and King, 2001; Raat, 2001; Close *et al*., 2002; Masters *et al*., 2006; Mateus *et al*., 2012). In Europe, sea lamprey *Petromyzon marinus*, river lamprey *Lampetra fluviatilis*, and brook lamprey *Lampetra planeri* are afforded protection through the European Commission (EC) Habitats and Species Directive, which requires special areas of conservation (SACs) to be identified and maintained in good condition for these species (EC, 1992). Regulatory control is applied to factors within or outside SACs that are likely to damage the condition of interest features within SACs. For lampreys, these factors include poor upstream access at barriers (Lucas *et al*., 2009) but also potential impacts to emigrating lampreys and drifting ammocoete larvae passing through hydroelectric turbines (Lucas *et al*., 2007). Impacts on downstream-moving mature adults are of somewhat lower concern, as migration is principally directed upstream and all lampreys die soon after spawning.

Until recently, the underlying research and mitigation methods concerning anthropogenic impacts on migrating fishes have been strongly biased towards the needs of anadromous salmonids and, to a lesser degree, a few other taxa (Lucas and Baras, 2001). For example, the mesh size of angled bypass screens to deflect downstream-migrating fish from water intakes in the UK is commonly 10–12 mm, a size that satisfactorily prevents Atlantic salmon *Salmo salar* and brown trout *Salmo trutta* smolts from gaining entry (Turnpenny *et al*., 2000) but will not exclude juvenile lampreys. Increasingly, regulatory bodies have given greater attention to other taxa and smaller life stages, including young lampreys, which may be susceptible to mortality during turbine passage (Dadswell and Rulifson, 1994). These small fish can easily be entrained through water intakes, and this has resulted in the increased use of finer mesh or narrow bar-space screens (e.g. 3 mm spacing) to prevent access (O'Keefe and Turnpenny, 2005). In high flows, weakly swimming species and life stages can be impinged on screens, causing high mortality (O'Keefe and Turnpenny, 2005), and this is a significant problem for juvenile Pacific lamprey *Entosphenus tridentatus* (formerly *Lampetra tridentata*) (Moursund *et al*., 2003; Dauble *et al*., 2006; Sutphin and Hueth, 2010) and probably also for other lamprey species. For low-head, small-scale hydropower schemes, fine-mesh screens are likely to hamper operation and dramatically reduce their efficiency.

Passage through turbines may cause a range of damage to fish, depending on the type and size of turbine, species, size and behaviour of fish, velocity of water, speed and magnitude of pressure fluctuations, roughness of materials, and the force and direction of contact with blades or other parts of the turbine (Office of Technology Assessment, 1995; Coutant and Whitney, 2000; Turnpenny *et al*., 2000; Cooke *et al*., 2011). In general, the greatest impacts of traditional (e.g. Kaplan-type) turbines are observed on large anguilliforms moving downstream (e.g. adult eels) and on fishes that lose scales easily or have a 'delicate' anatomy (e.g. clupeids). On this basis, it might be expected that adult lampreys could be impacted if they were to move down through turbines. Emigrating transformers and drifting ammocoetes entering turbine chambers would be expected to be less susceptible to major damage by virtue of their small size and body characteristics (O'Keefe and Turnpenny, 2005). Moursund *et al*. (2003) found no evidence of health impacts on *E. tridentatus* transformers as a result of simulated turbine shear stress and pressure fluctuations; similarly, a field study at a hydropower station on the river Tay, Scotland, found no evidence of significant impact on *Lampetra* sp. larvae (Lucas *et al*., 2007).

Rapid escalation in low-head, run-of-river hydroelectric development in the UK and elsewhere in Europe has occurred in concurrence with the introduction of the Archimedes screw turbine (Spah, 2001; Kibel, 2007). These systems are relatively robust, low-maintenance hydroelectric screw turbines that can operate over a range of flows. The force of water rotates the screw's blade, and the mechanical power is converted to electrical power. These screw turbines are regarded as more fish friendly than conventional designs because of the relatively slow rotational speed, limited shear force, and small pressure changes compared with conventional turbines (Spah, 2001). Low rates of injury have been recorded for several non-lamprey species experimentally passed through screw turbines in some studies (Spah, 2001; Kibel, 2007) but not others (Schmalz, 2010). Injuries to fish passing through Archimedes screw turbines, especially on small, slender fish such as young lampreys are most likely to result from pinching between the screw blade and the trough. The aim of this study was to assess the potential for impacts of Archimedes screw turbines on downstream-moving juvenile and larval lampreys.

STUDY AREA

The river Derwent in North Yorkshire (mean discharge of *ca.* 15 $m^3 s^{-1}$) is a tributary of the river Ouse that joins the river Trent to form the river Humber (mean discharge of 250 $m^3 s^{-1}$) in North-East England (Law *et al*., 1997). In its headwaters, the Derwent is a shallow, fast-flowing, upland river. In the lower 55 km, it is a slower, deep, lowland river, with a very low gradient. Much of the drop in the lower river occurs at a series of weirs, where several small-scale hydropower plants exist or are planned. The lower Derwent does not presently have a significant migratory salmonid population and is characterized by a lowland river fish community (Whitton

DOI: 10.1002/rra

and Lucas, 1997). Freshwater spawning and larval habitats for lampreys are present in Ouse tributaries, including the Derwent, which provides suitable conditions for a substantial river lamprey population (Lucas *et al*., 1998; Jang and Lucas, 2005). Under the Habitats and Species Directive, the Derwent is an SAC, for which *L. fluviatilis* and *P. marinus* are listed species. The freshwater resident brook lamprey *L. planeri* is also present (Whitton and Lucas, 1997).

This study was carried out at the site of a three-bladed Archimedes screw (maximum power output 24 kW) at Howsham Mill (national grid reference SE 496 799; Figure 1), which was installed by the Renewable Heritage Trust in 2008. The facility is located at the left bank of an 80-m-wide, 1.8-m-high, oblique weir with a sloping apron. The turbine has a coarse trash screen with bar spacing of 10 cm but no fish diversion screen. The turbine's position relative to the weir and river bank topography results in it drawing water from an approximately 4-m-wide zone above the turbine and discharging it at the base of the weir on the left bank. A 4-m-wide flowing bypass canal exits the river on the left bank 80 m upstream of the turbine and reconnects with the river approximately 120 m downstream (Figure 1).

METHODS

To assess patterns of abundance of emigrating river lamprey transformers and drifting larval ammocoetes, drift nets were set in the river channel at Howsham Mill. Because the main emigration period of *L. fluviatilis* transformers is known to be from late winter to early spring (Hardisty *et al*., 1970; Potter and Huggins, 1973), including in the river Ouse catchment that contains the Derwent (Frear and Axford, 1991), year-round sampling was not carried out. Sampling was carried out over the periods of January to June 2009 and November 2009 to May 2010.

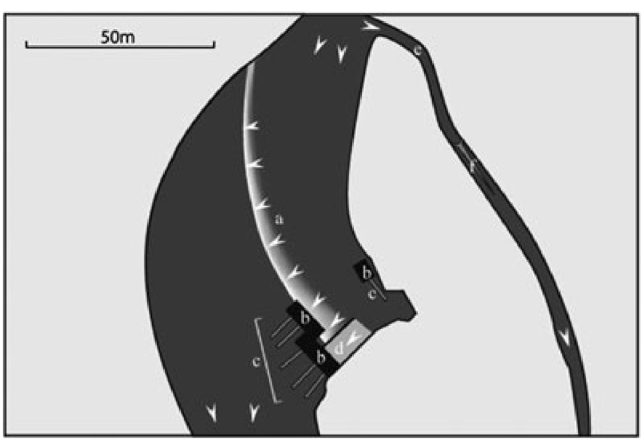

Figure 1. Schematic map of the study site: (a) weir, (b) floating pontoons for drift net deployment, (c) drift nets, (d) hydraulic screw, (e) bypass canal, (f) bypass canal net; arrows, flow direction. The map is drawn approximately to scale, with the exception of some items such as the turbine, which are exaggerated for clarity

Floating 2-m-wide pontoons were placed in the main channel above and below the weir to provide platforms for setting up to six drift nets. Flow at the left-hand bank margin 10 m upstream of the weir, flow from the turbine, and flow in the main channel 10–15 m from the left bank and immediately below the weir were sampled (Figure 1). Nets were 3 m long, with an opening of 0.50 × 0.40 m and a mesh size not exceeding 3 mm. The end of the net was weighted, so that it would sink towards the bottom. Pilot studies were conducted in January 2009 during which marked transformer (total $n = 18$, 91–118 mm length) and larval (total $n = 34$, 80–122 mm length) lampreys were placed in the sampling nets after dusk over three trials (2–14 h duration) to assess the retention capacity of the nets. At net entrance water velocities exceeding $0.2\,m\,s^{-1}$, all individuals were retained alive in the drift nets. The precise positioning of the nets varied between sampling dates and was adjusted according to the flow regime on the day, so that each net was typically set in flow exceeding $0.3\,m\,s^{-1}$. The nets were set with the top edge less than 0.1 m below the water surface and so fished within 0.5 m of the surface in depths of 1–2 m. A larger net with a 4-m-long cod end and two heavily weighted lateral wings, each measuring 4 m and with a mesh size of 3 mm, was set across the full width (*ca*. 4 m) and depth (*ca*. 0.7 m) of the bypass canal to capture downstream-moving fishes at that location.

Sampling was conducted monthly within the two study periods, and nets were fished for day or night periods (checked early in the morning and early in the evening), usually consisting of two nights and the intervening day period. A total of 132 0.5 × 0.4 m net samples were taken by night and 50 by day over the full study period. Eight canal net samples were taken by day and 19 by night. All captured ammocoetes, transformers, and adults were identified (Potter and Osborne, 1975; Gardiner, 2003) and measured under anaesthesia (MS-222, $0.1\,g\,L^{-1}$) and allowed to recover fully before being returned to the river. Because *L. planeri* and *L. fluviatilis* cannot be distinguished externally at the ammocoete stage, they were recorded as *Lampetra* sp.

Flow velocity measurements were taken (Valeport electromagnetic flow meter, model 801) at the mouth of each net when they were set and again when they were emptied over the period from December 2009 to March 2010. From these data, the volume sampled by each net and the number of lampreys caught per standard volume of water sampled were calculated. River discharge data, at 15-min intervals, were obtained from a gauging station 5 km downstream. Turbine discharge was also recorded. This proportion of river flow passing through each net was calculated, allowing estimation of the number of transformers passing through the river over sample periods and the fraction that could pass through the turbine.

DOI: 10.1002/rra

Experimental passage through the turbine

Some lampreys captured in drift nets exhibited local dermal haematoma and/or fin abrasion or were dead in the nets downstream from both the turbine and weir (control). Therefore, it was not possible to infer impact of passage through the turbine, so direct testing was necessary. Preliminary tests with dead and live lamprey larvae and transformers introduced immediately above the turbine showed that both categories were recaptured in drift nets (described above) placed 4 m from the turbine outfall. Subsequently, a total of 131 lampreys, consisting of 42 river lamprey transformers, 88 *Lampetra* sp. ammocoetes exceeding 80 mm, and one adult brook lamprey, were captured by electro-fishing and marked, under light anaesthesia, with an elastomer visible implant under the skin in the caudal third of the body. The lower size limit was chosen to facilitate marking and ensure retention in the net. Lampreys were measured, and body condition was assessed for any damage. On recovery from anaesthesia, all individuals were assayed for normal anguilliform swimming behaviour, in a white (to provide high contrast) water-filled tray, while viewed from above. All swam normally and were without damage. Six drift nets were placed, side by side, 4 m below the turbine spanning the main outflow and its periphery. Complete sampling directly at the outflow was not possible due to the intense flow. At dusk, lampreys were released immediately above the hydraulic screw. The nets were checked after 30 min, and each recaptured individual was measured and visually assessed for any discernible changes to body condition and swimming ability. A swimming impairment was defined as any notable deviation from normal sinusoidal undulatory swimming movement.

RESULTS

Diel and seasonal abundance

A total of 263 river lamprey transformers and 228 *Lampetra* sp. ammocoetes, as well as six adult brook lampreys (*L. planeri*), were caught in the drift nets. In the main channel, catch rates (mean and SE) were 1.86 ± 0.53 transformers per net period and 1.08 ± 0.14 ammocoetes per net period by night, and 0.08 ± 0.04 transformers per net period and 0.14 ± 0.04 ammocoetes per net period by day. Night catches in the main channel were significantly higher than daytime catches for transformers (Mann–Whitney test, $U = 1959$, $p < 0.001$) and ammocoetes (Mann–Whitney test, $U = 1917.5$, $p < 0.001$), with 24-fold and 8-fold greater differences, respectively. In the canal, the transformer catch rate by day did not differ significantly from that at night (Mann–Whitney test, $U = 44$, not significant), but only eight transformers were caught over 8-day and 19-night sampling periods. However, the ammocoete catch rate in the canal by day was significantly lower than that at night (Mann–Whitney test, $U = 25$, $p < 0.01$), with a total of 84 caught by night and 4 caught by day. Subsequent data presented are night-time catches only.

Ammocoetes were caught in all months, with a peak in mid-winter (Figure 2a) while *L. fluviatilis* transformers were caught from November to May, with peak catches from December to April (93% caught over this period) in the main channel (Figure 2b). Catch rates in the main channel varied significantly between months for both transformers (Kruskal–Wallis test, H (7) =55.5, $p < 0.001$) and ammocoetes (Kruskal–Wallis test, H (7) = 43.7, $p < 0.001$).

Ammocoete lengths ranged between 30 mm and 175 mm (Figure 3a). Ammocoetes displayed a wide range of sizes, but the majority of individuals caught were between 85 mm and 115 mm. Length of transformers varied less than that of ammocoetes and ranged from 75 mm to 124 mm, but

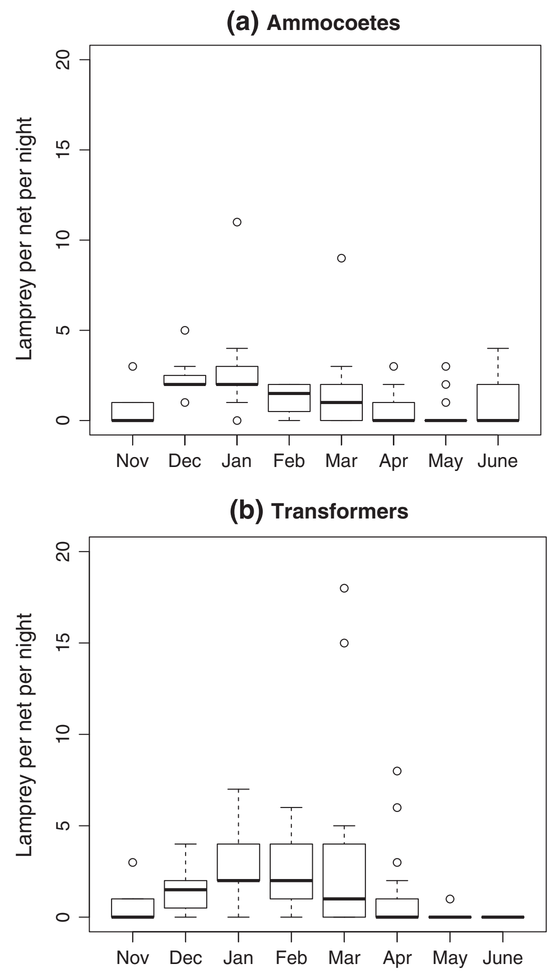

Figure 2. Seasonal distribution of (a) *Lampetra* sp. ammocoete and (b) *Lampetra fluviatilis* transformer catch per net night over the whole sampling period in the main channel. Boxes show median and quartiles; whiskers show the 10th and 90th percentiles; outliers are shown as circles

DOI: 10.1002/rra

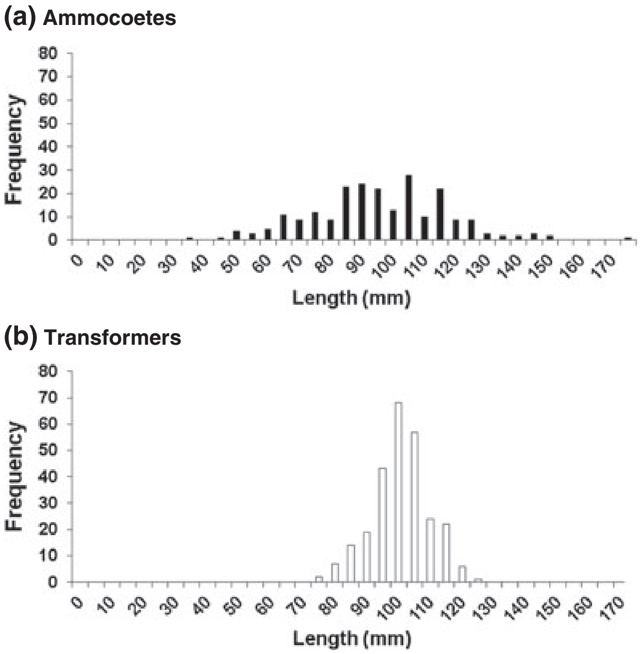

Figure 3. Length–frequency distributions of (a) all *Lampetra* sp. ammocoetes ($n = 228$) and (b) all *Lampetra fluviatilis* transformers ($n = 263$)

most individuals ranged between 95 mm and 100 mm (Figure 3b). The mean lengths for transformers and ammocoetes were 98.9 mm and 93.7 mm, respectively.

Risk of turbine entrainment

An estimate of the number of migrating transformers that passed through the turbine on several sampling dates was derived from estimates of densities of lamprey per unit volume of water flow and from the fraction of river flow passing through the turbine. All data below are expressed as mean ± SE and are derived from seven separate sampling nights between December and March 2010. Combined, nets sampled 1.96 ± 0.2% of estimated main river flow (36 ± 4.1 $m^3 s^{-1}$) volume at the weir.

By comparison, 0.3 ± .01 $m^3 s^{-1}$ (about 1% of river flow) passed through the canal. Assuming random distribution of lampreys across the river channel in proportion to flow and that drift behaviour dominates, the estimated number of emigrating transformers passing through the main channel was 677 ± 96 individuals per night and the proportion of water (and hence, entrained transformers) through the turbine was 6.13 ± 0.79%.

Experimental passage through the turbine

Out of 131 lampreys that were passed through the turbine, 50.4% were recaptured by drift nets at the bottom of the turbine within 30 min of release (Table I). There were no mortalities, but one transformer exhibited swimming impairment (1.5% of all lampreys recaptured).

Table I. Percentage of marked lampreys introduced to the screw turbine recaptured and effects of the turbine on these

Life stage	Number released	% recaptured	% mortality	% swimming impairment
Ammocoete	88	46.6	0	0
Transformer	42	59.5	0	2.4
Adult (*L. planeri*)	1	0.0	Na	Na
Total	131	50.4	0	1.5

Note: Na = not applicable.

Distribution within the channel

The abundance of ammocoetes and transformers standardized with respect to volume of flow sampled were compared across four categories of flow: marginal, upstream of the turbine; main flow below the weir; main flow below the turbine; and in the canal (Figure 4). There was no significant difference in the number of ammocoetes caught per standard volume sampled in each of the above-defined flow categories. However, there was a significant difference in the number of transformers caught in each flow category (Kruskal–Wallis test, H (3) =23.7, $p < 0.01$). The capture rates of transformers in the canal and in marginal areas were significantly lower than in the main flow downstream of the weir and downstream of the turbine (Mann–Whitney U with Bonferonni-corrected significance at $p = 0.0083$).

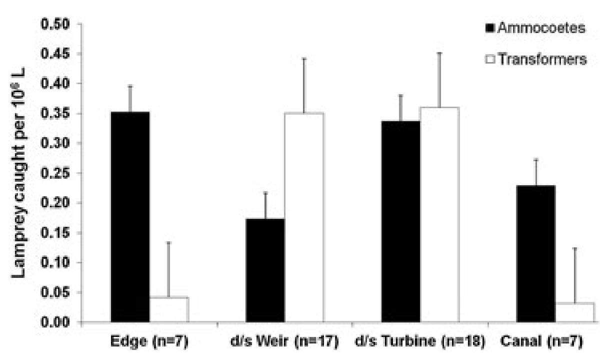

Figure 4. *Lampetra* sp. ammocoete and *Lampetra fluviatilis* transformer catches in differing flow habitat types expressed as mean and standard error of the number caught per 10^6 L of water sampled. Data are night-time catches for December 2009 to March 2010 combined, the main emigration period for transformers

DOI: 10.1002/rra

DISCUSSION

This study demonstrates that in the river Derwent, *Lampetra* sp. transformers and larvae occur in the water column over extended periods of the year and so are susceptible to entrainment by run-of-river hydropower, but that a single Archimedes screw caused low rates of acute damage to transformers and larvae passed through it.

Diel and seasonal abundance

Night catch rates for both ammocoetes and transformers were significantly greater than day catch rates. Ammocoetes and transformers are strongly negatively phototaxic, and previous studies also suggest that lamprey activity is principally nocturnal (Potter and Huggins, 1973; Potter, 1980; Dauble *et al*., 2006). It is therefore logical that more downstream movement, by either active (Quintella *et al*., 2005) or passive means, occurs within low-light conditions. Long (1968) reported that 62% of downstream migrating *E. tridentatus* passed the Dalles Dam powerhouse at night. During daylight, transformers either burrow (like ammocoetes) or move into protected areas that provide cover (Kelly and King, 2001). Strongly nocturnal behaviour in migrating lampreys has been interpreted as an anti-predator tactic (Sjöberg, 1989).

Analysis of monthly catches between November and June showed significant variations in the catch rates of both transformers and ammocoetes in the main channel. The peak period of river lamprey transformer emigration found in this study concurs with those described elsewhere (Hardisty *et al*., 1970; Potter and Huggins, 1973), including that for the Yorkshire Ouse (Frear and Axford, 1991), of which the Derwent is a tributary. However, the overall period of river lamprey emigration in this study was longer than that described in those literature sources. In UK rivers where *P. marinus* are abundant, peak emigration timing is in late autumn (Kelly and King, 2001), extending the key period of impingement risk for emigrants if both *L. fluviatilis* and *P. marinus* are considered.

Ammocoetes were caught in all months sampled, with a peak in mid-winter. Large size classes dominated catches, probably reflecting size selection by the mesh size employed. Ammocoetes longer than 120 mm are more likely to be *L. planeri* than *L. fluviatilis* (Gardiner, 2003). The downstream movement of larvae has previously been found to be season- and temperature-dependent (Kelly and King, 2001), which may be coupled with higher winter flows that displaced ammocoetes residing in silt beds (Hardisty and Potter, 1971). Migratory behaviour of transformers is also influenced by a marked increase in freshwater discharge (Potter, 1980). Pirtle *et al*. (2003) found that a substantial proportion of *E. tridentatus* ammocoete (and transformer) movement occurred during high flows, possibly associated with sediment scour, but movement occurred also in other periods.

The timing of the peak period of emigration and drift should be taken into account when considering how best to reduce the impacts of entrainment and impingement on lampreys, and running of turbines primarily during the day at sensitive sites and seasons could protect emigrating lampreys effectively. Turbines on the Columbia and Snake River systems (USA) are operated within 1% of peak efficiency during the juvenile and adult salmonid migration season to reduce injury and increase fish survival rates (Čada, 2001; Ferguson *et al*., 2006). However, this association is controversial, as peak efficiency encompasses a wide range of discharge levels, and therefore, the zone of operating conditions within 1% of peak efficiency will probably also encompass the maximum turbine passage survival (Mathur *et al*., 2000; Skalski *et al*., 2002). Thus, although this system may be a useful guide for managing turbine operating conditions, there can be an appreciable difference between peak observed survival and the survival at peak turbine operating efficiency (Skalski *et al*., 2002). Where 'fish friendly' turbines can be demonstrated to have very low impacts on fish, shutdown periods may be unnecessary.

Turbine entrainment

The proportion of water (and, potentially, entrained transformers) passing through the turbine was 6.13 ± 0.79 % during the main emigration period, with the highest estimated number of transformers passing through the turbine in late January and early February. Throughout the main transformer emigration period from December to March (based on this study, as well as those cited earlier) on a given night, the number of migrants passing through the turbine, and potentially at risk, ranged from 21 to 56 individuals and would equate to several thousand over the main emigration period at this site. Losses may be caused by actual damage incurred on passing through the turbine or indirect effects, such as increased predation of disorientated individuals. It is possible that lamprey predators concentrate in turbine outflow areas. Local aggregations of predatory fishes have been identified downstream of turbine outflows in other studies (Lucas and Baras, 2001).

Nearly 60% of transformers and 47% of ammocoetes were recaptured within 30 min of release, most within 15 min. Incomplete recapture was most likely due to incomplete sampling of the turbine flow. There were no mortalities, but one transformer (1.5% of all recaptures) exhibited swimming impairment. This impairment was assumed to be due to passage through the turbine, as preliminary tests showed that transformers and ammocoetes retained in drift nets for short periods of time (i.e. 2 h or less) did not exhibit any signs of altered physical appearance or swimming behaviour. For the lampreys passed through the turbine, no external damage

DOI: 10.1002/rra

or haematoma was observed, but lampreys were not subsequently retained to determine any delayed effects. Lucas *et al*. (2007) found that only 1.2% of ammocoetes were damaged in a small-scale run-of-river hydroelectric power station with a Kaplan turbine on the river Tay, Scotland. This suggested only a minimal impact to larval lampreys. At a Ritz-Atro hydraulic screw in Germany, 4.4% of teleost fish experimentally passed down the screw were injured during passage. This was most likely caused by contact with the metal edges at the leading edge of the helical blades (Spah, 2001). Merkx and Vriese (2007) found no damage to non-lamprey freshwater fish species that passed through an Archimedean screw at Hooidonkse Mill, The Netherlands, and Kibel (2007) found that entrained salmonids exhibited only minor (1.4%) scale loss at a screw turbine on the river Dart. Rates of damage to European eel *Anguilla anguilla* with similar body morphology to lampreys were low: zero (Spah, 2001) and 0.64% (Kibel *et al*., 2008). However, Schmalz (2010) found considerably greater rates of damage to a wide range of fish species that passed down hydraulic screws and demonstrated damage to the blades, possibly caused by gravel. Such damage could increase the severity of strike impacts to fish over extended operational periods, although rubber covers to blades (Kibel, 2007) may be effective in reducing such effects.

These findings, including the current study, support the suggestion of O'Keefe and Turnpenny (2005) that very small fish, including larval and juvenile lampreys, are likely to pass through low-head turbines, especially hydraulic screw designs, without substantial damage. They also support the view of Moursund *et al*. (2003) that juvenile lampreys are relatively robust in anatomy and physiology to turbine passage. For larval and juvenile lampreys, impacts of fine screens are likely to be greater than passage through the turbine itself (Moursund *et al*., 2003). Nevertheless, a wider range of studies of low-head turbine impacts on fishes, including those examining chronic, sublethal effects, is needed (Cooke *et al*., 2011).

Distribution within the channel

There was no significant difference in ammocoete catches, standardized to volume sampled, in differing parts of the channel. This suggests that ammocoetes captured were drifting downstream and behaving essentially as passive particles. Thus, numbers of ammocoetes entrained into turbine flow are likely to be directly related to the proportion of flow. Little behavioural avoidance is likely to be achieved by any inflow modification in the vicinity of the turbine entrance. In contrast, the data provide some evidence to suggest that transformers avoid edge and lateral water off-take. Higher catch rates of transformers per unit volume sampled occurred in the areas of greater flow that passed through the turbine and over the weir. This may be due to differences in our catch efficiency or by a non-random distribution of transformers, mediated by behaviour. Transformers have well-developed sensory systems, and their downstream migration has been linked to high water flows (Potter, 1980). It is therefore likely that river lamprey transformers preferentially move along main flow routes and orientate away from the areas near the river's edge. Lateral or slack-water off-takes may represent less of an entrainment risk to river lamprey transformers than water off-takes from the main current.

CONCLUSIONS

Any abstraction or diversion of water from rivers, lakes, estuaries, or the sea carries a risk of harm to fish that may be present (Turnpenny *et al*., 1998). Archimedes screw turbines appear to have little effect on lamprey transformer and ammocoete passage. The cumulative impacts of turbines, even 'fish-friendly' ones such as Archimedes screws, must, however, be considered. Cumulative impacts of multiple hydropower stations, dams, or small weirs are evident across a wide range of fish taxa, including lampreys (Williams *et al*., 2001; Moser *et al*., 2002; Gowans *et al*., 2003; Lucas *et al*., 2009). Even where the effects at one site or design are minor, future developments need to take into account cumulative within-catchment impacts as well as site-specific impacts. For example, even if an individual hydropower site causes just a 2% mortality rate, the cumulative impact to a cohort passing six successive sites is a reduction in escapement to a maximum of 88.6%. However, there are few examples of catchment-wide planning for cumulative impacts of small-scale hydropower (e.g. Entec, 2010). Small-scale hydropower in higher-order river channels generally has greater potential to impact diadromous fishes, including lampreys. It is therefore advisable to carefully limit the number, types, and locations of small-scale hydropower facilities.

The development of 'fish friendly' turbines could lead to the rapid multiplication of low-head power generation sites within river systems, enhancing renewable power contributions. However, further research is needed to assess wider and longer-term impacts, for example, indirect effects of increased predation risk. Entec (2010) advises that hydropower development in England and Wales should be concentrated in severely degraded areas, in the context of the European Water Framework Directive. This seems wise particularly while efforts are made to generate the knowledge needed to minimize potential environmental damage from low-head hydropower in ecologically sensitive catchments and sites.

DOI: 10.1002/rra

ACKNOWLEDGEMENTS

Support was provided by the Environment Agency, the Freshwater Biological Association, and ONE North East. We are grateful to the Renewable Heritage Trust for access to the field site.

REFERENCES

Baras E, Lucas MC. 2001. Impacts of man's modifications of river hydrology on the migration of freshwater fishes: a mechanistic perspective. *Ecohydrology and Hydrobiology* **1**: 195–200.

Čada GF. 2001. The development of advanced hydroelectric turbines to improve fish passage survival. *Fisheries* **26**: 14–23.

Čada GF, Hunsaker CT. 1990. Cumlative impacts of hydropower development: reaching a watershed in impact assessment. *The Environmental Professional* **12**: 2–8.

Close DA, Fitzpatrick MS, Li HW. 2002. The ecological and cultural importance of a species at risk of extinction, Pacific lamprey. *Fisheries* **27**: 19–25.

Cooke SJ, Hatry C, Hasler CT, Smokorowski KE. 2011. Literature review, synthesis and proposed guidelines related to the biological evaluation of "fish friendly" very low head turbine technology in Canada. *Canadian Technical Report of Fisheries and Aquatic Sciences* **2391**: 1–33.

Coutant C, Whitney RR. 2000. Fish behaviour in relation to hydropower turbines: a review. *Transactions of the American Fisheries Society* **129**: 351–380.

Dadswell MJ, Rulifson RA. 1994. Macrotidal estuaries: A region of collision between migratory marine animals and tidal power development. *Biological Journal of the Linnean Society* **51**: 93–113.

Dauble DD, Moursund RA, Bleich MD. 2006. Swimming behaviour of juvenile Pacific lamprey, *Lampetra tridentata*. *Environmental Biology of Fishes* **75**: 167–171.

EC. 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. *Official Journal* **L206 22/07/92**: 7–50.

Entec. 2010. *Opportunity and environmental mapping sensitivity for hydropower in England and Wales*. Environment Agency: Bristol.

Ferguson JW, Absolon RF, Carlson TJ, Sandford BP. 2006. Evidence of delayed mortality on juvenile Pacific salmon passing through turbines at Columbia River dams. *Transactions of the American Fisheries Society* **135**: 139–150.

Frear PA, Axford S. 1991. Impingement and mortality of fish associated with the River Ouse abstraction scheme. Science Report 62/91. National Rivers Authority, Yorkshire Region Fisheries.

Gardiner R. 2003. Identifying lamprey. A field key for sea, river and brook lamprey. Conserving Natura 2000 rivers, Conservation techniques No. 4, Peterborough.

Gowans ARD, Armstrong JD, Priede IG, McKelvey S. 2003. Movements of Atlantic salmon migrating upstream through a fish-pass complex in Scotland. *Ecology of Freshwater Fish* **12**: 177–189.

Hardisty MW, Potter IC (Eds). 1971. *The Biology of Lampreys*. Academic Press: London.

Hardisty MW, Potter IC, Sturge R. 1970. A comparison of the metamorphosing and macrophthalmia stages of the lampreys *Lampetra fluviatilis* and *L. planeri*. *Journal of Zoology* **162**: 383–400.

Jang MH, Lucas MC. 2005. Reproductive ecology of the river lamprey. *Journal of Fish Biology* **66**: 499–512.

Kelly FL, King JJ. 2001. A review of the ecology and distribution of the three lamprey species, *Lampetra fluviatilis* (L.), *Lampetra planeri* (Bloch) and *Petromyzon marinus* (L.): A context for conservation and biodiversity considerations in Ireland. *Biology And Environment: Proceedings of the Royal Irish Academy* **101B**: 165–185.

Kibel P. 2007. *Fish monitoring and live trials. Archimedes screw turbine, River Dart. Phase I Report: Live fish trials, smolts, leading edge assessment, disorientation study, outflow monitoring*. Fishtek Consulting: Moretonhamsted, Devon.

Kibel P, Coe T, Pike R. 2008. *Archimedes screw turbine fisheries assessment. Phase II Report: Eels and kelts*. Fishtek Consulting: Moretonhamsted, Devon.

Kosnik L. 2010. The potential for small scale hydropower development in the US. *Energy Policy* **38**: 5512–5519.

Law M, Wass P, Grimshaw D. 1997. The hydrology of the Humber catchment. *The Science of the Total Environment* **194–195**: 119–128.

Long CW. 1968. Diurnal movement and vertical distribution of juvenille anadromous fish in turbine intakes. *Fishery Bulletin* **66**: 599–609.

Lucas MC, Baras E. 2001. *Migration of Freshwater Fishes*. Blackwell: Oxford.

Lucas MC, Bubb DH, Jang MH, Ha K, Masters JEG. 2009. Availability of and access to critical habitats in regulated rivers: effects of low-head barriers on threatened lampreys. *Freshwater Biology* **54**: 621–634.

Lucas MC, Greaves RK, Bubb DH, Kemp PS. 2007. Stanley Mills lamprey report. Scottish Natural Heritage commissioned report no. 256 (ROAME No. F04LH03).

Lucas MC, Mercer T, Batley E, Frear PA, Peirson G, Duncan A, Kubecka J. 1998. Spatio-temporal variations in the distribution and abundance of fish in the Yorkshire Ouse system. *The Science of the Total Environment* **210–211**: 437–455.

Masters JEG, Jang MH, Ha K, Bird PD, Frear PA, Lucas MC. 2006. The commercial exploitation of a protected anadromous species, the river lamprey (*Lampetra fluviatilis* (L.)), in the tidal River Ouse, north-east England. *Aquatic Conservation: Marine and Freshwater Ecosystems* **16**: 77–92.

Mathur D, Heisey PG, Skalski JR, Kenney DR. 2000. Salmonid smolt survival relative to turbine efficiency and entrainment depth in hydroelectric power generation. *Journal of the American Water Resources Association* **36**: 737–747.

Mateus CS, Rodríguez-Muñoz R, Quintella BR, Alves MJ, Almeida PR. 2012. Lampreys of the Iberian Peninsula : distribution, population status and conservation. *Endangered Species Research* **16**: 183–198.

McDowall RM. 1992. Particular problems for the conservation of diadromous fish. *Aquatic Conservation: Marine and Freshwater Ecosystems* **2**: 351–355.

Merkx JCA, Vriese FT. 2007. *Archimedean screw and fish passage study, Hooidonkse Mill. Nieuwegein, The Netherlands*. VisAdvies BV: Utrecht.

Moser ML, Ocker PA, Stuehrenberg LC, Bjornn TC. 2002. Passage efficiency of adult Pacific lampreys at hydropower dams on the lower Columbia River, USA. *Transactions of the American Fisheries Society* **131**: 956–965.

Moursund RA, Dauble DD, Langeslay MJ. 2003. Turbine intake diversion screens: investigating effects on Pacific lamprey. *Hydro Review* **22**: 40–46.

Office for Technology Assessment. 1995. *Fish passage technologies: protection at hydropower facilities*. OTA-ENV-641: Washington DC.

O'Keefe N, Turnpenny AWH. 2005. *Screening for intake and outfalls: A best practice guide*. Environment Agency: Bristol, UK.

Paish O. 2002. Small hydro-power: technology and current status. *Renewable and Sustainable Energy Reviews* **6**: 537–556.

Pirtle J, Stone J, Barndt S. 2003. *Evaluate habitat use and population dynamics of lampreys in Cedar Creek*. Bonneville Power Administration: Portland.

Potter IC. 1980. Ecology of larval and metamorphosing lampreys. *Canadian Journal of Fisheries and Aquatic Sciences* **37**: 1641–1657.

Potter IC, Huggins RJ. 1973. Observations on the morphology, behaviour, and salinity tolerance of downstream migrating river lampreys (*Lampetra fluviatilis*). *Journal of Zoology* **169**: 365–379.

DOI: 10.1002/rra

Potter IC, Osborne TS. 1975. The systematics of British larval lampreys. *Journal of Zoology* **176**: 311–329.

Quintella BR, Andrade NO, Espanhol R, Almeida PR. 2005. The use of PIT telemetry to study movements of ammocoetes and metamorphosing sea lampreys in river beds. *Journal of Fish Biology* **66**: 97–106.

Raat AJP. 2001. Ecological rehabilitation of the Dutch part of the River Rhine with special attention to the fish. *Regulated Rivers: Research & Management* **17**: 131–144.

Renaud CB. 1997. Conservation status of Northern Hemisphere lampreys (Petromyzontidae). *Journal of Applied Ichthyology* **13**: 143–148.

Robson A, Cowx IG, Harvey JP. 2011. Impact of run-of- river hydro schemes upon fish populations. SNIFFR WFD114. http://www.sniffer.org.uk/Webcontrol/Secure/ClientSpecific/ResourceManagement/UploadedFiles/WFD114_Lit%20review_FINAL_AUG2011.pdf

Schmalz W. 2010. *Untersuchungen zum fischabstieg und kontrolle möglicher fischschäden durch die wasserkraftschnecke an der wasserkraftanlage walkmühle an der werra in meiningen*. FLUSS: Breitenbach.

Sjöberg K. 1989. Time-related predator/prey interactions between birds and fish in a northern Swedish river. *Oecologia* **80**: 1–10.

Skalski JR, Mathur D, Heisey PG. 2002. Effects of turbine operating efficiency on smolt passage survival. *North American Journal of Fisheries Management* **22**: 1193–1200.

Spah H. 2001. *Fishery biological opinion of the fish compatibility of the patented hydraulic screw from Ritz Atro*. Bielfield: Germany.

Sutphin ZA, Hueth CD. 2010. Swimming performance of larval Pacific lamprey (*Lampetra tridentata*). *Northwest Science* **84**: 196–200.

Turnpenny AWH, Clough S, Hanson KP, Ramsay R, McEwan D. 2000. *Risk assessment for fish passage through small, low-head turbines*. Harwell Laboratory, Energy Technology Support Unit: Oxon, UK.

Turnpenny AWH, Struthers G, Hanson KP. 1998. *A UK guide to intake fish screening regulations, policy and best practice, with particular reference to hydroelectric power schemes*. Harwell Laboratory, Energy Technology Support Unit: Oxon, UK.

Whitton BA, Lucas MC. 1997. Biology of the Humber rivers. *The Science of the Total Environment* **194**/195: 247–262.

Williams JG, Smith SG, Muir WD. 2001. Survival estimates for downstream migrant yearling juvenile slamonids through the Snake and Columbia Rivers hydropower system, 1966–1980 and 1993–1999. *North American Journal of Fisheries Management* **21**: 310–317.

DOI: 10.1002/rra