The importance of behaviour in predicting the impact of a novel small-scale hydropower device on the survival of downstream moving fish

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Abstract

Further exploitation of hydroelectric power is one strategy that may help European Union member states meet targets to increase the proportion of electricity produced by renewable means. Government subsidies and novel technologies are aiding the development of previously uneconomic, very low-head (< 2.5 m) hydropower sites. Legislation requires that environmental impacts of hydropower development must be assessed and mitigated for. This study incorporated numerical blade strike models (BSMs), open channel flume experiments, and field observations to determine the importance of behaviour when assessing impacts of a novel hydropower device (the Hydrostatic Pressure Converter [HPC]) on downstream moving fish. A Stochastic BSM predicted a lower probability of strike for small fish that travelled downstream faster, and when blades rotated slowly. When empirical data were incorporated into a BSM, predicted probability of strike was in agreement with that observed during a validation test in which freshly euthanized hatchery reared brown trout (*Salmo trutta*) were recorded passively drifting through a prototype HPC under an experimental setting. Forty four percent of trout were struck by a blade, of these, 64% sustained obvious visible physical damage. Behavioural observations of rainbow trout (*Oncorhynchus mykiss*) and European eel (*Anguilla anguilla*) suggest that fish will pass through an unscreened HPC. When behavioural parameters (fish velocity, orientation / degree of body contortion) were incorporated into the BSM, probability of strike increased and decreased for trout and eel, respectively, compared with an assumption of passive drift with the flow. Field observations supported the suggestion that salmonid behaviour may increase risk of mortality during passage through small-scale hydropower devices. This study highlights the importance of considering interspecific variation in behaviour when

developing BSMs and conducting Environmental Impact Assessments of hydropower development.

Key words: Low-head hydropower, Turbine, Blade strike model, Flume, Fish injury

1. Introduction

As global energy demand continues to rise, hydropower offers a reliable, highly efficient, long term energy investment (Oud, 2002), and a move away from fossil fuel dependency. As part of a mixed power source portfolio, hydropower facilitates energy security for many nations, whilst contributing towards meeting targets to increase the proportion of electricity generated from renewable sources. In developed regions (e.g. Europe), hydropower operations increasingly focus on small-scale (often defined as ≤ 10 MW) installations, as larger-scale opportunities have either been exploited or are considered environmentally unacceptable (Paish, 2002). In many countries, a high density of redundant low-head infrastructure (e.g. weirs and mill systems) that was until recently judged economically unsuitable for hydroelectric development, are now being assessed again in light of government subsidies designed to help meet renewable electricity generation targets.

Hydropower development can alter water quality and flow regimes, and negatively impact biotic communities, e.g. by impeding movements of aquatic organisms due to the construction of impoundments, or by damaging those that pass through turbines (Čada, 2001; Ovidio and Philippart, 2002; Trussart et al., 2002;

Santucci Jr et al., 2005). For fish, downstream passage through turbines can cause injury and mortality due to blade strike, grinding, rapid pressure fluctuations, cavitation, shear stress and turbulence (for overviews see Coutant and Whitney, 2000; Čada, 2001). In Europe, hydropower development and operation must be achieved within constraints imposed by legislation designed to reduce environmental impacts. These include the Convention on Biological Diversity, the Habitats Directive (92/43/EEC), Water Framework Directive (WFD) (2000/60/EC), and Eel Regulation (1100/2007/EC). The WFD, in particular, is often viewed as a constraint to hydropower development as deterioration in ecological quality due to hydromorphological pressures created by impoundments and off-takes is prohibited. Under the WFD, river development should include measures to protect, enhance or restore the aquatic environment. Fish fauna is a key indicator of ecological status and thus requires protection from impacts of development.

A variety of techniques are employed to quantify impacts to fish passing through hydropower facilities. Experimental research is conducted to simulate the conditions fish experience during, and to determine the impact of, turbine passage (e.g. exposing fish to high shear stresses using jets of water; Neitzel et al., 2004; Deng et al., 2005, or to rapid pressure changes in enclosed chambers; Stephenson et al., 2010; Brown et al., 2012). Field studies, utilizing mark-recapture and tagging techniques (among others, e.g. Deng et al., 2010) allow empirical injury and mortality rates to be quantified. For example, balloon, radio, and combinations of the two tags (Bell and Kynard, 1985; Stier and Kynard, 1986; Skalski et al., 2002; Ferguson et al., 2007; Calles et al., 2012) are used to identify positions of fish to be retrieved after passage through turbines, enabling evaluation of injury. However, results from field studies are often site specific, considering turbine geometry and operating conditions during the test period, and frequently focus on a limited number of species. Instead, numerical blade strike models (BSMs) provide a generic method to predict damage to multiple species of fish passing downstream through turbines. BSMs are useful decision-support tools prior to installation because they can provide estimates of injury and mortality for alternative turbine designs and geometries, under a range of operating conditions (Ferguson et al., 2008). BSM inputs frequently include direction and velocity of water approaching the turbine, number of blades, rotational speed, and fish body length (Montén, 1985). However, as not all strike events result in acute anatomical damage, BSMs historically over estimate direct mortality (Turnpenny et al., 2000).

Behaviour of fish during approach to, and passage through, turbines will influence probability of strike and ultimately mortality rates (Coutant and Whitney, 2000). However, behaviour is often ignored when quantifying the impacts of hydropower on downstream moving fish, and as a consequence detailed information is limited (Ferguson et al., 2008). Recent flume studies provide an insight into fine-scale behaviour and how it differs between species. For example, for downstream moving salmonids, abrupt accelerations of velocity, a condition common at turbine intakes, may initiate avoidance and the associated switch from a downstream (negative rheotaxis) to upstream (positive rheotaxis) facing orientation, delaying downstream progress (Kemp et al., 2005; Vowles and Kemp, 2012). In contrast, downstream migrating eels, often considered particularly vulnerable to injury during turbine passage due to their large adult size and elongated bodies, may be more responsive to contact with physical structure than the fine-scale hydrodynamic conditions to which salmonids react (Russon and Kemp, 2011). Such interspecific behaviours are likely to play an important role in the probability of fish entering, and severity of strike during passage through, hydropower turbines. Current BSMs assume fish of a specified length to be oriented perpendicular to blades, or incorporate stochastic models that randomise body length (and thus account for variability in orientation during passage), by running multiple iterations (Deng et al., 2007). Although BSMs can be improved by incorporating empirical information, such as a "mutilation ratio" (a measure of the BSM strike rate relative to injury or mortality observed during validation studies), the identification and incorporation of behaviour into future BSMs is needed to further improve accuracy.

To develop the low-head hydropower resource in Europe (and elsewhere) there is a need to progress novel technologies that minimize ecological impacts and ensure environmental legislative standards are met. A new technology, the Hydrostatic Pressure Converter (HPC), similar in appearance to historic waterwheels, has been designed to provide a technical and economic solution to the development of very low-head (here considered to be < 2.5 m) hydropower (Senior et al., 2010). Two designs currently exist (see Senior et al. 2010 for technical details). The first, the Hydrostatic Pressure Wheel (HPW), is suitable for exploiting head differences between 0.3 and 1.0 m. The HPW consists of a large diameter wheel with vertical blades, which when moving act as a weir, maintaining the head difference between up- and down-stream (Fig. 1.a, b). The resulting differential hydrostatic pressure acting on the blades causes the machine to rotate around a horizontal axis at the velocity of flow. The second and more complex design, the Hydrostatic Pressure Machine (HPM), operates under the same principal but can exploit head differences between 1.0 and 2.5 m (Fig. 1.c; Senior et al., 2010). HPMs employ a central hub, equal in diameter to the hydraulic head difference. Simplicity in design, in combination with potential for high efficiencies at very low-head differences indicate that these machines provide a technological solution to the challenge of exploiting the underutilized very low-head hydropower resource available within Europe (Senior et al., 2010; Paudel et al., 2013). However, the environmental performance of HPCs has yet to be assessed.

The aim of this study was to determine the importance of behaviour when assessing the impact of a novel small-scale hydropower device (the HPC) on downstream moving fish. Four objectives were identified: 1. develop a BSM to estimate the probability of a fish being struck by a rotating HPC blade, it is predicted that strike will increase with fish length and speed of blade rotation, but decrease as fish move downstream faster; 2. validate the BSM using empirical strike data and determine nature of damage sustained during passage; 3. quantify the behaviour of multiple species of fish as they approach a HPC in the presence and absence of visual cues, and incorporate responses into the BSM; 4. assess rates of damage to fish passing through a HPC in a field setting. Findings from this study will help inform the development of BSMs in general and highlight the need to consider multi-species fish behaviour when assessing the environmental impact of hydropower development.

2. Materials and methods

2.1. Blade strike model

A numerical BSM was developed to predict the probability (*P*) of the leading edge of a HPW blade striking a downstream moving fish. Fish swimming into the back of a rotating blade was not considered by the model as contact with the blade tip was the area suspected to cause damage to fish. The model was based on the principle that for a fish to pass through the HPW without being struck by a blade it must pass between the sweep of one blade and the next. One hundred iterations were computed per model simulation and P was calculated as:

$$P = 100\left(\frac{N_{\text{strike}}}{N}\right) \quad (1)$$

where N_{strike} is the number of model iterations where the fish is struck by a blade and N is the total number of model iterations. Strike is deemed to occur when the time taken for the body of the fish to move past the arc of water swept by the blades (T_{fish}) is greater than the time taken for the next blade to reach the location where the fish approached the arc (T_{sweep}) (Fig. 2). T_{fish} (sec) is calculated as:

$$T_{\text{fish}} = \frac{L_{\text{fish}}}{V_{\text{fish}}} \quad (2)$$

where L_{fish} and V_{fish} are the fish length perpendicular to a HPW blade (m) and the downstream velocity of the fish relative to the ground (m s^{-1}), respectively. T_{sweep} (sec) is calculated as:

$$T_{\text{sweep}} = \frac{L_{\text{sweep}}}{\bar{u}} \quad (3)$$

where $\bar{u}$ is the water velocity (m s^{-1}) and L_{sweep} is the arc length between the blade and fish locations (m) (diagrammatically the same as T_{sweep} in Fig. 2), calculated as:

$$L_{\text{sweep}} = (rA_{\text{blade}}) - (rA_{\text{fish}}) \quad (4)$$

where r is the radius of the HPW (m). A_{blade} is the location along the arc of the nearest blade tip to the fish at the time the fish approaches the arc (Fig. 2). This value was randomised within the model to reflect any point along the arc, from the the location where the blade tip first sweeps past the base of the channel (pinch point) to a maximum arc distance upstream equal to the gap between two blades, by adjusting θ in equation 5 between 0 and 30° (0.52 rad) unless otherwise stated (see Section 2.2). A_{fish} is the approach location of the fish along the arc (Fig. 2) and was randomised within the model (anywhere between the pinch point and the water surface, again by adjusting θ in equation 5), unless otherwise stated (see Section 2.2). A_{blade} and A_{fish} were both determined as:

$$= \left(\left(\frac{r}{\sin((180-\theta)/2)}\right)\sin\theta\right)\sin\left(\alpha - \left((180-\theta)/2\right)\right) \quad (5)$$

where θ is the angle between A_{blade} or A_{fish} and the pinch point (Fig. 2), and α is the angle between the blade face as it sweeps the pinch point and the channel floor (this was set at 120° [2.09 rad] based on a prototype HPW used during validation tests; Fig. 2). If the nearest blade to the fish has already passed A_{fish} or is at the pinch point, then the probability of the fish being struck by the next blade must be considered. The location of the second blade is calculated using:

$$A_{\text{blade2}} = A_{\text{blade}} + \left((2\pi r/r)/n\right) \quad (6)$$

where n is the total number of HPW blades. In these instances the model replaces A_{blade} with A_{blade2} in equation 4.

One hundred BSM simulations were computed, with randomly assigned fish length (L_{fish}), fish velocity (V_{fish}), and water velocity ($\bar{u}$) values from a uniform distribution (within a specified range, see Stochastic BSM Table 1), to determine their influence on P. As $\bar{u}$ determines the rotational speed of the HPW (in revolutions per minute, RPM), it is the influence of RPM on P that is subsequently referred to, and is calculated as:

$$\text{RPM} = 60 \,/\left(\frac{2\pi r}{\bar{u}}\right) \quad (7)$$

The HPW geometry (*r* and *n*) and water depth (*d*) remained constant and were based on a quarter-scale prototype HPW used during validation tests (Section 2.2).

2.2. Model validation

To validate the BSM, 100 hatchery reared brown trout, *Salmo trutta* (mean total length ± SD was 27.5 ± 2.9 cm), were euthanized (using an anaesthetic overdose) and individually released 1.5 m upstream of a prototype HPW installed in an outdoor concrete re-circulating flume (60.0 x 2.1 x 0.5 m) at the International Centre for Ecohydraulics Research (ICER) experimental facility, University of Southampton (UK). Water driven by a centrifugal pump was delivered at a constant discharge (approximately 80 L s^{-1}). The HPW had a radius of 0.8 m and 12 blades that spanned the width of the intake channel (0.5 m). The mean mid-column water velocity (measured 20 cm upstream of the blades and at three equidistant points that spanned the intake channel) was 70.4 cm s^{-1}, and depth was 23 cm. Although released perpendicular to the blades, changes in orientation occurred for some fish during passive drift. Passage outcome was determined from video footage and categorised as: 1. 'No contact' with the rotating blades; 2. 'Slap' with the back of a blade after passing the leading edge (no observable external damage); 3. 'Strike' with the leading edge of the blade causing no or minor observable damage (see Section 3.2); and 4. 'Grinding' of the fish between the blade and base of the channel at the pinch point, leading to severe damage (see Section 3.2). Visual macroscopic assessment immediately after passage through the HPC and photographs, taken pre- and post-passage, were used to determine the nature of any damage.

Fish 'Strike' and 'Grinding' occurred during contact with the leading edge of a blade and were compared with the predictions of two BSMs. The first modelled the validation study setup (subsequently referred to as the Validation BSM, Table 1) and for each model iteration (100 per simulation) randomly assigned fish and blade approach positions (i.e. A_{fish}, A_{blade} and A_{blade2} in the BSM formulation outlined in Section 2.1), and a L_{fish} that corresponded to the mean total length of the euthanized fish. One hundred simulations of the Validation BSM were computed to determine whether the proportion of fish observed being struck by a blade during the validation tests fitted within the model distribution of P. The second BSM (referred to as the Empirical Validation BSM, Table 1) assigned A_{fish}, A_{blade}, and A_{blade2} positions for each iteration according to their observed locations, digitised from video footage, and L_{fish} values based on the actual stream-wise length of fish as they drifted through the blades (thus taking into account variability in orientation as fish passively moved downstream). One simulation (consisting of 100 iterations) was computed for this model.

2.3. Fish behaviour

To determine the influence of behaviour on the probability of a blade striking a fish, experiments were conducted in an indoor re-circulating flume (20.4 x 1.4 x 0.6 m) at the ICER facility. Discharge (approximately 100 L s^{-1}) and upstream water depth (18.9 cm) were maintained constant. The HPW had the same geometry as the prototype used during validation tests, but extended across the width of the flume (1.4 m). Mean mid-column water velocity, measured 20 cm upstream of the blades at five equidistant points that spanned the channel width, was 37.9 cm s^{-1}.

Rainbow trout, *Oncorhynchus mykiss* (obtained from a local hatchery on 26 September 2008; mean total length and mass: 26.3 ± 2.5 cm, 138.2 ± 50.7 g) and actively downstream-migrating adult European eels, *Anguilla anguilla* (sourced from a commercial trapper on the River Stour, Dorset, UK, on 5 September 2008; mean total length and mass: 56.6 ± 8.8 cm, 340.6 ± 174.7 g) were selected as the test species as they represent families of economic and conservation interest with distinctly different life history characteristics and body morphologies. Trout and eels were transported in aerated containers and held in 3000 L (max density: 10.5 kg/m^3) and 900 L (max density: 20.4 kg/m^3) tanks, respectively. Under ambient temperature and natural photoperiod, water quality was maintained using aeration and filtration systems.

During the experiments, fish were contained within a section of flume by two fine mesh screens placed 0.07 and 6.7 m upstream of the rotating blade tips. The most downstream screen was installed to prevent fish passing the device where they were at risk of injury from the rotating blades. Black plastic sheeting erected along the length of the flume prevented visual disturbance to the fish. Fish were placed into a perforated container located 6.8 m upstream of the HPW and allowed to acclimatise for a minimum of one hour prior to trials commencing. At the start of each trial fish were released individually and allowed to explore the channel. After one hour, fish were removed from the flume and measured and weighed. Each fish was used once only. Trials were conducted during night and day to determine the influence of visual cues on behavioural response. Night (19:00 – 01:00 hrs) and day (10:00 – 16:00 hrs) trials were conducted between 29 September and 9 October, and 27 and 30 October 2008, respectively. The study was conducted under strictly controlled conditions.

Experimental procedure, flume discharge, water depth, and HPW rotational speed remained constant, and water temperature was similar between night (17.1 ± 1.1˚C) and day (16.0 ± 1.1˚C).

Overhead and side-view cameras recorded fish behaviour on entering the area 1 m upstream of the downstream screen, subsequently referred to as the observation zone. Behaviour was quantified for each trial as: 1. number of entrances to the observation zone; 2. orientation on entry; 3. period of occupancy (sec) within the observation zone; 4. downstream fish velocity (represented as V_{fish} in the BSM and subsequently referred to as observed V_{fish}, OV_{fish}); and 5. stream-wise length (perpendicular to the blades and taking into consideration the orientation / contortion of the body, represented as L_{fish} in the BSM and subsequently referred to as observed L_{fish}, OL_{fish}). OV_{fish} and OL_{fish} were determined one second prior to first contact with the downstream screen using video tracking software (Logger Pro v3.8.2, Vernier Software, Beaverton, OR, USA). BSM simulations where L_{fish} and V_{fish} were defined as the mean total length of trout and eel used during behaviour tests (measurements taken after each flume trial) and the velocity at which fish passively drift with bulk flow, respectively (subsequently referred to as the Passive BSM), were compared with simulations where OV_{fish} (13.9 cm s^{-1} [trout] and 34.1 cm s^{-1} [eel]) and OL_{fish} (22.7 cm [trout] and 37.8 cm [eel]) were used (values obtained from video footage of the behavioural tests). This model is subsequently referred to as the Behaviour BSM (Table 1).

In the BSM simulations, the HPW diameter was doubled to accommodate observed eel body length that would otherwise have resulted in 100% strike rate, independent of whether behaviour was incorporated into the model.

2.4. Field observations

As part of the EU Framework 7 research project (HYLOW), field studies were conducted in collaboration with the Division of General and Applied Hydrobiology, Sofia University "St. Kliment Ohridski" (Bulgaria), which assessed the environmental impact of a full scale (10 kW) HPM (2.4 m diameter, 2 m wide, and with 10 blades) installed on a low-head weir on the River Iskar (a tributary of the Danube River), Bulgaria (Uzunova and Kisliakov, 2014). Hatchery reared salmonids (rainbow trout [*O. mykiss*] and brook trout [*Salvelinus fontinalis*]) were transported in aerated containers to the study site, and held in perforated pens in the river for at least 2 hours prior to release approximately 2 m upstream of the HPM intake. Fish were able to move upstream away from the release point or pass downstream through the HPM. Mean water velocity at the intake was 66 cm s^{-1}. Fish were divided into four size groups (Table 2). Each group was tested separately and released between 43 and 175 minutes apart. The largest size range utilised live and euthanized fish to allow a comparison between fish exhibiting behaviour versus those passively drifting downstream. Fish were collected downstream using a fyke net positioned in the tailrace. Fish were removed from the net (that was continually checked) and placed into aerated containers immediately prior to macroscopic external examination. Injuries observed were; severing of the body, severe incision / pinch marks, tears / cuts to the skin, fin damage, and scale loss. Direct mortality was recorded if the fish was dead during examination. Injured fish were euthanized after examination and thus not retained for assessment of delayed mortality. Fish not injured during passage were released into the river below the device.

2.5. Statistical analysis

Data was assessed for normality and homogeneity of variance using a Shapiro-Wilk and Levene's test, respectively. Non-parametric tests were performed on data that could not be successfully normalised through transformation. For the Stochastic BSM, multiple regression analysis was used to investigate the relationships between L_{fish}, V_{fish}, RPM and probability of strike (*P*), and determined how much of the variability in *P* was explained by these parameters. Standardized beta coefficients (beta coefficients divided by standard error) were calculated to determine the sensitivity of *P* to each parameter. Pearson's chi-square tests were used to identify differences between the Empirical Validation BSM estimate of *P* and number of fish observed contacting the leading edge of a HPW blade during evaluation. Mann-Whitney U tests determined if number of approaches, or period of occupancy within the observation zone was influenced by time of day (day or night) or species (trout or eel). The influence of species and BSM type (passive or behaviour) on mean probability of strike (after 100 simulations per model) was analysed using univariate two-way ANOVA.

3. Results

3.1. Blade strike model

The probability of blade strike (*P*) was positively related to L_{fish} and RPM, but negatively correlated with V_{fish} (Fig. 3). The three variables explained 85% of variability in P ($R^2 = .85$, $F_{3,96} = 176.36$, $p < 0.001$). L_{fish} was the most significant predictor, with RPM and V_{fish} having similar contributions towards P (Fig. 3).

3.2. Model validation

The Validation BSM overestimated P compared to that observed (Fig. 4). However, when empirical values for A_{fish}, A_{blade}, A_{blade2}, and L_{fish} were incorporated into the Empirical Validation Model, estimated P did not differ significantly from the observed strike rate during the validation tests (Pearson chi-square: $\chi^2 = 0.18$, d.f. = 1, $p = 0.670$; Fig. 4).

As fish passively drifted through the HPW, the most common outcome was 'No contact', followed by 'Grinding' (Table 3). Only two fish sustained injuries during 'Strike' events; one minor graze to the snout and one small bruise near the caudal fin. All grinding events resulted in visible damage deemed sufficient to have resulted in mortality had fish been alive. During grinding fish were pinched at the small gap (approximately 5 mm) between the blade tip and base of the flume and drawn through the device. This resulted in severe incision at the point of contact with the fish, leading to clear skeletal / internal damage, tears / cuts to the skin, damaged fins, and extensive abrasive scale loss. Strike and grinding occurred in 44% of fish drifting through the HPW, 28 (64% of those struck by a blade) sustained visible damage.

3.3. Fish behaviour

Number of approaches to the observation zone did not differ with time of day for trout (Mann-Whitney U: $U = 10.5$, z = -0.45, $p = 0.655$) or eels (Mann-Whitney U:

$U = 8$, $z = -1.00$, $p = 0.340$) so data were pooled across treatments. Eels approached the observation zone more frequently than trout (mean ± SD = 8.7 ± 5.5 and 1.8 ± 1.4 for eel and trout respectively; Mann-Whitney U: $U = 10$, $z = -3.07$, $p < 0.01$). Seventy two and 91% of approaches resulted in contact with the downstream screen (7 cm upstream of the blade tips) for trout and eels, respectively.

Orientation differed between species. Overall, trout and eel were predominantly positively and negatively rheotaxic, respectively, although for eel, orientation was more variable during the night (Table 4).

Occupancy time did not differ with time of day for trout (Mann-Whitney U: $U = 8$, $z = -0.94$, $p = 0.347$) or eels (Mann-Whitney U: $U = 7$, $z = -1.15$, $p = 0.251$) so data were pooled across treatments. Period of occupancy did not differ between species (Mann-Whitney U: $U = 38$, $z = -0.91$, $p = 0.364$). Neither species avoided the observation zone with mean occupancy times representing a large proportion of the experimental period, considering over 6 m of flume was available for exploration (35.72 minutes for trout; 24.47 minutes for eels).

Trout moved downstream slower (mean OV_{fish} ± SD = 13.9 ± 9.0 cm s^{-1}) than the bulk flow ($\bar{u} = 37.9$ cm s^{-1}). In contrast eels tended to drift downstream at a speed that closely matched that of the water velocity (mean OV_{fish} ± SD = 34.1 ± 13.0 cm s^{-1}). For trout, OL_{fish} (22.7 ± SD 3.4 cm) was similar to their mean total length (26.4 ± SD 2.7 cm). Due to the contortion of the body, OL_{fish} (37.8 ± SD 11.6 cm) for eels was less than the mean total length (56.0 ± SD 7.4 cm).

There was an interaction effect between species (trout or eel) and BSM type (passive or behaviour) on the probability of being struck by a HPW blade (two-way ANOVA: $F_{1, 396} = 4479.06$, $p < 0.001$). When behaviour was incorporated into the BSM, probability of strike decreased and increased for eel and trout, respectively, in comparison to the passive BSM, where fish were assumed to drift with bulk flow perpendicular to the blades (Fig. 5).

3.4. Field observations

The proportion of live fish sustaining visible injuries was positively related to total length (Fig. 6). Direct mortality was < 2% for fish smaller than 15 cm in length, but 26% for the largest size range (22 – 31 cm). In contrast, 8% of euthanized fish of the largest size range, which passively drifted through the HPM, sustained damage deemed sufficient to have resulted in mortality had they been alive (Fig. 6).

4. Discussion

A primary concern regarding low-head hydropower development is the potential injury of fish due to turbine blade strike (Bracken and Lucas, 2013). A Stochastic blade strike model (BSM) intuitively predicted the probability of strike for fish that pass through a Hydrostatic Pressure Wheel (HPW) to be positively related to body length and blade rotational speed, and negatively related to downstream fish velocity.

The BSM designed to simulate conditions created during validation tests (Validation BSM), where euthanized brown trout passively drifted through a HPW in an experimental flume, overestimated probability of strike compared to that observed. There are likely two explanations for this discrepancy. First, the BSM was based on the assumption that fish were evenly distributed through the water column. However, during validation tests, fish were observed to "sink" when passively drifting. On average, this caused fish to be farther away from the sweeping blades, and thus suffer lower strike rates than predicted. Second, deviation in orientation away from the axis parallel to the direction of flow (and perpendicular to the blades) during passive drift resulted in body length exposed to the blades being lower than the mean value used in the BSM. Interestingly, Deng et al. (2007) suggested fish orientation on entry into the plane of water swept by Kaplan turbines to be one of the most significant factors influencing probability of strike. Their BSMs were improved when body length was randomly adjusted at each iteration (according to various uniform or normal distributions), than when assumed to be perpendicular to the blade (Deng et al., 2007). In the current study, bias in fish depth and orientation was controlled for by digitising actual blade and fish locations and incorporating them into an improved BSM (the Empirical Validation BSM) which more accurately predicted probability of strike. The distribution and orientation of fish during passage through hydropower turbines are important considerations when developing BSMs. This information has traditionally been difficult to collect at large hydroelectric dams, but could be more readily attainable at small-scale, low-head hydropower schemes.

During validation tests, passively drifting euthanized fish sustained severe damage, deemed sufficient to have caused mortality had they been alive, during events in which they became trapped between the blade tips and the base of the channel. The slow rotational speed of the blades (< 1 m s^{-1}) meant that other contact (e.g. slap and strike) resulted in minor or no physical damage following visual macroscopic evaluation. To reduce risks to downstream moving fish, novel small-scale hydropower devices should eliminate potential "pinch points". For example, the mortality of adult European eel was reported to be < 1% when passed through an Archimedean Screw Turbine, and injury to large salmonids was eliminated when the leading blade edge was protected with compressible rubber (Kibel, 2008; Kibel et al., 2009). It should be recognised, however, that this study focused on macroscopic physical injury and direct mortality. In reality fish are likely to suffer less easily quantified, sub-lethal effects (such as physiological stress, behavioural alterations, and increased susceptibility to disease or predation), which may compromise individual fitness, and thus should be considered further in future hydropower impact assessments (Cooke et al., 2011).

Trout and eels did not exhibit a strong avoidance response to hydrodynamic, visual, or acoustic cues experienced when approaching the intake to the prototype HPW installed in an experimental flume. Indeed, both species spent approximately half of their time in the immediate vicinity upstream of the device, with eels being more active and entering the observation zone more frequently than trout. The lack of avoidance and frequent contact with the screen suggests that neither species was reacting to the screen itself and that if unscreened, would have likely passed through the device.

European eel carry a high risk of blade strike due to their elongated body morphology and tendency to swim near the substrate, where turbine intakes are situated (Gosset et al. 2005). Interestingly, when eel behaviour was incorporated into the BSM, probability of strike was reduced as body contortion limits the length available to strike. However, the tendency to be substrate oriented would likely lead to a high probability of grinding between the blade and channel floor. Consequently, severe injury (and thus mortality per strike event) during downstream passage will likely be higher for this (and other) benthic oriented species. In contrast to eels that tended to move downstream passively, trout exhibited strong positive rheotaxis and thus their groundspeed was slower than the flow. The trout exhibited an escape response by swimming back upstream only after making contact with the protective screen. This suggests that the fish used in this study did not perceive the rotating blades as a hazard at close distance. By approaching the blades slowly, trout spent longer in the hazardous area resulting in a higher probability of strike.

In comparison between rates of damage to live and euthanized fish that passed through a full-scale Hydrostatic Pressure Machine (HPM) on the River Iskar (Bulgaria), mortality rates for trout of 22-31 cm body length was approximately three-fold greater than would have occurred if they had passively drifted through the device. This is in agreement with the predictions of the BSM that accounts for salmonid behaviour. Mortality rates can be elevated for salmonids due to behaviour exhibited, influencing probability of survival during passage through hydropower turbines when velocities are sufficiently low.

Quantifying the influence of behaviour on fish survival during passage through turbines presents an interesting future research challenge. Behaviour may exert a strong influence on probability of strike during passage through small-scale, low-head hydropower devices, but have a less significant effect when applied to traditional large or high-head turbines. For example, at hydroelectric dams on the Columbia River (USA), blades rotate quickly at approx. 80 RPM, and water velocity accelerates rapidly from around 1 m s^{-1} at turbine intakes to 15 – 18 m s^{-1} at the blades. Fish may be unable to avoid blades, or control orientation and speed of passage under such conditions (Coutant and Whitney, 2000). Conversely, for small-scale, low-head hydropower devices that rotate relatively slowly, and without rapid fluctuations in water velocity, the probability of strike is more likely to be influenced by behaviour, an aspect rarely considered when assessing impacts of hydropower on downstream moving fish.

5. Conclusions

The environmental impact of novel low-head hydropower technologies requires rigorous assessment to ensure environmental legislative commitments are fulfilled. This study highlights the importance of fish behaviour when assessing variation in probability and severity of blade strike. Behaviour should be considered when developing future BSMs and when conducting Environmental Impact Assessments. For hydropower devices that create a pinch point (such as HPCs), screens should be used to prevent severe damage caused by grinding of fish between moving and stationary components. Screens should direct fish towards bypass systems, providing safe, alternative routes of passage.

Acknowledgments

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Table captions:

Table 1. Parameter values used for the BSMs outlined in Section 2.1 (Stochastic BSM), Section 2.2 (Validation and Empirical Validation BSM), and Section 2.3 (Passive and Behaviour BSM). Key model parameters are illustrated in Fig. 2.

Table 2. Size and number of hatchery trout released upstream of a HPM installed on a low-head weir on the River Iskar (Bulgaria), to assess injury / mortality during downstream passage.

Table 3. The passage outcome and frequency of damage sustained to freshly euthanized brown trout ($N = 100$) passively drifting through a prototype HPW.

Table 4. Percent of total approaches to the observation zone (1 m upstream of a prototype HPW), during which fish faced upstream (positive rheotaxis), downstream (negative rheotaxis) or were perpendicular to the flow.

Figure captions:

Figure 1.a. A prototype HPW installed in an outdoor flume at the ICER experimental facility. **b.** The basic operating principle of HPCs. The hydrostatic pressure force ($F_1 - F_2$) causes the device to travel with the water velocity V_1 and generate power. Energy conversion becomes a function of the ratio d_2 / d_1. **c.** A HPM installed on a low-head

weir in the River Iskar (Bulgaria). Note the fyke net placed in the dewatered tailrace, used as part of a field evaluation to quantify injury rates to fish.

Figure 2. Schematic representation of the BSM. This fish approaches (A_{fish}, location indicated by X_1) after the sweep of blade 1 (A_{blade}, location indicated by X_2) but will be struck by blade 2 (A_{blade2}, location indicated by X_3) if T_{fish} is greater than T_{sweep}. The red circle marks the pinch point, and the arc swept by the blade tip is shown as a light grey dashed line.

Figure 3. Standardized ß coefficients from a multiple regression analysis indicating the sensitivity of P to three parameters; L_{fish}, RPM, and V_{fish}. All parameters significantly contributed to the regression model ($p < 0.001$).

Figure 4. Results of 100 Validation BSM simulations (mean $P = 64.8\%$), the Empirical Validation BSM ($P = 47\%$) and the observed number of euthanized fish being struck by the HPW blade as they passively drifted downstream during the validation tests (observed strike = 44%). The errors bar is + 1 SD of the Validation BSM simulations.

Figure 5. Probability of strike (P) for trout (black bars) and eel (clear bars) when passively drifting through a HPW while perpendicular to the flow (Passive BSM), and when OL_{fish} and OV_{fish} values were incorporated into the model (Behaviour BSM). Errors bars are + 1 SD.

Figure 6. Total percent of hatchery trout that sustained obvious physical injury (black bars) and direct mortality (clear bars) as a result of passage through a HPM installed on the River Iskar (Bulgaria). The percentage for the 'euthanized' group reflects physical damage (black bars) and damage deemed sufficient to result in direct mortality had the fish been alive (white bars).

Figure 1

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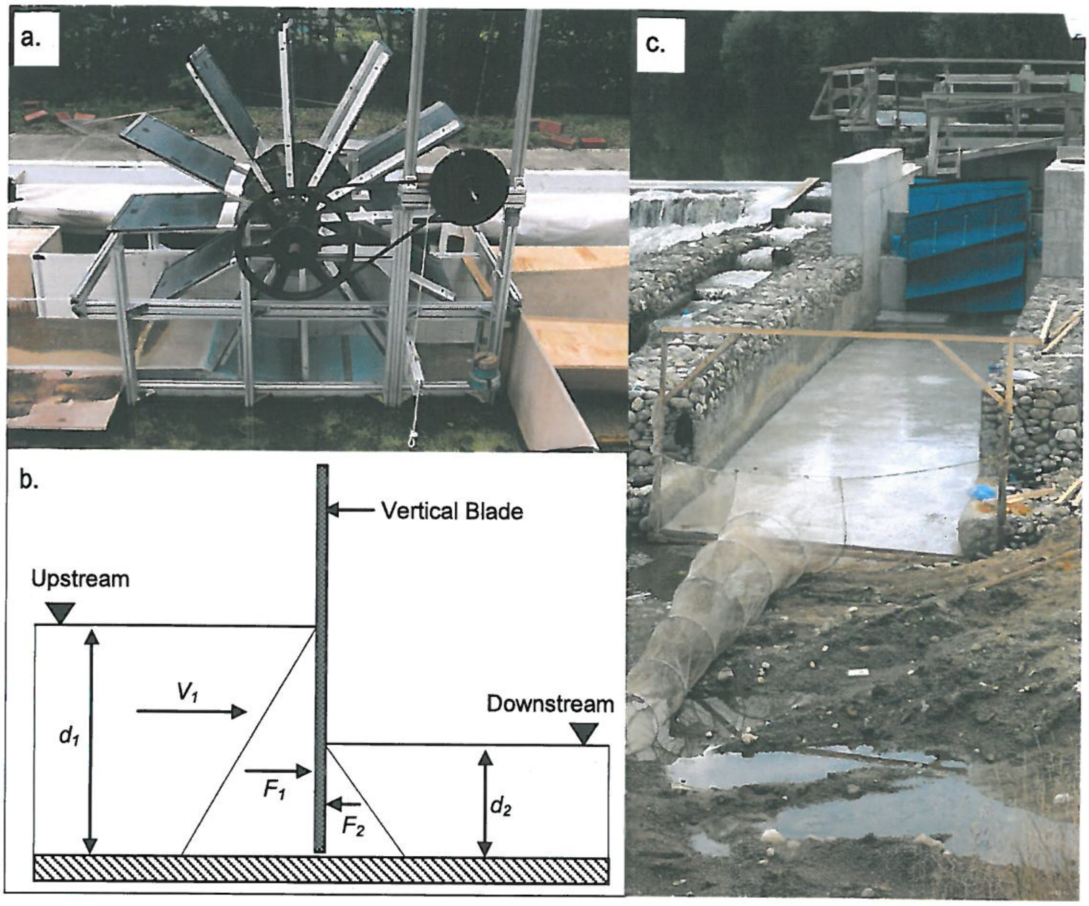

Figure 2
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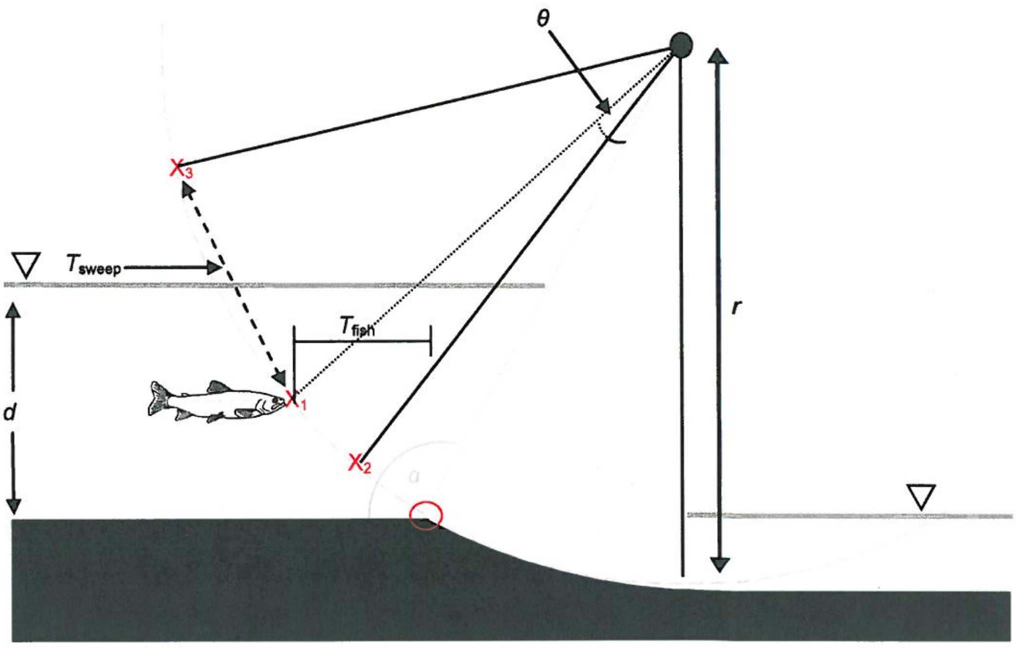
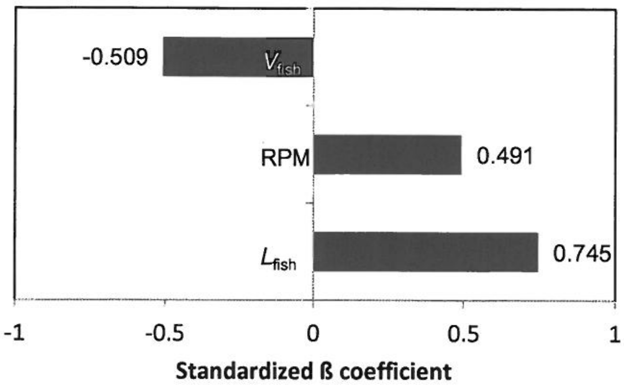


Figure 3



-0.509
V_{fish}
RPM
0.491
L_{fish}
0.745
-1
-0.5
0
0.5
1
Standardized ß coefficient

Figure 4
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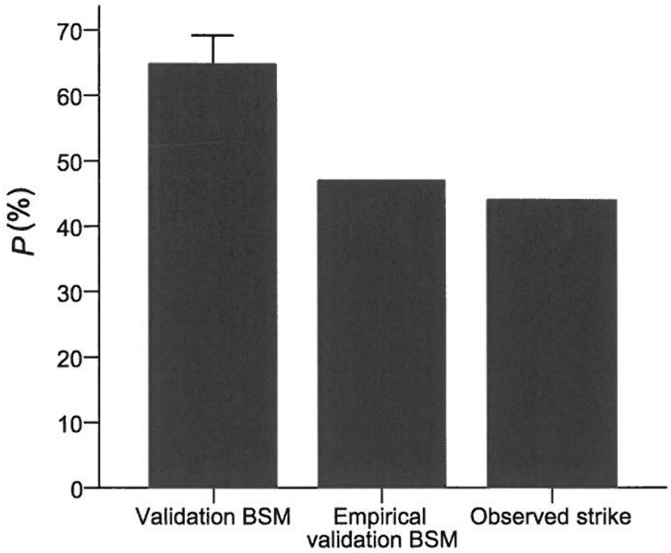

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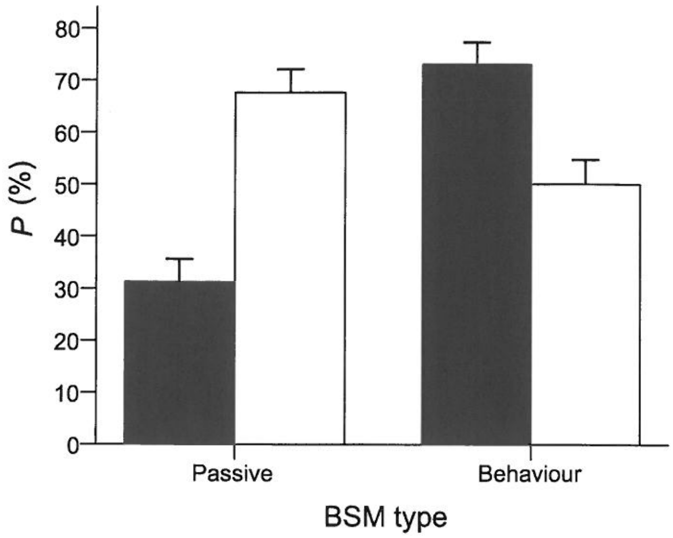

Figure 6
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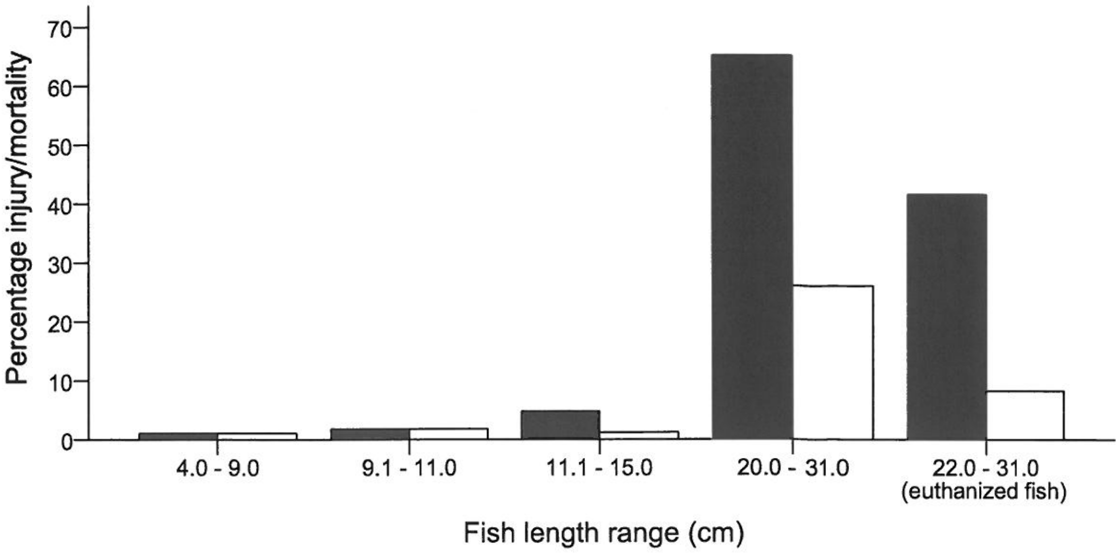

Table 1

Parameter	Stochastic BSM	Validation BSM	Empirical Validation BSM	Passive BSM	Behaviour BSM
r (m)	0.8	0.8	0.8	1.6	1.6
θ (°)	0 – 30 for A_{blade}, 0 – 25 for A_{fish}	0 – 30 for A_{blade}, 0 – 25 for A_{fish}	0 – 30 for A_{blade}, 0 – 25 for A_{fish}	0 – 30 for A_{blade}, 0 – 21 for A_{fish}	0 – 30 for A_{blade}, 0 – 21 for A_{fish}
d (m)	0.23	0.23	0.23	0.38	0.38
α (°)	120 (2.09 rad)	120 (2.09 rad)	120 (2.09 rad)	120 (2.09 rad)	120 (2.09 rad)
RPM	01-Oct	8.4	8.4	2.3	2.3
u (m s^{-1})	0.083 - 0.83	0.704	0.704	0.379	0.379
L_{fish} (m)	0.01 - 0.50	0.275	Specified per iteration	0.263 and 0.566**	0.227 and 0.378**
V_{fish} (m s^{-1})	0.01 - 1.00	0.704	0.704	0.379	0.139 and 0.341**
T_{fish} (s)	Dependent on L_{fish} and V_{fish}	0.39	Dependent on L_{fish}	0.69 and 1.49**	1.63 and 1.66**
L_{sweep} (m)	Dependent on A_{blade} and A_{fish}*	Dependent on A_{blade} and A_{fish}	Dependent on A_{blade} and A_{fish}	Dependent on A_{blade} and A_{fish}	Dependent on A_{blade} and A_{fish}
T_{sweep} (s)	Dependent on L_{sweep} and u	Dependent on L_{sweep}	Dependent on L_{sweep}	Dependent on L_{sweep}	Dependent on L_{sweep}

* A_{blade} and A_{fish} were randomised based on a uniform distribution during all simulations, apart from the Empirical Validation BSM where positions were specified for each iteration of the model.

** For trout and eel, respectively.

Highlighted cells represent observed L_{fish} and observed V_{fish} values.

Table 2

Size range (cm)	Number	Mean (SD) total length (cm)
4.0 - 9.0	92	8.2 (0.5)
9.1 - 11.0	57	9.7 (0.5)
11.1 - 15.0	84	12.5 (0.7)
22.0 - 31.0	23	27.0 (2.2)
22.0 - 31.0 (euthanized fish)	12	27.5 (2.5)

Table 3

Passage outcome	Frequency of outcome	Frequency damaged
No contact	51	0
Slap	5	0
Strike	18	2
Grinding	26	26

Table 4

Species	Positive		Negative		Perpendicular	
	Day	Night	Day	Night	Day	Night
Trout	88	100	12	0	0	0
Eel	7	26	78	56	15	18