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UNIVERSITY OF SOUTHAMPTON

FACULTY OF ENGINEERING AND THE ENVIRONMENT

Civil, Maritime and Environmental Engineering and Science Academic Unit

**Experimental quantification of the response of fish to conditions
associated with low-head hydropower and fish passage facilities**

By

Andrew Stuart Vowles

Thesis for the degree of Doctor of Philosophy

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ABSTRACT

FACULTY OF ENGINEERING AND THE ENVIRONMENT
CIVIL, MARITIME AND ENVIRONMENTAL ENGINEERING AND SCIENCE ACADEMIC UNIT

Doctor of Philosophy

EXPERIMENTAL QUANTIFICATION OF THE RESPONSE OF FISH TO CONDITIONS
ASSOCIATED WITH LOW-HEAD HYDROPOWER AND FISH PASSAGE FACILITIES

by Andrew Stuart Vowles

This thesis assessed the impact of a novel low-head hydropower device, the Hydrostatic Pressure Converter (HPC), on downstream moving fish, and investigated factors that may limit both up- and down-stream fish pass efficiency. This was achieved through the use of a blade strike model (BSM) and experimental studies conducted in large open channel flumes.

A BSM predicted a lower probability of strike with a HPC blade for small fish that travelled downstream faster, and when blades rotated slowly. A major pinch-point between the blade tips and the base of the flume caused severe damage to euthanized brown trout (*Salmo trutta*) as they passively drifted through a prototype HPC. Damage ranged from abrasive scale loss to skeletal deformation and breakage. Rainbow trout (*Oncorhynchus mykiss*) and European eel (*Anguilla anguilla*) did not exhibit avoidance behaviours when approaching the intake to a HPC located within a flume. When behavioural data (speed of downstream movement and orientation) were incorporated into BSM simulations, probability of strike increased and decreased for trout and eel, respectively, compared with an assumption of passive drift with bulk flow. Species specific behaviours influenced probability and severity of strike with a HPC blade. Management recommendations are made to ensure HPC developments meet the required environmental standards.

Ensuring efficient fish passage around low-head hydropower developments presents a major ecological challenge. Behavioural data on individual fish encountering conditions ubiquitous to fish pass structures was used to investigate and identify factors that may limit passage efficiencies. Although upstream migrant adult river lamprey (*Lampetra fluviatilis*), a species of conservation concern in Europe, were predicted to avoid areas of elevated turbulence, little evidence in support of this was found. Instead lamprey appeared to alter their migration strategy based primarily on water velocity. Behaviours were indicative of a time conservation strategy, i.e. altering behaviour to expedite passage through energetically expensive environments. For downstream moving fish, delay due to avoidance of conditions created at bypass entrances (e.g. abrupt accelerations of velocity) can negatively impact fitness. Velocity gradients created by a constricted flume section had a clear influence over downstream moving brown trout. Avoidance behaviours occurred at a similar threshold spatial velocity gradient when dark (*ca.* $0.4 \text{ cm s}^{-1} \text{ cm}^{-1}$), and the addition of a light stimulus served to reduce this threshold by approximately 50%. Elevated avoidance to velocity gradients was also evident when downstream migrant juvenile salmon (*Oncorhynchus tshawytscha*) were able to navigate using mechanosensory and visual senses. Avoidance behaviour significantly impacted subsequent rate of passage.

Information provided in this thesis significantly enhances our understanding of how fish respond to environmental stimuli, has direct application to fish passage, and the potential to improve fish survival at low-head hydropower developments.

KEY WORDS: habitat fragmentation, blade strike model, migration, behaviour, hydrodynamics, multimodal stimuli

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Declaration of authorship

I, Andrew Stuart Vowles, declare that this thesis and the work presented in it are my own, and have been generated by me as the result of my own original research.

Title: Understanding fish behaviour: Application to low-head hydropower and fish passage development

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Parts of this work have been published as:

Vowles, A.S. & Kemp, P.S. (2012). Effects of light on the behaviour of brown trout (*Salmo trutta*) encountering accelerating flow: Application to downstream fish passage. *Ecological Engineering* **47**: 247-253.

Vowles, A.S., Eakins, L. R., Piper, A.T., Kerr, J.R. & Kemp, P.S. (In Press). Developing realistic fish passage criteria – An ecohydraulics approach. In Maddock, I., Harby, A., Kemp, P., Wood, P. (eds.). *Ecohydraulics: An integrated approach*. Wiley, Chichester, West Sussex, England.

Signed:

Date:

Glossary

A. Fish Families

COMMON NAME	LATIN NAME
Carp	Cyprinidae
Characins	Characidae
Eel	Anguillidae
Galaxiids	Galaxiidae
Herring	Clupeidae
Lamprey	Petromyzontidae
Paddlefish	Polyodontidae
Perch	Percidae
Salmon	Salmonidae
Sculpin	Cottidae
Smelt	Osmeridae
Sturgeon	Acipenseridae
Sunfish	Centrarchidae
Suckers	Catostomidae
Temperate basses	Moronidae
Temperate perches	Percichthyidae

B. Fish Species

COMMON NAME	LATIN NAME
Alewife	<i>Alosa pseudoharengus</i>

American eel	<i>Anguilla rostrata</i>
American shad	<i>Alosa sapidissima</i>
Atlantic salmon	<i>Salmo salar</i>
Barbel	<i>Barbus barbus</i>
Brook trout	<i>Salvelinus fontinalis</i>
Brown trout	<i>Salmo trutta</i>
Creek chub	<i>Semotilus atromaculatus</i>
Chinook salmon	<i>Oncorhynchus tshawytscha</i>
European eel	<i>Anguilla anguilla</i>
European perch	<i>Perca fluviatilis</i>
Gizzard shad	<i>Dorosoma cepedianum</i>
Iberian barbel	<i>Luciobarbus bocagei</i>
Japanese eel	<i>Anguilla japonica</i>
Pacific lamprey	<i>Lampetra tridentata</i>
Pink salmon	<i>Oncorhynchus gorbuscha</i>
Rainbow trout	<i>Oncorhynchus mykiss</i>
River lamprey	<i>Lampetra fluviatilis</i>
Sea bream	<i>Sparus auratus</i>
Sea lamprey	<i>Petromyzon marinus</i>
Smallmouth bass	<i>Micropterus dolomieu</i>
Smelt	<i>Osmerus mordax</i>
Sockeye salmon	<i>Oncorhynchus nerka</i>
White sturgeon	<i>Acipenser transmontanus</i>

C. General Terms

Abiotic: Non-living aspects of the environment, used in reference to physical or chemical features of the environment.

Accelerating velocity: The rate of change of velocity (with particular reference to water throughout this thesis), with time.

Acclimation: The physiological adjustment of an organism to environmental conditions under laboratory settings.

Anadromous: Diadromous fishes in which most feeding and growth take place at sea prior to the migration of adults into freshwater to reproduce.

Anthropogenic: Relates to an effect or object resulting from or induced by human activity.

Behavioural barrier / screen: A system used to deter fish from certain locations (such as hydropower intakes) by using a stimulus that fish can detect or sense and respond to with either a repulsion or attraction behaviour.

Benthic: Bottom dwelling; living on or positioned near to the substrate of rivers.

Biotic: Living or biological aspects of the environment, such as the influence of other individuals or organisms.

Bypass: An alternative route for downstream moving fish, allowing them to bypass anthropogenic river barriers. Designed to be a safer or more benign route than that of the bulk flow of the river (e.g. where the majority of water may be passing through a hydropower turbine).

Catadromous: Diadromous fishes in which most feeding and growth take place within freshwater prior to migration of adults to the sea to reproduce.

Conservation: The principles and practice of the science of preventing species extinctions.

Diadromous: Fish migrations that occur between fresh and marine environments.

Discharge: The rate at which a volume of water is flowing per unit time, typically measured in $\text{m}^3 \text{s}^{-1}$ or L s^{-1} .

Dispersal: The spreading of individuals away from each other or to different habitats, e.g. from regions of high to low density.

Energy Conversion Efficiency: typically a value between 0 – 1 (or 0 – 100%) describing the useful output of an energy conversion device in relation to the input, in energy terms (e.g. electrical output for hydropower).

Fecundity: Number of eggs, or offspring, produced by an individual. An individual's reproductive potential.

Fish pass: A structure (such as a series of stepped pools), that water flows down, located on or around anthropogenic barriers and designed to allow fish to pass upstream of the barrier (e.g. dam or weir). Fish pass is synonymous with 'fishway', which is the more commonly used term in North America.

Fishway: See Fish pass

Fitness: The contribution an individual makes to the gene pool of the next generation, relative to the contribution made by others in its present population.

Habitat: An area that provides the resources (e.g. food, space) necessary for the existence of an organism or particular life-stage.

Habitat connectivity: The size and distribution of suitable habitat patches and the ease with which a species can move through the landscape between patches.

Habitat fragmentation: The subdivision of a specific habitat into smaller and more isolated fragments or patches, through both natural and anthropogenic activities (although typically in reference to anthropogenic activities in this thesis), resulting in changes to the landscape composition, structure and function.

Habitat patch: Areas distinguished from their surroundings by environmental discontinuities, which are often of biological relevance to a particular species or life-stage.

Habituation: A reduction in the magnitude of a response to a stimulus after repeat encounter or exposure to it.

Hydraulics: The study of the conveyance and behaviour of liquids through pipes or channels

Hydrodynamics: The study of liquids in motion, used synonymously with hydraulics.

Hydrostatic Pressure: The pressure exerted by a fluid due to gravitational forces.

Inter-specific: In reference to between different species.

Intra-specific: In reference to within the same species.

Kelt: A spent or post-spawned salmonid, until it re-enters saltwater environments.

Lotic: Meaning or in reference to flowing water environments.

Migrant: The life-stage of a fish (including resident species) which moves from one location, habitat or system (e.g. river or ocean) to another.

Migrating: Moving from one area of residence to another.

Migration: The seasonal movement of an animal from one area to another.

Mitigation: An action intended to reduce the adverse impact of a specific project, development, or activity.

Parr: Resident juvenile life-stage that actively feeds in freshwater before transformation into the downstream migrant smolt life-stage in anadromous salmonids.

Physical screen: A device used to excluded, deflect or guide fish from hazardous locations, such as water abstraction points or hydropower intakes, and towards more benign routes / locations (such as bypasses). A large number of alternative designs (e.g. Passive mesh screens, rotary disc screens) exist; see Turnpenny and O’Keeffe (2005) for more information.

Physoclist: Fish that lack a duct between the swim bladder and the alimentary canal (gut). Air within the swim bladder is adjusted through a gaseous exchange procedure.

Physostome: Fish that have a pneumatic duct connecting the swim bladder to the alimentary canal. Air within the swim bladder can be adjusted by gulping in or out air.

Potamodromous: Fish migrations that occur entirely within freshwater.

Precautionary Approach / Principal: “Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-

effective measures to prevent environmental degradation” European Commission (2000). In essence, the formalisation of the phrase, better safe than sorry.

Rheotaxis: The behavioural orientation of fish to water currents.

Smolt: The life-stage of anadromous salmonids between parr and adult, when they undergo downstream migration and are adapted to saline environments. The fish are characteristically silver in colouration.

Spline interpolation: A common interpolation method in which values are estimated using mathematical functions creating a smooth surface contour plot that passes through measured input values.

Sub-yearling: Fish less than one year old.

Tailrace: The section of a river immediately downstream of a hydropower facility.

Trash rack: A physical structure, typically metal and supported by masonry, which prevents the ingress of debris (e.g. logs, branches, aquatic weed) into water abstraction or hydropower turbine intakes.

Velocity gradient: The change in velocity over a given distance.

Water velocity: The speed with which water is flowing, typically measure in cm s^{-1} or m s^{-1} .

Structure of the thesis

This research project was undertaken to assess the impact of a novel low-head hydropower technology on downstream fish behaviour and survival, and to investigate factors that may limit both up- and down-stream passage efficiency (e.g. at low-head hydropower schemes and associated weirs and fish passes). Research focused on the importance of fish behaviour in addressing these issues.

The individual chapters of this thesis are intrinsically linked. Chapter 1 provides a broad overview of the challenges in developing Europe's remaining hydropower potential while concurrently protecting or improving the ecological status of the aquatic environment. The value of inland fisheries and key impacts of hydropower on fish are identified. Chapter 2 provides detailed background literature, summarising and discussing research trends, biases and gaps in knowledge, and critically reviews literature relevant to fish passage at hydropower facilities. Information from the first two chapters guided the development of comprehensive research aims and objectives (Chapter 3). In Chapter 4, the methodological techniques, equipment and fish species utilised during this research project are outlined.

Chapters 5-8 present the results, the first of which incorporates blade strike modelling, empirical validation tests, and fish behavioural observations (under experimental flume conditions), to identify the impact of a new technology, the Hydrostatic Pressure Converter, on fish behaviour and survival. In Chapter 6, exploration of the behaviour of upstream migrant adult river lamprey, a species of conservation concern within Europe, was quantified in response to water velocity and turbulence to aid to the development of more realistic multi-species fish pass facilities. Despite decades of research, efficient downstream bypasses are still generally lacking. The final two results chapters (7 and 8) advanced our understanding of how downstream moving salmonids respond to conditions associated with bypass facilities and quantify the impacts of variation in behaviour on subsequent passage success. Chapter 9 provides an overall discussion and conclusions from the research contained within this thesis, in addition to recommendations for management and future research. The final chapter provides some overall closing remarks on the future of low-head hydropower.

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To members of our research group, affectionately (or so I’m lead to believe) known as ‘Team Fish’ (in order of start date, rather than helpfulness): Tom, Iain, Laura, Adam, Simon, Gill, Lyn and Jim, and my under-grad students: Sam, Jason and James, thanks for all the input and support over the years and well done for spending so many long hours in a cold and darkened flume, typically in the middle of the night, in the middle of winter! In addition to providing essential support in a work capacity, many of you have also become great friends, proving to be most useful drinking partners (you know who you are). And Tom, if we had lost Paul’s high speed camera for good that fateful night, I would have held you solely responsible!!

A big thank you also goes to all non ‘Team Fish’ friends, those both in Southampton and elsewhere. To those of you in Cornwall, there is nothing better than getting home and forgetting PhD life for a few days with those that have no real idea what I do (despite me explaining on many an occasion). Particular thanks to Chloë for her unwavering support

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Chapter 1

Research background

1.1. Renewable energy and the potential for hydropower in Europe

The challenges facing Europe's future energy supply stem from an over dependence on imported supplies of finite fossil fuels from geopolitically sensitive regions, unpredictable fuel prices, and the harmful environmental and economic consequences of climate change (Stern, 2006; European Renewable Energy Council, 2010). These challenges have resulted in a drive to increase the amount of energy produced from low-carbon sources (e.g. nuclear power or renewable energies) or to decrease greenhouse gas levels through more efficient or mitigative practices (e.g. carbon sequestration) (Department of Trade and Industry, 2007; European Commission, 2007; the Renewables Directive, 2009/28/EC). For renewables, the specific target is for a 20% share of Europe's gross final energy consumption to come from renewable sources, and considers three sectors; consumption of electricity, energy for heating and cooling, and energy consumption in transport (the Renewables Directive, 2009/28/EC). In 2008 the contribution of renewable energy to Europe's final energy consumption was 10.3%, while 16.6% of electricity consumption was derived from renewable sources (Eurostat, 2010a; 2010b). However, the contribution from individual Member States varies considerably (Eurostat, 2010b). For example only 5.5% of UK electricity production came from renewable sources in 2009; targets for 2050 will be for a 80% contribution (relative to 1990 levels, Department of Trade and Industry, 2007). Meeting future renewable energy targets will be challenging (European Commission, 2007) and will require considerable investment in the development of renewable technologies to reach policy goals (Department of Trade and Industry, 2007).

Currently, the UK generates approximately 3 GW of wind energy, enough to supply 1.5 million households with electricity (Department of Energy and Climate Change, 2009). With future consented wind farms powering 5 million additional households wind energy is considered to play a prominent role in future energy supply. However, no one renewable sector alone will meet renewable energy requirements. The development of renewable energy schemes up to a capacity of 5 MW, a sector historically deemed largely economically unviable, have recently been incentivised within the EU by the introduction

of Feed-In Tariffs (FITs), a scheme that provides financial support per GW of energy produced to the energy supplier. Such government subsidies are enabling this sector to undergo development and aid to renewable energy generation. A mix of both mature and innovative technologies from a range of sectors will be required to satiate energy demands and achieve renewable targets.

Hydropower represents one of the most reliable and established renewable technologies and within Europe the exploitation of most large-scale hydropower opportunities has caused the focus to shift towards developing more small-scale (≤ 10 MW power output) installations (Paish, 2002). In 2006 the small-scale hydropower sector had a generating capacity of 13 GW, contributing 1.2% to Europe's total electricity production (European Small Hydropower Association, 2008). Within England and Wales it has been estimated that the total potential capacity for hydropower developments based on developing all existing infrastructure (an unlikely scenario) would contribute approximately 1% to the UK's projected 2020 electricity demand (Environment Agency, 2010a). However, nearly half (46%) of impoundments required to generate this hydroelectric power were classified as having high environmental sensitivity, largely due to the presence of migratory fish species (Environment Agency, 2010a). Whilst there is opportunity to mitigate for negative impacts (i.e. through the provision of up- and down-stream fish passage facilities and protective screening) or improve river habitat connectivity by developing an existing barrier that already restricts fish movements (referred to as a win:win development), such schemes may come at considerable additional financial cost (Environment Agency, 2010a). Within the small-scale hydropower sector, very low-head hydropower schemes (schemes with a hydraulic head difference of less than 2.5 m) are an underutilized source of low-carbon energy (600-1000 MW in England for example, Müller & Kauppert, 2002). However, the exploitation of low-head hydropower remains problematic as traditional turbines (e.g. Kaplan turbines) require large flow volumes, large diameters and extensive civil engineering works at low-head differences (Müller & Kauppert, 2002). This, in addition to an accurately manufactured and constructed turbine to achieve high efficiencies and the need for a trash rack, makes such facilities economically unfeasible (Müller and Kauppert, 2002). Low-head hydropower therefore requires technological developments that enable the efficient utilisation of this under-exploited energy source.

1.2. Technological developments in low-head hydropower

The Archimedean Screw, historically used for pumping water from low to high elevations, has recently been operated in a reverse role and employed as an efficient low-head energy converter. Although estimates vary, the Archimedean Screw Turbine could be effective at head differences between 1 – 8 m (Späh, 2001), with a 2.2 m diameter screw operating at 4.5 m head capable of achieving a maximum electrical output of 65 KW (Bard, 2007). Consisting of a hollow shaft and helical vanes (Figure 1.1.a), their simplistic design ensures less civil engineering works than modern turbines, whilst the ability to pass small debris can reduce the need for trash screens and racks (Müller and Kauppert, 2002), although fish screening may still be required.

The Very Low Head Turbine (VLH Turbine), a novel version of a Kaplan, is an innovative concept designed specifically to offer a high degree of reliability and value per KW produced from low-head sites. This is achieved largely through a design concept requiring very little civil engineering works (Leclerc, 2007). The VLH Turbine has a large diameter runner (turbine blades and hub) which is mounted within a single block (Figure 1.1.b). One of five standard designs (with runners ranging from 3.55 - 5.6 m diameter) slot into existing infrastructure (e.g. sluice gates) at 45° to the vertical plane and operate at head differences between 1.4 – 3 m, generating between 100 – 500 KW of electricity (Leclerc, 2007).

The waterwheel is a traditional technology currently experiencing resurgence due to its hydroelectric potential. The first of two common designs is the overshot wheel, which depends on water flowing into cells at the top, and to maximize efficiency, releasing water at the lowest elevation possible (Müller and Kauppert, 2002). Through the use of modern materials (e.g. steel) the geometry of the cells has been refined to allow energy conversion efficiencies of up to 80% (Müller and Kauppert, 2002). Although overshot waterwheels can efficiently exploit power at head differences between 2 - 7.5 m, at higher head sites larger wheels are required (Müller and Kauppert, 2002), which can be more costly to manufacture, impractical to install and visually intrusive. The second traditional design is the undershot waterwheel (Figure 1.1.c), deployed at very low-head sites (0.5 - 2.5 m). The inflowing water contacts the blades below the height of the axle, with head being gradually reduced as water flows through the wheel (Müller and Kauppert, 2002). Through the

incorporation of hydraulic principles the development of more efficient undershot waterwheels was achieved; with a slight curvature of the blades the Zuppinger wheel enabled the conversion of some of the potential water energy into kinetic energy, resulting in less turbulence and improved efficiencies.

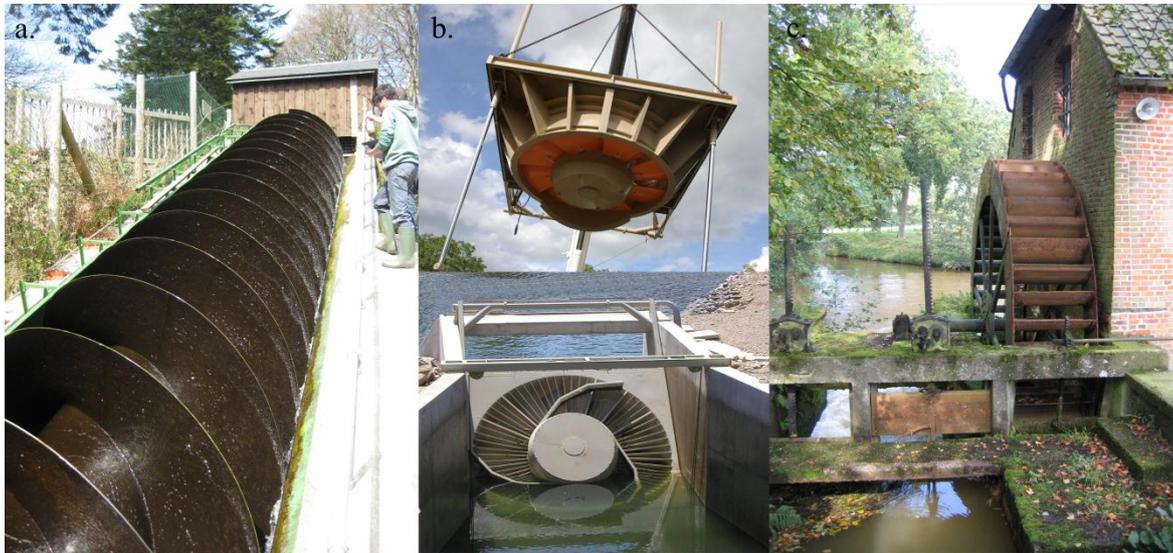


Figure 1.1.a. An operating Archimedean Screw Turbine (photograph: Paul Kemp), **b.** the VLH Turbine (photographs: Marc Leclerc) and, **c.** undershot waterwheel (photograph: Paul Kemp).

The traditional undershot waterwheel design is currently undergoing adaptation to create a novel technology, the Hydrostatic Pressure Converter (HPC). HPCs appear similar in design to undershot waterwheels, and comprises of three design variations (Figure 1.2). In contrast to the impulse or potential forces employed by traditional designs, HPCs utilize the hydraulic head difference between up- and down-stream, and operate using the hydrostatic pressure exerted on the blades (Senior *et al.*, 2010). Initial testing suggests that this operating principle allows high efficiencies at head differences less than 2.5 m, and can produce approximately 60 KW per meter wheel width (Senior, 2009; Senior *et al.*, 2010). Although traditional waterwheels are considered to have a low impact on fish, thus typically only require a trash screen (Environment Agency, 2009), this is not assumed to be true for modern adaptations to waterwheels (Environment Agency, 2009). This precautionary approach ensures that technological developments to waterwheels undergo ecological assessment to identify environmental acceptability. The development of HPCs has received funding from the European Community's Seventh Framework Programme,

the specific work package designed to assess impacts to fish behaviour, movements and survival funded the research contained within this thesis.

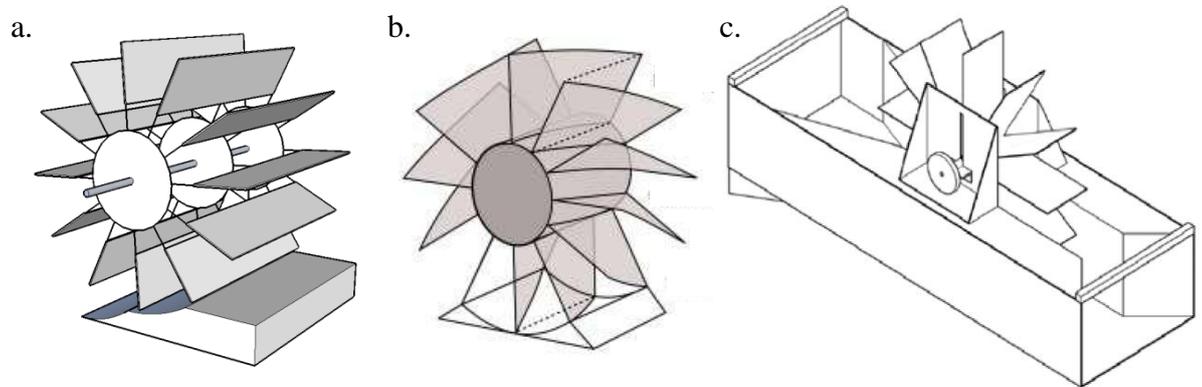


Figure 1.2. There are three HPC designs; **a.** Hydrostatic Pressure Wheels (HPW) consist of large diameter wheels with the blade maintaining the head difference, **b.** Hydrostatic Pressure Machines employ a central hub to help create and maintain the head difference, therefore reducing the diameter of the installation, **c.** Free Stream Energy Converters comprise of a HPW located within a floating pontoon to exploit the energy in surface flows, no in-river barrier (e.g. weir) is required and under tidal situations has the potential to be bi-directional.

1.3. Environmental legislation and hydropower

Technological innovations are providing solutions to the economic exploitation of low-head hydroelectric power, a positive step towards enabling this sector to contribute to renewable electricity generation. However, environmental impacts can remain evident, even at low-head sites. The Archimedean Screw Turbine, VLH Turbine, traditional waterwheels and HPCs have potential ecological benefits over other hydropower turbines (e.g. Kaplan, Francis and Pelton turbines), particularly for downstream moving fish, as they have slow rotational speeds and water is maintained at near atmospheric pressures during operation. Nevertheless, all developments in low-head hydropower require high environmental standards as outlined by European commitments to preserve biodiversity (e.g. by adopting a strategy to halt the loss of biodiversity and ecosystem services in line with the Convention on Biological Diversity) and legislation such as the Habitats Directive (92/43/EEC), and in particular, the Water Framework Directive (WFD) (2000/60/EC), which is often seen as a barrier to hydropower development.

The WFD requires that water courses and water bodies in all EU member states meet definitions of either “good ecological status” or, where heavily modified (by human activity that alters hydrogeomorphological character, e.g. a dam or weir), “good ecological potential”. To reach these targets there are two general obligations; first, that any deterioration in ecological quality is prohibited, and second, that any alterations should lead to the protection, enhancement or restoration of the water body (Water Framework Directive 2000/60/EC). Unfortunately, it is often difficult for hydropower to meet these obligations as negative impacts on the aquatic environment can result due to the effects of impoundments on fluvial processes and movements of biota (Ward and Stanford, 1983), as well as damage and mortality caused by passage of organisms through turbines (Čada, 2001). In the case of hydropower development and operation, EU directives create a contradictory pressure which must be translated into national law. To achieve renewable energy targets by environmentally sensitive means remains a significant challenge, resulting in the necessity for future hydropower development to occur in parallel with robust and effective measures that mitigate environmental impacts.

Maintaining longitudinal river connectivity for fishes is a major ecological challenge for hydropower (Calles & Greenberg, 2005; Santos *et al.*, 2006). Although low-head structures tend to cause less dramatic local effects to the river environment and neighbouring habitat than larger dams (Lucas *et al.*, 2009) they still constitute a major barrier to the longitudinal movements of both migratory and resident fish species (Lucas & Frear, 1997; Ovidio and Philippart, 2002; Lucas *et al.*, 2009). In-river barriers associated with hydropower facilities (such as dams and weirs) can prevent, limit or delay fish from moving between essential refuge, feeding or reproductive habitats by fragmenting previously continuous aquatic systems (Kubečka *et al.*, 1997; Moss, 1998; Katano *et al.*, 2006; Arnekleiv & Rønning, 2004). In recognition of this, anadromous salmonid species have historically been afforded the most comprehensive legislative protection (e.g. in the UK through the Salmon and Freshwater Fisheries Act (England and Wales) 1975; the Salmon (Fish Passes and Screens) (Scotland) Regulations 1994; and The Fisheries Act (Northern Ireland) 1966), largely due to their historic commercial importance. However, with imminent requirements to meet obligations imposed by the EU (i.e. no deterioration in the ecological status of rivers, through the WFD), there is a need to ensure free passage for potentially any fish species past hydropower facilities. As an example, the Salmon and Freshwater Fisheries Act (1975) only applies fish passage and screening regulations to waters in which Atlantic

salmon (*Salmo salar*) and anadromous brown trout (*Salmo trutta*), commonly referred to as sea trout, occur. To comply with the WFD, the Department for Environment Food and Rural Affairs (DEFRA) has proposed modernisation of this legislation (currently under consultation), which could require protection for all fish species, including non-salmonid and non-migratory fish and areas where no salmon or sea trout reside. Any new hydropower scheme may therefore be required to incorporate appropriate fish passage and screening provisions, at additional cost, to meet these more stringent requirements.

The provision of rigorous environmental legislation is vital in the drive to preserve biodiversity and maintain the ecological status of inland fisheries, which additionally are of significant economic and social importance (Peirson *et al.*, 2001). The Atlantic salmon and sea trout fishery was estimated at £3 million in England and Wales in 2001 (Environment Agency, 2008), and the total value of the commercial European eel (*Anguilla anguilla*) fishery (including glass, yellow and silver eels) in Britain, although variable, has been estimated at £1.6 million per annum (DEFRA, 2009). Despite this commercial utilization, across Europe inland fisheries resources are generally exploited more for recreational than consumptive purposes (Welcomme *et al.*, 2010). For example, in England and Wales freshwater angling expenditure was estimated at £1.18 billion per annum and directly employed over 35,000 people (Radford *et al.*, 2007). In Scotland, Atlantic salmon and sea trout angler expenditure was estimated at £10.8 million per annum (Butler *et al.*, 2009). Therefore, the socio-economic value of inland fisheries is considerable, and necessitates protection from the growing interest in low-head hydropower development.

For future low-head hydropower technologies, it appears that two clear areas will determine environmental viability. First is the impact these devices have on fish survival should they pass downstream through a turbine / energy converter. If a scheme cannot be shown to pass fish without significant risk then downstream bypass and screening provisions are required at additional cost. At such low-head low-output installations, this additional cost often makes such schemes economically unviable. Second is the requirement for free passage for all fish species past the associated impoundment. With low-head structures being identified as a major barrier to fish movements (Larinier, 2000; Ovidio and Philippart, 2002) ensuring effective multi-species fish passage around new low-head hydropower facilities will be important for proposed hydropower schemes to be granted installation consent.

1.4. Initial research Aims & Objectives

Injury / mortality sustained to fish passing through turbines and fragmentation of river habitats are significant environmental impacts of low-head hydropower. Based on background information obtained, two key research aims are identified:

1. Assess the impact of a novel low-head hydropower technology, the Hydrostatic Pressure Converter (HPC), on fish behaviour and survival.
2. Investigate and identify factors that may limit up- and down-stream fish pass efficiency.

To effectively meet these aims, an initial objective has been recognised:

1. Identify methodological techniques and highlight research trends, biases and gaps in knowledge on the ability of fish to move through hydropower installations and around associated impoundments (in both up- and down-stream directions), through use of quantitative and narrative literature reviews.

The information obtained through completion of objective 1 will guide the development of additional research objectives, allowing the research aims to be comprehensively addressed.

Chapter 2

The current state of fish passage at hydropower facilities

2.1. Summary

To fulfil objective 1, quantitative and narrative literature reviews, highlighting trends within current literature pertaining to the impact of hydropower and anthropogenic barriers on fish movements, and behavioural responses to features associated with fish pass systems was conducted. Results indicate this to be a growing area of research regionally biased towards North America (particularly the USA). Taxonomically, the literature was biased towards the family Salmonidae and upstream moving, adult life stages. Although telemetry / tagging studies comprised the largest methodological group, experimental based research has increased. The literature review suggests that fish passes are considered well developed for upstream migrant, adult salmonids. For species of less commercial or legislative importance and downstream migrant life-stages, fish passage historically received less attention and efficient passage facilities are generally lacking. Considering current legislation, fish passage must consider a wide range of species, with more research on upstream moving non-salmonids needed. For downstream moving fish, behaviour in response to environmental stimuli appears to largely determine bypass efficiency. How fish react to hydraulic and other environmental stimuli associated with bypasses and hydropower systems, in addition to understanding the behavioural mechanisms underpinning these reactions is required. This information will aid efforts to manipulate environmental stimuli within river systems to improve safe, efficient passage at hydropower and fish pass facilities.

2.2. Introduction

The continual development of rivers for hydroelectric power will help meet commitments to combat the threat of climate change and governments to realise renewable energy targets. However, river impoundments, generally required during hydroelectric generation, have significantly reduced habitat connectivity for fish (Clay, 1995; Odeh, 1999), while

fish that pass through turbines risk physical injury and mortality (Čada, 1990). For both migratory (diadromous) and resident (potamodromous) fish species, anthropogenic development has compromised the cost benefit ratio of longitudinal movements, often resulting in population declines, as seen in e.g., salmon (Salmonidae) (Williams, 2008), eel (Anguillidae) (Starkie, 2003), sturgeon (Acipenseridae) (Lenhardt *et al.*, 2006) and lampreys (Petromyzontidae) (Kelly and King, 2001). For over 50 years it has been recognized that to overcome these problems, two important solutions need consideration. One, a modification of current and change in the design of future hydropower facilities to make them safer for downstream moving fish; and two, the discovery and development of effective methods of passing or guiding fish around hydropower facilities and associated structures is needed (Fields, 1957).

The remainder of this chapter is divided into two main parts:

- First, a quantitative literature review (Section 2.3) identifies methodological techniques and highlights research trends and biases in literature on the ability of fish to move through hydropower installations (e.g. turbines) and around associated structures such as dams or weirs (e.g. via upstream or downstream fish passage provisions).
- Second, a narrative literature review (Section 2.4) determines the current state of fish passage knowledge at hydropower and fish pass facilities.

2.3. Trends in fish passage research – A quantitative review

A quantitative review provides a systematic method of conducting a synthesis of the published literature (Gurevitch and Hedges, 1999). This technique effectively summarises large amounts of information on a given topic to determine research trends (Haxton and Findlay, 2008). Furthermore, by highlighting trends and gaps in knowledge, it better allows the development of original future research, whilst the systematic search method helps limit bias and aids to the reliability of any conclusions drawn (Mulrow, 1994).

2.3.1. Literature search method

Peer reviewed literature pertaining to the impact of hydropower and anthropogenic impoundments on fish movements, and behavioural responses to features associated with

fish pass systems was collected. Although relevant “gray” literature (i.e. Government or Technical Reports) has been produced on this topic, these were not included as they may not be accessible to the public, therefore only peer reviewed publications represent the current state of knowledge that is widely available (Roscoe and Hinch, 2010). A literature search was conducted using two bibliographic search engines, ISI Web of Knowledge and Google Scholar. Key words were developed into eight search strings, which were then used to locate the literature:

- (1) hydropower + fish + movements
- (2) hydropower + fish + behaviour
- (3) hydropower + fragmentation + fish
- (4) hydro + low-head + fish
- (5) fish + behaviour + hydraulics
- (6) fish + passage + behaviour
- (7) fish + movements + behaviour
- (8) fish + response + hydraulics

Literature searches were conducted between 20 August and 16 September 2009. All titles were screened and applicable articles sourced. Next, the abstracts of all bibliographic articles were evaluated and relevant literature was added to a database. During March 2010 further relevant literature was added to the database. To avoid compromising the integrity of the systematic search method, additional relevant literature published after March 2010 was not included in the quantitative review.

Articles were categorised in terms of year of publication, geographical location, fish family, life-stage, direction of longitudinal movement, research methodology, and focus of the study. Up to two fish families were reported per article, if fish from more than two families were cited in an article they were categorised as “mixed”. Articles that were not applicable to a particular category were excluded from the percentage calculations for that category.

Research methodology was divided into the following categories:

- (1) Experimental (and included swim chamber and open channel flume apparatus)

- (2) Literature Review / Meta-analysis / Subject Overview
- (3) Modelling (computational / numerical)
- (4) Telemetry / tagging
- (5) Hydroacoustics (e.g. split beam hydroacoustic techniques)
- (6) Other field based (e.g. Electrofishing surveys / visual counts)
- (7) Combination of two or more from above

Similarly, focus of the study was categorised as:

- (1) Effects of hydropower or anthropogenic barriers (excluding culverts) on fish movements and / or behaviour
- (2) Efficiencies / effectiveness of fish passage facilities
- (3) Fish behavioural responses and / or swimming abilities in relation to hydraulic factors
- (4) Fish behavioural responses to other environmental stimuli / deterrents
- (5) Effects of specific conditions associated with turbine passage (e.g. shearing forces)
- (6) Test the effectiveness of technological / methodological advancements or techniques
- (7) Estimating injury / mortality associated with hydropower and / or dam passage
- (8) Other
- (9) Combination of 2 or more from above

2.3.2. Results

The initial literature search produced a total of 199 relevant peer reviewed publications, and an additional 17 papers that were added to the bibliography in March 2010. The earliest study entered into the database was 1963, where the influence of water velocity on the swimming performance of migrant adult salmonids was investigated in a large experimental channel (Weaver, 1963). Since that time the number of publications moderately increased until 1989. From 1990 to 1999 the number of studies increased more than threefold, and 2000 to Present (2010 at time of writing) saw a fivefold increase in publications (Figure 2.1).

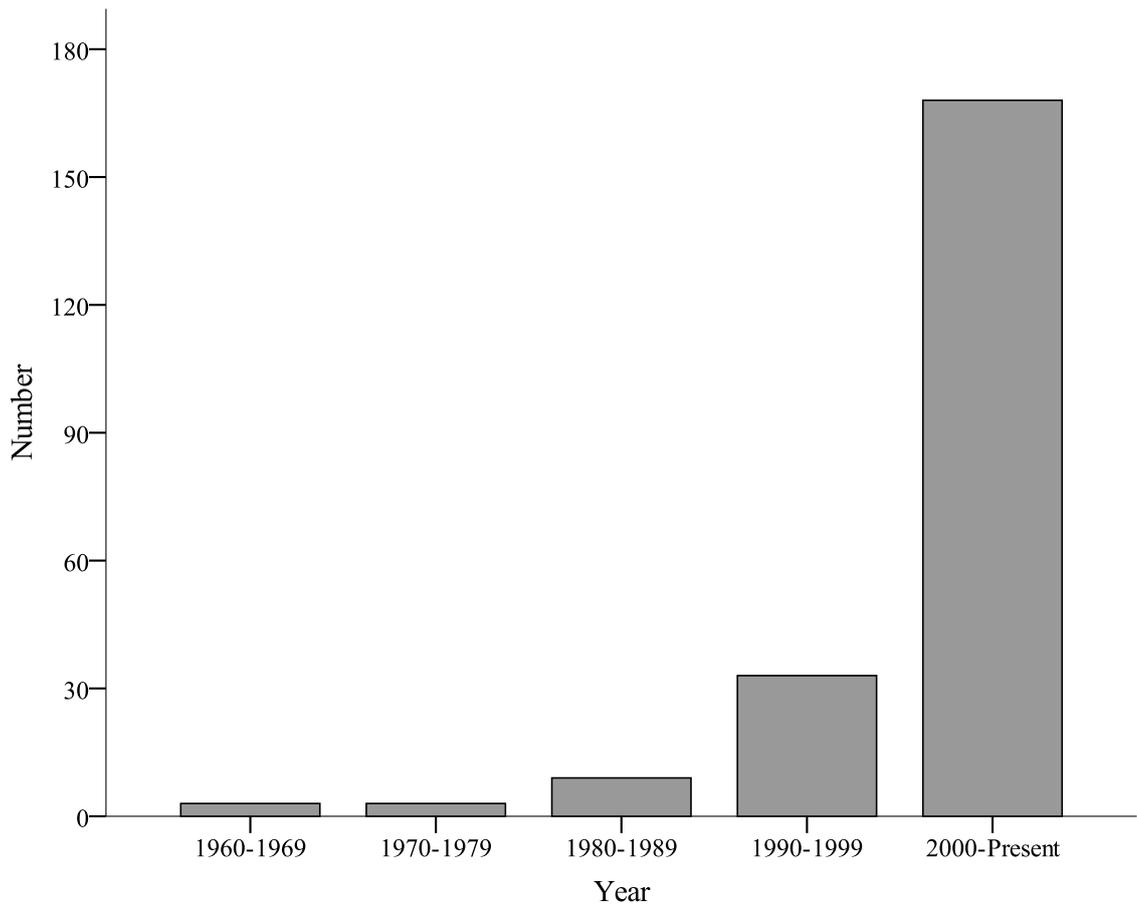


Figure 2.1. Number of citations relating to the impacts of hydropower and in-river barriers on fish movements and behaviour, and fish response to hydraulic features associated with fish passage systems, since 1960.

Publications were regionally biased. Despite studies being carried out in 25 countries, grouping the literature into larger geographical regions allowed this bias to be better identified. One hundred and thirty one (61%) were based in North America, the majority of which (79%) were from the United States. The bulk of the remaining literature was European based (28%). Asia, Australia / New Zealand, Russia and South America accounted for the remaining 11% (Table 2.1). Australia / New Zealand and South America account for 59% of these remaining articles.

Table 2.1. Geographical locations from which the published literature included in the quantitative review was based.

Geographical Location	Number	% of Evaluated Publications
North America	131	60.6
Europe	61	28.2
South America	10	4.6
Australia / New Zealand	9	4.2
Russia	3	1.4
Asia	2	0.9
Total	216	100

The majority of research studied a single fish family (75%), 7% studied two fish families and 18% of publications focused on more than two families. Five articles were not applicable to this category and were often literature reviews / meta-analyses discussing general topics (e.g. Murchie *et al.*, 2008; Roscoe and Hinch, 2010) or numerical / computational models of e.g. virtual fish movements around hydropower facilities (e.g. Baigún *et al.*, 2007). Salmonidae was the most studied fish family (Table 2.2). The number of publications focusing on this family was sixfold greater than any other. Clupeidae was the next most frequently studied family (Table 2.2). Families containing species that have recently attained conservation status, such as Petromyzontidae and Anguillidae, appear to be increasingly popular with researchers (highlighted as red triangles in Figure 2.2).

Table 2.2. Frequency and percentage of fish families studied within the literature included in the quantitative review. Five articles were not applicable to this category.

Family	Number	% of Evaluated Publications
Salmonidae	101	44.7
Clupeidae	17	7.5
Petromyzontidae	13	5.8
Anguillidae	12	5.3
Cyprinidae	12	5.3
Acipenseridae	10	4.4
Centrarchidae	6	2.7
Percidae	6	2.7
Catostomidae	2	0.9
Galaxiidae	2	0.9
Moronidae	2	0.9
Characidae	1	0.4
Cottidae	1	0.4
Osmeridae	1	0.4
Percichthyidae	1	0.4
Polyodontidae	1	0.4
Mixed	38	16.8
Total	226	100

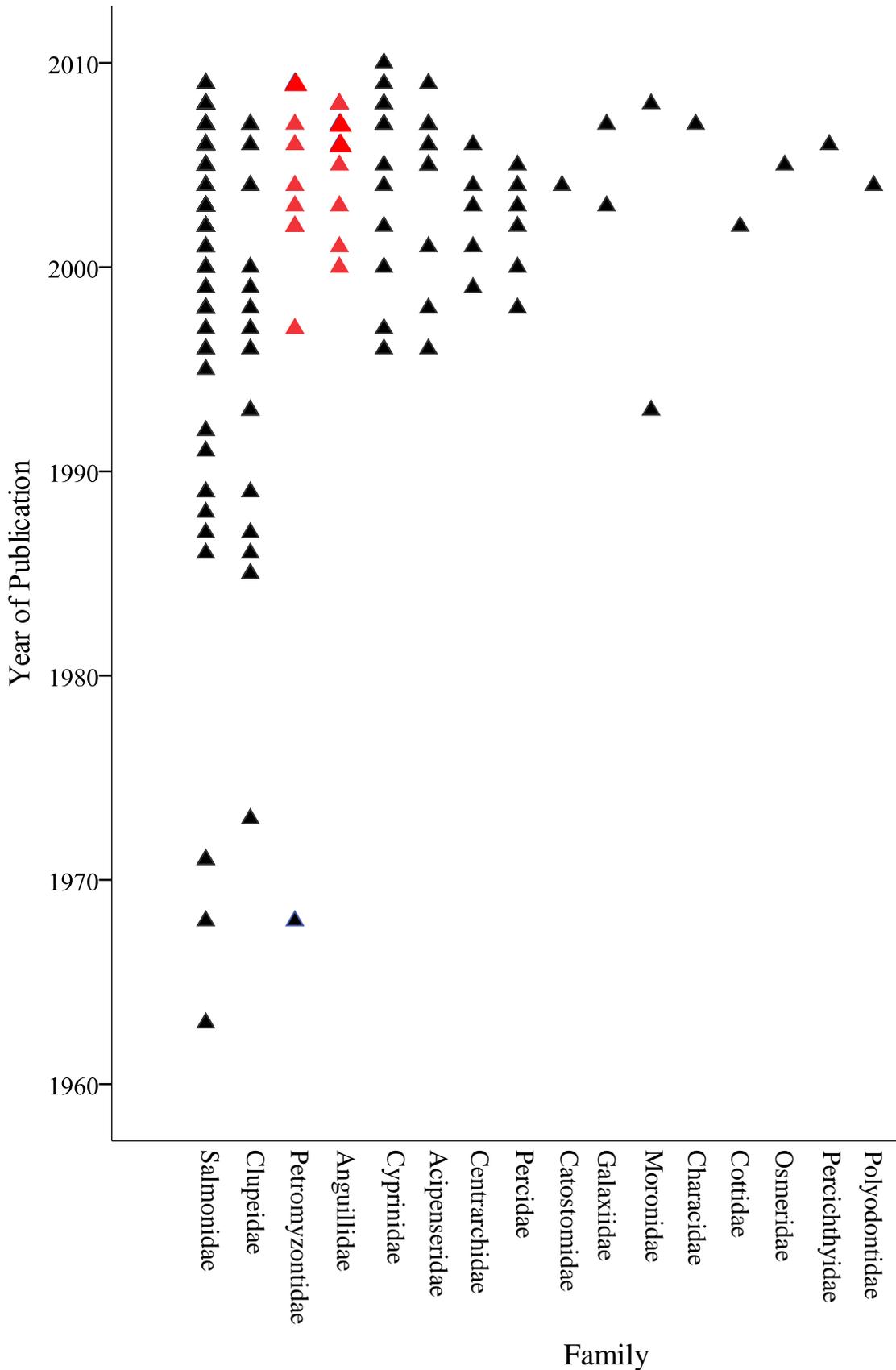


Figure 2.2. Distribution of publications per family over a 50 year period (triangles indicate at least one publication). Red triangles highlight years where publication focused on either Petromyzontidae (the lamprey family) or Anguillidae (the eel family), families containing species of conservation concern in Europe.

At 46%, ‘Adults’ were the most commonly studied life-stage closely followed by ‘Juveniles’ at 36% (Table 2.3). Research into both these life stages has increased exponentially over the last 50 years (Figure 2.3). Egg / larval and mixed comprised the remaining life history stages studied (Table 2.3). Most citations focused on upstream (43.0%) rather than downstream (36.5%) fish movements, 11.5% looked at fish moving in both directions and 9% were classified under “other”. Articles classed as “other” often investigated fish behaviour / movement in response to environmental stimuli (such as light or acoustics) under experimental (still water conditions) e.g. Nemeth & Anderson (1992). Sixteen articles were not applicable to this category (e.g. Becker *et al.*, 2003 where damage to fish from laboratory generated shear stress was investigated).

Table 2.3. Percentage of publications included in the quantitative review that focused on the various life history stages. Five articles were not applicable to this category and 23 did not supply sufficient information.

Life-stage	Number	% of Evaluated Publications
Adult	87	46.3
Juvenile	67	35.6
Egg / Larval	2	1.1
Mixed	32	17.0
Total	188	100

A variety of methods were employed to determine the impact of hydropower and anthropogenic impoundments on fish movements, and behavioural responses to features associated with fish passage systems (Table 2.4). Telemetry / tagging was the most common methodological approach identified (31%), followed by experimental techniques (25%).

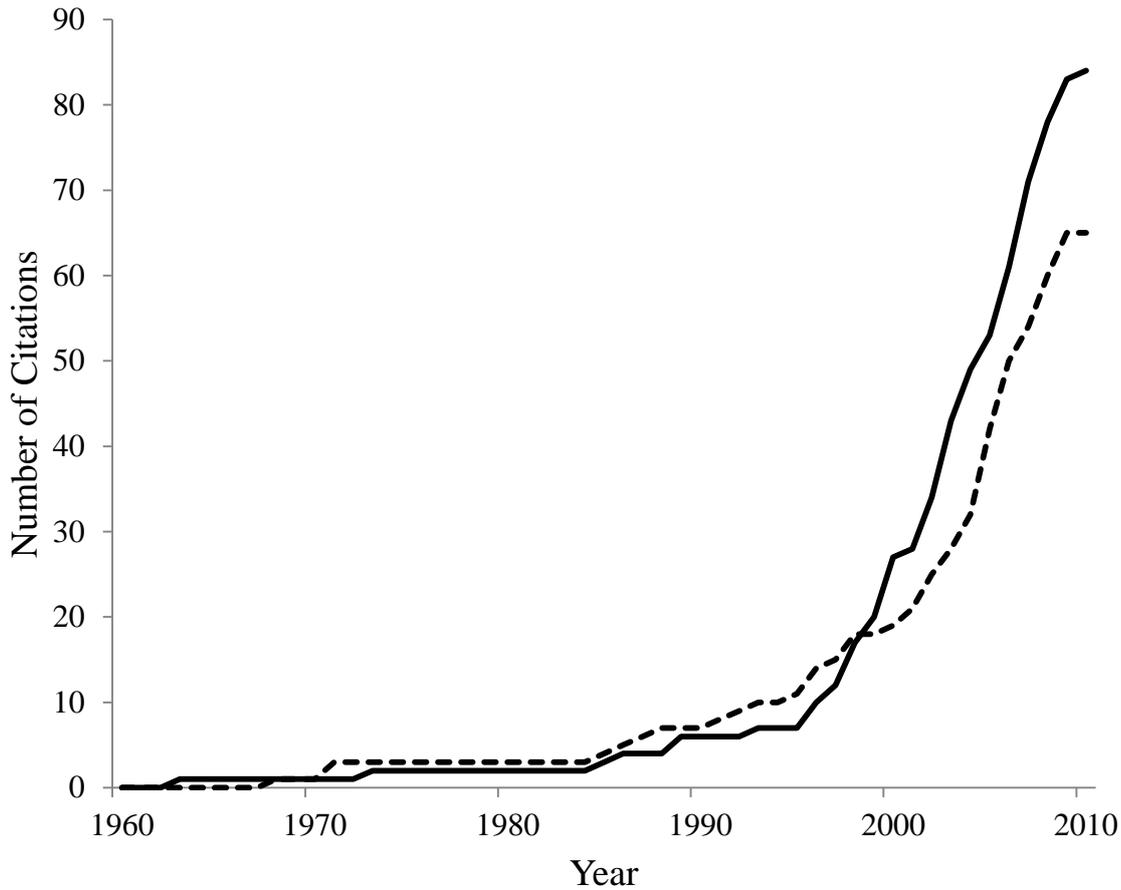


Figure 2.3. Cumulative number of citations focusing on adult (solid line) or juvenile (dashed line) fish life-stages.

Table 2.4. Methodological groups utilised to evaluate the impact of hydropower / river barriers and associated conditions on fish behaviour and survival.

Methodological Group	Number	% of Evaluated Publications
Telemetry / Tagging	67	31
Experimental	53	24.5
Other field based	41	19
Literature Review / Meta-analysis	22	10.2
Numerical / Computational Modelling	8	3.7
Hydroacoustic Techniques	6	2.8
Combination of 2 or more from above	19	8.8
Total	216	100

This research area tended to focus on the efficiencies / effectiveness of fish passage facilities (23%) or the effects of hydropower or anthropogenic barriers on fish movements and / or behaviour (20%). The focus of the remaining literature was split across seven remaining categories (Figure 2.5). For literature that focused on two or more categories, the most common combination was “the effects of hydropower or anthropogenic barriers on fish movements and / or behaviour” (category 1 in methods section), and “efficiencies / effectiveness of fish passage facilities” (category 2 in methods section).

Table 2.5. The research focus taken by studies included in the quantitative review.

Focus of Study	Number	% of Publications
Efficiencies / effectiveness of fish passes	50	23.1
Effects of hydropower / river barriers on fish	44	20.4
Fish behavior / capabilities in relation to hydraulics	36	16.7
Estimating injury associated with hydropower passage	16	7.4
Fish response to environmental stimuli	13	6
Technological / methodological advancements	10	4.6
Effects of conditions associated with turbine passage	6	2.8
Other	5	2.3
Combination of 2 or more from above	36	16.7
Total	216	100

2.3.3. Discussion

The majority of articles in this quantitative review (78%) were published in the last decade, a figure that corresponds closely to the percentage reported (76%) for the same time period by a recently published meta-analysis focusing on a similar topic (the evaluation of fish movements through fish passage facilities, see Roscoe and Hinch, 2010). Although the date of literature included within our analysis could be biased by the internet based search method, our support for the findings of Roscoe and Hinch (2010) illustrates a growing trend for research aiming to mitigate the impact of anthropogenic activities on fish within river systems. The global importance of developing renewable energy, while concurrently

improving fish passage and survival at hydropower facilities, is likely to consolidate interest within this subject in the future. Such research is of critical importance if global environmental standards set by legislative frameworks are to be achieved (e.g. in Europe by the Water Framework Directive, in the United States by the Endangered Species Act and in Canada by the Species at Risk Act; Enders *et al.*, 2009).

Given the legislative importance of anadromous salmonids within North America (e.g. Pacific salmon are listed under the US Endangered Species Act, Williams, 2008) and Europe (e.g. Atlantic salmon are afforded protection under the Habitat and Species Directive 92/43/EEC), it is unsurprising that the majority of articles stemmed from these geographic locations. Despite other regions having vast socio-economic inland fisheries resources (e.g. in Southeast Asia 80-90% of households in the southern lowlands of Laos conduct some form of fishing, contributing up to 30% of rural household income, and, in Cambodia *ca.* 60% of human consumption of animal protein is obtained from inland fisheries, Smith *et al.*, 2005a), the low proportion of literature originating from these areas could relate to either a lack of environmental awareness or environmental legislative frameworks. With the omission of North America and Europe, the recent expansion of hydropower facilities in South America (Agostinho *et al.*, 2005), and the recognition that dams and weirs are a major cause of declining native fish populations in Australia (Stuart and Mallen-Cooper, 1999), possibly resulted in the high proportion of remaining citations stemming from these regions.

Political drivers in North America and Europe are likely to have facilitated research into Salmonidae and Clupeidae (the two most frequently studied fish families), resulting in upstream passage technologies being termed “well developed” for certain anadromous species of both families (Larinier, 2000; Larinier and Marmulla, 2004). In support of the idea of legislation driving research trends, families containing species that have recently attained conservation status (such as Anguillidae) appeared to be increasingly popular with researchers. Given the growing recognition for the need for multi-species fish passage (Castro-Santos *et al.*, 2009), in addition to legislative requirements, more research into non-salmonid migratory and resident fish species is needed and, based on trends highlighted in this quantitative review, could be expected in the future.

It is generally accepted that fish passage research has focused on facilitating the upstream passage of adult life-stages (Clay, 1995; Odeh, 1999; Larinier and Marmulla, 2004; Castro-Santos and Haro, 2006). Downstream bypass facilities for juvenile migrants are thought to have received less attention and have proved to be much more complex, and generally less successful (Larinier, 2000; Williams *et al.*, 2012). However, the greater proportion of studies focusing on adults in the current review is unlikely to have resulted from this historic bias as number of citations for both adult and juvenile life-stages showed exponential increase over the last 50 years. The large body of research focused on aiding successful out migration for juvenile salmonids (particularly in the Columbia River Basin, USA) since the 1960s (Williams, 2008), likely insured that adult based research was not vastly greater than that of juveniles in the current literature search. Furthermore, a wealth of recent research into the outmigration (i.e. downstream movement) of adult eels (Haro *et al.*, 2000; Behrmann-Godel and Eckmann, 2003; Boubée *et al.*, 2008; Durif *et al.*, 2008; Calles *et al.*, 2010) could further mask any historic bias in life-stage / direction of migration studied.

The introduction of telemetry methods to fisheries research the late 1950's (Baras and Cherry, 1990) proved to be one of the most important advances for studying fish behaviour and migration (Lucas and Baras, 2001). Modern Passive Integrated Transponder (PIT), radio, acoustic and archival data storage tags have enabled the movement patterns, distribution, home range and habitat use of fishes to be studied in their natural environment, greatly improving our knowledge and understanding of fish behavioural ecology (Lucas and Baras, 2001). Telemetry / tagging methods are also widely used to study more specific problems associated with fish migration, as illustrated by this quantitative review. Telemetry / tagging was the most common methodological group used to determine the impact of hydropower and anthropogenic impoundments on fish passage and has the advantage of examining fish movements in their natural environment over broad temporal and spatial scales. Disadvantages often centre around negative post-operative effects on fish, restricted tag life, imposition of a minimum size of fish that may be used, and large financial costs. Furthermore, this method may yield site specific results that are not easily transferable to other locations, making it difficult to develop more generic behavioural rules that could be used to improve fish passage facilities (Guiny *et al.*, 2003). Due to the resolution of the data collected, results derived from telemetry / tagging studies (such as passage efficiency) often fail to provide insights into the behavioural

responses of target species to specific causative factors (Larinier and Marmulla, 2004). As a result, aspects of hydropower or fish pass systems that are critical in achieving (for example) safe or efficient passage are often not identified (Anderson, 1988). Other techniques capable of supplying fine-scale information should be used to compliment that derived from telemetry studies.

Fish passage research and the impacts of hydropower facilities have historically taken a site specific approach (Rice *et al.*, 2010). Mitigation has therefore focused on incremental improvements to meet target passage or survival efficiencies for selected species (Goodwin *et al.*, 2006; Rice *et al.*, 2010). These improvements rarely utilise scientific advancements in the understanding of fish behaviour, an aspect thought to be of critical importance in fish passage development, particularly for guiding downstream moving fish (Anderson, 1988; Goodwin *et al.*, 2006). Not only is such a trial and error approach expensive, the time taken to improve the structure can negatively impact fish populations (Rice *et al.*, 2010). One widely applicable method of examining complex interactions between fish and their physical / hydraulic environment is to use experimental methods such as large, open channel flumes (as used by Haro *et al.*, 2004; Webber *et al.*, 2007; Enders *et al.*, 2009; Kemp *et al.*, 2011). In the current review, 87% of “experimental” studies were conducted within the last 10 years, suggesting a growing acknowledgement within the scientific community of the advantages of this approach for investigating fish passage issues. The use of large open channel flumes has recently allowed direct fine-scale (at the organismal or individual level) data of fish behaviour and swimming capabilities to be collected by manipulating specific parameters of interest (e.g. hydrodynamic or environmental features) whilst controlling confounding variables such as discharge and light levels (Kemp *et al.*, 2006). While this facilitates the development of a non-site specific, transferable approach to fisheries research and management, the scale, and therefore realism and applicability of results derived from experimental studies pose potential drawbacks to the approach. Furthermore, natural environmental cues that may govern (or at least influence) fish behaviour and migration are likely to be lacking under experimental laboratory setups. For example, the upstream spawning migration of salmon may be influenced by changes in river discharge, temperature, and water quality among other factors (see Thorstad *et al.*, 2008), and upstream migrating river lamprey may be attracted to larval pheromones in the water (Gaudron and Lucas, 2006). The lack of these cues may raise concerns about the motivational state of fish used in open channel flume experiments; however, they do

provide a valuable method of supplying fine-scale data that can be used to compliment the broad-scale information gathered through telemetry / tagging studies.

In the current quantitative review, the majority of research focused on the efficiencies / effectiveness of fish passage facilities or the effects of hydropower or anthropogenic barriers on fish movements and / or behaviour. Despite this, two recently published meta-analyses have shown fish passes to be poorly functioning (see Bunt *et al.*, 2012 and Noonan *et al.*, 2011). Mean up- and down-stream fish passage efficiencies of approximately 40 and 70%, respectively were reported, well below target levels (Noonan *et al.*, 2011). It therefore appears that current fish passage facilities are not achieving their primary goal of restoring habitat connectivity. Research aiming to identify factors that may be limiting the efficiencies of fish passes is required.

How a fish responds to their environment is of vital importance to fish passage. It is therefore encouraging to find studies focusing on behavioural responses and / or swimming abilities in relation to hydraulic and other environmental factors in the current quantitative review. However, the historic site specific approach, where fish passage at a particular barrier or hydropower facility is improved, has been acknowledged by various authors (Anderson, 1988; Goodwin *et al.*, 2006) and is supported by the most common methodological group (telemetry / tagging studies) and focus of study (efficiencies / effectiveness of fish passes). Although studies aiming to estimate injury / mortality associated with turbine passage (e.g. through blade strike modelling) comprised a relatively small proportion of studies (just 7%), this approach should not be overlooked. It has the advantage of being able to estimate injury and mortality under various hydropower operating conditions, turbine geometries and for different fish species. Consequently, analogous to flume based studies, they mark a move away from site specific empirical estimates and towards a broader spectrum application (Ferguson *et al.*, 2008). Accordingly, a numerical blade strike modelling approach seems an appropriate method for estimating the potential impact alternative hydropower designs or new technologies have on downstream moving fish, without the need to install an operating hydropower facility in the field, in the first instance. This precautionary approach will minimise the impact of future hydropower development on inland fisheries.

2.4. The state of fish passage knowledge – A narrative literature review

To determine the current state of fish passage knowledge at hydropower facilities and to further guide the development of comprehensive research objectives, a critical evaluation of the literature was conducted in addition to a quantitative review. The following narrative literature review is divided into three major sections. The first section (2.4.1) focuses on the influence of hydropower facilities on fish survival, the second (2.4.2) and third (2.4.3) sections focus on longitudinal river fragmentation caused by anthropogenic barriers, and behavioural aspects of barrier passage, respectively.

2.4.1. Fish survival during passage through hydropower turbines

Mortality to fish passing through hydropower turbines can be high, although variable depending on turbine geometry, mode of operation, head difference and species characteristics (Larinier and Travade, 2002). For example, mortality estimates of less than 5% to over 90% for juvenile salmonids passing Francis turbines, and between 5% and 20% for passage through Kaplan turbines were quoted by Larinier (2000). Accordingly, the cumulative effects of passage through several hydropower facilities could compromise downstream migrant fish populations (Therrien and Bourgeois, 2000; Williams, 2008).

Despite suggestions that small-scale hydropower has little environmental impact (Paish, 2002; Santos *et al.*, 2006) the key sources of mortality to fish passing through turbines can remain (Therrien and Bourgeois, 2000). Mortality is derived from six general stress types; 1. Mechanical strike, 2. Grinding, 3. Rapid pressure changes, 4. Cavitation, 5. Shear stress and 6. Turbulence (Clay, 1995). Mechanical strike occurs when fish collide with turbine structures, particularly the turbine blades, whereas grinding occurs as fish are squeezed through narrow gaps between moving and fixed structures (Čada, 2001). The probability of mechanical strike varies with operating conditions and turbine dimensions, as well as species characteristics such body length (Čada, 2001; Hecker and Cook, 2005). Adult eels (*Anguilla* spp.) are considered particularly vulnerable to mechanical injury during turbine passage due to their large elongated morphology and preference for benthic depths during downstream movements (Behrmann-Godel and Eckmann, 2003). Rapid pressure fluctuations during turbine passage can cause ruptured or distended swim bladders when fish quickly move from high to low pressure areas and the swim bladder rapidly expands.

For species capable of regulating swim bladder pressures relatively quickly (physostome fish e.g. salmonids), rupturing of the swim bladder is less common than in species that have a much slower gaseous exchange procedure (physoclist fish e.g. perch, *Perca fluviatilis*). Extremely low pressures within a turbine can lead to cavitation, which is where vapour bubbles violently collapse (Čada, 1990) creating localised shock waves capable of pitting turbine machinery. Consequently, the potential to cause severe physical damage to fish is high. Pressure fluctuations during passage through turbines can lead to direct or indirect mortality, such as a reduced ability to escape predators in the tailrace. Shear stress results when high and varying flow velocities produced by two bodies of water move past one another (Čada, 1990). Shearing forces applied parallel to a fish's body can lead to severe physical damage with typical injuries resulting in torn opercular and damaged eyes (Neitzel *et al.*, 2004; Deng *et al.*, 2005). Finally, fluctuations in water motion (turbulence) has the ability to cause localised injury to fish (such as scale loss), whilst large scale turbulence often leads to disorientation and a subsequent increase in predation risk, particularly in the tailrace of turbines (Larinier and Travade, 2002).

Little published literature exists on the impact of emerging, low-head hydropower technologies on downstream moving fish. However, various reports available from the “gray” literature suggest the Archimedean Screw Turbine and VLH Turbine to be beneficial in this respect due to a lack of significant shearing forces or pressure changes within the device during operation. Assessment of the Archimedean Screw Turbine indicates that this technology can facilitate safe passage of downstream moving fish, including adult European eel and Atlantic salmon and sea trout kelts (in Germany, Späh, 2001; Holland, Merckx and Vriese, 2007; and England, Kibel, 2008). In one study conducted on the River Dart (England), modification to the leading blade edge reduced injury to European eels from 8 to < 1% (Kibel, 2008). Despite being able to pass fish with little harm if appropriately designed, Merckx and Vriese (2007) noted that mostly small fish, possibly less able to resist the velocities at the intake, passed through the screw, while larger fish tended to actively avoid the intake, preferring to pass a bypass channel. The degree of delay and associated costs of this avoidance were not ascertained but should be considered capable of influencing migratory successes, until shown otherwise. In England and Wales, Archimedean Screw Turbines do not require extensive fish screening owing to their perceived low impact on fish. However, appropriate protection to the leading blade edge is required to avoid grinding of fish between moving and stationary components

(Environment Agency, 2009). For the VLH Turbine, when live fish were forced (via a PVC pipe) into an installation on the Tarn River (France), survival rates were around 92% and 97% for adult European eels and Atlantic salmon smolts, respectively (Leclerc, 2007). By redesigning the blades into a more spherical shape, further testing on an installation on the Moselle River (France), indicated that survival rates had improved for both eels (*ca.* 97%) and smolts (*ca.* 100%).

Traditional waterwheels also provide an opportunity to address several environmental concerns associated with low-head hydropower, in addition to providing economic benefits (i.e. approximately 33 – 66% cheaper than comparable Kaplan installations; Müller and Kauppert, 2002). Like the Archimedean Screw Turbine and VLH Turbine, the lack of significant shearing forces or pressure changes, are qualities that could aid the safe passage of downstream moving fish. Furthermore, slow rotational speeds (resulting in a blade tip velocity of $< 4 \text{ m s}^{-1}$, Turnpenny *et al.*, 2000) ensure that during blade contact, injury to fish is negligible. For overshot waterwheels fish would likely be carried downstream in water filled cells, however for undershot wheels and Hydrostatic Pressure Converters, the main potential source of injury could stem from grinding of fish at a “pinch-point” between moving blades and the stationary channel base (Figure 2.4). Should this occur the likelihood of direct mortality would be high. In demonstration of this, one of the few studies investigating the impact of a waterwheel on fish passage likened this effect to a guillotine (Ely, 2003). Whether modification of blade tips or alternative designs can ameliorate this risk is a valuable area of research given the interest in developing low-head hydropower potential and the financial costs of environmental mitigation (e.g. between £5000 and £250,000 each for physical screens or fish pass installations; DEFRA, 2009). However, in the first instance, quantifying the potential risks new technologies such as HPCs pose to downstream moving fish is a necessity.

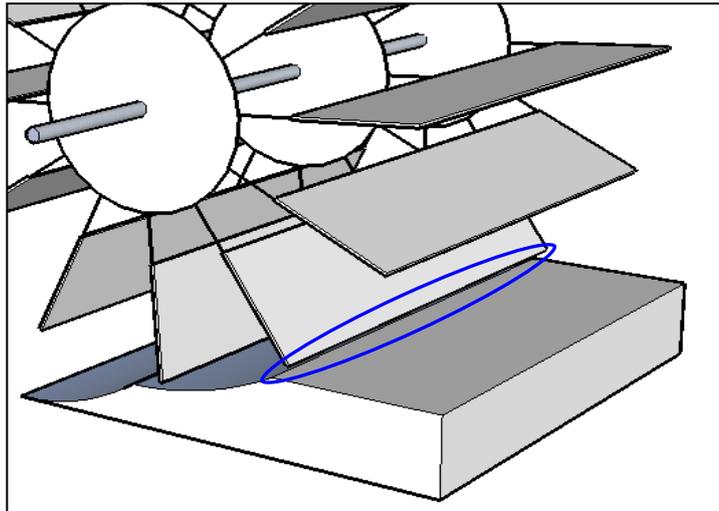


Figure 2.4. The major pinch point created between a HPC blade tip and the base of the channel, presenting a potential grinding risk to downstream moving fish.

Historically, studies attempted to empirically estimate injury / mortality risk to turbine passed fish by utilising mark-recapture and tagging methods, amongst others (Taylor and Kynard, 1985; Dubois and Gloss, 1993; Dedual, 2007). Bell and Kynard (1985), and Stier and Kynard (1986) investigated mortality of adult American shad (*Alosa sapidissima*) and downstream migrant juvenile Atlantic salmon (smolts), respectively, passing through a 9.6 m high hydroelectric facility on the Connecticut River, USA. By tracking live tagged fish that passed through the Kaplan turbine they produced an estimate of mortality caused by turbine passage. A mean turbine mortality of 21.5% and 11.3% was calculated as a minimum estimate for American shad and Atlantic salmon smolts, respectively (Bell & Kynard, 1985; Stier & Kynard, 1986). This empirical approach proved useful in obtaining realistic estimates of mortality. However, the results were specific to the turbine geometry and operating conditions during that particular study period. Such estimates derived from a single study can be unsuitable for estimating mortality rates for alternative species or for passage through alternative turbine operations, geometries or designs. In summary, they tend to be site and species specific.

An alternative to mark-recapture and tagging methods is to use models that predict the probability of fish coming into contact with a turbine blade during downstream passage (Ferguson *et al.*, 2008). These numerical models have the advantage of being able to estimate the probability of strike under various operating conditions, turbine geometries and for different fish species, and as such mark a move away from site specific estimates

and towards a broad spectrum application (Ferguson *et al.*, 2008). Von Raben (1957) was the first to develop numerical strike models for hydroelectric turbines (cited in Turnpenny *et al.*, 2000; Ferguson *et al.*, 2008). The formulation was based on the direction and velocity of the water as it approached the turbine, and the number and speed of blade rotations. Numerical strike models tend to overestimate injury to fish as in reality not all strike events result in damage. In an attempt to correct for this, Von Raben (1957) incorporated empirical observations, relating injury or mortality observed during validation tests with those predicted by blade strike models. More recently a spreadsheet model, “STRIKER”, was developed to compute the probability of injury to juvenile salmonids from pressure fluxes, shear stresses and blade strike during passage through Kaplan and Francis turbines (of < 30 m in height) (Turnpenny *et al.*, 2000). By assessing damage to live, naturally downstream migrating salmonids as well as freshly euthanized hatchery fish that had passed through one of two operating turbines, it was possible to validate model predictions (Turnpenny *et al.*, 2000). Injury from blade strike was shown to be 3-4 times more common than the hydraulic (pressure and shear) sources of injury (Turnpenny *et al.*, 2000). Subsequent blade strike models have further adapted the ideas of Von Raben (1957), and incorporated additional empirical data (e.g. using scale-models and field passage data, Deng *et al.*, 2007) and life cycle modelling (e.g. Ferguson *et al.*, 2008) to ensure increasingly accurate estimates of fish survival and potential impact to fish populations.

Numerical blade strike models are a useful management tool due to their wide application (e.g. to alternative turbine designs and geometries or under various operating conditions), and provide a promising means of highlighting the potential ecological impact of new hydropower technologies prior to installation. Through this, it is possible to identify specific design characteristics likely to be damaging to fish, and highlight these features at the prototype stage. However, empirical data are important for validating model results (Deng *et al.*, 2007).

Where the risks to turbine passed fish are deemed to be high, screens diverting fish to alternative, more benign downstream routes of passage should be provided, allowing hydropower schemes to operate within the standards required by environmental legislation.

2.4.2. Longitudinal river fragmentation

In river systems, fish migrations can have longitudinal, lateral and vertical components, typically undertaken for refuge, feeding and reproductive purposes (Lucas & Baras, 2001). Although the importance of lateral river-floodplain interactions (e.g. the flood pulse concept, Junk *et al.*, 1989) and wider negative effects of disrupting ecohydrological processes with anthropogenic structures (e.g. the river discontinuity concept, Ward and Stanford, 1983) are understood, mitigating the impact of river fragmentation on the longitudinal movements of fish has been a central focus of rehabilitation efforts due to their economic, ecological and cultural significance. As such, this literature review focuses on fish movements in up- and down-stream directions.

2.4.2.1. The problem with anthropogenic barriers

River infrastructure associated with hydropower facilities (dams and weirs) prevent, limit or delay fish from moving between essential seasonal and life-stage specific habitats by fragmenting previously continuous aquatic habitats (Kubečka *et al.*, 1997; Moss, 1998; Katano *et al.*, 2006; Arnekleiv and Rønning, 2004). The concept of fragmentation to upstream habitats is frequently associated with the height of the barrier. However, even low-head weirs constitute major obstructions to upstream migrations (Larinier, 2000; Ovidio and Philippart, 2002; Schilt, 2007). Historically fish passage research focused on the impact river barriers had on migratory salmonids (Calles and Greenberg, 2005). Yet, river fragmentation is a significant issue for the longitudinal movements of all diadromous species, as life cycle completion necessitates movement between fresh and marine waters (Larinier, 2000). Consequently, it is unsurprising that populations of infrequently studied, diadromous non-salmonids are also in decline, in some instances to the extent that conservation protection is warranted (e.g. species of sturgeon, eels, and lamprey; Maitland, 2004).

Fish passes are a common solution to river fragmentation as they theoretically restore river connectivity for fishes (Baumgartner and Harris, 2007; Arnekleiv *et al.*, 2007). Sadly, there is often an assumption that fish passage is well developed and efficient; often this is not the case (see Noonan *et al.*, 2011; Bunt *et al.*, 2012). Upstream passage technologies are considered well developed for certain anadromous species, namely salmonids and clupeids

that are of economic importance in North America and Europe (Larinier, 2000; Larinier and Marmulla, 2004). However, in recent years even newly installed passage facilities have shown low efficiencies for migratory salmonids (Aarestrup *et al.*, 2003; Arnekleiv *et al.*, 2007). The notion that upstream fish passage is well developed for these species must therefore be viewed with caution. In support of this, despite more than 3 decades of research in the Columbia River basin (USA) and over US\$7 billion, 13 out of 16 evolutionary significant Pacific salmon (*Oncorhynchus* spp.) runs are listed as threatened or endangered under the U.S. Endangered Species Act (Ferguson *et al.*, 2007; Williams, 2008). Thus, worldwide the difficulties in managing river systems fragmented by in-river barriers persist, even for “well studied” species.

2.4.2.2. *The case for non-salmonid fish passage research*

The historic legislative bias towards ensuring the upstream movements of migratory salmonid species has resulted in comparatively little consideration for migratory non-salmonids or resident (potamodromous) species. Yet, due to the large seasonal movements undertaken by many resident species (e.g. for feeding and reproductive purposes) (Larinier and Trevade, 2002; Lucas and Batley, 1996), it is acknowledged that any species of fish may occupy seasonal and life stage specific habitats (Bunt *et al.*, 2001) and therefore be vulnerable to river fragmentation.

The lack of information concerning the movements and behavioural patterns of resident species prompted some decisive work that aimed to address this issue (Lucas and Batley, 1996; Lucas and Frear, 1997). Using radio-tracking equipment, Lucas and Batley (1996) revealed quantitative intra-specific differences in the activity of a common resident European species, the barbel (*Barbus barbus*), within the River Nidd (a tributary of the River Ouse, Yorkshire, UK). They found that adult movements ranged from 2 – 20 km, with restricted upstream movements attributed to the presence of anthropogenic structures (Lucas and Batley, 1996). Despite this variable range, the study provided good evidence that barbel make seasonal migrations within river systems. Lucas and Frear (1997) found that a flat-V flow gauging weir in the same reach caused delay and, in some instances, prevented upstream movements of barbel. While 40% of barbel successfully negotiated the weir, not all fish that attempted to pass the weir succeeded, with 45% making more than one attempt. Together, these studies illustrate that not only do adult barbel occupy a range

of habitats within the river system, but that even low-head barriers (< 1 m head difference) obstruct upstream movements. Without suitable spawning habitat downstream, the spawning success of this species and subsequent recruitment to the population is compromised (Lucas and Frear, 1997). Despite this, the specific conditions associated with the weir leading to poor passage were not ascertained. As such, the causative factors or conditions leading to poor passage efficiency could not be quantified. In view of this, it is difficult to attain transferable information on the behavioural characteristics of non-salmonids to the environmental conditions created by low-head weirs. This underscores the site-specific nature of many field investigations that employ telemetry methods, and highlights the advantages of using controlled experimental techniques, such as open channel flumes, to complement field based research.

Alongside the study of resident species, research into migratory non-salmonids is also essential. The development of appropriate fish passage criteria is lacking, but should be considered a priority for the anadromous river (*Lampetra fluviatilis*) and sea (*Petromyzon marinus*) lamprey given the conservation status of these species (listed under Annex II of the EC Habitats and Species Directive (92/43/EEC), Annex III of the Bern Convention on the Conservation of European Wildlife and Natural Habitats (1979) and named as a Long List Species (or Species of Conservation Concern) in the UK Biodiversity Action Plan (Maitland, 2004)). Lampreys are considered weak swimmers owing to their elongated body morphology and resulting anguilliform locomotion (Vogel, 1994; Quintella *et al.*, 2004). Laboratory studies confirmed the poor swimming ability of both adult (Mesa *et al.*, 2003) and juvenile (Dauble *et al.*, 2006) Pacific lamprey (*Lampetra tridentata*) when compared to salmonids, species that exhibit a more powerful (sub-carangiform) locomotive style (Figure 2.5). During anguilliform swimming, whole body undulations with large amplitude, particularly towards the tail, create forward propulsion (Gillis, 1996; Wootton, 1998). In contrast, sub-carangiform locomotion is characterised by posterior undulations, allowing rapid accelerations (Sfakiotakis *et al.*, 1999). These differences in locomotive swimming style, and associated swimming ability, are important when considering fish passage design. While upstream migrant salmonids can ascend the velocities found in fish passes designed specifically for their use, the same velocities often obstruct anadromous lamprey and other non-salmonid species. Furthermore, on encountering high velocities, lampreys typically attach to structures using their oral disc, behaviour attributed to energy conservation, before surging upstream to reattach (Moser *et al.* 2002a; Quintella *et al.*

2004; Kemp *et al.*, 2011). In locations that prevent utilization of this natural behaviour, passage success can be further compromised (Moser *et al.* 2002a), highlighting the importance of understanding species specific behaviours when developing multi-species fish passage.

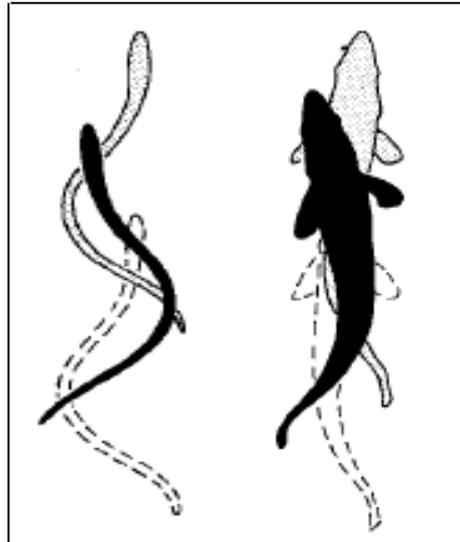


Figure 2.5. Body amplitude and movement patterns generated during anguilliform (left) and sub-carangiform (right) locomotion (modified from Sfakiotakis *et al.*, 1999).

In addition to water velocity, there are suggestions that upstream passage of lampreys is negatively impacted by other hydrodynamic features (Haro and Kynard, 1997). An in-situ evaluation of a fish pass (the Cabot Fishway, Turners Falls, USA) used video recording equipment to illustrate that the combination of turbulence and air entrainment, in addition to high water velocities, inhibited upstream passage of adult sea lamprey. Furthermore, when exposed to experimental weirs placed within a flume, the upstream movements of migrant river lamprey were impeded (Kemp *et al.*, 2011). Passage rate was lower during an overshoot compared to undershot weir configuration, possibly because plunging flows created turbulent environments that were particularly challenging for a species with an elongated anguilliform body morphology and that lack paired fins (Liao, 2007).

Interestingly, oral disc attachment (a behaviour that delays upstream progress) was utilised more during undershot configurations. Based on previous work (Quintella *et al.*, 2004) this behavioural response could have been expected to reduce energy expenditure under the higher velocities experienced during this configuration. Research of this nature further highlights the importance of understanding behavioural aspects to barrier passage in

addition to swimming capabilities, in this instance swimming ability was not dictating successful passage over the weirs presented as the weir configuration characterised by lower water velocities posed the greater barrier to migration.

Another aguilliform species recently popularised by researchers is the catadromous (i.e. matures in freshwater before migrating to ocean spawning grounds) European eel. Rapid recruitment and catch declines have resulted in their protection under Appendix II of the Convention on International Trade in Endangered Species (CITES), restricting trade in European eel. Furthermore, the EU Eel Regulation (No 1100/2007) specifies a minimum of 40% escapement of silver eel biomass to sea (DEFRA, 2009). To meet this target, safe out migration of adult silver eels is a necessity. Unfortunately, as previously noted, adults migrating down river are particularly vulnerable to injury at hydropower facilities (Larinier, 2000; Gosset *et al.*, 2005).

In addition to the aforementioned migratory anguilliforms, other migratory non-salmonids are in decline globally due to barriers to migration, such as sturgeon (Auer, 1996). In a recent flume study, Webber *et al.*, (2007) investigated migration behaviour and attraction velocities for the adult white sturgeon (*Acipenser transmontanus*) around experimental fish pass baffles. It was shown that higher flow velocities tended to stimulate upstream movement, resulting in faster rates of passage, but only for treatments containing vertical baffles (Webber *et al.*, 2007). In a treatment containing a horizontal ramp baffle, passage was likely reduced by the unstable hydraulic conditions it created (Webber *et al.*, 2007). This interesting finding clearly demonstrates that these experimental baffles did not pose a velocity barrier for the adult white sturgeon, which is often assumed as the cause of poor passage of non-salmonids (Knaepkens *et al.*, 2006). Rather, it was the influence unstable, turbulent flow had on behaviour that was the likely cause of poor passage efficiency. Furthermore, it was suggested that an important aspect of successful passage was the use of the pectoral fins, angled against the substrate in an anchoring fashion (Webber *et al.*, 2007). Presumably this behaviour represents either a recovery time between movements or a hold fast energy saving response to high or turbulent flows. In either case, the study provides an insight into specific behavioural responses of sturgeon that facilitate their upstream movement. Moreover, this experimental approach allowed non-site specific suggestions to be made on the design of upstream passage structures for sturgeon, and highlights the influence various hydrodynamic features have on fish movements.

Declining populations of non-salmonids often reflects a poor understanding of swimming abilities and behavioural responses to the hydraulic environment created at barriers to migration (Lucas and Frear, 1997; Almeida *et al.*, 2002; Quintella *et al.*, 2004).

Furthermore, current literature suggests that these barriers, in conjunction with fish passes designed primarily for salmonid movements, prevent or limit the success of many non-salmonid migrations (Moser *et al.*, 2002b; Cheong *et al.*, 2006; Mallen-Cooper & Brand, 2007). The potential to manipulate fish behaviour and facilitate more efficient upstream fish passage for a multitude of species relies on gaining a greater understanding of the movement patterns and behaviours of fish as they encounter environmental conditions associated with fish passes and in-river barriers. For upstream moving fish, research priority should be given to species of conservation importance and species representing alternative body morphologies which are likely to differ greatly in swimming abilities and behaviour to those species more frequently studied.

2.4.2.3. The challenge for downstream fish passage

Mortality to fish passing downstream through hydropower turbines can be high, thus mitigation measures are often a necessity (Čada, 2001). An effective means of mitigating these losses and reconnecting river systems is to provide safe, alternative routes of downstream passage (Weber *et al.*, 2006). Typically, downstream bypasses have been located high in the water column due to the surface orientation of migrant juvenile salmonids (Coutant and Whitney, 2000; Larinier and Marmulla, 2004). Unfortunately, such designs exhibit variable effectiveness for target species (Johnson and Moursund, 2000; Castro-Santos and Haro, 2003; Goodwin *et al.*, 2006), as well as failing to account for the behaviour of other species (e.g. eels tend to migrate at more benthic depths).

To date, most attempts to evaluate downstream passage success have focused on coarse resolution fish movements within dam forebays (Nestler *et al.*, 2008) or percent surviving passage through a series of hydropower dams (Muir *et al.*, 2001). Although such a field based approach reveals interesting results with regards to passage efficiencies, the resolution, accuracy and speed at which both fish movements and complex hydraulic environments are measured often makes it difficult to ascertain high resolution information (i.e. at the organismal level). It is therefore hard to determine causative factors initiating

rejection or progression through a bypass channel or other alternative route. Technological advances are starting to overcome this disadvantage of field based research. Through the use of hydroacoustic (multi-beam sonar) techniques, paths of individual Pacific salmon smolts were observed as they milled or held in the close vicinity of bypass entrances in the forebay of Bonneville Dam on the Columbia River, USA (Johnson and Moursund, 2000). Additionally, recent advances in acoustic telemetry now provide the potential for 2-D or 3-D fish movements to be tracked at near-continuous, sub-metre resolution. Brown *et al.* (2009a) used acoustic telemetry to generate 3-D positional and movement data of silver-phase American eels (*Anguilla rostrata*) within a dam forebay. Diurnal movement patterns, depth preferences and circling behaviours were identified, with eels rarely found to utilise a surface bypass as a route of downstream passage. It was suggested that as eels exhibit searching behaviours within the forebay, a submerged or bottom bypass entrance might be a more effective alternative route of passage than the traditional surface-oriented bypasses designed for species such as juvenile salmonids (Brown *et al.*, 2009a). Although acoustic telemetry provides a more comprehensive measure of movement patterns than conventional radio telemetry techniques, similar disadvantages, such as site geometry, negative post-operative effects on fish, restricted tag life and minimum size of fish, may all pose limitations to the wide scale use of this method. It is also considerably more expensive than both radio and Passive Integrated Transponder (PIT) telemetry equipment.

Through the utilisation of flume facilities, researchers have been able to define fine-scale (at the organismal level) behaviours of fish as they encounter hydraulic and other environmental conditions associated with downstream bypass facilities. When four species of juvenile Pacific salmon smolt were placed in a large open channel flume (located at McNary Dam, Columbia River, USA) and allowed to voluntarily pass through either an unobstructed or constricted channel (passing 70% and 30% of the flow respectively) it appeared that the constricted channel initially acted as an attractant (Kemp *et al.*, 2005a). This was implied by a significantly higher number of smolts entering the constricted channel than expected had movement been passive with the flow. However, it was shown that rejection was greater for fish that entered this restricted channel, indicating that the abrupt acceleration of flow experienced as fish progressed down this channel (at the point of constriction) led to behavioural avoidance (Kemp *et al.*, 2005a).

Additional examination of Kemp *et al.*'s (2005a) research reveals that both the positive (facing upstream) and negative (facing downstream) rheotactic orientations observed as smolts moved downstream could be advantageous. Negative rheotaxis facilitates rapid migration, whereas positive rheotaxis, enhances the ability of fish to avoid potentially harmful downstream conditions by burst swimming in the upstream direction (Kemp *et al.*, 2005a). In either case, orientation was likely a volitional behavioural response to the specific hydraulic conditions created during the study. As smolts approached accelerating velocity gradients, they tended to switch and exhibit positive rheotaxis. This clearly illustrates that at fine-scales downstream migration is not passive, but that fish actively respond to hydraulic heterogeneity, in this instance with avoidance. This is advantageous if it prevents entrance into suboptimal routes such as turbine intakes (Kemp *et al.*, 2005a). Conversely, if the hydraulic conditions at bypass entrances are unfavourable to passage (i.e. induce avoidance by creating unsuitable velocity gradients), then this research could also provide an explanation for the poor efficiencies of some bypass facilities.

In an attempt to ascertain the hydraulic conditions leading to poor passage, another flume based study quantified the passage efficiency of juvenile Atlantic salmon and American shad as they passed through a prototype bypass entrance (Haro *et al.*, 1998). The design specified a uniform spatial flow velocity increase of $1 \text{ m s}^{-1} \text{ m}^{-1}$ of linear distance (Haro *et al.*, 1998). The study also aimed to define fish behavioural responses as they passed the prototype weir compared to passage at a traditional sharp-crested weir. It was shown that the prototype weir passed Atlantic salmon smolts faster and in higher numbers per trial than the traditional weir (Haro *et al.*, 1998). In contrast, no significant difference in passage rate or numbers passed between the two weir configurations was recorded for juvenile American shad. Such a result would imply that expansion of the velocity transitional zone at bypass entrances could improve passage efficiency for certain species (Haro *et al.*, 1998). During the study both species exhibited strong positive rheotaxis on encountering the velocity gradients presented. Furthermore, Atlantic salmon smolts appeared to react to a critical flow velocity (*ca.* 2.5 m s^{-1}) by burst swimming upstream to avoid entrainment or by continuing downstream (but with an associated switch to negative rheotactic orientation). However, visual cues could have also influenced movements (Haro *et al.*, 1998). Consequently, the causal factors (hydraulic gradients or response to some visual stimulus) responsible for initiating the avoidance or retaining behaviours remained speculative.

How fish sense, process and respond to their environment is influenced by multiple sensory stimuli (Liao, 2007). Fish detect changes in fluid motion using the mechanosensory lateral line (Montgomery *et al.*, 1997; Chagnaud *et al.*, 2008), which comprises of sensory receptors termed neuromasts that are distributed across the body and head of fishes either on the skin itself (superficial neuromasts) or below the skin in subdermal canals (canal neuromasts) (Coombs *et al.*, 1988). While capable of detecting small changes in water velocity, the lateral line also mediates rheotaxis (Montgomery *et al.*, 1997), aids prey detection / predator avoidance (Hoekstra and Janssen, 1985), maintenance of school integrity (Partridge & Pitcher, 1980) and detection of physical objects (von Campenhausen *et al.*, 1981). However, fish could be responding to additional stimuli detected through other sensory modalities at passage facilities (e.g. auditory, visual, and olfactory; Evans, 1998). In support of this, Pacific salmon smolts have been shown to avoid overhead cover irrespective of discharge in an experimental flume (Kemp *et al.*, 2005b), and in the field, avoidance of overhead cover has been used to guide sea trout smolts towards preferred downstream passage routes (Greenberg *et al.*, 2012). Such research demonstrates that multiple environmental stimuli influence fish behaviour. As fish have a multisensory physiology, how combinations of stimuli influence behaviour could be of importance in fish pass design, but has rarely been considered. To allow more efficient downstream passage facilities to be developed based on natural behaviours, future research must ascertain how environmental stimuli, detected through multiple modalities, influence fish behaviour and why downstream migrant fish avoid (or progress through) conditions associated with passage structures.

Surface orientated bypasses, designed primarily for salmonid smolts, are likely to be inadequate for passing benthic orientated species, such as the European eel (Gosset *et al.*, 2005). Accordingly, increasing numbers of studies into the behaviour of migrant eels aid to safer, more efficient outmigration of this species (e.g. Behrmann-Godel and Eckmann, 2003; Acou *et al.*, 2008). As downstream migrant eels are predominantly benthic oriented and follow bulk flow, they tend to be directed towards turbine intakes (Behrmann-Godel and Eckmann, 2003) where they are susceptible to physical injury. Delay caused by river barriers can further compromise spawning success by temporarily or, in some instances, completely halting migrations (Acou *et al.*, 2008). Should this occur, individuals undergo both physiological and morphological transitions back to the feeding, sedentary (yellow

eel) life stage (Acou *et al.*, 2008). Given such direct and indirect impacts of hydropower and river barriers to spawning success, in conjunction with EU Eel Regulations, facilitating the safe downstream passage of this migratory species past low-head hydropower facilities and other in-river barriers is a priority, and is reflected in various recent publications (e.g. Brown *et al.*, 2009a; Calles *et al.*, 2010; Russon *et al.*, 2010).

In summary, successful river fragmentation mitigation requires that passage be facilitated in both up- and down-stream directions (Castro-Santos *et al.*, 2009; Enders *et al.*, 2009). Unfortunately, effective downstream passage solutions are generally considered lacking (Larinier and Travade, 2002; Behrmann-Godel and Eckmann, 2003) and efficiencies for target salmonid species have generally remained low despite decades of research (Enders *et al.*, 2012), largely due to behavioural avoidance of conditions associated with bypass entrances. Research that aims to quantify the behavioural patterns of downstream moving fish as they encounter environmental stimuli associated with hydropower intakes and bypass entrances is required.

2.4.3. Behavioural aspects to fish passage

The need to facilitate successful passage at anthropogenic barriers has been recognised for centuries and has led to the development of several types of fish pass (Clay, 1995; Armstrong *et al.*, 2004). The stereotypical fish ladder provides a series of stepped pools (Beach, 1984; Clay, 1995) through which water flows downstream, and fish pass upstream, typically over weirs or through vertical slots, orifices, or notches. These traverses can generate jetting, plunging, streaming and re-circulatory hydraulic conditions within pools (Larinier, 1998; Silva *et al.*, 2011). The ability of fish to navigate these conditions varies with species (Knaepkens *et al.*, 2006), body morphology (Webb, 2004), body length (Lupandin, 2005) and water temperature (Rustadbakken *et al.*, 2004) among other factors. Despite the complexity of flow, early research applied to fish passage principally focused on swimming capability experiments, designed to determine the kinematics of swimming and the physiological capabilities of fish, under controlled, uniform conditions. The pioneering work of Webb (1975) and Beamish (1978) considered swimming performance as the relationship between swimming speed and endurance and categorised these as: sustained, prolonged and burst swimming. This provided data used to predict the ability of

fish to ascend velocity barriers of various lengths and magnitudes, and formed the basis for velocity criteria in fish passes.

Sustained swimming speed describes that which can be maintained for hours without fatigue and is fuelled only by aerobic, red myotomal muscles (Brett *et al.*, 1958). For convenience during laboratory tests, sustained swimming is commonly defined as the speed which can be maintained for over 200 minutes (Hammer, 1995). Burst swimming, used for low duration high energetic activities such as passing short velocity barriers, is fuelled by anaerobic metabolism of white myotomal muscles and has commonly been considered to be that maintained for less than 20 seconds before fatigue (Beamish, 1978). Within this category, the exceptionally high velocities reached when swimming for only 1 or 2 seconds, important in ambush prey capture and predator escape, is termed the fast start performance or sprint swimming speed of the fish (Domenici and Blake, 1997; Nelson *et al.*, 2002). Prolonged swimming results in fatigue between 20 seconds and 200 minutes and is fuelled mainly by red muscles, with white muscles contributing at higher speeds (Brett, 1964). Within the prolonged performance category is the ‘critical swimming speed’ (U_{crit}), first defined by Brett (1964) and now the most common measure of fish swimming capability. Fish are swum at incremental velocity levels for predetermined time intervals (traditionally 30-60 minutes; Hammer, 1995) until fatigue (normally impingement on a downstream screen which may be electrified to encourage fish to swim to exhaustion). The U_{crit} is an easily comparable measure of performance between species or under varying environmental conditions (for review see Hammer, 1995) and provides velocity values that fish can swim against for a period of time equivalent to the time interval used. U_{crit} values have been commonly used to define suitable water velocities in culverts and fish passes of various lengths (e.g. Jones *et al.*, 1974; Santos *et al.*, 2007), and although short time intervals (of e.g. 2, 5 and 10 minutes; Peake and McKinley, 1998) have been used, it is often rapid bursts of a few seconds (e.g. through vertical slots, orifices or notches) that determine successful fishway passage (Gowans *et al.*, 2003; Kemp *et al.*, 2011). The suitability of swimming performance metrics commonly used in fish pass design could therefore be questioned under some scenarios.

Although traditional swimming performance research proved essential in establishing water velocity criteria for fish pass design (Armstrong *et al.*, 2004; Peake, 2004), the data were based on a number of assumptions, such as equal glycogen stores between and within

species, and that fish will swim to physiological exhaustion when attempting to ascend velocity barriers. Recent research has concluded that these assumptions are unrealistic, raising concerns about their universal application for multi-species fish passage (for full discussion on the topic, see Castro-Santos and Haro, 2006). Furthermore, data from traditional swimming performance research was largely obtained under unnatural hydraulic conditions (Haro *et al.*, 2004). Swim chambers used during swimming performance experiments enabled researchers to strictly control test conditions, such as velocity, temperature, and oxygen levels. However, fish were confined within chambers of limited size; such constraints hamper natural swimming behaviours, ignoring their positive influence on performance. A recent comparison of the critical swimming speeds of common carp (*Cyprinus carpio*) shows that longer swim chambers are less restrictive to burst-coast swimming and more conducive to higher performance (Tudorache *et al.*, 2007), resulting in higher swimming speeds and duration of burst-coast locomotion. This indicates that swimming in constrained space limits exhibition of performance enhancing behaviour and tests in shorter chambers may not accurately represent maximum locomotory capability (Tudorache *et al.*, 2007). In a similar study, smallmouth bass (*Micropterus dolomieu*) exhibited lower critical swimming speeds (between 65 and 98 cm s⁻¹) when confined to swim chambers in comparison to free-swimming fish in a long open channel (fish were observed ascending water velocities of 120 cm s⁻¹) (Peake, 2004). Fatigue during respirometer tests occurred at a velocity that closely matched the gait transitional speed to burst-coast swimming in the open channel, suggesting that fatigue in swim chambers is a behavioural response to energetically inefficient or biomechanically difficult locomotion rather than physiological exhaustion (Peake and Farrell, 2006). The swimming ability of migratory anguilliform fish with elongated morphologies have also been observed in large open channel flumes. When ascending experimental weirs, river lamprey (*Lampetra fluviatilis*) and European eel (*Anguilla anguilla*), species of conservation concern in Europe, attain burst velocities greater than 1.75 - 2.12 m s⁻¹ (Russon and Kemp, 2011a). These values are higher than previously reported, further supporting the observation that greater performance is obtained for a range of species swimming in large flumes compared to swim chambers.

Swimming performance data derived from swim chamber experiments have been further criticised as uniform flow profiles rarely occur in natural systems, where flows are characterised by varying levels of turbulence (Enders *et al.*, 2005; Haro *et al.*, 2004; Liao

et al., 2003; Plaut, 2001). In acknowledgement of this limitation, recent research has attempted to determine the influence of turbulence on fish swimming performance. Turbulent flows can increase fish swimming costs. By integrating turbulence into swim chamber respirometer experiments, Enders *et al.* (2003) were able to assess the energetic costs of swimming for juvenile Atlantic salmon under more realistic conditions. Turbulent flows were generated by modulating the power supply to an electric water pump, creating two mean velocities (18 and 23 cm s⁻¹) and two standard deviations of velocity (5 and 8 cm s⁻¹) within the swim chamber. These four hydraulic conditions enabled the effects of turbulence intensity (the magnitude of flow fluctuation around a time averaged flow rate) on fish swimming costs to be assessed, as well as allowing comparisons between the costs of swimming in turbulent flows to those predicted under traditional respirometer experiments (Enders *et al.*, 2003). For a given mean flow velocity, a positive correlation was found between energy expenditure and turbulence intensity, with swimming costs increasing 1.3 to 1.6-fold. In addition, the overall energetic cost of swimming was shown to be 1.9 to 4.2-fold larger than those predicted by traditional respirometer tests. A contributing factor influencing swimming performance under turbulent environments could stem from the unsteady swimming required to maintain stability (e.g. changes in speed and direction) being more energetically costly than the steady swimming (maintenance of speed and direction) required during forced swimming experiments (Enders *et al.*, 2003).

Methods employed by Enders *et al.*, (2003) focused predominantly on the mean and standard deviations of flow velocity; research has also explored other facets that influence fish swimming capabilities within turbulent environments. Lupandin (2005) identified the importance of turbulent scale as a vortex diameter of $\geq 2/3$ the body length of perch decreased critical swimming speeds (Lupandin, 2005). Tritico and Cotel (2010) advanced this work by exposing creek chub (*Semotilus atromaculatus*) to a distribution of vortex sizes, vorticities (angular velocity) and orientations to assess impacts to swimming speed and stability. Only the largest vortices, of similar diameter to the fish length caused stability challenges, termed ‘spills’ these were characterised by spins in an orientation consistent with the rotation of the vortices and subsequent translocation of the fish downstream (Tritico and Cotel, 2010). However, vortex diameter alone was not the causative factor. During low velocity, large vortex diameter treatments, spills were not observed. Stability challenges were associated only with higher velocity treatments, when vortices rotated at greater speeds generating higher vorticity. Larger vortices also tended to

have the greatest impact on swimming performance, particularly when rotating around a horizontal rather than vertical axis (Tritico and Cotel, 2010). The importance of both turbulence scale (vortex diameter), vorticity and vortex orientation on the swimming performance and stability of fishes was illustrated. Within the fluvial environment, turbulence has the potential to influence habitat selection, station holding and migratory abilities of fishes (Smith *et al.*, 2005b; Tritico and Cotel, 2010), and as such is a key hydraulic component that requires consideration during fish pass design, a factor often overlooked during traditional swim chamber experiments.

Steep, technical fish passes (e.g. the Denil Fishway or Super-Active Baffle (Lariner) pass) incorporate physical structures (baffles) into their design to dissipate energy via turbulence and reduce mean water velocities to enable upstream progress (Clay, 1995; Castro-Santos *et al.*, 2009). However, by dissipating energy so that velocity is reduced to suitable levels, relative to swimming capabilities of target species (defined under uniform flows), the turbulent conditions produced may limit passage efficiency. Thus, recent research illustrates there may be a trade-off between energy dissipation using turbulence and the disadvantages of increased complexity of flow during fish passage design. As such, fish passes present contradictory challenges. The negative impacts of turbulence on swimming performance ensure that fish passes designed exclusively on swimming capability criteria should have limited functionality, particularly for a wide range of species which differ in both swimming capability and behaviour.

Although turbulence has been documented to increase fish swimming costs, there is evidence to the contrary during some scenarios. It has long been suggested that fish can reduce swimming costs by exploiting turbulence generated by the propulsive movements of other fishes (Weihs, 1973). More recently, Liao *et al.*, (2003) demonstrated that juvenile rainbow trout (*Oncorhynchus mykiss*) were able to voluntarily alter their body kinematics when exposed to predictably shed vortices generated in the wake of a structure (a vertically mounted D-shaped cylinder). As the vortices were shed, a von Kármán vortex street formed behind the cylinder (Vogel, 1994), Figure 2.6.

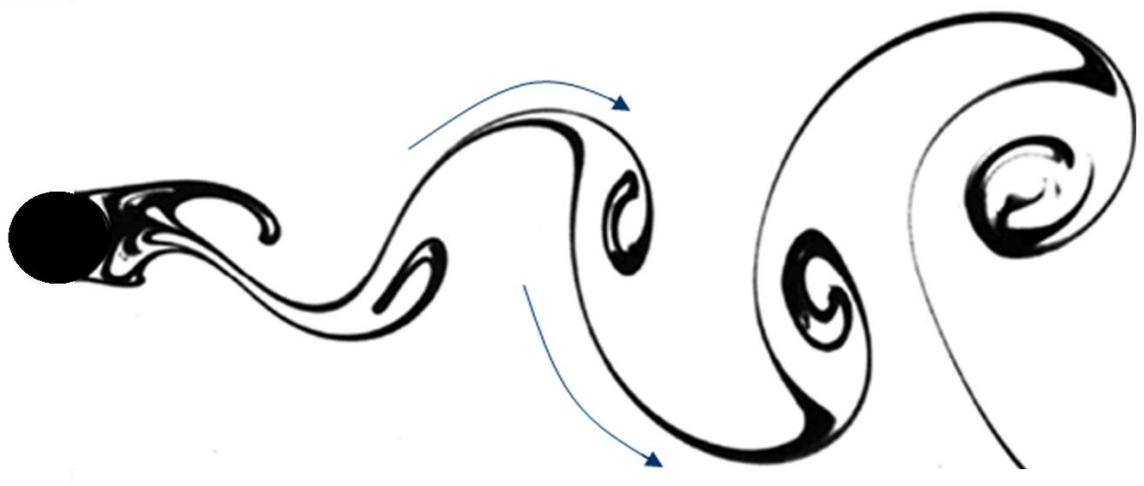


Figure 2.6. Von Kármán vortex street shed behind a cylinder. Each vortex rotates in the opposite direction to the preceding and succeeding vortices. Modified from: www.simerics.com/animation/karman_vortex_street_experiment.gif.

As the fish took up position within the vortex street a unique pattern of locomotion was identified, and termed the Kármán gait. Fish kinematics were characterised by large lateral body oscillations and a tail beat frequency that matched the vortex shedding frequency of the cylinder (Figure 2.7). Visualisation of the Kármán Street (using Particle Image Velocimetry) and movements of the trout (using high speed video) revealed that the trout were able to slalom between the vortices (Liao *et al.*, 2003).

Further experiments confirmed that muscle activity was reduced during Kármán gaiting, suggesting that the cost of swimming for fish utilising these vortices could be lower than more uniform flows of comparable velocity (Liao, 2004). Vision, in addition to lateral line sensing of the hydrodynamic environment, was also shown to be of importance. Trout would prefer to Kármán gait when visual cues were available but entrain behind the cylinder under dark conditions, regardless of whether the lateral line was functioning (Liao, 2006), illustrating that fish behaviour is influenced by multiple sensory modalities. In natural rivers, eddy shedding is often unpredictable and variable in scale, vorticity and orientation, unlike the controlled laboratory conditions (Tritico, 2009). Despite this, the potential to apply this knowledge to fish pass design (i.e. in an unnatural channel located in the field) presents an interesting avenue for future research.

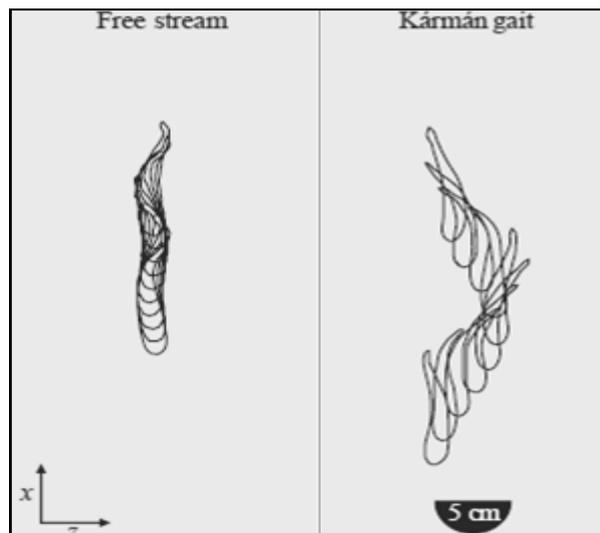


Figure 2.7. Body outlines of a rainbow trout (*Oncorhynchus mykiss*) swimming in the free stream and Kármán gaiting behind a vertically mounted D-shaped cylinder. Body outlines show approximately one tail beat cycle (modified from Liao *et al.*, 2003).

Turbulence has been found to have negative (e.g. Enders *et al.*, 2003; Lupandin, 2005; Tritico and Cotel, 2010), positive (Liao *et al.*, 2003; Liao, 2004) and inconclusive (Nikora *et al.*, 2003) results on fish swimming performance and kinematics. However, its influence on migrant fish behaviour has received less attention, with previous research focusing on selection of resting locations (e.g. Cotel *et al.*, 2006) or drift feeding focal positions (e.g. Smith *et al.*, 2005b) of resident species. Despite having an application to habitat restoration, they tend to provide less information for engineers designing fish pass facilities.

Insufficient knowledge regarding the influence of turbulence on the behaviour of upstream migrating fish at passage facilities has prompted innovative research. Silva *et al.*, (2011) assessed the effect of turbulent features on the behaviour of an upstream moving non-salmonid using a full-scale indoor prototype fish pass. Hydraulic conditions were measured using Acoustic Doppler Velocimetry and two turbulent parameters calculated; turbulent kinetic energy (*TKE*), a measure of the added kinetic energy to a flow due to the presence of vortices (or eddies); and Reynolds shear stress, a measure of force per unit area occurring when two water bodies of different velocities move past one another (Silva *et al.*, 2011). Iberian barbel (*Luciobarbus bocagei*) tended to occupy zones of lower velocity and *TKE*, and *TKE* and Reynolds shear stress were negatively correlated with transit time

through pools, particularly for smaller individuals (Silva *et al.*, 2011). The use of a non-salmonid species provided a good indication of how turbulence may influence other weak swimmers. Furthermore, by quantifying various turbulent parameters the study may have direct application to future fish passage designs, specifically by identifying hydraulic features fish avoid during upstream movements (Silva *et al.*, 2011).

Within flumes, fish behaviour has been quantified using descriptors such as rheotactic orientation (Haro *et al.*, 1998; Kemp *et al.*, 2005a; 2005b), proportion of time spent within specific zones (Wang *et al.*, 2010), time to pass physical or hydraulic barriers (Guiny *et al.*, 2003; Haro *et al.*, 2004; Castro-Santos, 2005), number of approaches prior to passage (Kemp *et al.*, 2011), water depth preferences (Russon *et al.*, 2010), tail beat frequency (Liao *et al.*, 2003), and swimming gait transitions (Peake & Farrell, 2004) among others. In addition to the identification of fish responses, it is essential that future research attempts to understand the mechanisms that induce observed behaviours. This would enable the manipulation of the hydraulic environment with the specific aim of inducing a particular response to facilitate more efficient passage of fish around anthropogenic structures. Such theoretical behavioural research has been infrequently applied to fish passage, but could be a promising approach in the future (see Kemp *et al.*, 2012).

Ultimately, effective fish passage depends on successful location and entry of the pass followed by progression through the length of the channel (Bunt, 2001). As fish passage is volitional, behaviour as well as the physiological capabilities of fish requires consideration. Unfortunately, owing to the traditional methods employed, this behavioural information is often lacking, but is starting to emerge through the use of large open channel flumes as a research methodology and the quantification of the hydraulic conditions created within them.

2.5. Conclusions

Through completion of a quantitative and narrative review of the literature it is clear that low-head hydropower facilities pose a number of threats to fishes; they may: 1. lead to physical injury and mortality during passage through the device, and 2. prevent, limit and delay their longitudinal (both up- and down-stream) movements.

Despite some potential benefits of emerging low-head hydropower designs over traditional turbine technologies (i.e. negative impacts from rapid pressure changes, cavitation, shear stress and turbulence are negligible), blade strike and grinding of fish between moving and stationary components remains a potentially significant source of direct mortality. New technologies, such as Hydrostatic Pressure Converters must undergo environmental assessment to determine the probability and severity of these risks, prior to installation. To achieve this, numerical blade strike modelling would be a valuable research approach, allowing estimates of strike, injury and mortality to fish to be calculated prior to installation in a natural setting. This allows design modifications and recommendations for improving environmental acceptability (if required) to be made, without risking damage to wild fish populations.

Mitigating longitudinal river fragmentation is a major challenge for current and future low-head hydropower developments. Research has tended to focus on salmonids, with upstream fish passes typically designed for these species. This has resulted in comparatively less research into non-salmonid fish passage; more research is required on non-salmonids in the future. Until recently, fish swimming capabilities determined using swim chambers formed the main biological component for fish pass design. However, this traditional approach underestimated the locomotory capacity of fish swimming under more natural conditions where performance enhancing behaviours can be expressed (Haro *et al.*, 2004; Peak and Farrell, 2006; Russon and Kemp, 2011a). Further, the unidirectional flows generated within swim chambers are rare in nature, where flows are inherently complex. Due to these limitations, future research with a focus on fish behaviour in response to conditions associated with fish passage facilities is necessary. Fundamental to successful upstream passage is the ability to successfully locate a fish pass entrance, enter and then progress upstream through the length of the channel (Bunt, 2001). This process is governed as much by behavioural constraints as by physiological limits.

Developing successful downstream bypass structures remains difficult, even for frequently studied species, as behaviour rather than swimming capability largely determines successful passage (Williams *et al.*, 2012). Understanding behavioural responses of fish as they encounter hydraulic and other environmental stimuli associated with bypass entrances will greatly improve the ability to manipulate environmental stimuli, influence fish behaviour and facilitate safer, more efficient passage. Research that can supply this

information will provide quantitative criteria enabling more effective fish passage and ecologically sensitive hydropower facilities to be developed.

Chapter 3

Finalised research Aims & Objectives

Injury / mortality sustained to fish passing through turbines and fragmentation of river habitats have been highlighted as significant environmental impacts of low-head hydropower. In light of this, two key research aims were identified:

1. Assess the impact of a novel low-head hydropower technology, the Hydrostatic Pressure Converter (HPC) on fish behaviour and survival.
2. Investigate and identify factors that may limit up- and down-stream fish pass efficiency.

To effectively meet these aims, an initial objective was identified:

1. Identify methodological techniques and highlight research trends, biases and gaps in knowledge on the ability of fish to move through hydropower installations and around associated impoundments, through use of a vote counting meta-analysis and critical review of current literature.

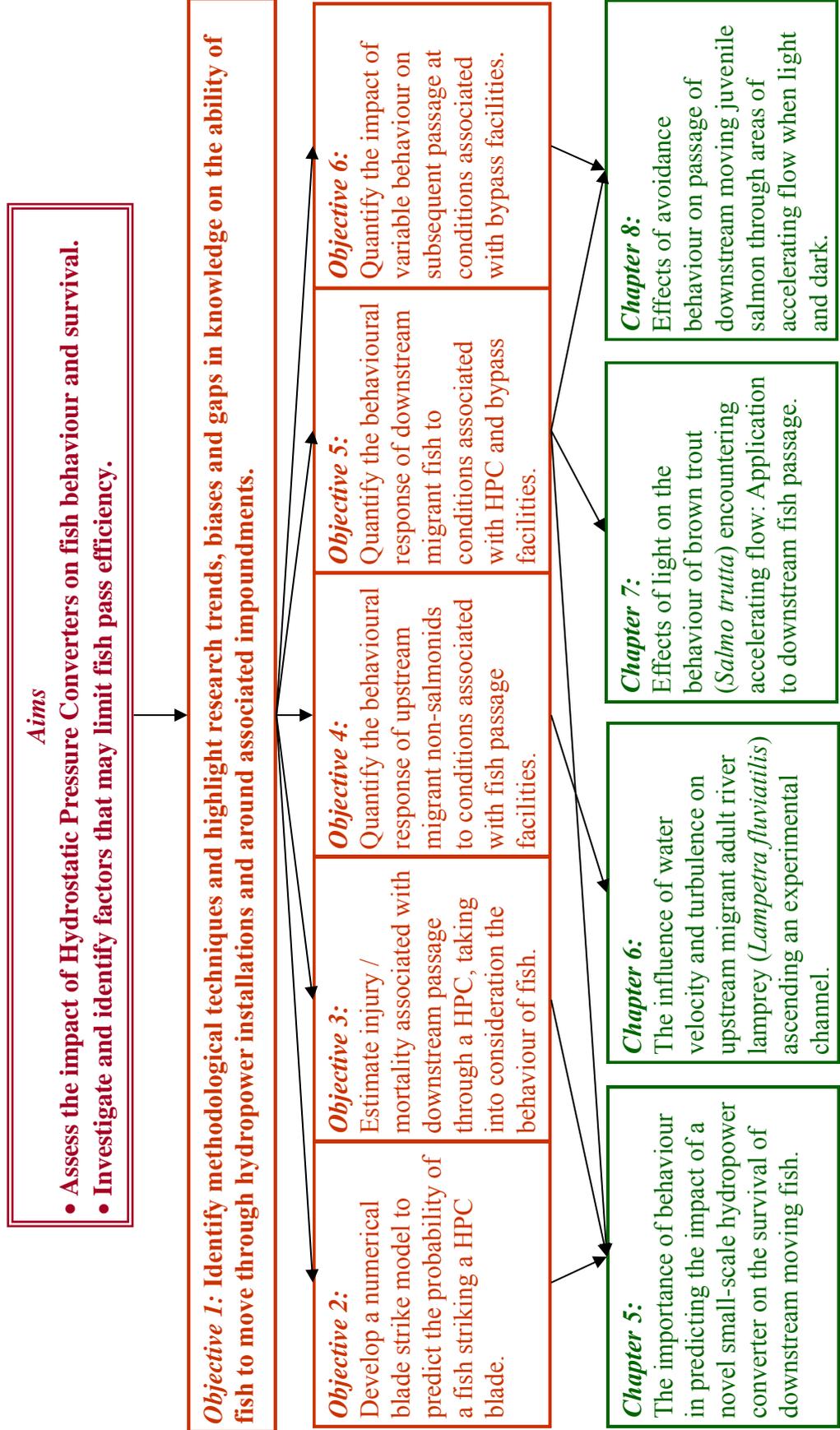
Through the completion of objective 1 (see Chapter 2), research methods of value for fulfilling the aforementioned aims were identified, while gaps in knowledge were highlighted, enabling additional research objectives to be identified and refined. This allows research aims to be comprehensively addressed while contributing to existing knowledge and thinking in the field of fish passage and low-head hydropower development. Additional objective are to:

2. Develop a numerical blade strike model to predict the probability of a fish striking a HPC blade.
3. Estimate the injury / mortality associated with downstream passage through a HPC, taking into consideration the behaviour of multiple species of fish.
4. Quantify the behavioural response of upstream migrant non-salmonids to hydrodynamic conditions associated with fish passage facilities.

5. Quantify the behavioural response of downstream migrant fish to conditions associated with HPC and bypass facilities.
6. Quantify the impact of variable behaviour on subsequent passage at conditions associated with bypass facilities.

The research conducted during my candidature and how individual experiments aid to the realisation of the aforementioned 'Aims and Objectives' are summarised in Figure 3.1.

Figure 3.1. Schematic summary of the research aims and objects and corresponding results chapters (5 – 8) undertaken in pursuit of the objectives identified.



Chapter 4

Research methodology

The following chapter outlines the methodological techniques, equipment and fish species utilised during this programme of research. More detailed methodology sections can be found in the individual results chapters (Chapter 5 – 8).

4.1. Blade strike modelling

Injury and mortality caused by rapid pressure fluctuations, cavitation, shear stress and turbulence during passage of fish through Hydrostatic Pressure Converters (HPCs) will be negligible owing to the design and operating principle of the device. Risks of injury and mortality sustained through blade strike and grinding between moving and stationary components remain. Through the development of a blade strike model it becomes possible to estimate the proportion of fish being struck by a rotating HPC blade. Furthermore, this approach enables an assessment of this risk prior to installation in the field and at a prototype stage, where, if necessary, design alterations and mitigation options can be recommended to make the device safer for downstream moving fish.

A spreadsheet blade strike model (formulated in Microsoft Office Excel 2007) was developed in Chapter 5 based on the intuitive principle that for a fish to pass through a HPC without being struck, it must pass between the sweep of one blade and the next. A range of operational as well as biological conditions were incorporated into the model to illustrate collision under various scenarios. In reality, collision with a blade does not necessarily result in injury to the fish. We therefore introduced freshly euthanized (due to UK Home Office and University of Southampton Ethics Committee advice owing to the potential for injury and stress to live fish), hatchery reared brown trout into the intake of an operating, prototype HPC to validate the model and determine the severity of injury should a strike or grinding event occur. The detailed blade strike formulation and validation method can be found in Chapter 5.

4.2. Open channel flume facilities

The typical techniques utilised in field based fish passage research (e.g. electrofishing surveys, mark-recapture methods or telemetry studies) are best suited to reach-scale studies, quantifying broad-scale movement patterns, tagged fish locations to a general area, or confirmed passage at a fixed point e.g. dam, weir or associated fish pass. Whilst offering insight into fish movements and a quantitative evaluation of fish passage efficiency, such studies can suffer from subjective interpretation of behaviours in relation to environmental factors owing to their poor spatial resolution. Research conducted as part of this thesis utilised large open channel flume facilities, enabling fine-scale behavioural data of multiple fish species to be obtained, whilst also allowing the manipulation of abiotic conditions, replication, and isolation of test variables. All practical experimental research was carried out in either an indoor or outdoor flume facility at the International Centre for Ecohydraulics Research (ICER), University of Southampton, UK or a flume facility located at the juvenile bypass system, McNary Dam on the Columbia River, USA.

The indoor re-circulatory flume at the ICER facility had a working length of 21.4 m, width of 1.4 m and a depth of 0.6 m. The flume had glass sided walls, a steel base and was driven by three centrifugal pumps (individual capacities of 0.09, 0.15 and 0.23 m³s⁻¹) providing a maximum flow capacity of 0.47 m³s⁻¹. Pumps could be used individually or in combination, with flow rate further controlled by adjusting valves associated with each pump. Water depth within the flume was controlled using a blocking weir located at the downstream end of the flume. Structures associated with each experiment were inserted into an otherwise uniform rectangular channel (Figure 4.1.a, b). Black plastic sheeting was erected along the length of the flume to prevent disturbance to the fish from the surrounding vicinity. Overhead and / or side view video cameras were used during all experiments to non-intrusively capture fish behavioural responses. The indoor flume was used for behavioural observations conducted in Chapter 5, and for studies conducted in Chapters 6 and 7. The outdoor flume at the ICER experimental facility was used for blade strike model validation tests only (Chapter 5) (Figure 4.1.c). This flume had a working length of 60 m, maximum width of 2.1 m and depth of 0.5 m. Up to three pumps supplied the trapezoidal channel with water from a large sump tank located at the upstream end of the flume, maximum flow rate through the flume was 0.8 m³s⁻¹.

McNary Dam is located 470 river kilometres upstream from the mouth of the Columbia River. The through-flow aluminium flume (working length of 12 m, width of 1.5 m and depth of 0.75 m) was used to test the behavioural responses of out migrating juvenile salmonids to velocity gradients created by an orifice weir under light and dark illuminations (Chapter 8). The flume was located within the dam and above the juvenile bypass channel and was supplied directly with water from the McNary Dam forebay. Discharge was controlled by a pneumatic valve system. The flume utilised dark sheet coverings to prevent outside disturbance to test fish. All structures were placed within an otherwise uniform rectangular channel (Figure 4.1.d) and all behavioural responses were captured via overhead cameras.

4.3. Video analysis and fish tracking

All behavioural experimental trials were video recorded, typically during dark, night time hours to mimic the natural timing of migrations (e.g. Kelly and King, 2001 for river lamprey; Heggenes *et al.*, 1993 for brown trout; Haro, 2003 for eel), and / or to ensure navigation and consequently behavioural responses were mediated by the hydraulic test conditions (i.e. by eliminating visual cues). Analysis of video footage allowed parameters such as time to approach and pass through certain zones, rheotactic orientations and initial behavioural reactions on encountering hydraulic stimuli, among others, to be quantified.

A proportion of the experiments utilised video tracking software to analyse individual fish movements in an area of interest within the flume (e.g. areas of modified flow). Fish movements were either automatically tracked on a frame-by-frame basis using custom written software (FishTrack, Matlab v7.9; Mathworks, Natick, MA, USA) or manually tracked using Logger Pro Version 3.8.2 (Vernier Software, Beaverton, OR, USA). This novel method of assessing fish behaviour allowed accurate quantification of the paths, locations and orientations of fish as they experienced test conditions within a flume setting. By superimposing fish tracks onto empirical maps of the hydraulic environment, it was possible to determine hydraulic conditions of interest that fish were exposed to as they passed through a test area of flume.



Figure 4.1.a. Perspex sheet used during Chapter 6 to divide the indoor flume at the ICER experimental facility into two channels of equal width, **b.** Indoor flume channel constriction and spot light used during Chapter 7, **c.** The HPW installed in the outdoor flume at the ICER experimental facility and used during blade strike validation tests in Chapter 5, **d.** An orifice weir installed in the flume at McNary Dam, used to test the behavioural responses of salmon smolts to velocity gradients (Chapter 8).

4.4. Hydraulic measurements and mapping

To obtain accurate hydraulic data, flow measurements in the flume facilities were conducted using an Acoustic Doppler Velocimeter (ADV), as used by e.g. Guiny *et al.*, (2003) when investigating the preference of brown trout and Atlantic salmon parr for orifice or weir fish pass entrances, and Silva *et al.*, (2011) when assessing the influence of water velocity and turbulence on the behaviour of Iberian barbel.

At discrete points, ADVs measure a small sample of the flow allowing accurate three-dimensional (3-D) hydraulic data to be collected. The ADV probe emits short pairs of acoustic pulses, and receivers measure the change in pitch or frequency of the returned sound, giving a 3-D velocity reading (Voulgaris and Trowbridge, 1998). By recording the three planes of water velocity, hydraulic parameters including mean streamwise velocity (e.g. Enders *et al.*, 2009), turbulence intensity (level of fluctuation around the mean velocity, e.g. Russon *et al.*, 2010), turbulent kinetic energy (the kinetic energy extracted from mean velocities by vortices, e.g. Smith *et al.*, 2005b) and shear stress (two bodies of water of different velocities moving past one another, e.g. Silva *et al.*, 2011) can be calculated. A maximum / minimum threshold filter was applied to all raw ADV data to remove any outliers. Data within the maximum / minimum range were deemed valid while outlying data points were replaced with mean values in Microsoft Office Excel 2007 (using a method described by Cea *et al.*, 2007). Threshold values were calculated as:

$$u_{\min} = \bar{u} - \sqrt{2\ln(N)}\sigma_u \quad (4.1)$$

$$u_{\max} = \bar{u} + \sqrt{2\ln(N)}\sigma_u \quad (4.2)$$

where $u_{\min/\max}$ are the minimum and maximum velocity thresholds in the longitudinal direction, \bar{u} is the mean longitudinal velocity, σ_u is the standard deviation of u , and N is the total number of velocity readings. Similar expressions are used for the lateral and vertical velocity components (Cea *et al.*, 2007). Signal-to-noise ratios (SNR) (a measure of the relative quality of the acoustic signal received by the ADV) and correlation values (an indicator of the dispersion of the velocity during sampling, expressed as a percent, 100% indicates reliable measurements) were maintained within the range recommended by the

manufactured (SNR of 20-25, correlations of > 70%). Additional details of ADV sampling configurations can be found in individual results chapters.

Filtered ADV data was imported into ArcGIS 10 (ESRI, Redlands, CA, USA), where spline interpolation in the Spatial Analyst tool allowed hydraulic parameters (e.g. mean velocity vector, turbulent kinetic energy) to be mapped. Fish tracks (Chapter 6 and 8) or reaction locations (Chapter 7) generated from the coordinates derived from the tracking software were also imported in ArcGIS and overlain onto the hydraulic maps (Figure 4.2). Underlying, interpolated hydraulic data for each coordinate position was extracted, enabling the quantification of fish behaviour in response to the hydraulic parameters experienced (e.g. velocity gradients across a fish's body, cumulative velocity or level of turbulence encountered in specific zones).

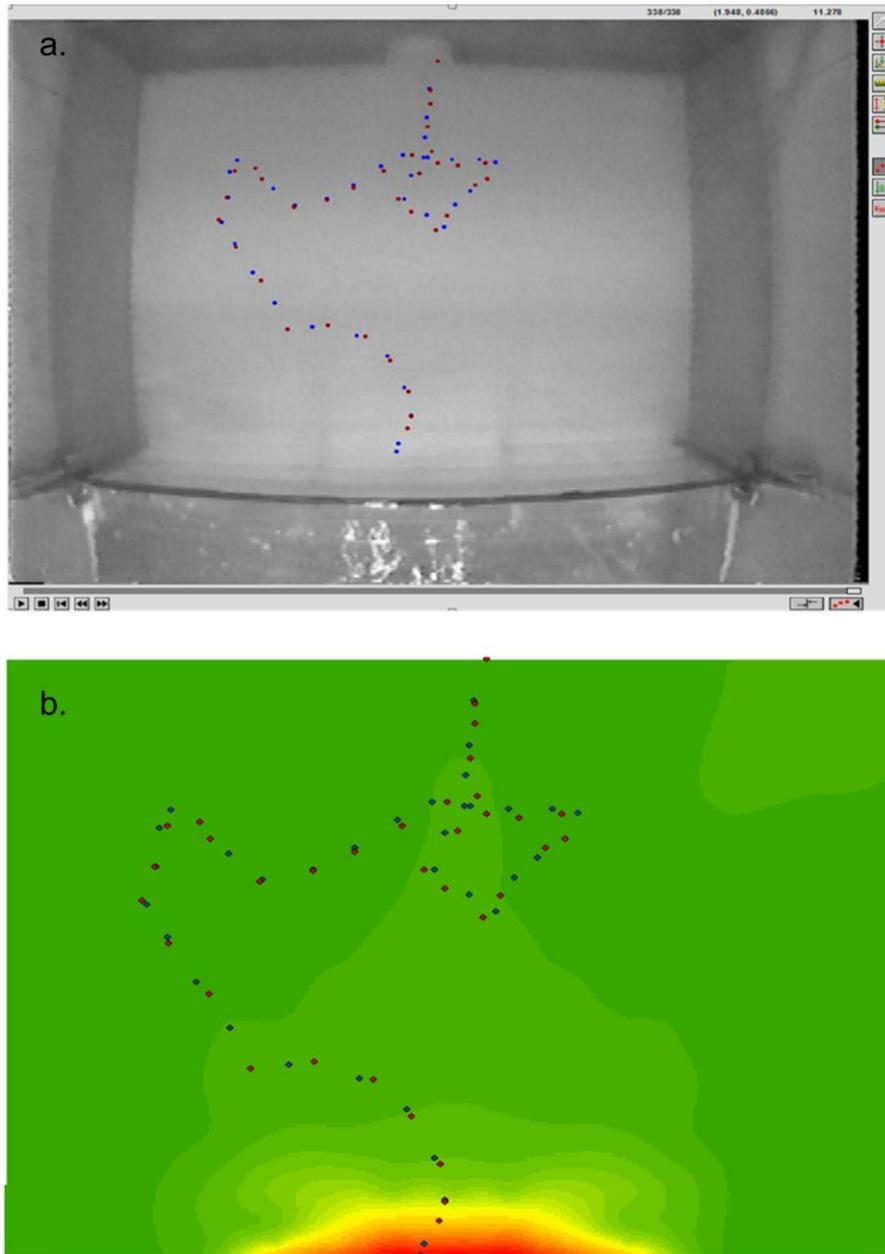


Figure 4.2. a. Head and tail locations of a Pacific salmon smolt (*Oncorhynchus* spp.) video tracked during passage through an orifice weir in an open channel flume (red and blue dots represent head and tail positions, respectively). **b.** The fish movements overlain onto the accelerating velocity profile ($0\text{-}1.53\text{ m s}^{-1}$) created by the weir.

ADVs provide excellent temporal resolution, but arrays of ADVs that simultaneously collect velocity data are required to improve spatial resolution (Tritico *et al.*, 2007). As an alternative, flow visualisation techniques can be utilised to visualise and quantify hydrodynamic conditions. The “whole-flow field” and “zero-flow disturbance” nature of such techniques (e.g. Particle Image Velocimetry, Okamoto *et al.*, 2000) makes them an attractive alternative for mapping turbulent environments. The more sophisticated

techniques, such as PIV, require specialist equipment and expertise, which were unattainable during experimentation. As a result, ink induced flow visualisation techniques were employed to confirm the presence of turbulent characteristics, such as vortices shed behind a cylinder (Figure 4.3). Using a glass tube (6 mm diameter) placed vertically into the flow (0.5 cm under the water surface), five millilitres of India ink was dispensed into the water. The ink trail was recorded using the same overhead cameras used during fish behavioural trials.



Figure 4.3. Vortex street shed in the wake of an 11 cm diameter vertical cylinder at the ICER indoor flume facility, University of Southampton, UK.

4.5. Test species

4.5.1. Brown trout

The geographic distribution of Brown trout (*Salmo trutta*) stretches across Europe (Maitland, 2004). Brown trout have a variable life-history strategy; freshwater resident (potamodromous) and sea-run (anadromous) fish may develop within the same population, the specific reason for this divergence is largely unknown but thought to be influenced by both genetic and environmental factors (Nielsen *et al.*, 2003). Within England and Wales,

anadromous salmonid species (which included sea-run brown trout) have been afforded legislative protection through the Salmon and Freshwater Fisheries Act (1975), governing, among other factors, the development of fish passage structures at anthropogenic barriers.

Hatchery reared salmonids have been extensively used in experimental research to determine e.g. swimming kinematics in altered hydraulic environments (Liao *et al.*, 2003), behavioural responses to turbulence (Smith *et al.*, 2006), and to light stimuli (e.g. Nemeth & Anderson, 1992). As such, hatchery salmonids have become an easily accessible “model” fish for behavioural studies. However, previous research has noted morphological differences between fish of hatchery and wild origin, with hatchery fish characterised by smaller heads and fins, and deeper bodies (Fleming *et al.*, 1994). Furthermore, hatchery brown trout have lower swimming capabilities than wild fish (e.g. by approximately 25%; Pedersen *et al.*, 2008), while the cost of swimming in turbulent flow can be up to 30% higher for hatchery compared to wild Atlantic salmon (Enders *et al.*, 2004). Although there have been no direct comparisons made between rearing condition (wild vs. hatchery) on behaviour when encountering hydraulic and other environmental stimuli, observed behaviours (e.g. switches in orientation) of downstream moving hatchery brown trout encountering an accelerating velocity gradient in an open channel flume (Russon and Kemp, 2011) appear similar to those expressed by wild, migrant juvenile salmonids encountering similar conditions (Kemp *et al.*, 2005a; Enders *et al.*, 2009). Hatchery fish have been used in this body of research (Figure 4.4) when wild specimens were unavailable. This represents an ecologically sensitive research approach (i.e. not removing fish from wild populations). While research findings are likely to be applicable to other salmonid species, as well as wild and migrant life-stages, using hatchery fish also represents an unavoidable compromise and the potential influence of morphological and swimming capability differences on behaviour between rearing conditions should be considered when drawing conclusions from this research.



Figure 4.4. Throughout their range, brown trout represent an important angling species and an indicator of the environmental well-being of rivers.

4.5.2. Rainbow trout

Rainbow trout (*Oncorhynchus mykiss*) have been widely introduced across Europe, and although few self-sustaining populations exist in the British Isles, they are annually stocked for recreational fishing (Maitland, 2004). Native to the Pacific coastal basins of North America and Asia, both freshwater resident and anadromous (steelhead) populations exist. Throughout this body of research, the native brown trout has been used when possible, however, initially only hatchery rainbow trout were available at time of experimentation, and so were selected due to their comparability to brown trout.

4.5.3. Chinook salmon

Chinook salmon (*Oncorhynchus tshawytscha*) are distributed along the coastal basins of the North Pacific Ocean. In highly regulated river systems (e.g. the Columbia River basin) anthropogenic barriers have disrupted their anadromous life-cycle by blocking upstream access to historic spawning grounds, and delaying or injuring (e.g. during passage through hydroelectric dams) downstream migrating juvenile life-stages (Williams, 2008). Accordingly, Chinook salmon (Figure 4.5) are afforded legislative protection under the US Endangered Species Act (Ferguson *et al.*, 2007).



Figure 4.5. As juvenile salmon develop into the downstream migrant ‘smolt’ life-stage, they undergo a number of physiological and behaviour adaptations and are characteristically silver in colouration.

Although not native to Europe, completing a portion of this research in the US provided a unique opportunity to conduct behavioural studies on a large number of wild, actively downstream migrating juvenile salmonids. Access to this life-stage and in the quantities used was not possible in the UK. Furthermore, research has shown both Pacific and Atlantic salmon smolts to actively avoid abrupt velocity gradients (Haro *et al.*, 1998; Kemp *et al.*, 2005a; Kemp and Williams, 2009); and Pacific salmon and brown trout smolts to avoid overhead cover (Kemp *et al.*, 2005b; Greenberg *et al.*, 2012). Therefore, analogous to hatchery vs. wild fish, Chinook salmon smolt behaviour to hydraulic and other environmental stimuli will also likely be comparable to other salmonid species.

4.5.4. European eel

The catadromous European eel (*Anguilla anguilla*) migrates from freshwaters to oceanic spawning grounds in the Sargasso Sea (Tesch, 2003). The larval life-stage (leptocephali) utilise ocean currents to migrate to continental waters, as they develop into “glass eels”, they drift into estuarine areas and only embark on active upstream migration after metamorphosis into the pigmented “elver” life stage (Chadwick *et al.*, 2007). The main growth stage occurs within freshwater environments where they develop into “yellow eels” before maturing into “silver eels” which undertake the arduous oceanic spawning migration (Chadwick *et al.*, 2007).

Concerns over a decline in recruitment and fisheries of European (but also seen in the American (*A. rostrata*) and Japanese (*A. japonica*)) eel has resulted in their designation as

critically endangered by the International Union for Conservation of Nature (IUCN). In addition, the European Commission requires member states to develop stock recovery and Eel Management Plans to help conserve the species (Knights *et al.*, 2009). Changes in oceanic conditions are thought to be a large cause of the observed declines, however, anthropogenic activities within freshwater environments, such as pollution, habitat destruction and barriers to their migration may also be significant (Dixon, 2003; Chadwick *et al.*, 2007). Silver-phase European eels used in Chapter 5 were sourced from a commercial eel trapper on the River Stour, Dorset, UK.

4.5.5. River lamprey

The river lamprey (*Lampetra fluviatilis*) is principally anadromous (although some land locked populations occur) with a distribution from Southern Norway to the Western Mediterranean (Jenkins, 1925). After hatching, young lamprey larvae move downstream to areas of fine silt in slack water, where they burrow and stay for several years (Maitland, 2003). The metamorphosis from larva to adult takes place in a relatively short time (usually a few weeks, after several years of larval development), with the lampreys then migrating downstream. Being parasitic as adults they feed on various fish species, on completion of the oceanic feeding phase adult lampreys undertake upstream migrations to spawn (Kelly and King, 2001; Maitland, 2003).

Despite the large distribution of the species, their numbers have been in decline over the last century (Masters *et al.*, 2006). Many human activities have been attributed to their decline, with the construction of dams and weirs being highlighted as important causes (Kelly and King, 2001; Masters *et al.*, 2006; Kemp *et al.*, 2011). The river lamprey receives protection at a European level through the Habitats Directive (Directive 92/43/EC), with member states required to designate Special Areas of Conservation (SACs) for sites containing the habitats of the river lamprey (Bell and McGillivray, 2006). Other designations include, Annex V of the Habitats Directive, listing animal and plant species of European Community interest whose exploitation and taking in the wild may be subject to management measures (Kelly and King, 2001), Annex III of the Bern Convention (Conservation of European Wildlife and Natural Habitats (1979)) which permits some exploitation of its population (Maitland, 2003), and a Long List Species (or

Species of Conservation Concern) in the UK Biodiversity Action Plan (Joint Nature Conservation Committee, 2006).

To assess the behavioural response of lamprey to hydraulic features associated with upstream fish passage facilities (see Chapter 6), the adult migrant life-stage was required during experimentation (Figure 4.6). Lamprey were sourced from a commercial fishery on the River Ouse (Yorkshire, UK) which removes approximately 2 tonnes per year for use as bait by anglers (Maitland, 2004).



Figure 4.6. Lampreys have an elongated body morphology and lack paired fins which other fish may utilise to aid stability in turbulent flows.

The experimental protocols used throughout this thesis were assessed and approved by the University of Southampton Ethics Committee, while permission to handle Chinook salmon was provided from Washington (permit no: 09-198) and Oregon (permit no: 14550) States, and under NOAA Permit 2-09-NWFSC9.

Chapter 5

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

5.1. Summary

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 uneconomical, very low-head (< 2.5 m) hydropower sites. Legislation requires that environmental impacts of hydropower development must be assessed and mitigated for. This chapter incorporated numerical blade strike models (BSMs) and open channel flume experiments to determine the importance of behaviour when assessing impacts of a novel hydropower device on downstream moving fish. A Stochastic BSM intuitively 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 Hydrostatic Pressure Converter (HPC) under an experimental setting. Forty four percent of trout were struck by a blade, of these, 64% sustained physical injury deemed sufficient to have resulted in mortality had the fish been alive. 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 flow. Subsequent 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.

5.2. 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 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 EU Habitats Directive (92/43/EEC), EU Water Framework Directive (WFD) (2000/60/EC), and EU Eel Regulations (1100/2007). 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 are a key indicator of ecological status and thus require 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; Brown *et al.*, 2009b). Field studies, utilizing mark-recapture and telemetry techniques among others, 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.*, 2010) 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 damage, BSMs historically over estimate direct mortality (Turnpenny *et al.*, 2000).

Behaviour of fish during approach to, and passage through, turbines is thought to 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, 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 juvenile 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 and Williams, 2009). In contrast, downstream migrating adult eels, often considered particularly vulnerable to injury during turbine passage due to their large 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 the accuracy of BSMs can be enhanced 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 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 (Figure 5.1.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 (Figure 5.1.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 chapter was to determine the importance of behaviour when assessing the impact of a novel small-scale hydropower device (the HPC) on downstream moving fish. Three 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. collect empirical strike data to validate the BSM and determine types of damage sustained during passage, and; 3. quantify the behaviour of multiple species of fish as they approach a HPC

in the presence and absence of visual cues, and incorporate behaviour into the BSM. 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.

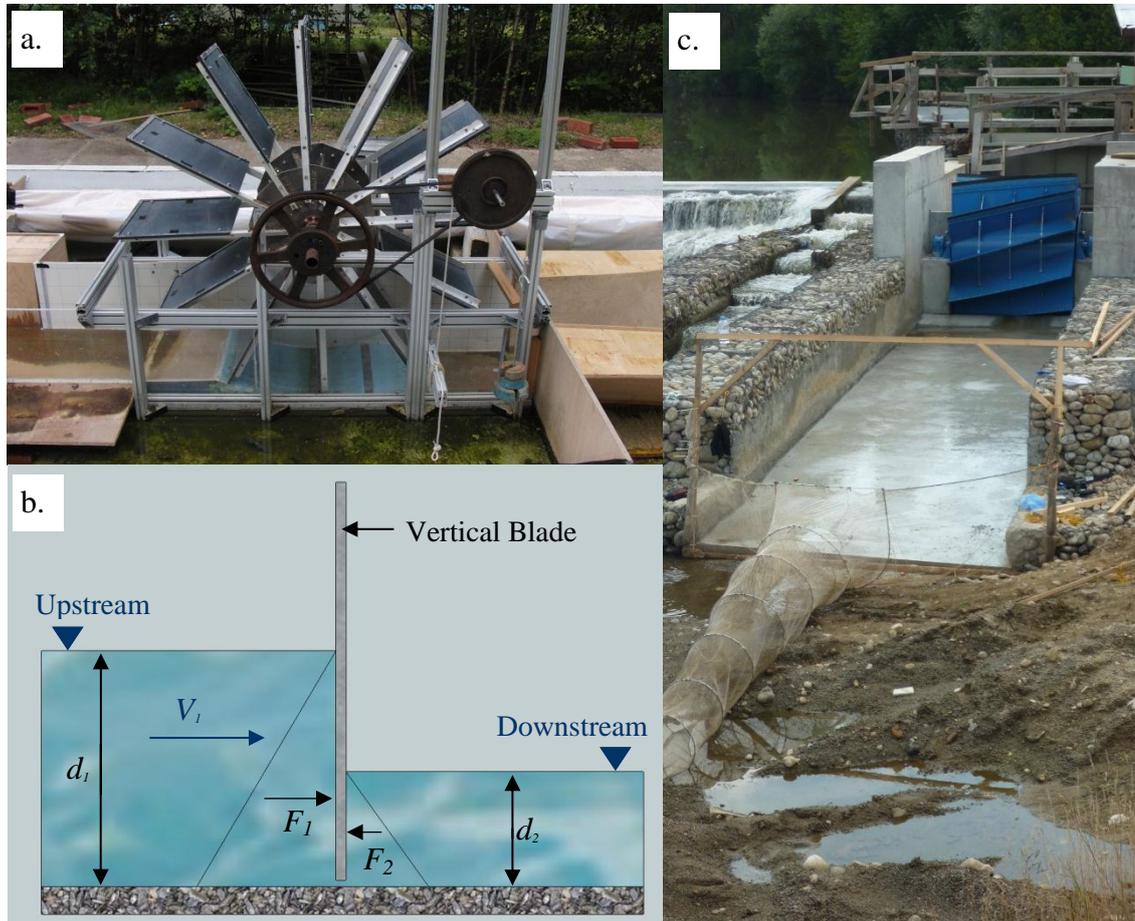


Figure 5.1.a. A prototype HPW installed in an outdoor flume at the ICER experimental facility. **b.** The basic operating principle of HPCs. The hydrostatic pressure force ($F_1 - F_2$) causes the device to travel with the water velocity V_1 and generate power. Energy conversion becomes a function of the ratio d_2 / d_1 . **c.** A HPM installed on a low-head weir in the River Iskar (Bulgaria).

5.3. Materials & methods

5.3.1. 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:

$$P = 100 \left(\frac{N_{\text{strike}}}{N} \right) \quad (5.1)$$

where N_{strike} is the number of model iterations where $T_{\text{fish}} > T_{\text{sweep}}$ and N is the total number of model iterations. T_{fish} is the time taken for the body of a fish to move past the arc of water swept by the blades (sec), and T_{sweep} is the time taken for the next blade to reach the location where the fish approached the arc (sec) (Figure 5.2). T_{fish} is calculated as:

$$T_{\text{fish}} = \frac{L_{\text{fish}}}{V_{\text{fish}}} \quad (5.2)$$

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} is calculated as:

$$T_{\text{sweep}} = \frac{L_{\text{sweep}}}{\bar{u}} \quad (5.3)$$

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 Figure 5.2), calculated as:

$$L_{\text{sweep}} = 2\pi r \left(\frac{A_{\text{blade}} - A_{\text{fish}}}{360} \right) \quad (5.4)$$

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 (Figure 5.2), this value was randomised within the model (anywhere along the arc, from the pinch point [the location where the blade tip first sweeps past the base of the channel] to a maximum arc distance upstream equal to the gap between two blades, by adjusting θ in equation 5 between 0 and 30°) unless otherwise stated (see Section 5.3.2). A_{fish} is the approach location of the fish along the arc (Figure 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:

$$= \left(\left(\frac{r}{\sin((180-\theta)/2)} \right) \sin \theta \right) * \sin(\alpha - ((180 - \theta)/2)) \quad (5.5)$$

where θ is the arc angle between A_{blade} or A_{fish} and the pinch point (Figure 5.2), and α is the angle between the blade face as it sweeps the pinch point and the channel floor (this was set at 120° based on a prototype HPW used during validation tests; Figure 5.2). 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 as:

$$A_{\text{blade2}} = A_{\text{blade}} + (2\pi r/n) \quad (5.6)$$

where n is the total number of HPW blades. In these instances the model replaces A_{blade} with A_{blade2} in equation 5.4.

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 5.1), 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:

$$\text{RPM} = 60 / \left(\frac{2\pi r}{\bar{u}} \right) \quad (5.7)$$

The HPW geometry (r and n) and water depth (d) remained constant and were based on a prototype HPW used during validation tests (see Section 5.3.2).

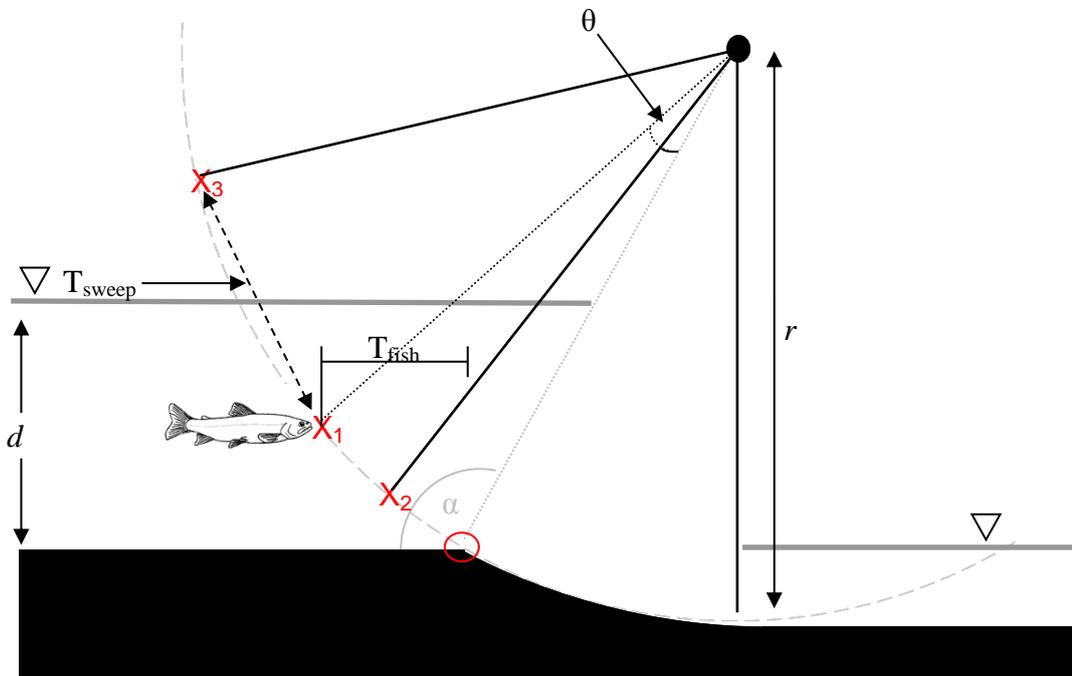


Figure 5.2. Schematic representation of the BSM. This fish approaches (A_{fish} , location indicated by X_1) after the sweep of blade 1 (A_{blade} , location indicated by X_2) but will be struck by blade 2 (A_{blade2} , location indicated by X_3) if T_{fish} is greater than T_{sweep} . The red circle marks the pinch point, and the arc swept by the blade tip is shown as a light grey dashed line.

Table 5.1. Parameters values used for the BSMs outlined in Section 5.3.1 (Stochastic BSM), Section 5.3.2 (Validation and Empirical Validation BSM), and Section 5.3.3 (Passive and Behaviour BSM). Key model parameters are illustrated in Figure 5.2.

Parameter	Stochastic BSM	Validation BSM	Empirical Validation BSM	Passive BSM	Behaviour BSM
r (m)	0.80	0.80	0.80	1.60	1.60
θ ($^\circ$)	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 ($^\circ$)	120	120	120	120	120
RPM	1 - 10	8.4	8.4	2.3	2.3
\bar{u} ($\text{m}^{-\text{s}}$)	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} ($\text{m}^{-\text{s}}$)	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}			
T_{sweep} (s)	Dependent on L_{sweep} and \bar{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 behavioural L_{fish} and behavioural V_{fish} values.

5.3.2. Model validation

To validate the BSM, 100 hatchery reared brown trout, *Salmo trutta* (mean total length \pm SD was 27.5 ± 2.9 cm), were euthanized and 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 damage); 3. ‘Strike’ with the leading edge of the blade causing no or minor damage; and 4. ‘Grinding’ of the fish between the blade and base of the channel at the pinch point, leading to severe damage. Photographs were taken pre- and post-passage to document 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 5.1) 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 5.3.1), 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) 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.

5.3.3. 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 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/m³) and 900 L (max density: 20.4 kg/m³) 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 mesh screens placed 0.07 and 6.7 m upstream of the rotating blade tips. 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 the start of each trial, where a single individual was released 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. While the date between experimental periods could introduce temporal bias into the results, practical considerations made it not possible to run day and night trials consecutively. However, 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 (night = $17.1 \pm 1.1^\circ\text{C}$; day = $16.0 \pm 1.1^\circ\text{C}$) between diurnal conditions. As such temporal biases are expected to be minimal.

Overhead and side-view cameras recorded fish behaviour on entering the area 1 m upstream of the most 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 5.1).

In the BSM simulations, the HPW diameter and upstream water depth during the flume tests were 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.

5.3.4. 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. For the Stochastic BSM, multiple regression analysis was used to investigate the relationships between L_{fish} , V_{fish} , and RPM with 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) determined the sensitivity of P to each parameter. Pearson's chi-square tested for differences between the Empirical Validation BSM estimate of P and number of fish observed contacting the leading edge of a HPW blade during validation tests. Mann-Whitney U tests determined if number of approaches, or period of occupancy within the observation zone was influenced by diurnal condition (day or night) or species. The influence of species (trout or eel) and BSM type (passive or behaviour) on mean probability of strike (after 100 simulations per model) was analysed using univariate two-way ANOVA.

5.4. Results

5.4.1. Blade strike model

The probability of blade strike (P) was positively related to L_{fish} and RPM, but negatively correlated with V_{fish} (Figure 5.3). 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 (Figure 5.3).

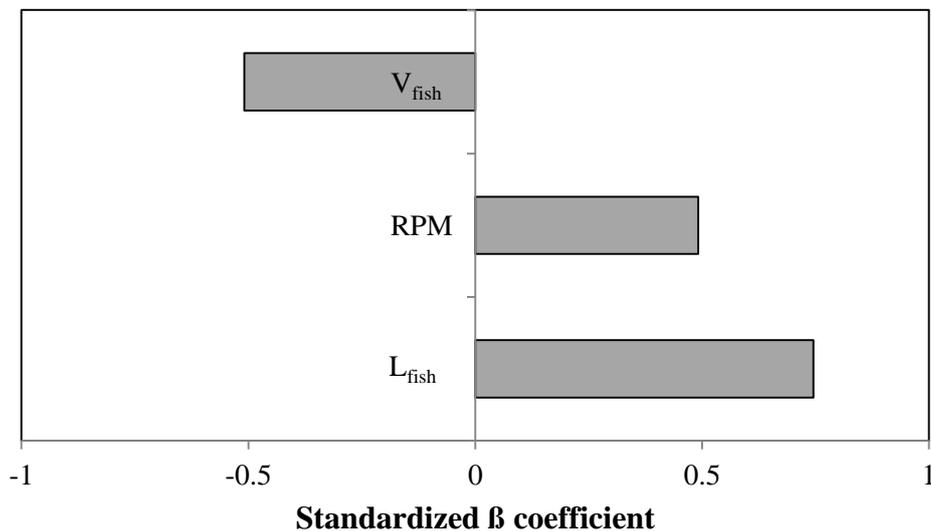


Figure 5.3. Standardized β coefficients from a multiple regression analysis indicating the sensitivity of P to three parameters; L_{fish} , RPM, and V_{fish} . All parameters significantly contributed to the regression model ($p < 0.001$).

5.4.2. Model validation

The Validation BSM overestimated P compared to that observed (Figure 5.4). 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 to the observed strike rate during the validation tests (Pearson chi-square: $\chi^2 = 0.18$, d.f. = 1, $p = 0.670$; Figure 5.4).

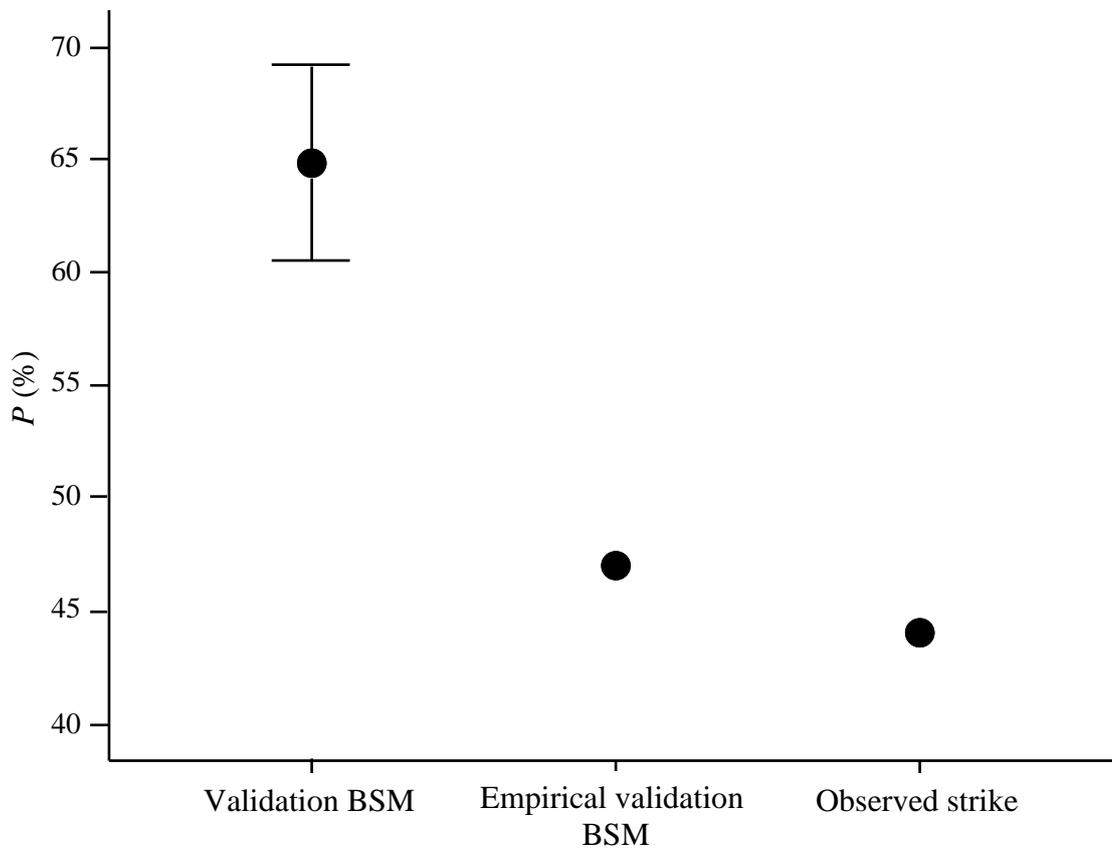


Figure 5.4. Results of 100 Validation BSM simulations (mean $P = 64.8\%$), the Empirical Validation BSM ($P = 47\%$) and the observed number of euthanized fish being struck by the HPW blade as they passively drifted downstream during the validation tests (observed strike = 44%). Error bars show the standard deviation of the Validation BSM simulations.

As fish passively drifted through the HPW, the most common outcome was ‘No contact’, followed by ‘Grinding’ (Table 5.2). All grinding events resulted in visible damage deemed sufficient to have resulted in mortality had fish been alive.

Table 5.2. The passage outcome and frequency of damage sustained to freshly euthanized brown trout ($N = 100$) passively drifting through a prototype HPW.

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

Damage sustained during grinding events included abrasive scale-loss, lacerations, and internal muscular and skeletal damage (Figure 5.5). Strike and grinding occurred in 44% of fish drifting through the HPW, 64% of these sustained damage.



Figure 5.5. Damage (a. abrasive scale-loss, b. lacerations, c. internal muscular and skeletal damage) sustained to brown trout passively drifting through a prototype HPW installed in an external flume at the ICER facility, University of Southampton (UK).

5.4.3. Fish behaviour

Number of approaches to the observation zone did not differ with diurnal period 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 \pm 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 exhibited a high level of positive and negative rheotaxis (Table 5.3), respectively. Trout were almost exclusively positively rheotactic both day and night. Eel orientation was more variable during the night (Table 5.3), although negative rheotaxis remained the dominant orientation during approach.

Table 5.3. Percent of total approaches to the observation zone (1m upstream of a prototype HPW), during which fish faced upstream (positive rheotaxis), downstream (negative rheotaxis) or perpendicular to the flow.

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

Occupancy time did not differ with diurnal period 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 (35:43 minutes for trout; 24:28 minutes for eels).

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

There was a significant 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 (Figure 5.6).

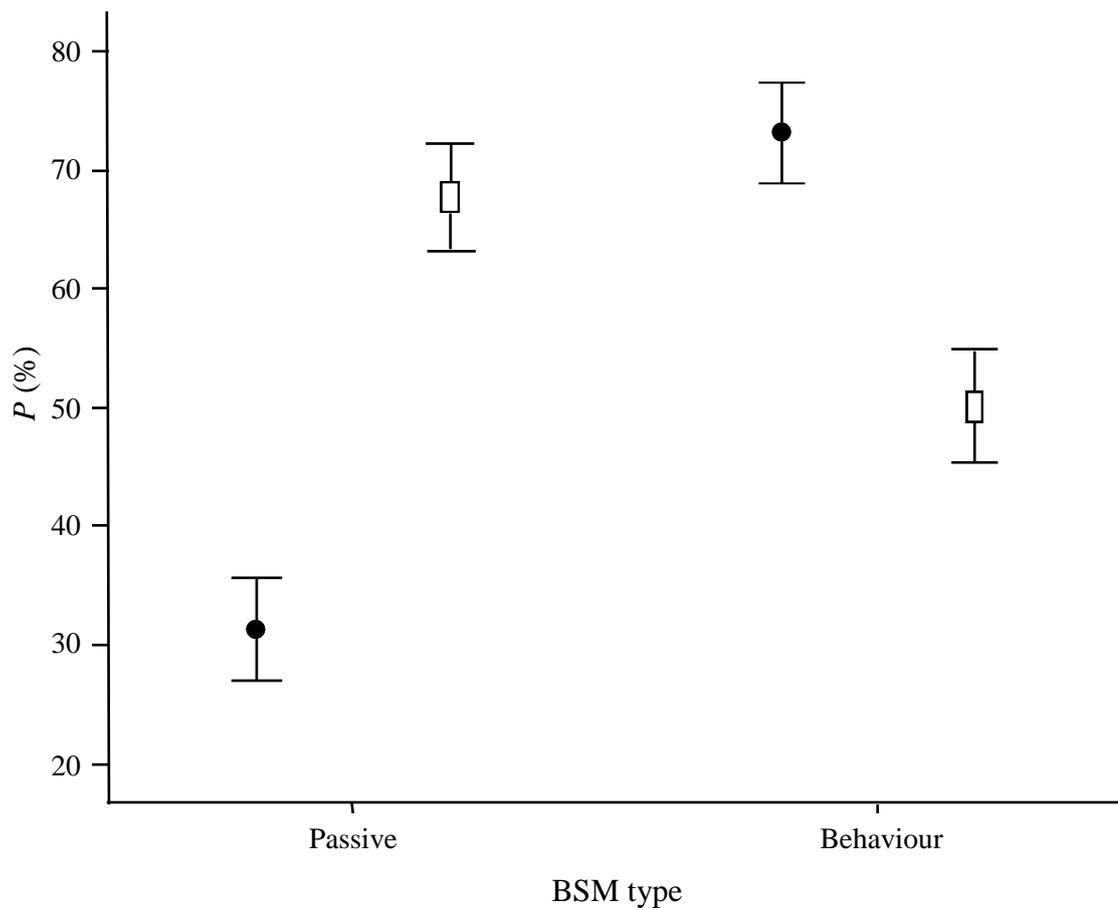


Figure 5.6. Probability of strike (P) for trout (black circles) and eel (clear rectangles) when passively drifting through a HPW while perpendicular to the flow (Passive BSM), and when OL_{fish} and OV_{fish} values were incorporated into the model (Behaviour BSM). Errors bars are $\pm 1 \text{ SD}$.

5.5. Discussion

A primary cause for concern related to the development of low-head hydropower is the potential for injury as a result of blade strike to fish that pass downstream through turbines (Bracken and Lucas, 2012). In this study, a Stochastic BSM intuitively predicted the probability of strike for fish that pass through a HPW to be positively related to body length and speed of blade rotation, and negatively related to speed of downstream movement.

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 main explanations for this discrepancy. First, the BSM was based on the assumption that fish were evenly distributed through the water column. However, during validation, fish were observed to “sink” somewhat during passive drift. On average, this caused fish to be farther away from the sweeping blades than predicted, and therefore strike rates were lower 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 accommodated when observed blade and fish locations were digitised and incorporated 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 fish sustained severe damage, deemed sufficient to have resulted in mortality had they been alive, during events in which they became trapped between the

blade tips and the base of the channel. The slow rotation speed of the blades ($< 1 \text{ m s}^{-1}$) meant that other contact (e.g. slap and strike) resulted in limited or no damage. 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 can be $< 1\%$ when passed through an Archimedean Screw Turbine with the leading blade edge protected with compressible rubber (Kibel, 2008; Kibel *et al.*, 2009).

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. For both species, approximately half of their time was spent immediately upstream of the device, with eels being more active and entering the observation zone more frequently. This lack of avoidance exhibited resulted in frequent contact with the screen, suggesting that both species would have likely passed through an unscreened 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 lower as contortion of the body reduced length available to be struck. However, their tendency to be substrate oriented increases probability of grinding between the blade and channel floor, and therefore severe injury during downstream passage. In contrast to eels that tend 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. A field study on a full-scale (10kW standalone) HPM (River Iskar, Bulgaria) showed severe injury to be approximately three-fold greater for live compared to dead brook trout (*Salvelinus fontinalis*) and rainbow trout passing downstream through the device (S. Karlsson, pers comm.; Vowles and Kemp, 2012), supporting the current finding that higher rates of mortality can be expected for salmonids, largely as a result of behaviour exhibited. Ultimately, behaviour influences probability of survival during passage through hydropower turbines when velocities are sufficiently low.

The influence of behaviour on fish survival during passage through turbines presents an interesting future research challenge. Behaviour could 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 approximately 1 m s^{-1} at turbine intakes to $15 - 18 \text{ m s}^{-1}$ at the blades. Fish may be unable to avoid blades, control orientation or 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.

5.6. Conclusions

The environmental impact of novel hydropower technologies requires assessment to ensure environmental legislative commitments are fulfilled. This chapter highlights that variation in probability and severity of blade strike with low-head hydropower devices is influenced by fish behaviour. For HPCs, severe injury is caused by grinding of fish at a pinch point created as blades sweep past the base of the channel. From an engineering perspective the gap between the blade tips and channel is reduced to a minimum to reduce leakage of water through the device, maximising energy conversion efficiencies (Senior *et al.*, 2010). Adapting the current blade design to leave a gap suitable for safe fish passage would eliminate the risks associated with the pinch point. However, the reduction in efficiency would reduce the economic viability of the device (G Müller, pers comm.). Flexible rubber blades have also been suggested as a potentially less damaging alternative to the current ridged blade design, with model testing indicating them to operate effectively from an engineering perspective (Paudel *et al.*, 2013). However, as the blades sweep the pinch point, the hydrostatic pressure exerted on the blade remains high, along with the likelihood of causing damage to fish (N Linton, pers comm.). Consequently, the engineers responsible for the design of HPCs have opted for the use of protective screens should a HPC be installed in the field. These physical screens would need to direct fish towards a bypass system, providing a safe, alternative route of passage. Delay to downstream moving fish associated with such mitigation strategies can impact individual fitness and requires

consideration during the design of hydropower facilities, a topic investigated further during Chapters 7 and 8. Behavioural screening devices could be considered in replacement of or in addition to physical screening if efforts to increase guidance and bypass efficiency are necessary. Additional considerations during low-head hydropower development are impacts to upstream migrating life-stages, whose movements can be blocked by the presence of low-head structures (an issue explored in Chapter 6).

Chapter 6

The influence of water velocity and turbulence on upstream migrant adult river lamprey (*Lampetra fluviatilis*) ascending an experimental channel

6.1. Summary

In this chapter the influence of water velocity and turbulence, hydrodynamic features ubiquitous with fish passes, on the behaviour of upstream migrant adult river lamprey (*Lampetra fluviatilis*), a species of conservation concern within Europe, was assessed in a large open channel flume. It was predicted that lamprey would; 1. at a coarse-scale avoid regions of elevated turbulence; 2. at a fine-scale select swim paths characterised by low velocity and low turbulence, and; 3. adjust swimming behaviour to minimise transit time through high velocity and turbulent environments. High velocity and turbulent flow did not attract or repel fish on a coarse- or fine-scale, nor did turbulence exert an influence on fish swimming speed. Turbulence, at least at the levels generated in this study, would not improve attraction to fish passes for lampreys. However, swimming speed was positively correlated with velocity encountered and water temperature. This may represent the adoption of a time conservation strategy, as suggested to occur in salmonids, where fish increase swimming speed to expedite passage through high velocity and more energetically costly environments. Such behaviour facilitates upstream passage, helping reduce delay for lampreys ascending fish passes. However, the impacts of temperature on swimming performance may have important implications for fish pass design and the efficiencies of these structures as the flow and temperature regimes of our rivers alter with shifts in future climate.

6.2. Introduction

Fish migrations for reproductive purposes are common (Lucas and Baras, 2001), and often considered adaptations to increase fitness through e.g. enhanced growth, fecundity or survival (Bernatchez and Dodson, 1987). These movements are also inherently costly, most obviously with regards to the energetic expenses of travelling large distances

(McDowall, 2001). For most anadromous fish, feeding stops prior to upstream migration and must be completed on finite energy reserves (Lucas and Baras, 2001). Anthropogenic development of river systems (e.g. the construction of dams and weirs) place additional energetic pressures on upstream fish migrations as they prevent, limit and delay longitudinal movements, fragmenting riverine habitats.

The construction of fish passes has been widely used to mitigate for longitudinal river fragmentation. Such structures can generate jetting, plunging, streaming and re-circulatory hydraulic conditions (Larinier, 1998; Silva *et al.*, 2011), with the aim of dissipating energy in flow via turbulence to reduce mean water velocities, and enable fish to progress upstream. However, recent research indicates the high levels of turbulence created in fish passes may negatively impact fish swimming performance (Tritico and Cotel, 2010), stability (Lupandin, 2005), and alter spatial preferences (Smith *et al.*, 2005b). For example, areas of high turbulent kinetic energy and the horizontal component of Reynolds shear stress have been linked with increased transit time of Iberian barbel (*Luciobarbus bocagei*) through an indoor full scale pool-type fish pass (Silva *et al.*, 2011; 2012). Avoidance of high turbulence environments was credited to the greater energetic expenditure required to maintain position within these locations (Silva *et al.*, 2011). Evaluations of existing fish passes have reported low efficiencies across a range of designs and species (Noonan *et al.*, 2011; Bunt *et al.*, 2012). Current fish passes are not achieving their primary function of restoring habitat connectivity, and may increase migration costs as fish have difficulty locating and ascending the high velocity, turbulent conditions they create.

Globally, many lamprey species are in decline (Beamish and Northcote, 1989; Nunn *et al.*, 2008). These declines have been attributed, at least in part, to anthropogenic barriers to their migration, which block access to large areas of suitable spawning habitat (Lucas *et al.*, 2009). Furthermore, fish passes are frequently reported as having low efficiencies for lamprey as they cannot ascend the high water velocities created (Moser *et al.*, 2002a) or may abandon upstream movement in response to disorienting turbulent flow (Haro and Kynard, 1997). For lampreys, turbulent environments may be particularly challenging as they have elongated morphologies and lack paired fins which other species use to facilitate stability (Webb, 2002; Liao, 2007). During upstream migrations lamprey may avoid areas of elevated turbulence, as was found with Iberian barbel, preventing or delaying entry into fish passes and progression up them.

Evidence indicates lamprey alter migratory behaviour when encountering hydrodynamic environments associated with anthropogenic barriers. When ascending an undershot weir in an experimental flume, river lamprey (*Lampetra fluviatilis*) express a burst-attach form of locomotion in response to the high velocities encountered. Lamprey would intersperse rapid bursts of upstream movement with periods of rest by attaching to the substrate using their oral disc (Kemp *et al.*, 2011). This behaviour was also evident in sea lamprey (*Petromyzon marinus*) during passage through constricted river sections characterised by elevated water velocity (Quintella *et al.*, 2004), and by sea and Pacific lamprey (*Lampetra tridentata*) encountering high velocity, turbulent conditions in fish passes (Haro and Kynard, 1997; Moser *et al.*, 2002b). Attachments could relate to a recovery time between burst swimming events used by lamprey to expedite passage through the high velocity and energetically expensive environments (Kemp *et al.*, 2011). Russon *et al.* (2011) further speculate that river lamprey select routes in an experimental flume characterised by reverse flows to reduce swimming costs (behaviour also suggested to occur in upstream migrating sockeye salmon, *Oncorhynchus nerka*, Hinch and Rand, 2000), although passage was still impeded by the experimental gauging weirs.

To help identify factors that may limit lamprey passage efficiency, additional behavioural information as they encounter hydrodynamic conditions associated with fish pass structures is required. This study assesses the influence of water velocity and turbulence, hydrodynamic features ubiquitous to fish passes, on the behaviour of upstream migrant adult river lamprey, a species of conservation importance in Europe (e.g. listed under the Habitats Directive 92/43/EEC), under experimental conditions. It was predicted that lamprey would; 1. on a coarse-scale avoid regions characterised by elevated levels of turbulence; 2. on a fine-scale select swim paths characterised by low velocity and low turbulence, and; 3. adjust swimming behaviour to minimise transit time through high velocity and turbulent environments.

6.3. Materials & methods

6.3.1. Experimental setup

Experiments were conducted in the indoor flume (21.4 m x 1.4 m x 0.6 m) at the ICER experimental facility. The flume was laterally divided by a 2 m Perspex sheet creating two channels of equal width (Figure 6.1). The channel divide was located 8 m upstream of a fine mesh screen that prevented experimental fish exiting the flume. Each trial consisted of a treatment channel containing either one 11 cm, or two 4 cm diameter vertical cylinders, and a control channel containing no cylinder (Figure 6.1). Different hydrodynamic conditions were created laterally across the flume downstream of each channel. A vortex street was created in the wake of the cylinders and propagated downstream of the treatment channels. This lateral half of the flume was characterised by elevated levels of turbulence and is subsequently referred to as the turbulent zone. Comparatively, flow was unidirectional downstream of the control channel, this lateral half of flume is subsequently referred to as the low-turbulent zone. A centrifugal pump (capacity $0.23 \text{ m}^3\text{s}^{-1}$) maintained a constant discharge throughout experimentation, however a blocking weir at the downstream end of the flume was adjusted to create a high (weir fully lowered) or low (weir raised 47.2 cm) velocity, generating different levels of turbulence between velocity setting. Water depth was 36.5 and 28 cm during the low and high velocity settings, respectively.

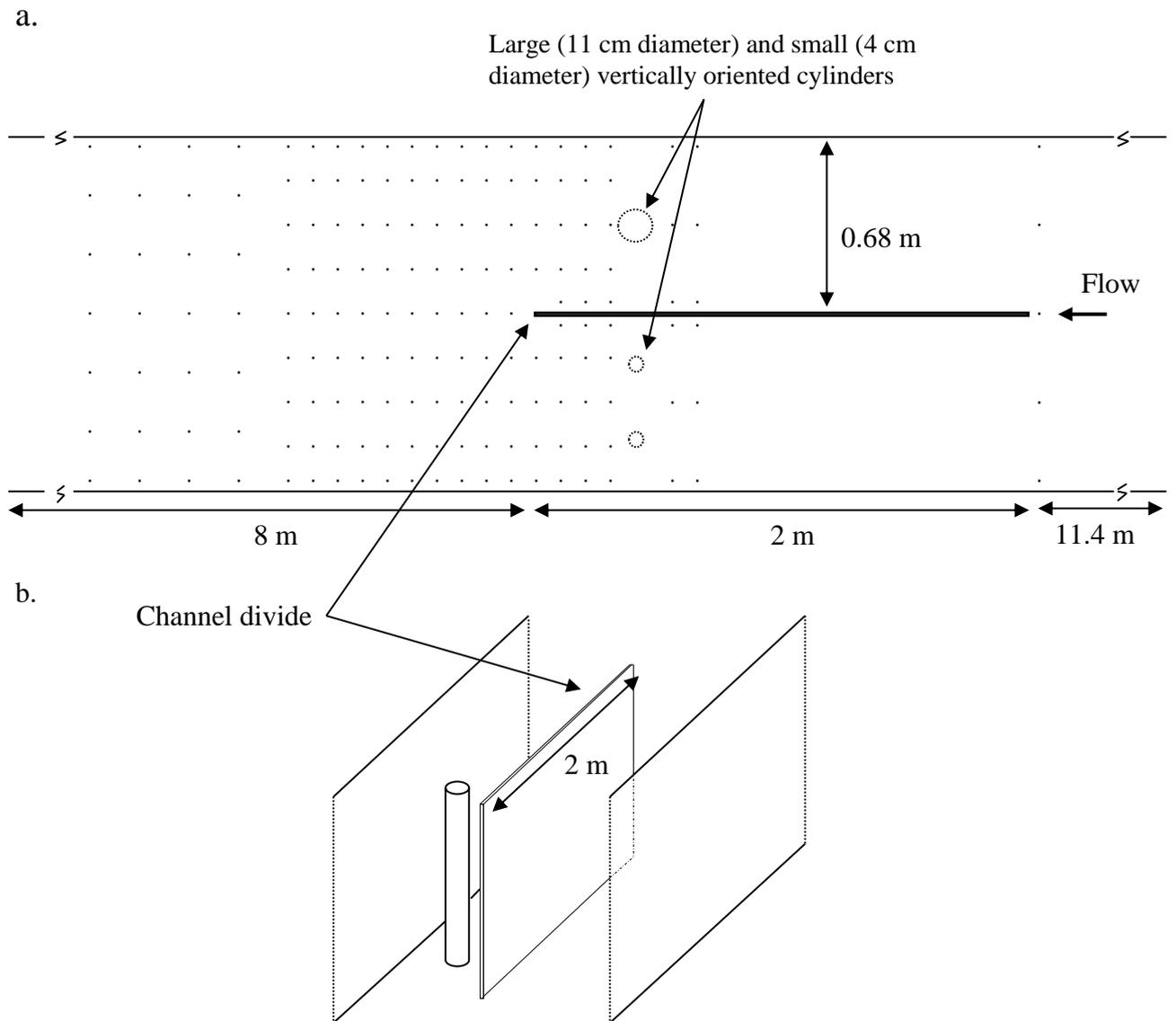


Figure 6.1.a. Plan view of the experimental channel used to assess the behavioural response of upstream migrating river lamprey as they encountered turbulence generated in the wake of vertical cylinders, dots on the channel floor represent ADV measurements locations, **b.** Three-dimensional view of the large vertical cylinder and the Perspex sheet which created two channels of equal width.

6.3.2. *Experimental protocol*

Trials were conducted during two experimental periods, 2009 and 2010. Eighty trials took place between 15-21 December 2009, and a further 52 between 8-14 December 2010. All trials were conducted during hours of darkness (18:00-04:00 in 2009, 17:00-01:00 in 2010) as lampreys are primarily nocturnal migrants (Kelly and King, 2001). In total 33 trials were conducted for each of four treatments; large vortex – high (LV - High), large vortex – low

(LV - Low), small vortex – high (SV - High) and small vortex – low (SV - Low). Trials were designated as large or small vortex, and high or low dependent on the cylinder size used to generate the vortices and water velocity setting, respectively. Vortex size (and location of cylinder, i.e. right or left channel), and velocity were alternated throughout the testing period to control for temporal or lateral bias. Continual running of the centrifugal pump caused water temperature to increase (see Kemp *et al.*, 2011). To control for this, trials ceased if flume temperatures increased by more than 2°C in comparison to that evening's start temperature. Average flume water temperature during experimentation was 10.7 (\pm SD 1.0), and 6.7 (\pm SD 0.8) °C during 2009 and 2010, respectively. At the start of each daily experimental period fish were placed into a perforated container located 8 m downstream of the channel divide and allowed to acclimatise for a minimum of 1 hour prior to the start of the first trial. As a trial commenced a single fish was released from the container and allowed to volitionally ascend the flume. Each trial either lasted until the lamprey had passed upstream through the divided section of flume or until 30 minutes had elapsed. At the end of each trial fish were removed from the flume before being measured and weighted. Each fish was used once only during the study. The passage behaviour of lamprey as they moved upstream was monitored until they entered the treatment or control channel using an overhead low light video camera. Infra-red lighting units allowed fish movements to be observed under low light levels (mean light level at channel divide = 0.14 \pm SD 0.15 lux).

6.3.3. Hydrodynamics

Mean and standard deviations (σ) of water velocity in the longitudinal (u), lateral (v) and vertical (w) plane were measured using an Acoustic Doppler Velocimeter (ADV) (Vectrino⁺, Nortec), sampling at 50 Hz with a sample volume set at 0.31 cm³. Three thousand velocity readings were taken over the 60 second sampling duration at each discrete sampling point (Figure 6.1). ADV measurements allowed the mean velocity vector (V), and turbulent kinetic energy (TKE) to be calculated. TKE is a measure of the kinetic energy added to a flow through the presence of vortices (per unit volume), and has been shown to influence the spatial positioning of fish in experimental flumes (Smith *et al.*, 2006) and transit time through prototype fishways (Silva *et al.*, 2011). V was calculated as:

$$V = \sqrt{\bar{u}^2 + \bar{v}^2 + \bar{w}^2} \quad (6.1)$$

where \bar{u} , \bar{v} and \bar{w} are the mean longitudinal, lateral and vertical velocity components (in m s^{-1}), respectively. TKE (J m^{-3}) was calculated as:

$$TKE = 0.5\rho(\sigma_u^2 + \sigma_v^2 + \sigma_w^2) \quad (6.2)$$

where ρ is water density (1000 kg m^{-3}) and σ_u , σ_v , and σ_w is the standard deviation of water velocity in the longitudinal, lateral and vertical velocity components, respectively. Hydrodynamic contour plots of the test conditions were generated using spline interpolation in the Spatial Analyst tool in ArcGIS 10 (ESRI, Redlands, CA, USA). Flow visualisation techniques confirmed the formation of vortex streets within the turbulent zone, and theoretical calculations provided estimates of the scale and structure of turbulence (vortex shedding frequency and wake wavelength). Vortex shedding frequency (f_s) was estimated as:

$$f_s = \frac{St * u}{D} \quad (6.3)$$

where St is the non-dimensional Strouhal number (0.2), commonly applied to predict shedding frequencies from structures in laboratory experiments (Blevins, 1990; Lacey *et al.*, 2012), u is water velocity around the cylinder, and D is the diameter of the cylinder shedding the vortices. u was calculated as:

$$u = u_1 * \left(\frac{W}{W-D} \right) \quad (6.4)$$

where u_1 is the mean water velocity immediately upstream of the cylinder and W is the width of the treatment channel. The wake wavelength of the vortex street, an indication of the distance between successive vortices, was calculated as:

$$\lambda = \frac{u}{f_s} \quad (6.5)$$

6.3.4. Fish behaviour

Fish that did not ascend the flume and pass through the channel divide within the 30 minute time limit were omitted from further analysis. Seventy-nine, 67, 81, and 79% of fish were included in the analyses for the LV - High, LV - Low, SV - High and SV - Low treatments, respectively.

6.3.4.1. Channel selected

The overhead camera monitored an area of flume that ranged from 0.2 m up- to 1.95 m down-stream of the channel divide, a longitudinal distance of 2.15 m (hereafter referred to as the test area). Video footage of fish ascending the test area, and passing into either the treatment or control channel, was post processed using Logger Pro Version 3.8.2 (Vernier Software, Beaverton, OR, USA). Channel selected was recorded and head locations manually tracked on a frame-by-frame basis for further behavioural analysis.

6.3.4.2. Hydrodynamics encountered

Coordinates derived from the tracking software were imported into ArcGIS and overlain onto hydrodynamic profiles enabling the extraction of underlying data values. To test whether lamprey selected paths characterised by low velocity and turbulence when ascending the flume, mean hydrodynamic values for the real fish paths were compared to those encountered by an equal number of “random” paths generated by a Correlated Random Walk (CRW) model (Hawth’s Analysis Tools for ArcGIS v3.27; Beyer, 2004). CRWs commenced at the downstream end of the test area with a lateral position randomly assigned according to a uniform distribution. Step length (l) and turn angle (τ) distributions for the CRWs were generated from mean and standard deviation values calculated from the actual swim paths of each treatment. Step length was calculated as:

$$l = D/S \quad (6.6)$$

where D is the distance travelled during passage through the test area, and S is the number of steps (or frames) derived from the video analysis. Distance between successive frames (d), relative to the ground, was calculated as:

$$d = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \quad (6.7)$$

where x_1 and y_1 are the head coordinates on the x and y axis respectively for a specific video frame, and x_2 and y_2 are the head coordinates for the following frame. By summing the distance between successive frames, the total distance travelled through the test area (D) was calculated for each fish. Turn angle (τ) between successive head locations was calculated as:

$$\tau_t = \theta_{t+1} - \theta_t \quad (6.8)$$

where θ_t is the angle between head locations at time t . θ_t was calculated as:

$$\theta_t = \arctan\left(\frac{\Delta y}{\Delta x}\right) * 180 / \pi \quad (6.9)$$

where Δy and Δx is the difference in coordinate position on the x and y axis, respectively, between successive points. The CRW model assigned an upstream directional persistence, ensuring CRWs ascended the flume. As with actual swim paths, CRWs were overlain onto hydrodynamic profiles and underlying data values extracted.

6.3.4.3. *Swimming speed*

Transit time through the test area was determined by calculating fish swimming speed, relative to water velocity. Swimming speed was calculated as the distance travelled divided by time taken to pass through the test area. The average V encountered during passage was then added to this value to correct for water velocity.

6.3.5. *Capture & maintenance of experimental fish*

Upstream migrant adult river lamprey (mean total length and mass = 36.3 ± 19.6 cm, 78.8 ± 10.1 g, respectively) were captured from the tidal River Ouse, Yorkshire, North-East England on 10 December 2009 using un-baited commercial eel traps (Masters *et al.*, 2006), and transported directly to the ICER experimental facility, in aerated tanks containing river water. Fish were placed into a 3000 L holding tank for 5 days under ambient water temperature ($9.3 \pm \text{SD } 0.3$ °C) and natural photoperiod until trials commencing (maximum

stocking density = 2.1 kg m^{-3}). No food was provided as lampreys do not feed during their spawning migration. Tank water was aerated and quality maintained (e.g. nitrite $< 1 \text{ mg L}^{-1}$ and nitrate $< 50 \text{ mg L}^{-1}$) using a submersible pond pump, filter system, and weekly water exchange (approximately 10%).

On 3 December 2010, adult river lamprey (mean total length and mass = $37.2 \pm 26.0 \text{ cm}$, $92.4 \pm 18.4 \text{ g}$, respectively) were collected from the same location, and transported and maintained in holding tanks using the same methods as in 2009. Ambient holding tank temperature and maximum stocking density was $6.1 (\pm 1.0) \text{ }^\circ\text{C}$ and 1.8 kg m^{-3} , respectively. Trials commenced 5 days after collection.

6.3.6. Statistical analysis

Tests of normality and homogeneity of variance were performed using a Shapiro-Wilk and Levene's statistic, respectively. Non parametric tests were used on data that could not be normalised. Differences between years were tested prior to further statistical analysis.

Where there was no difference between years, data were pooled. A binary logistic regression determined the influence of vortex size (large or small), velocity setting (high or low), temperature, and the interaction between these predictors on channel selected.

Differences between average V and TKE encountered by lamprey were compared with those of "random" swim paths, generated from Correlated Random Walk models, using Mann-Whitney U tests. The influence of vortex size and velocity setting (fixed factors) on swimming speed was assessed using two-way univariate analysis of variance. Temperature was included as a covariate. Multiple regression was used to investigate the relationship between V and TKE encountered, and water temperature on swimming speed.

6.4. Results

6.4.1. Hydrodynamics

Average velocity was similar in the turbulent and low-turbulent zones of the flume (Table 6.1). TKE was greater through the turbulent zones and under the high compared to low velocity treatments (Table 6.1). Water velocity accelerated as it flowed around the cylinders, while areas behind the cylinder were characterised by elevated levels of TKE that dissipated as it flowed downstream (Figure 6.2). Vortex shedding frequency increased

with velocity (for the large cylinder: 1.12 and 0.85 vortices per second during high and low treatments, respectively; for the small cylinder: 2.75 and 2.16 vortices per second during the high and low treatments, respectively), while wake wavelength remained constant between velocity settings (0.55 m and 0.20 m for the large and small cylinders, respectively), in keeping with hydrodynamic theory (Blevins, 1990).

Table 6.1. Mean and range of water velocity (V) and turbulence (TKE) for the total test area, turbulent and low-turbulent zones of the experimental flume, for the four treatments tested.

Treatment	Location	Statistic	V (m s ⁻¹)	TKE (J m ⁻³)
LV - High	Total test area	Mean	0.52	6.83
		Range	0.03 - 0.71	0.69 - 103.63
	Turbulent zone	Mean	0.50	12.13
		Range	0.03 - 0.71	0.90 - 103.63
	Low-turbulent zone	Mean	0.54	1.53
		Range	0.37 - 0.61	0.69 - 10.47
LV - Low	Total test area	Mean	0.39	4.27
		Range	0.05 - 0.49	0.47 - 74.45
	Turbulent zone	Mean	0.38	7.55
		Range	0.05 - 0.49	0.85 - 74.45
	Low-turbulent zone	Mean	0.41	1.00
		Range	0.27 - 0.45	0.47 - 4.87
SV - High	Total test area	Mean	0.53	4.10
		Range	0.37 - 0.60	0.66 - 55.59
	Turbulent zone	Mean	0.51	6.60
		Range	0.37 - 0.60	1.04 - 55.59
	Low-turbulent zone	Mean	0.54	1.42
		Range	0.37 - 0.60	0.66 - 8.77
SV - Low	Total test area	Mean	0.39	1.82
		Range	0.30 - 0.46	0.45 - 12.62
	Turbulent zone	Mean	0.39	2.68
		Range	0.30 - 0.46	0.78 - 12.62
	Low-turbulent zone	Mean	0.40	0.95
		Range	0.30 - 0.44	0.45 - 4.73

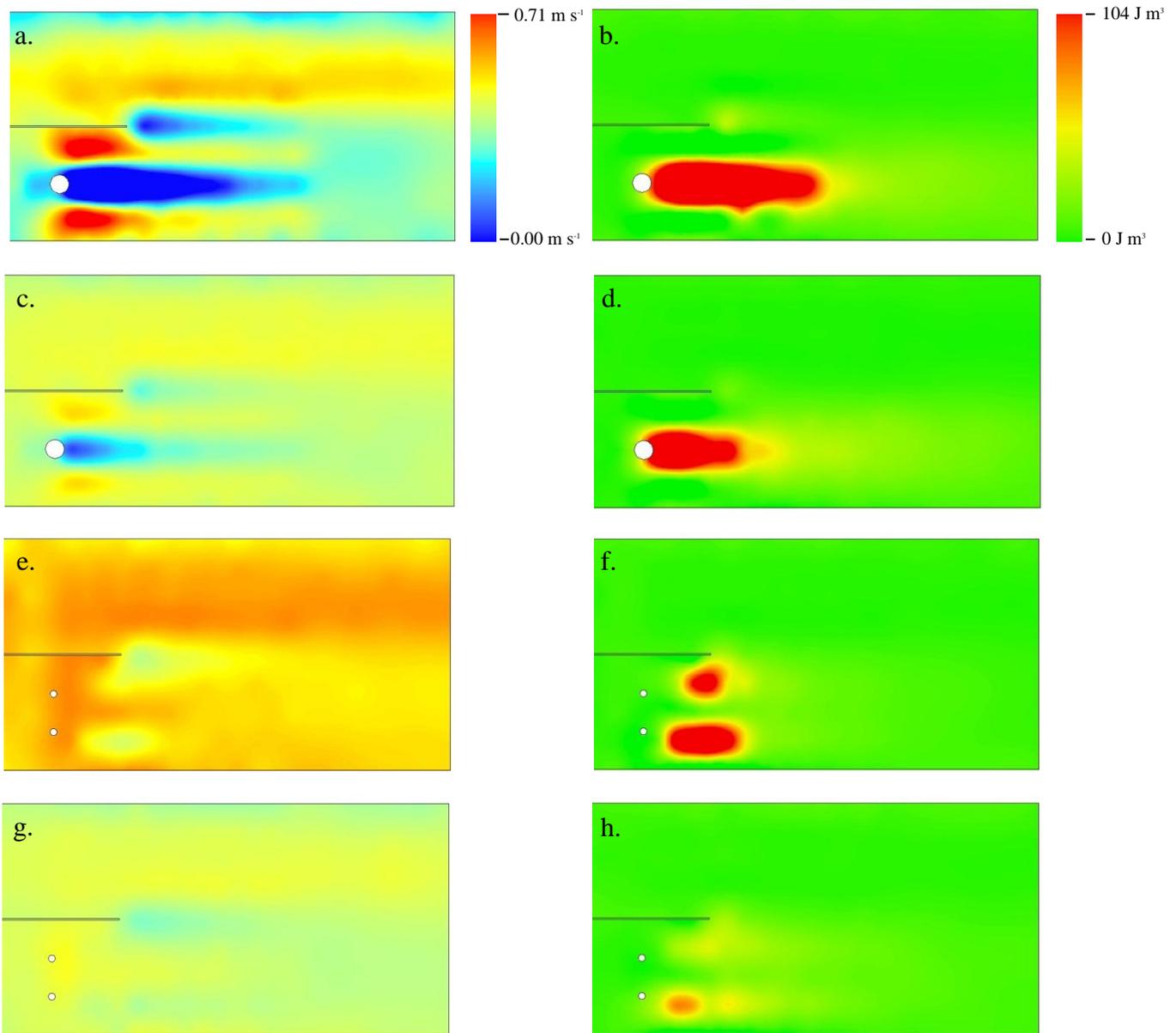


Figure 6.2. Velocity (V) profiles during the **a.** LV – high, **c.** LV – low, **e.** SV – high, **g.** SV – low treatments; and turbulence (TKE) profiles during the **b.** LV – high, **d.** LV – low, **f.** SV – high, **h.** SV – low treatments. Water flowing from left to right.

6.4.2. Fish behaviour

6.4.2.1. Channel selected

Channel selected (treatment or control) was not influenced by year ($\chi^2 = 0.01$, d.f. 1, $P = 0.943$) and so data between years were combined. Vortex size (large or small), velocity setting (high or low), flume temperature, nor the interaction between these variables were significant predictors of the channel selected by upstream moving lamprey (Logistic

regression model $\chi^2 = 9.18$, d.f. 7, $P = 0.240$). On a coarse-scale, lamprey did not avoid regions of elevated turbulence (Figure 6.3).

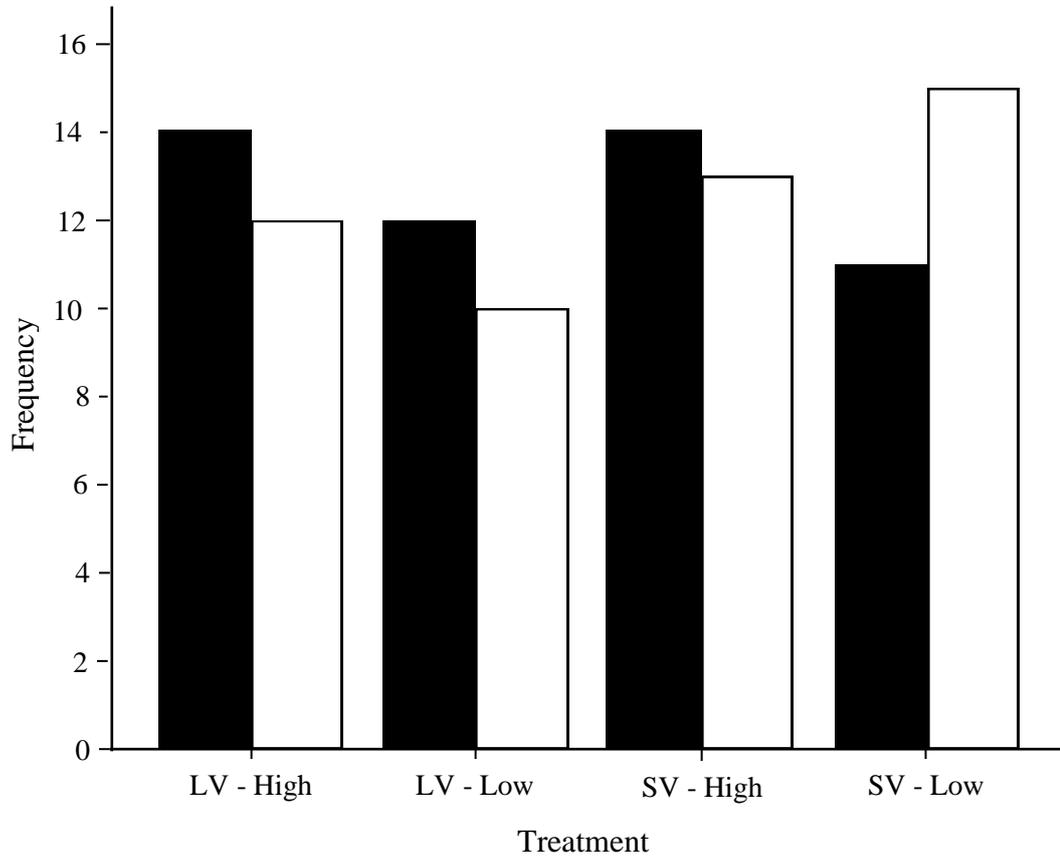


Figure 6.3. Channel selected by lamprey ascending an experimental flume and encountering either a turbulent treatment channel or a low-turbulent control channel. Black and clear bars represent the number of lamprey selecting the turbulent and control channels, respectively.

6.4.2.2. Encountered hydrodynamics

For the SV – High treatment, encountered levels of V ($U = 23$, $z = -2.98$, $p < 0.01$) and TKE ($U = 36$, $z = -2.32$, $p < 0.05$) differed between years. Lower V but higher TKE were encountered in 2009 compared with 2010. For the SV – Low treatment, higher levels of TKE were encountered in 2010 ($U = 34$, $z = -2.11$, $p < 0.05$), but no difference in V between years was found ($U = 66$, $z = -0.33$, $p = 0.739$). For the remaining two treatments hydrodynamics encountered did not differ between years (for LV - High, V : $U = 66$, $z = -0.57$, $p = 0.571$, TKE : $U = 57$, $z = -1.05$, $p = 0.293$, and for LV - Low, V : $U = 49$, $z = -0.48$,

$p = 0.633$, TKE : $U = 47$, $z = -0.61$, $p = 0.539$). For treatments with no statistical difference in encountered hydrodynamics between years, data were combined.

Lamprey did not encounter significantly different levels of V or TKE compared to those encountered by CRW models for any of the treatments tested (Table 6.2). On a fine-scale, lamprey did not select swim paths characterised by lower levels of velocity or turbulence in comparison to random swim paths.

Table 6.2. Mean velocity (V) and turbulent kinetic energy (TKE) encountered by lamprey as they ascended a test area of experimental flume during four different treatments, in comparison to those encountered by swim paths generated by Correlated Random Walk models.

Cylinder size	Velocity	Year	Sample size	Mean V (m s^{-1})		Mann-Whitney U	Mean TKE (J m^3)		Mann-Whitney U
				Lamprey	CRW model		Lamprey	CRW Model	
Large	High	Combined	26	0.52	0.53	$p = 0.176$	6.62	4.98	$p = 0.380$
Small	High	2009	18	0.51	0.50	$p = 0.825$	4.48	3.48	$p = 0.343$
Small	High	2010	9	0.54	0.53	$p = 0.270$	2.51	3.47	$p = 0.270$
Large	Low	Combined	22	0.39	0.39	$p = 0.981$	4.32	3.55	$p = 0.742$
Small	Low	2009	18	N/A	N/A	N/A	1.27	1.44	$p = 0.635$
Small	Low	2010	8	N/A	N/A	N/A	1.87	1.17	$p = 0.115$
Small	Low	Combined	26	0.39	0.39	$p = 0.784$	N/A	N/A	N/A

6.4.2.3. Swimming speed

When water velocity was high there was a difference in lamprey swimming speed between years for both the large ($t = 2.32$, d.f. 24, $p < 0.05$) and small ($t = 2.28$, d.f. 25, $p < 0.05$) vortex treatments. When water velocity was low, swimming speed did not differ between years (for large vortex: $t = 0.78$, d.f. 20, $p = 0.527$; for small vortex: $t = 0.87$, d.f. 24, $p = 0.384$; Figure 6.4). High water velocity ($F_{1,96} = 16.17$, $p < 0.001$) and temperature ($F_{1,96} = 11.00$, $p = 0.001$) significantly increased swimming speed, vortex size had no effect ($F_{1,96} = 0.44$, $p = 0.507$). There was no interaction between independent variables ($F_{1,96} = 1.29$, $p = 0.259$). Swimming speed was positively correlated with V encountered (Figure 6.5a) and temperature (Figure 6.5b), but not with TKE (Table 6.3).

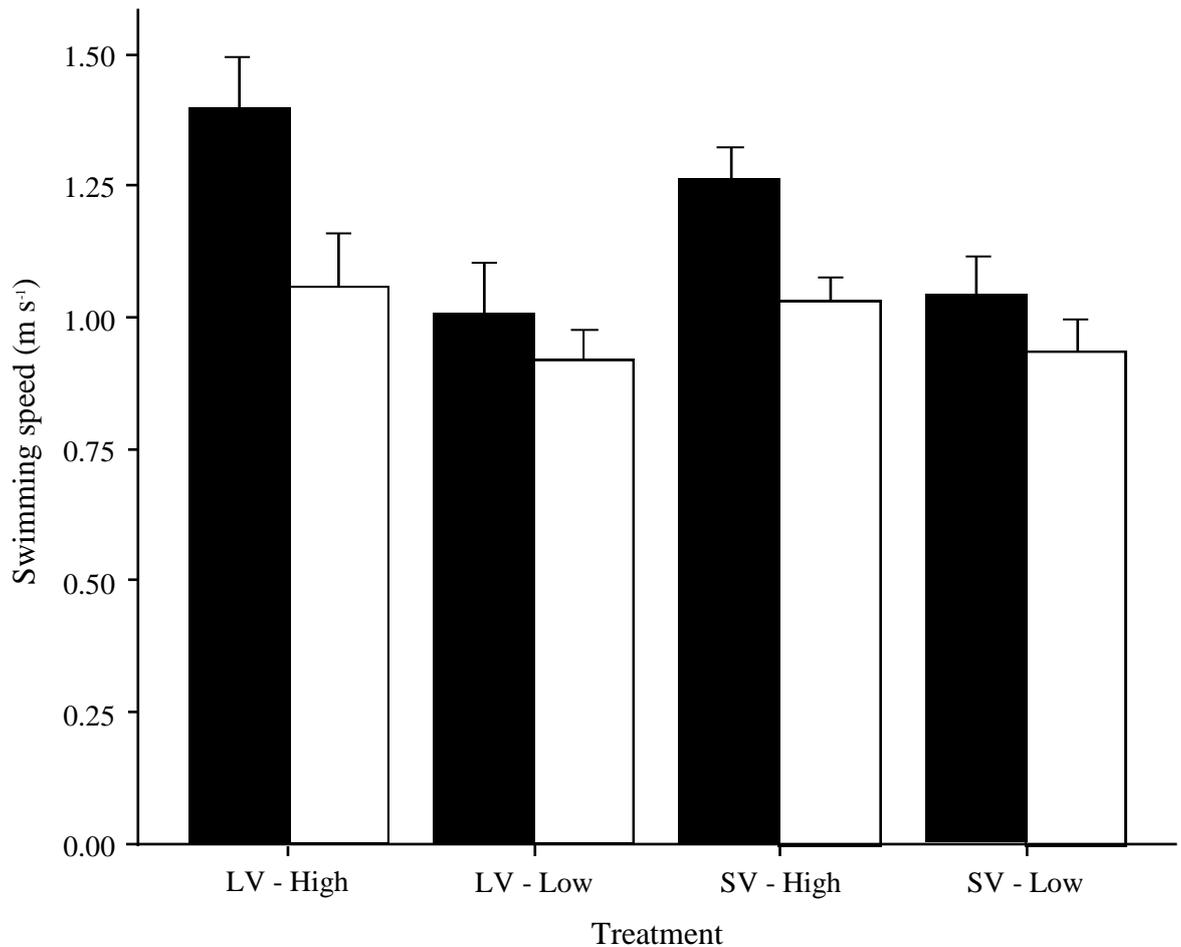


Figure 6.4. Mean swimming speeds of lamprey ascending a test area of experimental flume for four different treatments during the 2009 (black bars) and 2010 (clear bars) testing periods. Error bars depict + 1 SE of the mean.

Table 6.3. The influence of predictor variables on swimming speed, with 95% bias corrected and accelerated confidence intervals reported in parentheses. Confidence intervals and standard errors based on 1000 bootstrap samples.

Predictor	<i>b</i>	<i>SE B</i>	β	<i>p</i>
Constant	-0.15 (-0.61-0.28)	0.23	N/A	N/A
<i>V</i> encountered	1.78 (0.93-2.72)	0.43	.37	0.001
<i>TKE</i> encountered	0.00 (0.01-0.02)	0.01	.04	0.581
Temperature	0.05 (0.02-0.07)	0.01	.30	0.001

$R^2 = .23$. Model $F_{3,97} = 9.59$, $p < 0.001$

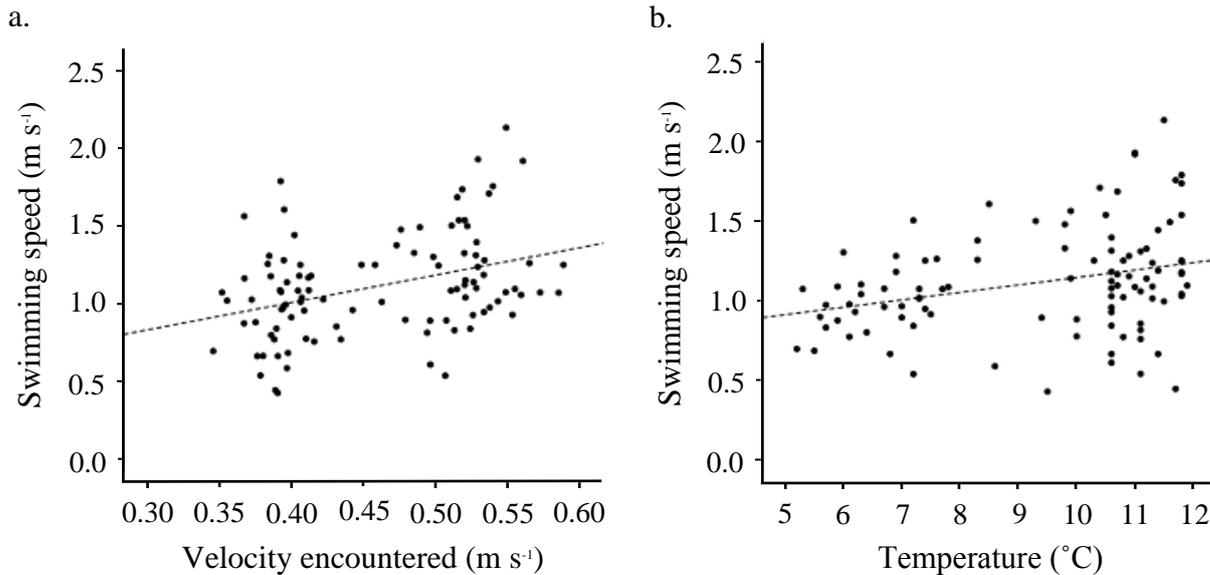


Figure 6.5.a. Mean velocity (V in m s^{-1}) encountered and **b.** flume temperature ($^{\circ}\text{C}$) during trials in relation to the swimming speed of lamprey ascending the test area of a large open channel flume at the ICER experimental facility.

6.5. Discussion

Fish passes are commonly used to mitigate for reduced habitat connectivity caused by anthropogenic barriers. To be effective, fish passes must attract fish to the entrance, create conditions that enable fish to ascend upstream against the flow, and do so with minimum delay and energetic cost (Bunt, 2001). For upstream migrant adult lampreys, fish passes are frequently reported as having low efficiencies, and for the river lamprey, a migratory species of conservation concern in Europe, efforts to improve fish pass facilities have only recently been undertaken (e.g. Kemp *et al.*, 2011). This study assesses the behaviour of upstream migrant river lamprey as they encounter hydrodynamic conditions associated with fish passes.

When ascending a large open-channel flume, river lamprey did not avoid regions of elevated turbulence. For fish passes, the elevated levels of turbulence generated at the downstream entrance may not be reducing attraction efficiencies by causing behavioural avoidance of these regions. This could be considered advantageous as turbulence is a hydrodynamic condition ubiquitous with such structures, and has been suggested to reduce the success of other non-salmonids at locating and using fish passes (e.g. Haro & Kynard,

1997; Bunt *et al.*, 2000). Conversely, there was no evidence that lamprey were attracted to the more turbulent regions of the flume, indicating it not to be a suitable stimulus for attracting and ensuring efficient entry into fish passes. This is in contrast to the suggestion that low levels of turbulence may be useful for guiding fish to preferred passage routes (Coutant, 2001). For example, a recent flume study reports attraction towards a turbulent plunging flow to be twice that of a low-turbulent alternative route for upstream migrant juvenile European eel (A Piper, pers comm.). Unfortunately, as no attraction or avoidance was evident in the current study, it is not possible to suggest the use of (or reduction in) turbulence to improve the efficiencies of fish passes for upstream migrating lampreys. However, generating extremely high levels of turbulence in fish passes should be avoided as they have previously been observed to disorient lamprey (Haro and Kynard, 1997).

When considering the fine-scale swim paths of lamprey as they ascended the test area of flume, encountered hydrodynamics did not differ to those generated by a Correlated Random Walk model. This suggests that lamprey did not alter their swimming trajectory to avoid high velocity and turbulent environments. Such behaviour has previously been observed in sockeye (*Oncorhynchus nerka*) and pink (*Oncorhynchus gorbuscha*) salmon when moving through small reaches of river; they select lower than average velocity routes, minimising exposure to high and more energetically costly flows (Standen *et al.*, 2002; 2004). Some differences in encountered hydrodynamics between years was evident; however there was no clear pattern. During the small vortex – high velocity treatment, lower levels of velocity but higher levels of turbulent kinetic energy (*TKE*) were encountered in 2009 compared to 2010. It could be that as water temperature dropped in 2010, so did lamprey swimming ability, resulting in greater avoidance of more challenging turbulent environments. However, for the small vortex – low velocity treatment, greater levels of *TKE* were encountered in 2010, when temperature was lower. Such contrasting results make it difficult to draw strong conclusions on examination of the fine-scale swim paths of river lamprey.

Lamprey are known to adapt their swimming behaviour to facilitate passage through more energetically costly environments, most commonly this has been observed as expression of a burst-attach swimming behaviour when encountering high velocities (Moser *et al.*, 2002b; Quintella *et al.*, 2004; Kemp *et al.*, 2011). In this study, attachments to the substrate (at least in the test area) were rare, and lamprey did not avoid high velocity and turbulent

environments at a coarse- or fine-scale. However, they did increase their swimming speed in response to high water velocities. A lack of correlation between swimming speed and *TKE*, suggests that lamprey were responding primarily to water velocity encountered. This may represent an increased motivation to migrate upstream due to rheotactic cues (Weaver, 1963). However, an increase in swimming speed with water velocity is also a finding consistent with a time conservation strategy (Standen *et al.*, 2004). Sockeye salmon increase ground speed above an energetically optimum level to expedite passage through high velocity areas (Standen *et al.*, 2004). Further to salmon migrating through rivers, this time conservation strategy has also been reported in a weak swimming, non-salmonid species. Transit time of Iberian barbel through pool-type fish passes is negatively correlated with velocity, turbulent kinetic energy and Reynolds shear stresses (Silva *et al.*, 2011; 2012). It was speculated that energetic expenditure was lower and ability to maintain position easier under low velocity, low turbulent conditions, and therefore more preferable to a species with limited swimming ability (Silva *et al.*, 2011). In addition to expediting passage through high velocity regions, lamprey may have increased swimming speed to facilitate stability in the more turbulent environments created when velocity was high. When swimming at higher speeds fish are more easily able to passively maintain stability through minor fin and body movements as momentum is higher; this becomes more demanding at lower velocities as momentum decreases (Webb and Cotel, 2011). The deployment of paired fins or spreading of them on the substrate in turbulent environments is common for other fish species, reflecting the difficulty in maintaining stability under such conditions (Webb, 2002; Tritico, 2009). As lamprey lack paired fins, it could be that they are reacting to destabilising flow by increasing their swimming speed, thus increasing momentum and stability under energetically expensive and biomechanically challenging conditions. Whatever the cause, for fish passes, this elevated swimming speed in response to water velocity should ensure minimum delay once the fish has located the pass. However, resting locations are a necessity where negotiation of the length of the structure in a single attempt is not possible.

Although water velocity was found to be the biggest predictor of swimming speed, temperature also had a significant effect. As temperature increases so too does the muscle twitch time of fish and therefore tail beat frequency, increasing maximum attainable speeds (Videler and Wardle, 1991). Temperature also increases metabolic rates, resulting in a faster time to fatigue (i.e. a reduction in endurance; Brett, 1971). This has important

implications for fish attempting to ascend fish passes; while they may be better able to attain the speeds required to swim upstream, their ability to negotiate the full length of the structure will be impaired. Such impacts of temperature on swimming performance raise some interesting future challenges for fish passage design and their efficiencies, particularly considering potential changes to flow and temperature regimes of rivers with future climate (e.g. milder and wetter winters, but hotter and dryer summers; UKCIP, 2002).

6.6. Conclusions

For low-head hydropower, impoundments required to create a hydraulic head difference for hydroelectric power generation can physically block the upstream movements of fishes. Where this occurs, fish passage facilities are often required. The design of fish passes should accommodate natural swimming behaviours to facilitate efficient entry and progression upstream. In this study, turbulent kinetic energy was not found to correlate with the behaviour of upstream migrant adult river lamprey. However, higher water velocities resulted in faster swimming speeds, an advantageous trait for minimising delay once the fish have located a pass. Velocities at passes should attract and enable upstream passage. Generating the appropriate flow for achieving these aims presents a challenge for fish passage design. There is a clear trade-off between providing high enough flow to attract fish but with velocities that don't exceed fish swimming capabilities. The provision of suitable resting locations is a necessity where negotiation of the length of the pass is not possible in a single attempt. This aspect of fish pass design is of particular importance as freshwater environments and the biological performance of fish are likely to change with shifts in future climate.

Chapter 7

Effects of light on the behaviour of brown trout (*Salmo trutta*) encountering accelerating flow: Application to downstream fish passage

7.1. Summary

Avoidance of abrupt accelerations of flow exhibited by downstream migrating fish at screens used to divert them, or at fishway entrances, can cause delay and adversely impact efficiency. The use of alternative stimuli to attract fish and mask the unwanted deterrent effects associated with velocity gradients is of interest to those working in fish passage engineering. The influence of light on the downstream movement of brown trout (*Salmo trutta*) as they encountered accelerating velocities created by a constricted channel in an experimental flume under three discharge regimes was assessed. It was predicted that: (1) in the absence of a light source, behavioural responses typical of downstream moving salmonids would be elicited on encountering velocity gradients, and that these responses would be initiated at some threshold spatial velocity gradient relative to body length, and (2) light would act as an attractant and mask the deterrent effects of a velocity gradient and thus reduce delay. Typical avoidance behaviours, e.g. rheotactic switches in orientation or retreating upstream before re-approaching a velocity gradient, were common. The spatial velocity gradient threshold at which a response was initiated when dark was similar (*ca.* 0.4 cm s^{-1} per cm) independent of discharge. Fish responded farther upstream at a lower spatial velocity gradient threshold (*ca.* 0.2 cm s^{-1} per cm) in the presence of both mechanosensory and visual cues when light. Contrary to the second prediction, downstream movement was further delayed by the addition of a light stimulus. The findings support an alternate hypothesis, that responsiveness (avoidance) can be enhanced when multimodal stimuli are presented.

7.2. Introduction

Anthropogenic structures that impound streams and rivers (e.g. dams and weirs) can fragment the river continuum, causing population declines and in some instances the local extinction of aquatic biota unable to effectively disperse between habitat patches (Odeh, 1999; Agostinho *et al.*, 2005). Habitat fragmentation is a particular problem for fishes as their life cycle depends on an ability to move (from tens of metres to hundreds of kilometres) to seek refuge, food, and mates (Lucas and Baras, 2001). For upstream moving fish, passage success at anthropogenic barriers provisioned with fish passage facilities is typically determined by the ability to find the entrance and then to ascend them under high velocity, turbulent conditions (Beach, 1984; Bunt, 2001; Chapter 6 this thesis). Similarly, for fish moving downstream, behaviour as well as swimming performance dictate movement trajectories and passage efficiency (Katopodis and Williams, 2011; Williams *et al.*, 2012). Understanding the relationship between hydrodynamic and other environmental stimuli encountered at barriers, and the behaviour of downstream moving fish in response to them, is important if efforts to mitigate for reduced habitat connectivity are to be facilitated.

Downstream passage facilities developed to facilitate migration of fish past river infrastructure have been widely employed, often in association with screening systems designed to block access to, and deflect fish away from, turbine and water intakes (Turnpenny *et al.*, 1998; Larinier and Travade, 2002). Bypass passage efficiency, however, can be unacceptably low (e.g. < 40% for postspawned American shad (*Alosa sapidissima*), Kynard and O'Leary, 1993; \leq 50% for silver-phase European eel (*Anguilla anguilla*), brown trout (*Salmo trutta*) smolts and brown trout kelts, Calles *et al.*, 2012), and variable depending on site specific characteristics (Whitney *et al.*, 1997; Scruton *et al.*, 2002). The route selected by downstream migrants at river infrastructure can strongly influence survival. For example, fish passing through hydropower turbines on the Columbia River have shown approximately 7% higher rates of mortality compared with fish passing bypass systems (Muir *et al.*, 2001). Furthermore, delay due to avoidance of conditions created at the bypass entrance, e.g. abrupt accelerations of velocity (Haro *et al.*, 1998; Larinier, 1998), can result in high rates of predation (Larinier and Travade, 2002), energetic expense, and may lead to greater probability of passage via alternate routes, e.g. turbines (Castro-Santos and Haro, 2003). Downstream migrant juvenile salmon (smolts) often

orient to face the prevailing flow on encountering accelerating velocity gradients, and in some instances swim back upstream to avoid the abrupt near field hydrodynamic transitions (Haro *et al.*, 1998 for Atlantic salmon smolts (*S. salar*); Kemp *et al.*, 2005a for Pacific salmon smolts (*Oncorhynchus* spp.)). Salmonids initiate a flight response (sudden change in swimming trajectory, often with switches in rheotactic orientation) at the same spatial velocity gradient across the body under different discharge regimes (Enders *et al.*, 2009 for Pacific salmon smolts; Russon and Kemp, 2011b for hatchery reared brown trout), indicating that once a threshold value is detected by the fish, an avoidance response is elicited.

Some stimuli may be used as attractants to mitigate for the adverse deterrent effects created at fish passes. Man has attempted to attract fish using lights, either to enhance commercial harvest (e.g. Marchesan *et al.*, 2005), or to protect them, e.g. by drawing fish away from hydropower intakes (Schilt, 2007). When attracted, fish typically become more active (Haymes *et al.*, 1984), form schools, and move towards the light source (Ben-Yami, 1976). Under experimental saltwater conditions, groups of sea bream (*Sparus auratus*) form closer aggregations and are more attracted to a Halogen light source as intensity is gradually increased (Marchesan *et al.*, 2005). Likewise, under experimental freshwater conditions, Alewife (*A. pseudoharengus*) are attracted to mercury vapour lights, which when deployed near a water abstraction off-take, have successfully attracted Alewife, smelt (*Osmerus mordax*) and juvenile gizzard shad (*Dorosoma cepedianum*) towards a site of collection (Haymes *et al.*, 1984). Artificial lighting is also used as an attractant on many of the Columbia River Dams, USA, in attempt to enhance passage of juvenile salmonids to bypass systems (Mueller and Simmons, 2008). Indeed salmonid smolts have been observed to be attracted towards light under some circumstances (see Nemeth and Anderson, 1992 for dim mercury light), although results have been variable (see Fields, 1957 for experimental conditions; Gessel *et al.*, 1991 for field conditions). As light may provide an attractant to effectively mask the deterrent effects of velocity gradients at bypass entrances and screening facilities, this study investigated whether a light source could be employed to reduce the avoidant effects of a velocity gradient associated with a constricted channel for downstream moving fish. The response of brown trout on encountering accelerating velocities in the presence and absence of a light source was assessed. Two predictions were made: (1) in the absence of the light stimulus, avoidance responses typical of downstream moving salmonids will be elicited on encountering accelerating velocity gradients, these

responses will occur at the same (threshold) spatial velocity gradient relative to body length, irrespective of discharge, and (2) the light stimulus will act as an attractant and mask the effects of accelerating flow and thus reduce avoidance.

7.3. Materials & methods

7.3.1. Experimental flume setup

Experiments were conducted in the indoor flume at the ICER experimental facility. A 2 m section of the channel was constricted by approximately 30% by installing Perspex inserts (Figure 7.1). Discharge was controlled by two centrifugal pumps (individual capacities of 0.15 and 0.23 m³ s⁻¹). Three discharge treatments created distinct velocity gradients (see below) at the entrance to the constricted channel. Mean water depths 1 m upstream of the constriction were 0.29, 0.34 and 0.40 m for the low, medium and high flows respectively.

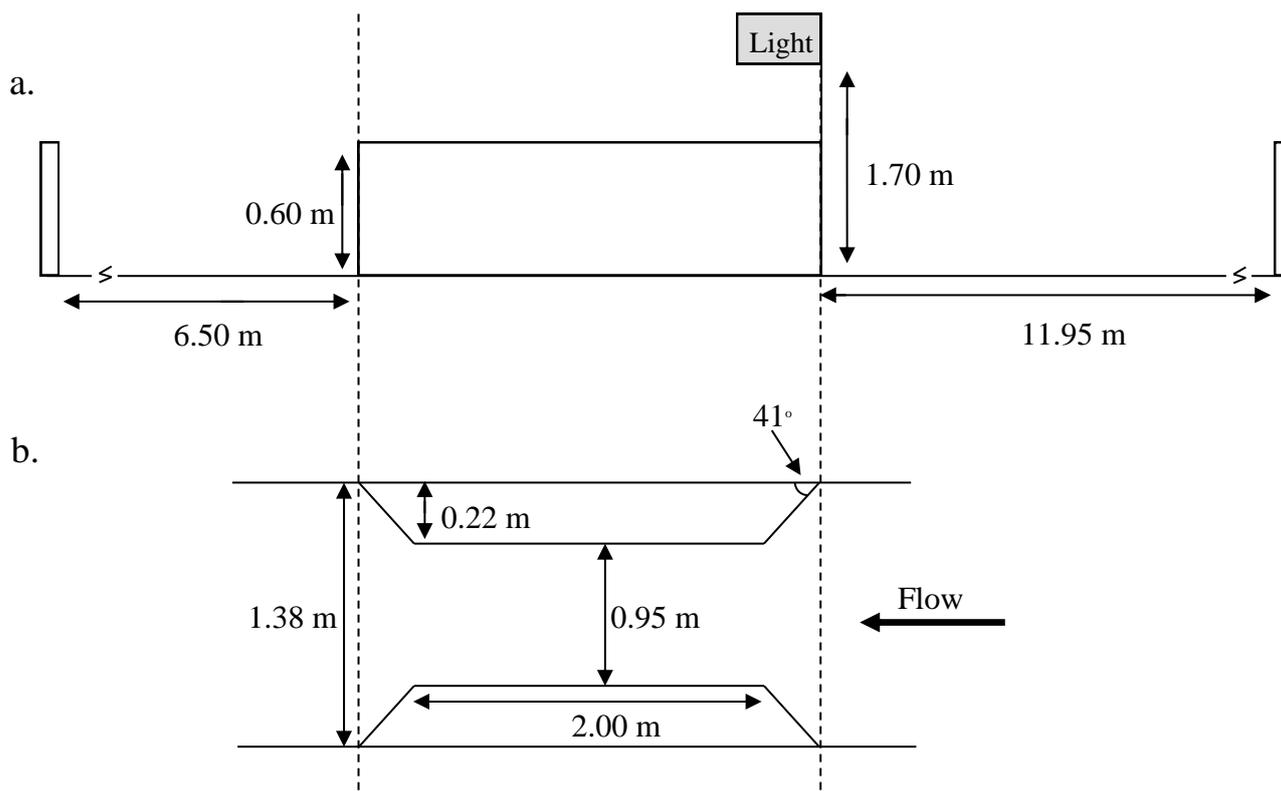


Figure 7.1.a. Schematic profile of the experimental channel at the ICER research facility used to observe the behavioural responses of brown trout as they moved downstream and encountered an accelerating velocity gradient. **b.** Plan view of the constricted channel.

Fish behaviour under two conditions of illumination were tested; ambient night (dark), and ambient night with a halogen light source (500 W) positioned directly over the entrance to the constricted channel (light) (Figure 7.1) to provide a distinct localised gradient of illumination (Figure 7.2). Low light, overhead video cameras and four infra-red lighting units (emitting infrared light at 850 nm) allowed fish movements to be observed at low light levels.

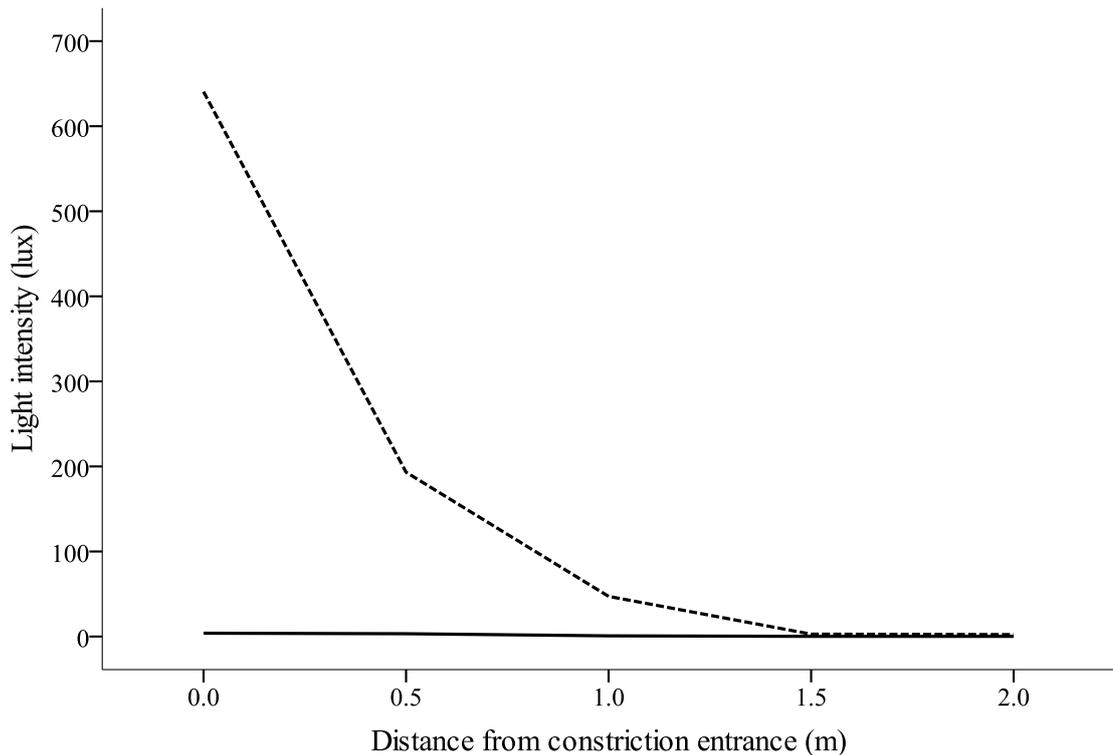


Figure 7.2. Light intensities during dark (solid line) and light (dashed line) treatments. Light readings taken at the entrance to the constricted flume channel (0.0 m) and at 0.5 m intervals to 2 m upstream.

Water velocities were measured using an Acoustic Doppler Velocimeter (ADV) (Vectrino+, Nortec), sampling at 50 Hz with a sample volume set at 0.31 cm³. Three thousand velocity readings were taken over the 60 second sampling duration at each discrete sampling point. Microsoft Office Excel (2007) was used to process ADV data, with the mean velocity vector calculated as:

$$V = \sqrt{\bar{u}^2 + \bar{v}^2 + \bar{w}^2} \quad (7.1)$$

where \bar{u} , \bar{v} and \bar{w} are the mean longitudinal, lateral and vertical velocity components (in m s^{-1}), respectively. Mean velocity vector contour plots were generated using the Spatial Analyst tool in ArcGIS 10 (ESRI, Redlands, CA, USA). Velocities ranged from 0.04 – 0.78, 0.23 – 1.06, and 0.31 – 1.14 m s^{-1} for the low, medium and high discharge treatments respectively. Assuming a linear gradient, velocity acceleration over the 1 m approach to the constricted channel entrance was 0.13, 0.21 and 0.33 m s^{-2} , for the low, medium and high discharge, respectively.

7.3.2. Fish transport & maintenance

Seventy brown trout, sourced from a local hatchery (Allenbrook Trout Farm, Dorset, UK), were delivered to the ICER facility in aerated transportation containers on 27 January 2009 and placed into a 3000 L holding tank for seven days prior to the start of trials (stocking density = 3.9 kg m^{-3}). A further sixty trout were delivered on 13 February 2009 (stocking density = 3.3 kg m^{-3}). The mean (\pm SE) wet mass and total length of test fish was 165.1 \pm 3.9 g and 242.4 \pm 1.8 mm, respectively. Tank water was aerated and quality maintained (e.g. nitrite < 1 mg L^{-1} and nitrate < 50 mg L^{-1}) using a submersible pond pump, filter system, and weekly water exchange (approximately 10%). Mean (\pm SE) holding tank temperature was 10.0 \pm 0.10°C.

7.3.3. Experimental protocol

A total of 120 trials were conducted between 3 and 25 February 2009. All trials were conducted at night (between 1700 and 0400 hrs) to control for use of visual cues during dark treatments and to create a strong contrast between background light levels and the light source during light treatments. Twenty trials were conducted for each of six treatments; low discharge-dark (LD), low discharge-light (LL), medium discharge-dark (MD), medium discharge-light (ML), high discharge-dark (HD) and high discharge-light (HL). At the start of each daily experimental period, up to 12 fish were placed into a perforated container located at the upstream end of the flume and allowed to acclimatise for a minimum of one hour before the start of the first trial. Immediately prior to the start of each trial, flume water temperature (mean \pm SE = 13.4 \pm 0.3°C) and light intensity (every 0.5 m from the entrance of the constricted channel upstream for 2 m) was measured, and a single fish was released 12 m upstream of the channel constriction. Fish were able to

hold position against the flow, particularly towards the channel walls, and volitionally move downstream. Each trial either lasted until the fish passed downstream through the constricted channel or until two hours had elapsed. At the end of each trial fish were removed from the flume before being measured and weighed. Each fish was used once only during the study.

7.3.4. Fish behaviour

As fish entered (*approach*) an observation zone (1 m upstream to 1 m downstream of the constricted channel entrance) and passed (*pass*) the entrance to the constricted channel, their (1) *orientation* (positive or negative rheotaxis), (2) *nature of response* initially exhibited, and (3) *time to pass* the observation zone, were recorded. Fish observed neither positively or negatively oriented (i.e. parallel to the flow) were rare, and were not included in the analysis on orientation. Four distinct behavioural responses were defined: (a) *Reject* passage by holding station for more than 5 seconds, (b) *Retreat* back upstream, (c) *React* by expressing rheotactic switches or an increase in tail beat frequency but continuing downstream, or (d) *No-response* visible to the observer during continued downstream movement. Head and tail locations when a response was observed were obtained using video tracking software (Logger Pro v3.8.2, Vernier Software, Beaverton, OR, USA), imported into GIS, and superimposed onto velocity profiles of the experimental setting. The (4) *distance of response* from the constricted entrance was calculated and underlying velocity data extracted to calculate the (5) *spatial velocity gradient* (along the fish body) at the point at which a response was initiated. The spatial velocity gradient was calculated using the formula described in Enders *et al.* (2009):

$$S_{VG} = \frac{|V_H - V_T|}{L} \quad (7.2)$$

where V_H and V_T represent the velocity at the fish's head and tail positions respectively, and L is the total length of the fish.

7.3.5. Statistical analysis

Tests of normality were performed using a Kolmogorov-Smirnov statistic. Non-normal data were normalised using log transformations. When this was unsuccessful, bootstrapped

(using 1000 iterations) confidence intervals of the mean difference were reported in association with parametric statistics to illustrate variation between treatments. The influence of discharge and illumination on (1) *approach* and *pass orientation* and (2) *nature of response* were analysed using Pearson chi-square tests. The influence of discharge and illumination (fixed factors) on (3) *time to pass*, (4) *distance of response*, and (5) *spatial velocity gradient* (dependent variables), were analysed using univariate two-way ANOVA. Tukey *post hoc* tests were performed to determine the sources of significant differences.

7.4. Results

Ten fish were omitted from analysis due to either not passing through the observation zone within the two hour maximum time limit or for exhibition of startle behaviours (as defined by Yasargil and Diamond, 1968) which were deemed not to be in response to the test conditions. This corresponded to 5% of LD, 0% of LL, 15% of MD, 15% of ML, 10% of HD and 5% of HL trials being excluded. Flume temperature did not differ between treatments (Kruskal-Wallis test: $H = 0.45$, d.f. = 5, $P = 0.995$).

The *orientation* of trout as they approached the observation zone was influenced by discharge (Pearson chi-square test: $\chi^2 = 10.28$, d.f. = 2, $P < 0.01$) but not by illumination (Pearson chi-square test: $\chi^2 = 0.00$, d.f. = 1, $P = 0.970$). Trout tended to approach the observation zone facing downstream under the low discharge (61% of fish were negatively oriented), but more often faced upstream during medium (75% positively oriented) and high (67% positively oriented) flows (Table 7.1). During passage through the constricted channel entrance, *orientation* was predominantly positive (Table 7.1) and did not differ with discharge (Pearson chi-square test: $\chi^2 = 2.43$, d.f. = 2, $P = 0.296$) or illumination (Pearson chi-square test: $\chi^2 = 1.84$, d.f. = 1, $P = 0.174$).

Table 7.1. Observed numbers of brown trout oriented facing upstream (positive) or downstream (negative) as they approached and passed through a constricted channel in an experimental flume. Expected frequencies are those generated during the Pearson chi-square test.

Flume position	Orientation	Discharge			Illumination	
		Low	Medium	High	Dark	Light
Approach: 1 m upstream of constricted channel entrance	Positive					
	Observed	15.0	24.0	24.0	31.0	32.0
	Expected	22.6	19.0	21.4	30.9	32.1
	Negative					
	Observed	23.0	8.0	12.0	21.0	22.0
	Expected	15.4	13.0	14.6	21.1	21.9
Pass: at entrance to the constricted channel	Positive					
	Observed	21.0	23.0	24.0	37.0	31.0
	Expected	24.6	20.7	22.7	33.7	34.3
	Negative					
	Observed	17.0	9.0	11.0	15.0	22.0
	Expected	13.4	11.3	12.3	18.3	18.7

Nature of response was influenced by both discharge (Pearson chi-square test: $\chi^2 = 14.06$, d.f. = 6, $P < 0.05$) and illumination (Pearson chi-square test: $\chi^2 = 7.88$, d.f. = 3, $P < 0.05$). The most common response type was *react*. *No-response* was uncommon, and *retreat* by moving upstream was more frequent (72% of all retreats) when light (Table 7.2). *Nature of response* influenced *time to pass* the observation zone (one-way ANOVA: $F = 8.355$, $df = 3$, $P < 0.001$). Fish that *reacted* by switching orientation tended to pass more quickly than either those that *rejected* (Tukey *post hoc* test: $P < 0.001$) or *retreated* ($P = 0.001$), for which there was no difference between response type (Tukey *post hoc* test: $P = 0.878$).

Table 7.2. Initial behavioural response types expressed by brown trout as they encounter accelerating velocities created under different discharges and during a light or dark illumination, in an experimental channel.

Discharge	Illumination	Response type (%)			
		Reject	Retreat	React	No response
Low	Dark	21.1	21.1	57.9	0.0
Low	Light	15.0	40.0	30.0	15.0
Medium	Dark	23.5	5.0	70.6	0.0
Medium	Light	11.8	23.5	64.7	0.0
High	Dark	33.3	16.7	33.3	16.7
High	Light	26.3	47.4	21.1	5.3

Time to pass (mean light = 489.5 seconds; mean dark = 161.7 seconds; Figure 7.3) and *distance of response* (mean light = 58 cm; mean dark = 36 cm; Figure 7.4) were greater under the light treatment, while the *spatial velocity gradient* was lower (*ca.* 0.2 versus 0.4 cm s^{-1} per cm; Figure 7.5). Discharge did not have an effect on these variables (Table 7.3).

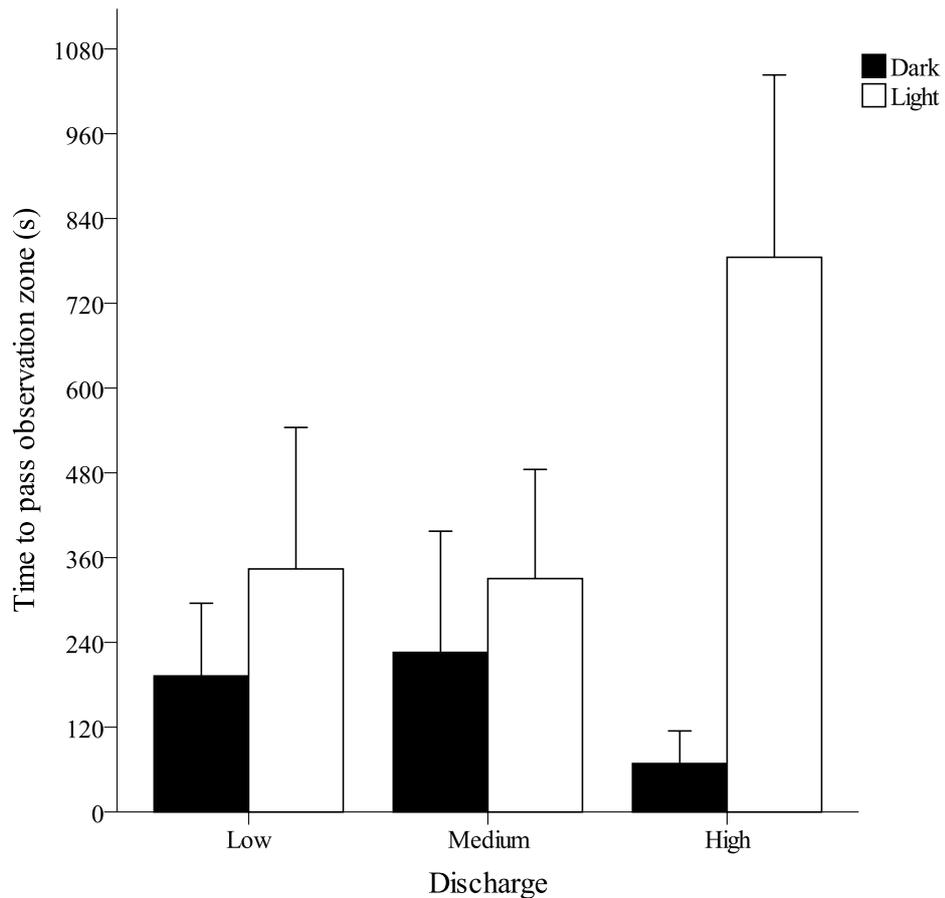


Figure 7.3. Mean time to pass an observation zone in an experimental flume by brown trout. Error bars depict + 1 SE of the mean.

Table 7.3. Two-way ANOVA results comparing the influence of discharge, illumination and their interaction on three dependent variables for brown trout moving downstream through an experimental flume.

Dependent variable	Discharge			Illumination			Interaction		
	<i>F</i>	df	<i>P</i>	<i>F</i>	df	<i>P</i>	<i>F</i>	df	<i>P</i>
Time to pass [#]	0.535	2	0.587	5.316	1	0.023*	1.934	2	0.150
Distance of response ^{##}	2.549	2	0.083	20.760	1	0.000***	0.297	2	0.744
Spatial velocity gradient	0.418	2	0.660	12.097	1	0.001**	1.468	2	0.236

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$

[#]95% bootstrapped CI of the mean difference: 0.85 to 4.72 for dark; 4.33 to 12.42 for light

^{##}95% bootstrapped CI of the mean difference: 0.22 to 0.36 for dark; 0.47 to 0.59 for light

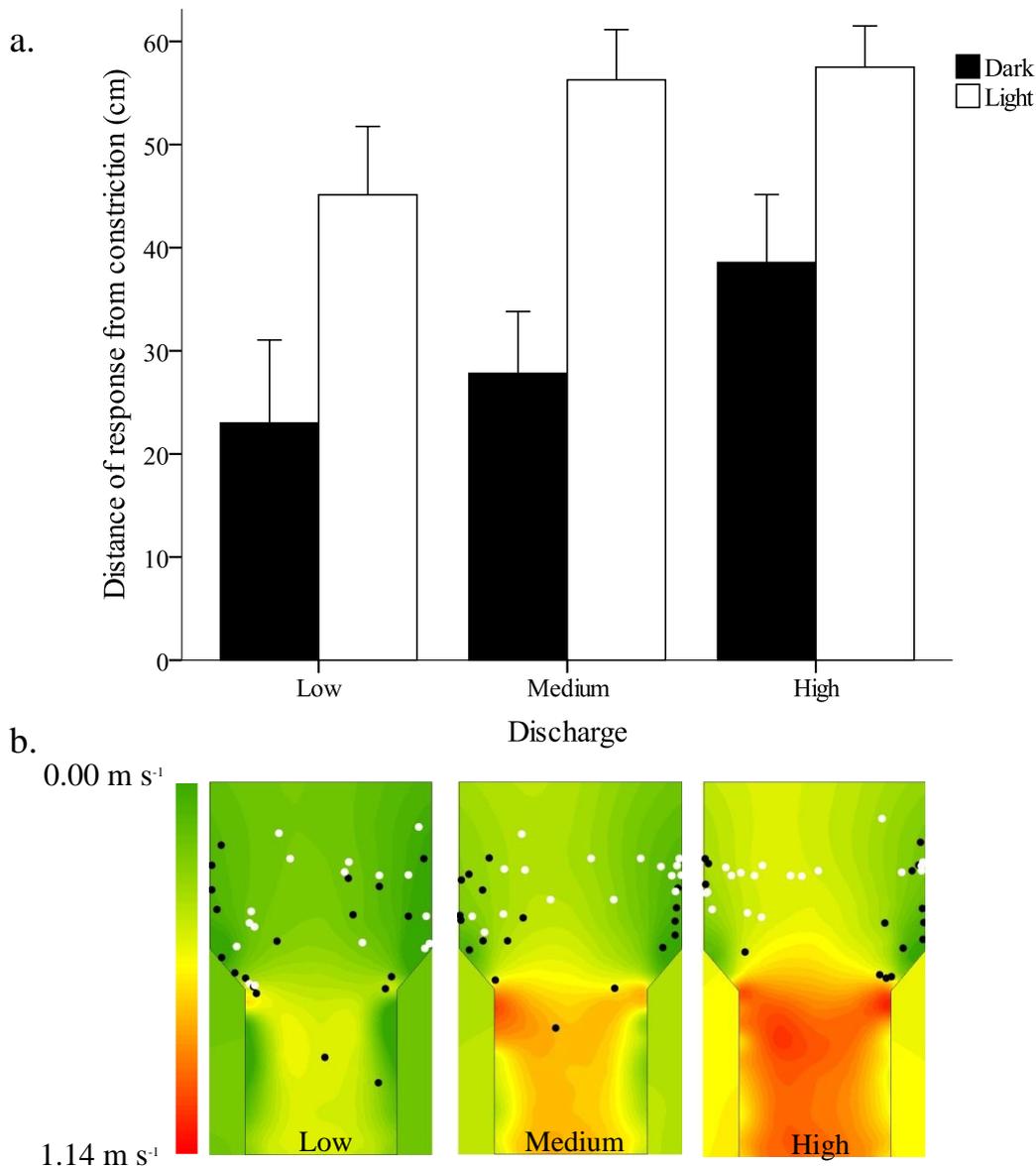


Figure 7.4.a. Mean distance of response exhibited by brown trout from the entrance to a constricted channel in an experimental flume. Error bars depict + 1 SE of the mean. **b.** Velocity profile (V) during low, medium and high discharge treatments, extending 1.25 m up- and 1 m down-stream of the constricted entrance. Black and white circles indicate head locations at the point the initial response by brown trout was exhibited during dark and light treatments, respectively.

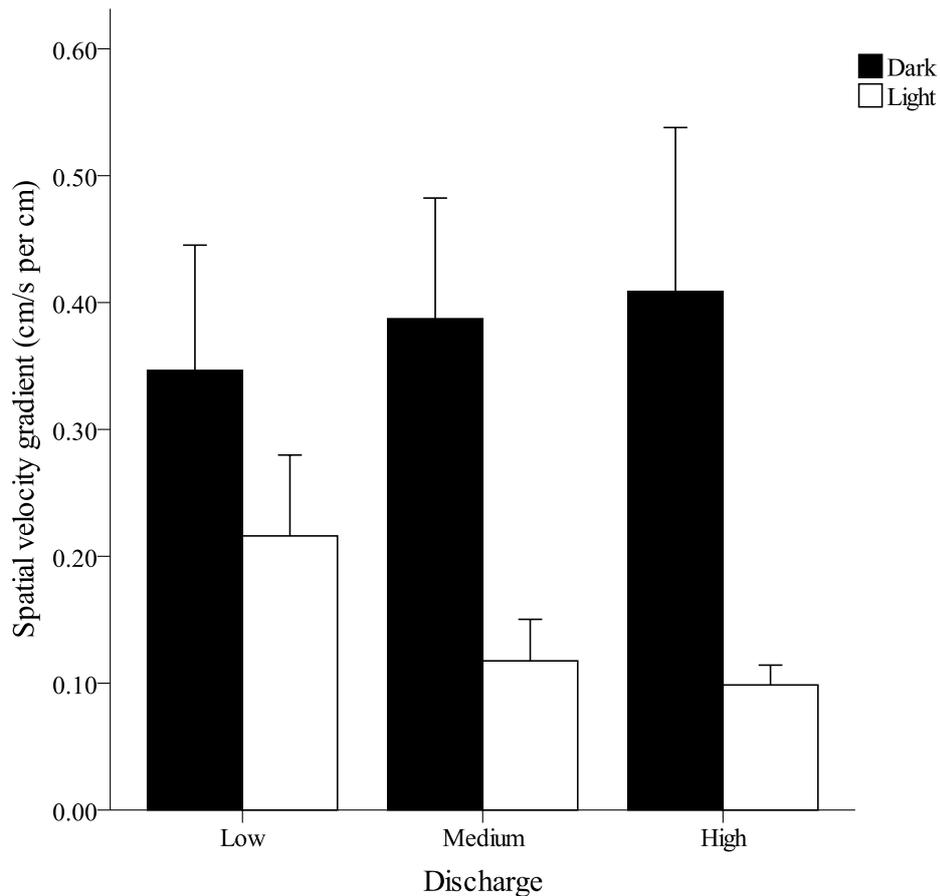


Figure 7.5. Spatial velocity gradient ($\text{cm s}^{-1} \text{cm}^{-1}$) along the body length of brown trout when initial responses were expressed. Error bars depict + 1 SE of the mean.

7.5. Discussion

On encountering the velocity gradients presented, downstream moving brown trout exhibited responses typical of seaward migrating juvenile salmonids, including rheotactic switches in orientation and retreating back upstream before re-approaching the velocity gradient (as described by Haro *et al.*, 1998; Kemp *et al.*, 2005a; 2006; Enders *et al.*, 2009). The accelerating velocity created under the alternative discharge treatments influenced approach orientation; under low discharge trout predominantly approached the constriction facing downstream, as observed by Kemp *et al.*, (2005a; 2006) for Pacific salmon smolts (*Oncorhynchus* spp.). During medium and high discharge, fish oriented into the prevailing flow during their approach, presumably due to the detection farther upstream of the more abrupt velocity gradients. This behaviour allows fish to maintain position and control during downstream movement, enabling rapid avoidance of potentially harmful locations (Kemp *et al.*, 2005a), and possibly to facilitate habituation to hydraulic gradients (see

Kemp *et al.*, 2012). At the entrance to the constriction, fish tended to face into the flow independent of discharge. Hydrodynamic stimuli alone had a clear influence on behaviour of downstream moving brown trout.

For fish encountering accelerating flow, a discrete spatial velocity gradient along the body can be calculated for the point at which a response is exhibited. In the absence of visual cues, trout tended to initiate a response at spatial velocity gradients of approximately 0.4 cm s^{-1} per cm independent of discharge. For Chinook salmon smolts (*O. tshawytscha*), Enders *et al.*, (2009) also observed reactions to occur at similar threshold spatial velocity gradients (approximately 1 cm s^{-1} per cm) irrespective of flow. Although behavioural responses are comparable, the lower threshold values calculated in the current study could relate to a number of factors acting in isolation or combination, such as; inter-specific differences, “naïve” hatchery fish expressing a more cautious strategy on encountering abrupt hydraulic transitions for the first time, an energy saving strategy due to swimming capability (see Pedersen *et al.*, 2008) or swimming cost (see Enders *et al.*, 2004) differences, or due to impacts of morphological differences (see Fleming *et al.*, 1994) on performance when compared to wild fish.

The constant light source was predicted to act as an attractant and mask the deterrent effects of the velocity gradient. However, when visual and mechanosensory stimuli were provided, trout took longer to pass the velocity gradient than when hydrodynamic cues alone were present. Delay to passage was elevated when trout experienced distinct multimodal signals. This may be explained by the light stimulus acting as a backup signal (see Partan and Marler, 2005), to improve responsiveness to a dominant hydrodynamic cue. Alternatively, the light may have acted independently as a deterrent and dominated over the influence of the hydrodynamic cue to dictate passage through the observation zone. Given that both discharge and illumination influenced nature of initial response and the strong reactions expressed on encountering velocity gradients in this and previous research (e.g. Haro *et al.*, 1998; Kemp *et al.*, 2005a; 2006; Enders *et al.*, 2009; Kemp and Williams, 2009), it seems likely that both stimuli influenced the behavioural responses observed. Retreating upstream before subsequently moving back downstream was common during light treatments and provides an explanation for the greater time required to pass the constricted channel. This negative phototactic behaviour could be related to a level of retinal adaptation, where fish acclimatised to dark conditions are likely to show stronger

avoidance to a light stimulus (Fields, 1957; Feist and Anderson, 1991). Indeed, in addition to acting as attractants, strobe lights, in particular, have also been used to repel fish in the field (Patrick *et al.*, 2001; Ploskey and Johnson, 2001).

Brown trout responded farther upstream and at a lower velocity gradient threshold (approximately 0.2 cm s^{-1} per cm) on encountering both the flow acceleration and light source, indicating that under these conditions responsiveness was improved. Pacific salmonid smolts have been reported to avoid light of more than 400 lux in some instances (Mueller and Simmons, 2008), in this study initial responses occurred at approximately 270 lux, the lower value possibly a result of the detection of two abrupt environmental signals. The use of strong multimodal stimuli, rather than a single unimodal cue, appears favourable for use in situations where the ability of fish to successfully discriminate a hydrodynamic signal is beneficial e.g. deterring fish from suboptimal routes of passage such as hydroelectric power intakes. However, such a response would be deemed disadvantageous to fisheries managers aiming to improve downstream bypass efficiencies limited by delay influenced by abrupt accelerations of flow at the entrance.

7.6. Conclusions

Identifying how fish respond to combinations of hydrodynamic and other environmental stimuli is crucial for the development of more effective methods of guiding fish towards more benign downstream routes of passage at anthropogenic structures. This study highlights the potential for multisensory environmental stimuli to influence fish behaviour. A fish's responsiveness to a hydrodynamic cue (in this instance an accelerating velocity gradient) was improved by the addition of a strong light stimulus (e.g. when two stimuli, operating through visual in addition to lateral line modalities, were detected). Although light was used in this study, previous research has illustrated light to have attractant, repellent and no influence over fish behaviour. Effectiveness can be further influenced by e.g. ambient light levels, species, and water clarity (Haymes *et al.*, 1984; Nemeth and Anderson, 1992; Popper and Carlson, 1998; Marchesan *et al.*, 2005). Furthermore, fish have variety of sensory organs (e.g. auditory and olfactory). Therefore, combinations of strong multimodal signals in general may be more effective at altering fish behaviour than either a single stimulus or two unimodal stimuli (Welton *et al.*, 2002; Lovelace *et al.*, 2003; Partan *et al.*, 2009). This information could be of use in deterring fish from

potentially hazardous locations (e.g. at hydropower dams or water abstraction points).

When diverting fish to preferred downstream routes of passage, hydrodynamic (e.g. louver systems; Bates and Vinsonhaler, 1957; Kynard and Horgan, 2001) and other environmental stimuli (e.g. overhead shade; Greenberg *et al.*, 2012) have been used, but the influence of combinations of stimuli on successful fish passage should also be considered.

In addition to identifying how fish respond to conditions associated with bypass facilities, future research should aim to quantify the impacts of variation in behaviour on subsequent downstream passage. This issue is investigated further in Chapter 8.

Chapter 8

Effects of avoidance behaviour on passage of downstream moving juvenile salmon through areas of accelerating flow when light and dark

8.1. Summary

To mitigate for negative impacts of delayed migration it is necessary to understand the causes of avoidance exhibited by animals at behavioural barriers. For downstream migrating juvenile salmon (*Oncorhynchus tshawytscha*), avoidance of velocity gradients at anthropogenic structures can compromise fitness. Building on previous experimental investigations into the behaviour of salmonids encountering velocity gradients, this study aimed to quantify impacts of behaviour on subsequent passage. In an experimental flume, downstream moving juvenile salmon encountered either a high or low velocity gradient created by an orifice weir, under light or dark conditions. The majority of fish reacted on encountering the accelerating velocity gradients, with elevated levels of avoidance associated with light treatments. More time was spent facing the flow when the velocity gradient was high. Fish that exhibited avoidance behaviour were delayed by approximately 8 fold, travelled 3.5 times further and experienced a higher mean cumulative velocity gradient across the body length (spatial velocity gradient) prior to successful downstream passage. This study highlights the impact variation in response has on subsequent passage, and the potential for multimodal signals (in this instance visual and mechanosensory) to be used in combination to repel fish, e.g. from hazardous areas associated with river infrastructure, such as turbine intakes. Conversely, by limiting information available, undesirable delay, e.g. at entrances to downstream fish bypasses, may be reduced.

8.2. Introduction

Periodic or seasonal movements between habitats are common for many terrestrial and aquatic taxa (McFarland, 1999; Skov *et al.*, 2010). In a physically diverse environment, barriers may fragment habitats by impeding migration and dispersal of individuals. Under severe cases, often as a result of anthropogenic development, populations can become

small and genetically isolated, increasing their risk of extirpation (Newmark, 1991; Winston *et al.*, 1991; Morita and Yamamoto, 2001). Barriers to animal movements are most often perceived as physical structures such as fences (e.g. for Wildebeest [*Connochaetes* spp.], Williamson and Williamson, 1984), roads (e.g. for foraging hedgehogs [*Erinaceus europaeus*], Rondinini and Doncaster, 2002), and dams (e.g. for migratory fishes, Pringle, 2003; Fukushima *et al.*, 2007). However, non-physical features associated with anthropogenic structures or activities that inhibit the dispersal ability of animals by behavioural means can also have significant effects. For example, artificial lights have been shown to hinder the sea-finding performance of hatchling turtles, (*Caretta caretta*) (Witherington and Bjorndal, 1991) and disorient migratory birds (Ogden, 1996). These behavioural barriers may prevent, limit, disorient or delay movements of animals; leading to increased energetic costs, predation risk, and/or fragmentation of populations. While mitigation of the negative impacts of physical barriers (e.g. fish passes at hydroelectric dams and wildlife passes under highways) has been widely developed, greater understanding of how associated environmental conditions influence migratory behaviour is needed to enhance conservation efforts to restore habitat connectivity.

Fish are frequently selected as models in behavioural research due to their short generation time providing easy access to subjects at the life stage of interest (e.g. zebrafish *Danio rerio*, Miklósi and Andrew, 2006; Blaser and Goldsteinholm, 2012), because they can be readily bred or obtained from wild stocks, and their use does not generally require large laboratories and sophisticated, expensive equipment (Gouveia *et al.*, 2005). Fish also present discernible behavioural repertoires that are not unmanageably complex (Huntingford, 1986). For salmonids, the juvenile life-stage is of particular interest as their ability to pass barriers in the downstream direction is not dictated by swimming performance (a significant factor for upstream migrating fish) and hence behaviour is the key determinant of success (Williams *et al.*, 2012). They therefore provide an ideal candidate for exploring behavioural avoidance to environmental stimuli encountered during migration.

Actively migrating juvenile salmonids (smolts) have previously been observed to avoid constant and strobe light (Nemeth and Anderson, 1992), sound (Knudsen *et al.*, 2005), overhead cover (Kemp *et al.*, 2005b; Greenberg *et al.*, 2012), and combinations of stimuli (e.g. bubbles and sound, Welton *et al.*, 2002). Hydrodynamic signals also play a prominent

role, and smolts have demonstrated avoidance of velocity gradients created by structures (Haro *et al.*, 1998 for Atlantic salmon smolts [*Salmo salar*], Kemp *et al.*, 2005a; 2006; Enders *et al.*, 2009; 2012 for Pacific salmon smolts [*Oncorhynchus* spp.]). Reactions are often expressed as a switch from a negative (facing downstream) to positive (facing upstream) rheotactic orientation as a threshold velocity gradient along the body length (spatial velocity gradient) is encountered (Enders *et al.*, 2009; 2012; Chapter 7, this thesis). Subsequent responses are variable and include continued progression downstream, or retreating upstream away from the gradient followed by further approaches, and either rejection or continued downstream movement (Kemp and Williams, 2009; Chapter 7, this thesis). This oscillatory or milling behaviour, where fish move in and out of areas of hydrodynamic transition, has been described in the field for salmonids (e.g. Johnson and Moursund, 2000 for Pacific salmon smolts in the vicinity of bypass entrances; Svendsen *et al.*, 2011 for Atlantic salmon smolts at water abstraction sites), as well as other migratory fish (e.g. Behrmann-Godel and Eckman, 2003; Winter *et al.*, 2006 for European eel [*Anguilla anguilla*] approaching hydropower facilities).

For fish, the importance of hydrodynamic relative to other sensory stimuli (e.g. auditory, visual, olfactory; Evans, 1998) remains unclear. For example, overhead cover has induced avoidance in Pacific salmon smolts irrespective of discharge under experimental conditions (Kemp *et al.*, 2005b), and in the wild has been used to enhance guidance of downstream migrant brown trout (*Salmo trutta*) towards preferred passage routes at hydroelectric power dams (Greenberg *et al.*, 2012). In Chapter 7, elevated avoidance of velocity gradients when presented with a strong light stimulus, suggested that visual cues may supplement information supplied by the mechanosensory system to enhance responsiveness to hydrodynamic signals. Despite numerous experimental investigations of the behaviour of salmonids at velocity gradients, the extent to which different responses impact subsequent passage is yet to be quantified.

Building on the results of Chapter 7, the aim of this study was to determine how variation in behaviour exhibited by juvenile salmonids encountering accelerating velocity gradients, when light and dark, influenced subsequent downstream migration. It was predicted that under a steeper accelerating velocity gradient and when light, downstream moving fish would: 1) exhibit greater avoidance by expressing more oscillatory behaviours, and 2) spend a greater proportion of time positively rheotactic. Fish that exhibit greater avoidance

were predicted to: 3) travel further distances while assessing the gradient, 4) take longer to pass downstream, and 5) experience a higher mean cumulative spatial velocity gradient along the body prior to passage. In this experimental study downstream migrating juvenile salmon (*O. tshawytscha*) encountered either a low or high velocity gradient created under two discharge regimes. The hydrodynamic signals were presented both when dark and light, the latter providing the opportunity to employ both mechanosensory and visual modalities. The study findings highlight the impact variation in response exhibited by downstream migrant fish encountering behavioural barriers has on subsequent passage, and the requirement to manipulate stimuli to influence behaviour in a manner desirable from a fisheries management perspective.

8.3. Materials & methods

8.3.1. Study area & flume setup

At McNary Dam on the Columbia River, USA (45°55' N, 119°17' W) a Perspex barrier (152 cm wide, 45.8 cm high) with a rectangular orifice (45.8 cm wide, 7.7 cm high) was centrally positioned perpendicular to the flow on the channel floor of a through-flow flume (12.0 x 1.52 x 0.75 m; Figure 8.1). The flume was supplied with water from the McNary Dam forebay and an accelerating velocity gradient was created upstream of the orifice. A high (30 L s⁻¹) or low (10 L s⁻¹) discharge created two different velocity gradients which are subsequently referred to as high-light, high-dark, low-light or low-dark treatments dependent on whether the trial was conducted under light (mean level = 95.4 lux, similar to dusk / dawn levels) or dark (infrared illumination only; mean light level = 0.2 lux, darker than a moonlit sky) conditions.

Within the flume, a test area was created using a wire mesh screen spanning the channel width placed 1.20 m upstream of the barrier at a point where there was no discernible velocity gradient. A 0.15 m diameter PVC pipe entered the test area 1.10 m upstream of the barrier. The pipe extended 0.91 m upstream of the mesh screen and into a 1.20 x 1.20 m perforated and submerged acclimation tank, into which the fish were placed prior to the start of each trial (Figure 8.1).

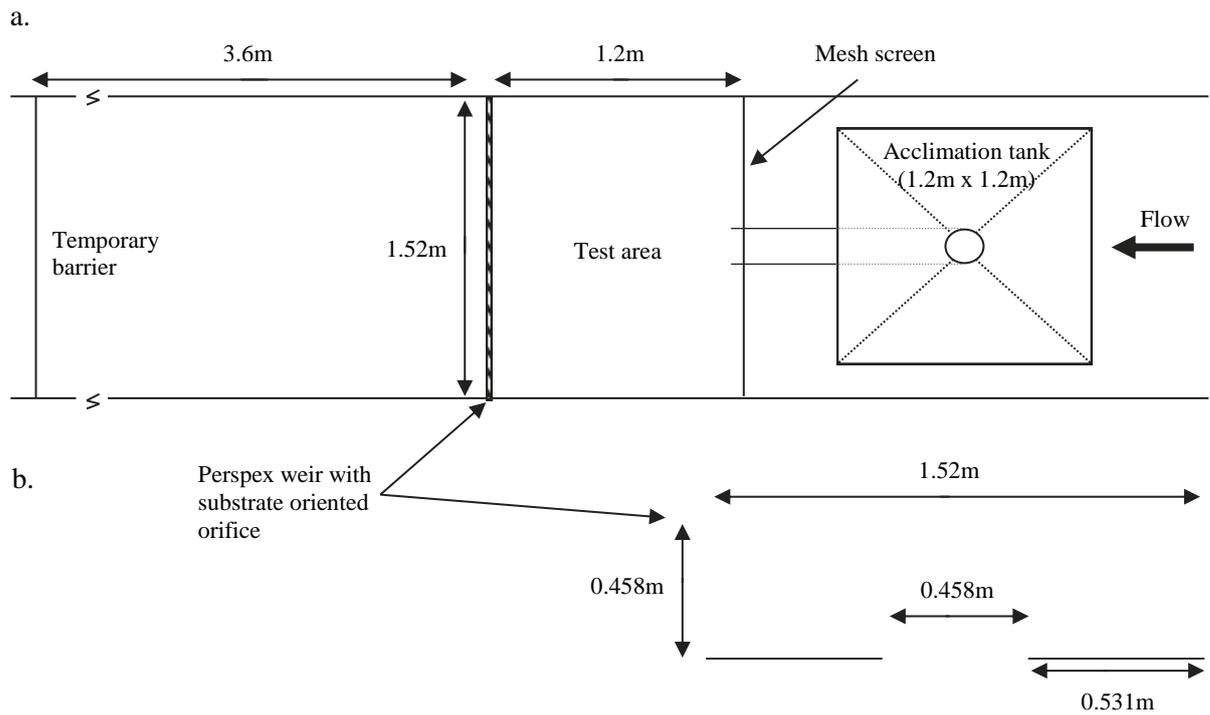


Figure 8.1.a. Plan view of the experimental channel used to observe migrant juvenile salmon behaviour under two velocity gradients during both dark and light conditions, **b.** side view of orifice weir, opening 7.7 cm high.

The water depth within the test area was maintained constant and equal to barrier height independent of discharge by placing a weir 3.6 m downstream of the barrier under the low velocity gradient treatment. Mean (\pm SD) water velocity was measured using an Acoustic Doppler Velocimeter (ADV) (Vectrino+, Nortek AS), sampling at 25 Hz for 60 seconds with a sample volume set at 0.31cm^3 . Microsoft Office Excel (2007) was used to post process ADV data, and incorporated a maximum / minimum threshold filter (as described in Cea et al. 2007). The three planes of water velocity were measured simultaneously allowing the mean velocity vector (V) to be calculated as:

$$V = \sqrt{\bar{u}^2 + \bar{v}^2 + \bar{w}^2} \quad (8.1)$$

where \bar{u} , \bar{v} and \bar{w} are the mean longitudinal, lateral and vertical velocity components (m s^{-1}), respectively. Mean velocity vectors were plotted using spline interpolation in the Spatial Analyst tool in ArcGIS 10 (ESRI, Redlands, CA, USA).

Mean water velocity in the test area was $0.23 (\pm 0.16)$ and $0.11 (\pm 0.08) \text{ m s}^{-1}$ for the high and low velocity gradient treatments, respectively. At approximately one body length upstream from the orifice (11 cm), a distance where the orifice may be considered detectable by the fish (Coombs, 1999), the rate of water acceleration was greater during the high (9.98 m s^{-2}) compared to low (6.87 m s^{-2}) discharge. The gradient extended further upstream and a higher maximum velocity was reached during the high (1.53 m s^{-1}) compared to low (1.23 m s^{-1}) velocity gradient treatment (Figure 8.2).

An overhead low light video camera was placed above the test area to monitor sub-yearling Chinook salmon behaviour during trials. Overhead strip lighting or four 50 W infrared lighting units (emitting infrared light at 840-1200 nm), mounted above the flume, were used during light and dark treatments, respectively. Water temperature increased from 18.2 to 19.4°C over the nine day study period.

8.3.2. *Experimental protocol*

A total of 23 trials were conducted between 1 and 9 July 2009. Between two and four 1-hour trials were conducted per day (alternating between the four treatments) between 08.00 and 13.00 hours. Physical screens diverted fish approaching the dam into a gateway where they subsequently entered the juvenile bypass channel through one of 84 (0.3 m diameter) orifices (Gessel et al. 2004). At one of these orifices, water was routed to a holding tank to collect actively migrating fish. Trials commenced after collection of 30 fish, which took a maximum of approximately one hour. For each trial, five fish were randomly netted from the holding tank and transported to the test flume. Fish were then placed into the submerged acclimation tank from which they could voluntarily exit via the PVC pipe. The conditions in the acclimation tank were the same as in the test area of the flume, allowing fish time to adjust to the light intensity and recover from effects of handling before they entered the test area. An additional five fish were added to the acclimation tank every 10 minutes for the first 50 minutes of each trial. All fish that passed through the orifice in the test flume were collected downstream, anaesthetized in 10 mg L^{-1} solution of tricaine methanesulfonate (MS-222), and measured. Each fish was used once during the study and returned to the bypass system after recovering from anaesthesia (a maximum of approximately 2 hours after collection).

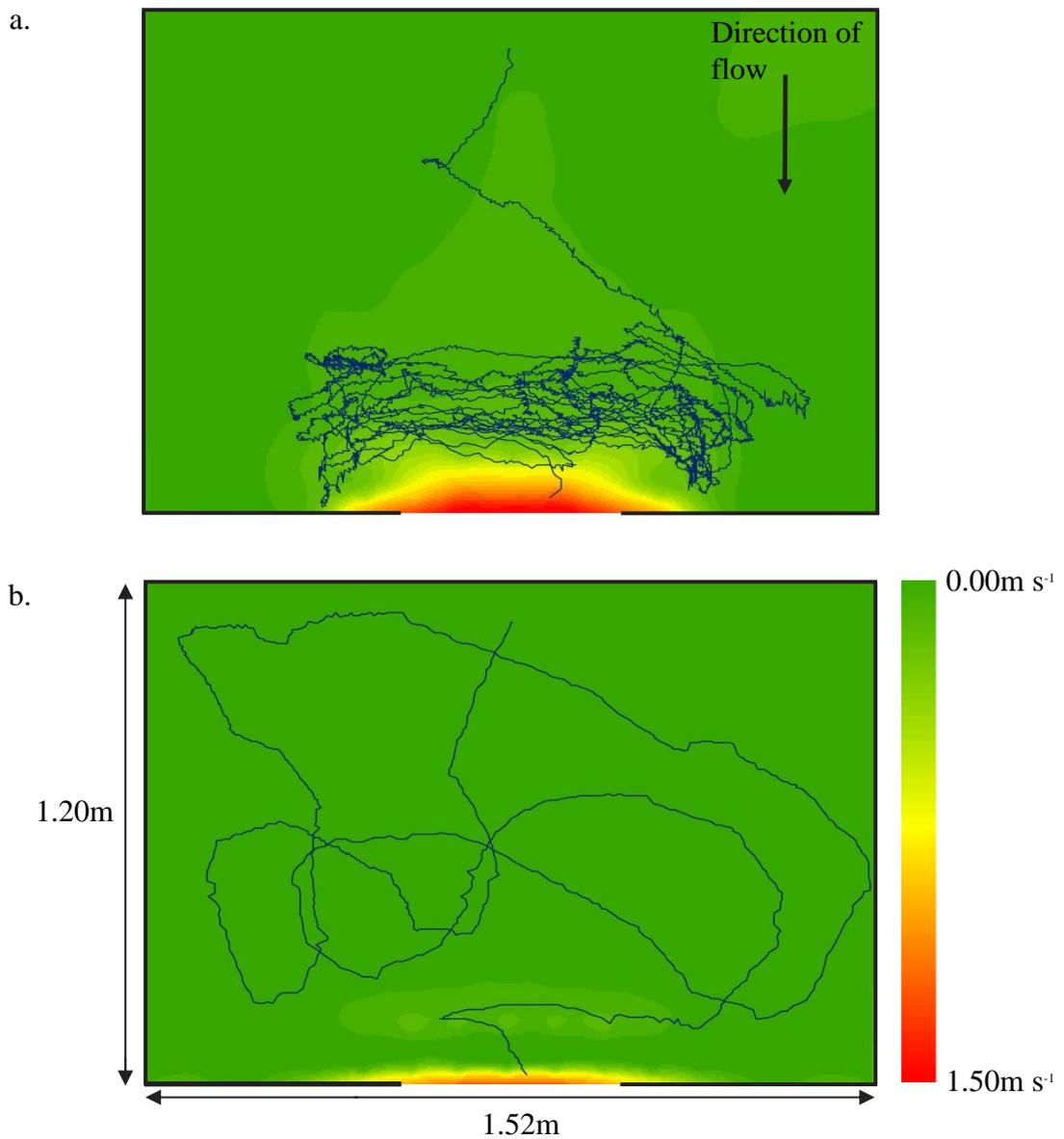


Figure 8.2. Velocity (V) profile during **a.** high and **b.** low velocity gradient treatments. Lines indicate **a.** ‘Reject’ and **b.** ‘Retreat’ behaviours, respectively.

8.3.3. Fish behaviour

Any fish that passed the barrier within 5 body lengths of another was omitted from the analysis to avoid the influence of potential group effects (i.e. the aggregation of two or more fish that forms when they react to each other by remaining in close proximity, Keenleyside 1955). Based on this, 43, 72, 30 and 62% of fish under the high-light, high-

dark, low-light and low-dark treatments, respectively, were included in the analyses. Video footage was post processed using either custom written software (FishTrack, Matlab v7.9; Mathworks, Natick, MA, USA) or Logger Pro Version 3.8.2 (Vernier Software, Beaverton, OR, USA). FishTrack automatically tracked head and tail locations for each video frame during passage through the test area. Automated tracking operated on a colour contrast principle and was not possible for all trials (e.g. due to image quality during dark treatments). Logger Pro was used to manually (also on a frame wise basis) track head and tail locations for fish under conditions where automated tracking was not possible. A sample comparison of an automated and manually tracked video indicated little difference (< 5%) in coordinate position due to method.

8.3.3.1. Nature of response

Five distinct behaviours were expressed as fish initially encountered the accelerating velocity gradients. These were defined as either avoidance behaviours, and consisted of 1) ‘Retreat’ and 2) ‘Reject’; or non-avoidance behaviours, which consisted of 3) ‘React’, 4) ‘Drift-with-bulk-flow’, and 5) ‘Swim-with-bulk-flow’. Behaviours were ranked in terms of magnitude of avoidance (Figure 8.3).

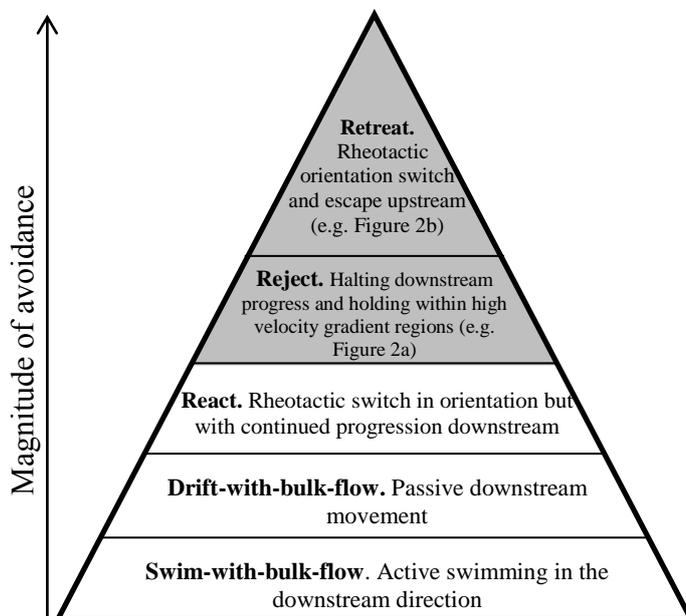


Figure 8.3. Hierarchy of behavioural avoidance expressed as smolts initially encountered an accelerating flow created by an orifice weir in an experimental flume. Grey and clear segments indicate avoidance and non-avoidance behaviours, respectively.

8.3.3.2. Orientation

Using the coordinates derived from the tracking software, the rheotactic orientation (RO) of the fish was calculated for each frame as:

$$RO = 2 * \arctan \left[\frac{Head_y - Tail_y}{\sqrt{(Head_x - Tail_x)^2 + (Head_y - Tail_y)^2} + (Head_x - Tail_x)} \right] \quad (8.2)$$

where \arctan is the inverse tangent trigonometric function used to calculate the angle between head and tail locations. $Head_x$, $Tail_x$, $Head_y$, and $Tail_y$ represent head and tail coordinates on the x and y axis, respectively. Based on the angle between head and tail locations, the proportion of time spent positively or negatively rheotactic during trials was calculated. Fish were only observed parallel to the flow as they switched orientation, and were deemed to be positively oriented until the point their head was further downstream than their tail.

8.3.3.3. Distance travelled

The distance fish travelled (D), relative to the earth frame of reference, between successive frames was calculated as:

$$D = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (8.3)$$

where x_1 and y_1 are the head coordinates on the x and y axis respectively for a specific video frame, and x_2 and y_2 are the head coordinates for the following frame. The distance travelled prior to passing the barrier was calculated for each trial by summing the distances between consecutive points.

8.3.3.4. Time to pass

Time to pass was the period between a fish's head entering the test area and exiting through the orifice.

8.3.3.5. *Spatial velocity gradient*

Fish tracks, generated from the coordinates derived from the tracking software, were overlain onto hydraulic profiles to enable the extraction of underlying velocity data (i.e. the mean velocity vector [V] at head and tail locations) for each coordinate position. This allowed the spatial velocity gradient (SVG) across a fish's body to be calculated, using the formula described by Enders *et al.* (2009):

$$\text{SVG} = \frac{|V_H - V_T|}{L} \quad (8.4)$$

where V_H and V_T represent the velocity at the fish's head and tail position respectively, and L is the total length of the fish. The SVG experienced by smolts while passing through the flume was quantified as the cumulative SVG prior to passage, and was calculated by summing SVG values for each fish prior to passage through the orifice.

8.3.4. *Statistical analysis*

Tests of normality and homogeneity of variance were performed using a Shapiro-Wilk and Levene's test, respectively. Non-normal data were normalized using Box-Cox transformation; when this was unsuccessful non-parametric tests were performed.

Proportion of time spent positively rheotactic was arcsine square root transformed prior to statistical analysis. Binary logistic regression determined the influence of velocity gradient and illumination on (1) nature of response. A Mann-Whitney U or Independent samples t -test (dependent on distribution of the data) determined the influence of velocity gradient and illumination on (2) orientation; and nature of response on (3) distance travelled, (4) time to pass, and (5) spatial velocity gradient.

8.4. Results

One hundred and eleven juvenile salmon (mean fork length \pm SD = 107 \pm 9.66 mm) were included in the analysis. Fish did not exhibit startle or escape responses (as defined by Yasargil and Diamond, 1968) when entering the test area.

8.4.1.1. *Nature of response*

Illumination (Wald = 6.20, $p < 0.05$) rather than velocity gradient (Wald = 0.15, $p = 0.697$) predicted nature of behavioural response (avoidance or non-avoidance) ($R^2 = .21$, $\chi^2 = 16.66$, d.f. = 3, $p = 0.001$). Non-avoidance responses were more common during all treatments, but levels of avoidance increased when light compared to when dark (Figure 8.4). When dark, 88% of responses were of a non-avoidance nature, compared to 55% when light. The most common response expressed as smolts initially encountered the gradient under the high-light treatment was 'Retreat'. 'React' was more common during high-dark and low-dark, while 'Retreat' and 'React' were expressed equally during the low-light treatment (Table 8.1).

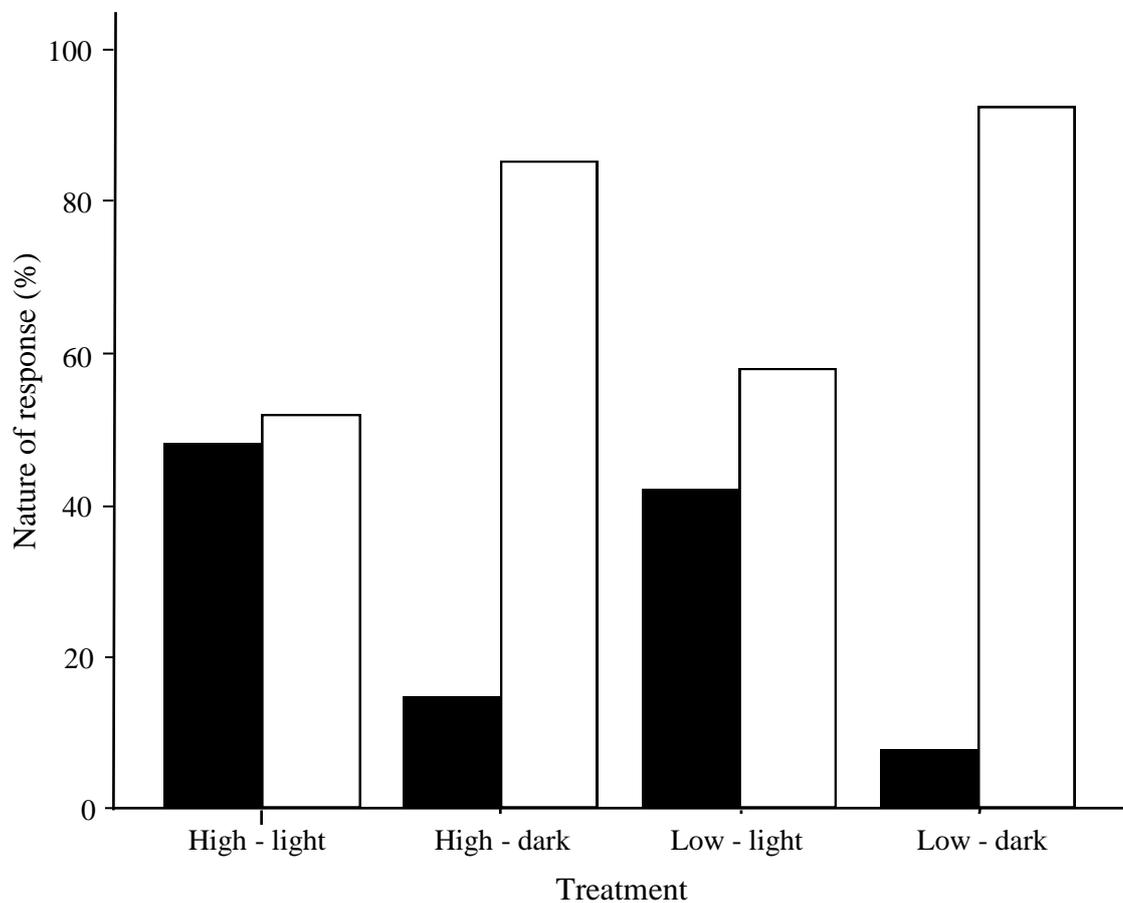


Figure 8.4. Percentage of smolts exhibiting avoidant or non-avoidant behaviours when first approaching an orifice weir in an experimental flume. Black and clear bars represent avoidant and non-avoidant responses respectively.

Table 8.1. Percentage of initial response types expressed as smolts encountered the accelerating velocities created by an orifice weir.

Treatment		Percentage of initial behavioural response types ($N=111$)				
					No response	Swim-with-bulk-flow
Discharge	Illumination	Retreat	Reject	React		
High	Dark	7.3 (3)	7.3 (3)	53.7 (22)	26.8(11)	4.9 (2)
High	Light	36.0 (9)	12.0 (3)	32.0 (8)	20.0 (5)	0.0 (0)
Low	Dark	7.7 (2)	0.0 (0)	53.8 (14)	38.5 (10)	0.0 (0)
Low	Light	26.3(5)	15.8 (3)	26.3 (5)	15.8(3)	15.8 (3)

8.4.1.2. Orientation

Under the high velocity gradient treatment, more time on average ($25.6 \pm \text{SD } 72.1$ seconds or $42 \pm 36\%$) was spent positively rheotactic compared to fish passing through the low velocity gradient ($6.3 \pm \text{SD } 15.0$ seconds or $22 \pm 24\%$) ($U = 1020$, $z = -2.80$, $P < 0.05$).

Illumination had no effect on orientation ($U = 1237$, $z = -1.43$, $P = 0.153$).

8.4.1.3. Distance travelled

Fish that exhibited an avoidance response travelled on average 3.5 times farther than those that did not ($U = 323$, $z = -5.70$, $P < 0.001$; Figure 8.5).

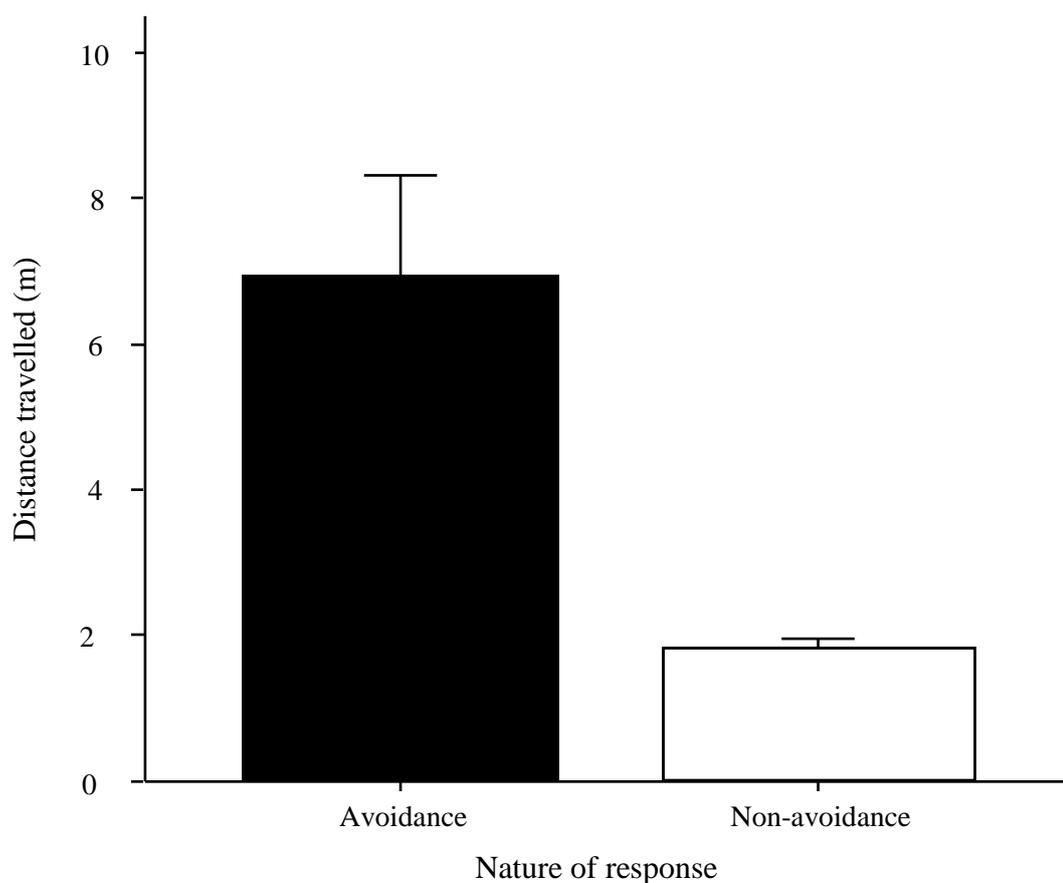


Figure 8.5. Distance travelled by smolts prior to passing the test area of flume (+ 1 SE) in relation to the nature of response expressed on first encountering accelerating velocity created by the orifice weir in an experimental flume.

8.4.1.4. Time to pass

The time taken to pass the test area was highly skewed (Figure 8.6), with most (85.6%) fish doing so within the first 30 seconds of entering (mean time \pm SD = 8.14 \pm 6.19 seconds). Fish taking more than 30 seconds were delayed by an average of 14 times (mean time \pm SD = 114.11 \pm 117.38 seconds). Fish were delayed approximately 8 times longer when expressing avoidance responses compared to those exhibiting non-avoidance behaviours ($t = 7.431$, d.f. = 109, $P < 0.001$; Figure 8.7).

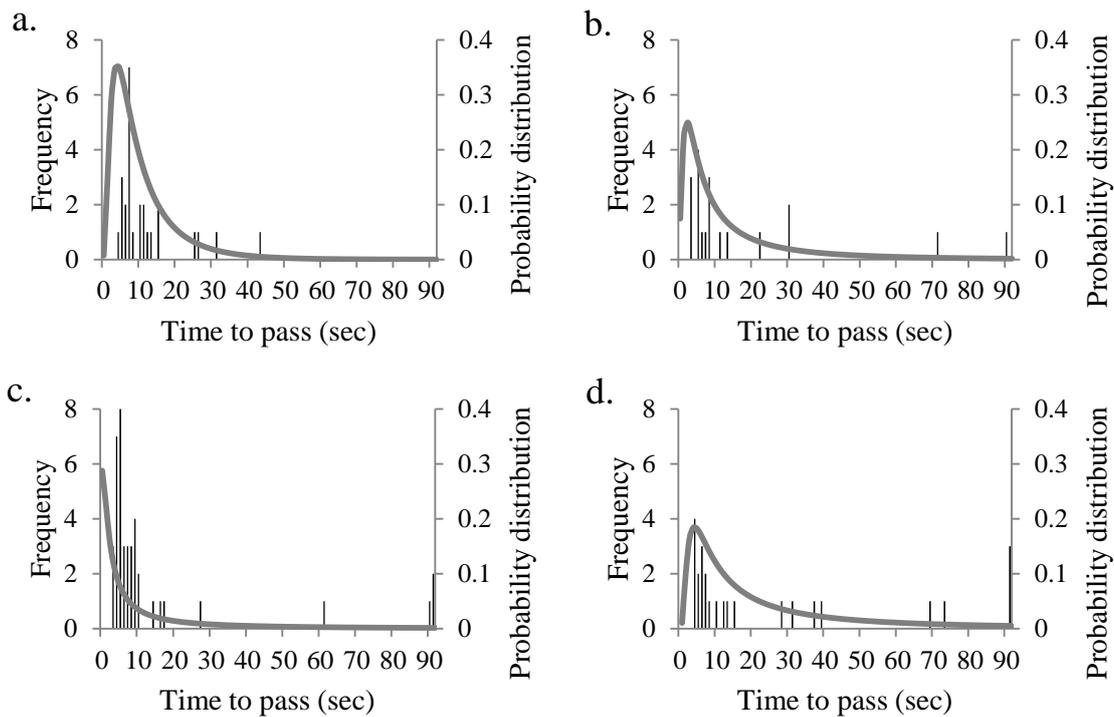


Figure 8.6. Frequency distribution of time taken for smolts to pass through the orifice weir located within an experimental flume under **a.** low-dark, **b.** low-light, **c.** high-dark, and **d.** high-light treatments. An Inverse Gaussian distribution probability density for the different treatments overlying the histograms illustrates the skew in passage time.

8.4.1.5. Spatial velocity gradient

Fish encountered a higher mean SVG prior to passage when expressing avoidance rather than non-avoidance behaviours ($t = 6.514$, d.f. = 109, $P < 0.001$; Figure 8.8).

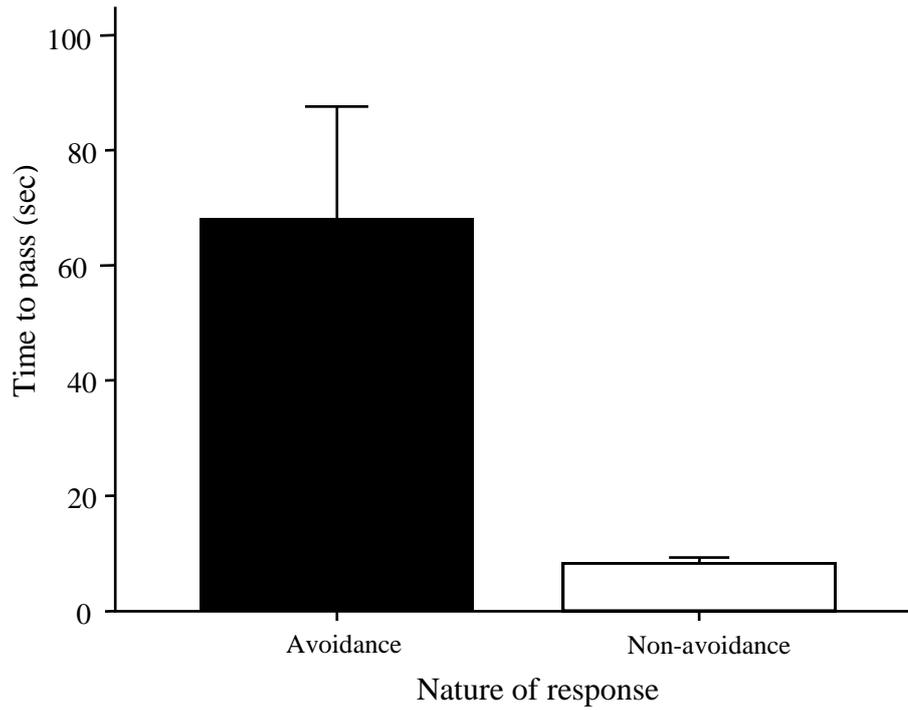


Figure 8.7. Time taken for smolts prior to passing the test area of flume (+ 1 SE) in relation to the nature of response expressed on first encountering the accelerating velocity gradients.

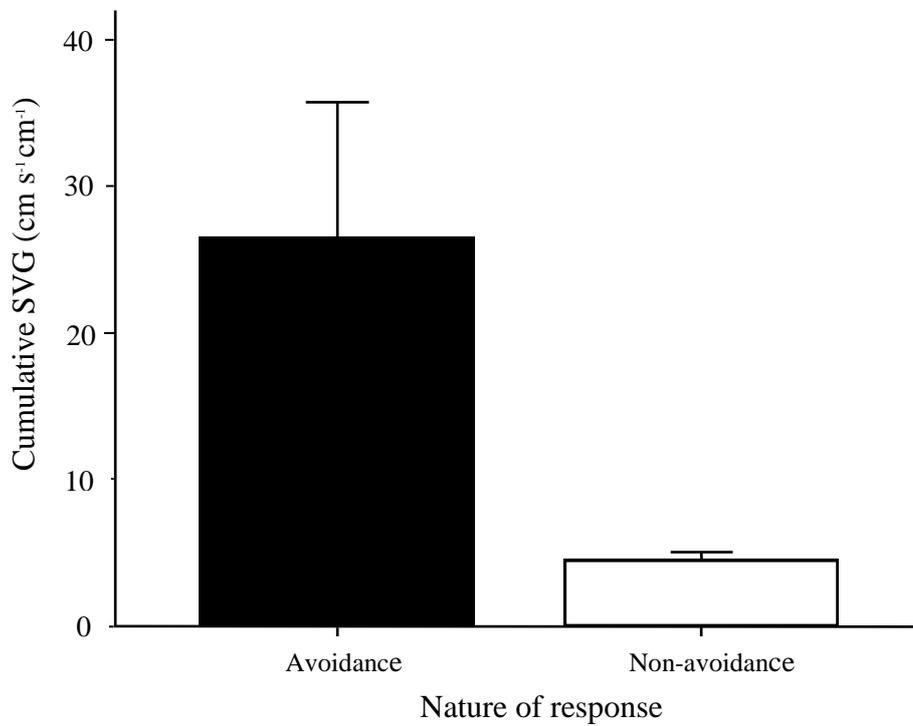


Figure 8.8. Mean cumulative SVG (cm s⁻¹ cm⁻¹) prior to passage, (+ 1 SE) in relation to the response type expressed on encountering the accelerating velocity gradients.

8.5. Discussion

The current study assessed the response of migrant juvenile Chinook salmon to velocity gradients, behavioural barriers commonly encountered during downstream migration, when light and dark, and aimed to quantify the influence of behaviour on passage. It was predicted that greater levels of avoidance would be expressed on encountering a stronger hydrodynamic signal and when light, significantly impeding subsequent downstream migration.

Salmon exhibited a range of behaviours when encountering the accelerating velocity gradients presented. More avoidance responses were associated with illuminated treatments; hydrodynamic signal strength was not influential. The oscillatory behaviour 'Retreat', where fish move in and out of areas of hydrodynamic transition, was the most common response type under the high-light treatment. 'Retreat' and 'React' (a switch in rheotactic orientation in response to the velocity gradient) behaviours were equally frequent under low-light conditions, and fish more commonly exhibited 'React' behaviour when dark. Although 'Retreat' was infrequent across all treatments, it was more often elicited when fish could navigate using visual senses, and is in agreement with Kemp and Williams (2009) who, in a similar study, also show oscillatory behaviour to be more common when light. 'Swim-with-bulk-flow' was the least common response type and although 'Drift-with-bulk-flow' was rare when light, this behaviour was more common during dark treatments.

A greater propensity to express an avoidance response when visual in addition to hydrodynamic signals were presented suggests that additional environmental stimuli improve the responsiveness of migratory fish, supporting the general conclusions of Chapter 7. However, in Chapter 7 it was found that both hydrodynamic signal strength and illumination to influence the nature of response in downstream moving brown trout. In the current study, visual cues dictated the behavioural response, despite the barrier being predominately of hydrodynamic nature. An assumption that fish react predominantly to hydrodynamic cues or that responses to hydrodynamic stimuli will be similar during light and dark conditions may be incorrect. Indeed, in the field, radio tagged Chinook salmon smolts were delayed for longer at a hydropower dam during daylight hours, despite travelling through the reservoir during both day and night (Beeman and Maule, 2001). In

animal behaviour, combined multisensory stimuli can improve detectability, discriminability and memorability of a stimulus within receiving animals (Rowe, 1999). For example, multimodal signals enhance predator avoidance (e.g. Rowe and Guilford, 1999), mate selection (e.g. Uetz *et al.*, 2009), and communication (e.g. Partan *et al.*, 2009). Its use during fish migrations has received little attention, but based on the findings presented here is an important factor to consider when attempting to mitigate for delayed migration at anthropogenic barriers.

Although nature of response was dictated by illumination, rheotactic orientation was influenced by velocity gradient. Smolts predominantly moved downstream head first (a strategy also observed by Kemp *et al.*, 2005b and Enders *et al.*, 2009), however, a higher proportion of time was spent in a positive rheotactic orientation on encountering the high compared to low velocity gradient treatment. By maintaining positive rheotaxis, control over downstream movement is enhanced, facilitating avoidance of potentially harmful conditions by burst swimming in the upstream direction (Kemp *et al.*, 2005b). This enhanced control also enables fish to maintain position within high velocity gradient regions. Indeed, Enders *et al.* (2009) show Chinook salmon smolts facing the flow exhibit an escape response in the upstream direction at higher velocity gradients across the fish's body compared to smolts approaching in a negative rheotactic orientation. Avoidance of dangerous conditions may enhance individual fitness, and so switching to positive rheotaxis when encountering hydrodynamic transitions seems logical if associated with potential hazards, e.g. in natural river systems, accelerating velocity gradients occur near waterfalls and rapids, areas that could disorient fish, leaving them more susceptible to predation (Enders *et al.*, 2009).

The exhibition of avoidance behaviour had a dramatic impact on subsequent passage. Fish that exhibited avoidance to the velocity gradients were delayed by approximately 8 fold, travelled 3.5 times further and encountered a higher mean cumulative spatial velocity gradient prior to passage than those exhibiting non-avoidance behaviours. In the field, up to 20% of radio tagged Chinook salmon have been delayed by 8 – 11 times during passage through a hydropower dam forebay (Venditti *et al.*, 2000). This delay equated to forebay residence times of 7 or more days, with observed behaviours including lateral movement across the forebay and upstream excursions (Venditti *et al.*, 2000), behaviours comparable to the avoidance responses exhibited (albeit on a much smaller scale) during the current

study. Delayed downstream migration at anthropogenic barriers impacts migration success due to elevated predation risk (Poe *et al.*, 1991), energetic costs (Schilt, 2007), risk of disease (Garcia de Leaniz, 2008), and propensity to pass through suboptimal routes (Castro-Santos and Haro, 2003; Svendsen *et al.*, 2011). Results from this study suggest that multimodal signals increase delay and that more efficient passage through areas of accelerating water velocity may be achieved by reducing the amount of environmental information available to fish on which to base a response. The influence of multimodal stimuli has been well documented in other aspects of animal behaviour; e.g. predator detection can be impaired when mosquitofish (*Gambusia holbrooki*) are presented with visual or chemical cues, rather than both stimuli simultaneously (Ward and Mehner, 2010). Similar mechanisms may be affecting the fine-scale behaviour of downstream migrant salmonids encountering hydrodynamic stimuli. Future research should consider the importance of environmental stimuli (particularly those operating through different sensory modalities) on behaviour when acting together rather than separately. While a hydrodynamic gradient was presented in the presence and absence of visual cue in this study, other environmental factors were unaltered during experimentation (e.g. sound levels). As fish have a range of sensory modalities, the manipulation of stimuli that operate through e.g. auditory or olfactory senses, could equally be of use in influencing fish behaviour in a manner deemed desirable from a management perspective.

8.6. Conclusions and directions for future research

Building on previous research into the response of salmonids encountering velocity gradients, this study investigated variation in individual behaviour and its influence on migration success. Response type had a significant impact on subsequent passage. Understanding causes of variation in downstream migrant fish behaviour presents an important challenge; interesting topics for future research include the following. First, do fish habituate to hydrodynamic gradients? A recent agent-based model coupled with a computational fluid dynamics simulation proposed that avoidance exhibited by migrant juvenile salmonids can be induced by hydrodynamic gradients (increasing velocity and hydraulic strain) created by physical structures that constrict the movement of water (Goodwin *et al.*, 2006; Nestler *et al.*, 2008). This model suggests that a more abrupt hydrodynamic signal will induce greater avoidance as fish are required to habituate to conditions that deviate further from background levels. Habituation should be achieved by

adopting behavioural strategies that allow exposure to the gradient, such as hesitating or milling until some hydrodynamic threshold is exceeded, no longer inducing avoidance. In areas of low hydrodynamic transition or if already habituated, fish should swim towards increasing water velocity; resulting in passage through the gradient (Goodwin, 2004; Nestler *et al.*, 2008). To date, the idea that fish must habituate to hydrodynamic conditions at behavioural barriers prior to continued downstream movement is an untested hypothesis. However, it may, in part, explain the variable behaviour observed during the current study, and why fish pass at locations they initially reject. Second, what is the influence of more complex ecological interactions on fine-scale behaviour? For example, do fish progress through areas they would otherwise reject when in the presence of conspecifics or predators? The advantages of maintaining group integrity or avoiding predation may override the potential risks associated with passage through hydrodynamic gradients. Third, how does behaviour vary between species during downstream migration? For example, eels have been reported to express oscillatory behaviours on encountering hydropower intakes (e.g. Behrmann-Godel and Eckmann, 2003). However, fine-scale observations suggest eels may respond predominantly to physical structures and less so to the velocity gradients to which salmonids are frequently observed to react (Russon and Kemp, 2011). Much scope remains for research aiming to mitigate delay of multiple species of fish at anthropogenic barriers. For migratory fish, this study highlights the impacts of behaviour on downstream passage and the potential for multimodal signals to be used in combination to repel fish, e.g. from hazardous areas associated with river infrastructure, such as turbine intakes. Conversely, by limiting information available, undesirable delay, e.g. at entrances to downstream fish bypass systems, may be reduced. If successful, the survival of downstream moving fish passing through anthropogenically altered river systems could be improved.

Chapter 9

Thesis discussion

Within the EU the resurgence in low-head hydropower has already begun. For example, in England and Wales the number of hydropower licences granted between 2008 and 2010 increased more than six-fold (Environment Agency, 2011). With the drive to preserve the biodiversity and ecological integrity of our aquatic environments, it follows that future developments in low-head hydropower should be environmentally (as well as economically) viable. The research reported in this thesis assessed the impact of a novel low-head hydropower technology, the Hydrostatic Pressure Converter (HPC) on downstream moving fish, and identified factors that may limit both up- and down-stream fish pass efficiencies. This was achieved through blade strike modelling and flume based experimental studies (presented in Chapters 5-8). This chapter discusses key findings and provides recommendations for management and future research.

The lack of avoidance behaviour and high level of contact with a screen placed upstream of a prototype HPC installed within a flume, by rainbow trout and European eel, raises concerns as the probability of fish passing through an unscreened device is high. Furthermore, species specific behaviours influenced the probability of a fish being struck by a HPC blade. European eels are considered to be at particular risk during downstream passage through hydropower devices largely due to their elongated body morphology. However, when behavioural parameters were incorporated into the blade strike model (BSM) probability of strike decreased compared with an assumption of passive downstream drift. So, although severe injury associated with mechanical contact is expected to be high for this species of European conservation importance, risks were significantly reduced when behaviour was considered. In contrast to eels, probability of strike increased for trout when behaviour was incorporated into the BSM. Chapter 5 is the first study to incorporate fish behaviour into a hydropower blade strike model, and clearly highlights that risks to downstream moving fish are significantly influenced by species specific behaviours and not simply their physical characteristics.

Considering the potential for direct mortality to downstream moving fish passing through a HPC, design alterations should be considered that eliminate the pinch point (e.g. a gap between the blade tips and base of the river channel, or flexible rubber blades). Despite such suggestions being made early in the developmental stages of the technology, the trade-off between hydroelectric efficiency and fish mortality due to blade strike were deemed undesirable from an engineering perspective. Without design modifications to improve the environmental performance of HPCs, a screen preventing downstream moving fish entering the device is required. For screens that are placed at intakes, a default bar spacing for Kaplan and Francis turbines should be used, which according to the Environment Agency (UK) guidelines is 10 mm (Environment Agency, 2009). For the heavily protected European eel a 10 mm bar spacing would appear appropriate as eels can pass through racks with 12 mm spacing when placed perpendicular to the flow under experimental conditions (Russon *et al.*, 2010). A 10 mm spacing would also be appropriate for exclusion of salmonid smolts, and other similar sized fish. The screens should be angled diagonally across the flow (Figure 9.1) to reduce probability of impingement and entrainment and to deflect fish towards a bypass entrance. The velocity perpendicular to the screen face (referred to as the approach or escape velocity) measured 10 cm upstream of the screen should be low even when the axial channel velocity is high, and should be lower than the sweep velocity along the screen face which will help deflect fish towards a bypass entrance (Figure 9.2; Environment Agency, 2009). The UK fish screen guidelines suggest approach velocities not in excess of 25, 30, 50 and 60 cm s⁻¹ for coarse fish and shad, lamprey, eels, and salmonids respectively (Environment Agency, 2009). Where screens are designed to exclude multiple species, the lowest common acceptable approach velocity must be used (Environment Agency, 2009). It is generally accepted that rectangular section bars or perforated plates are preferable to round or oval section bars, which are more likely to injure fish through catching on their gills (Turnpenny and O’Keeffe, 2005).

Despite these recommendations (based on current UK screen guidelines), it should be noted that some species are reported contacting physical screens at velocities much below their measured swimming capabilities, suggesting that application of traditional swimming performance data to the development of screen criteria may be insufficient, and that behaviour plays a prominent role (Swanson *et al.*, 2004; 2005). Furthermore, poorly designed and inappropriately placed screens can negatively impact fish that are either

impinged against them at high velocities (resulting in suffocation and mortality) (e.g. Calles *et al.*, 2010) or are injured due to abrasion and de-scaling when making contact, resulting in delayed mortality (e.g. Hughes *et al.*, 2011). Behavioural screening devices (e.g. lights, acoustics, bubbles) have also been used, either to replace or complement physical screens. However, the effectiveness of behavioural screens is currently variable depending on site-specific condition and species, and is generally lower than that attained for physical screens (Turnpenny *et al.*, 1998). Research conducted during Chapters 7 and 8 may help to improve the effectiveness and consistency of behavioural screens, e.g. by providing hydrodynamic thresholds and additional insight into how multiple stimuli influence and impact observed behaviour. Practical application of this research to a field setting is required before behavioural barriers can be recommended as a generic environmental impact mitigation option for HPCs.



Figure 9.1. A 30 m long near vertical bar screen (12.5 mm bar spacing) installed diagonally across a mill channel leading to a small-scale (0.34 megawatt) hydropower facility on the River Tay, Scotland (UK). A fish bypass system is located at the end of the screen (photograph: Paul Kemp).

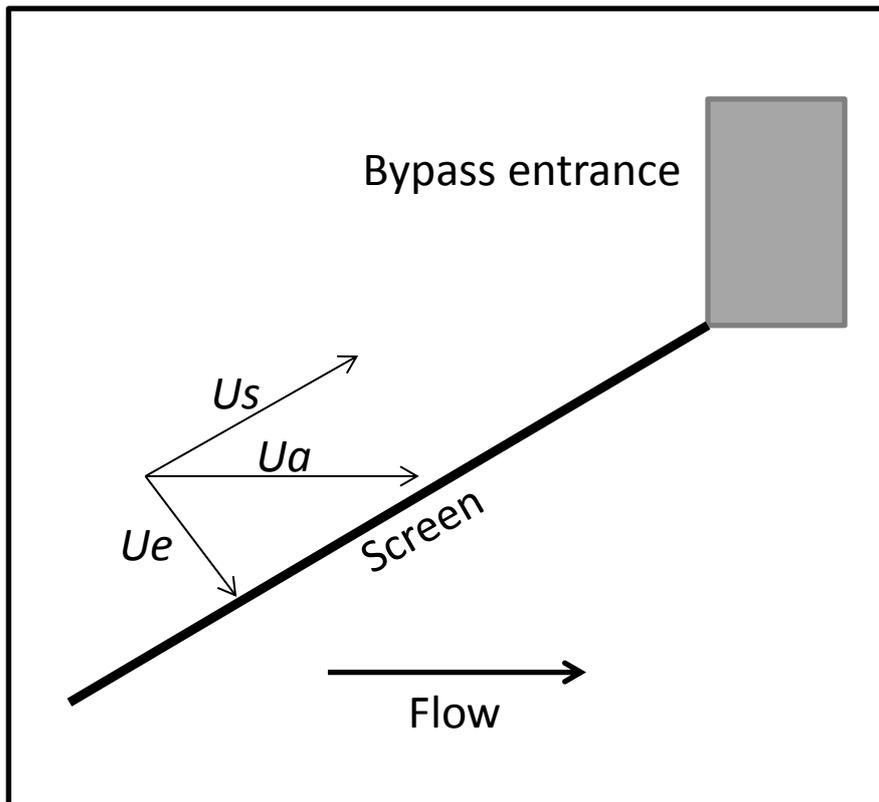


Figure 9.2. Flow velocity components in front of an angled bar screen. U_a is the axial velocity, U_e is the escape velocity and U_s is the sweep velocity along the screen face (adapted from Turnpenny and O’Keeffe, 2005).

For upstream migrating fish, the anthropogenic barriers required to provide the head difference for low-head hydropower generation can physically block, restrict or delay access to habitat patches. Considering the low-head nature of HPCs, nature-like fish passes (e.g. Calles and Greenberg, 2005) would appear appropriate for providing optimal upstream fish passage efficiency. Nature-like fishways mimic the natural water course in both form and function (Larinier and Marmulla, 2004; Santos *et al.*, 2005), so are characterised by low gradients ($\leq 5\%$) and a heterogeneous structure, creating velocity and depth variation (Aarestrup *et al.*, 2003). The advantage of nature-like designs is the potential for both up- and down-stream movements of a wide range of fish species, body sizes and morphologies, whilst also providing habitat for resident biota (Aarestrup *et al.*, 2003). Nature-like fish passes have higher fish passage efficiencies (e.g. the proportion of fish that successfully ascend or descend once they have entered the fish pass) than technical fish passes (e.g. Denil designs). However, due to their low gradient, nature-like channels are typically long, often requiring more land space than technical fish passes, making it difficult to position the downstream entrance near the barrier, thus reducing

attraction efficiency (i.e. proportion of fish which enter the local vicinity that are attracted to the fish pass entrance) (Bunt *et al.*, 2012). For HPCs (and other hydropower developments) the efficiency of the fish pass to both attract and pass fish in both directions should be monitored and quantified post construction, and the costs of doing so should be considered at the design stage of any hydropower development.

Traditionally, fish passage research has focused on the physiological capabilities of fish to pass barriers; behavioural aspects to barrier passage have been largely ignored. This is an important oversight as barrier passage is largely volitional, and as such, is governed as much by behavioural constraints as by physiological limits (Binder and Stevens, 2004). For physical and / or behavioural screens that divert downstream moving fish away from HPC intakes, they must be used in combination with a more benign alternative route around the hydropower facility (i.e. a bypass channel). However, delay due to behavioural avoidance of conditions created at bypass entrances (particularly abrupt accelerations of water velocity) may reduce individual fitness through e.g. increased energetic costs or predation risk (Scruton *et al.*, 2007). Chapter 7 illustrated that the simultaneous detection of a velocity gradient and light stimulus enhanced the avoidance of brown trout rather than masking the velocity gradients and reducing delay. Findings from Chapter 7 significantly enhanced our understanding of how downstream moving salmonids react to their environment, and while this increase in avoidance may be deemed disadvantageous for those aiming to facilitate more efficient passage through downstream bypass channels, it could be considered advantageous for those aiming to deflect or deter fish from hazardous locations (such as low-head hydropower intakes or water abstraction sites). Although (as previous noted) light has a number of disadvantages when deployed in a natural setting (e.g. effectiveness influenced by time of day and water turbidity), combinations of multimodal stimuli in general are likely to be more effective at guiding fish than a single stimulus. Building on Chapter 7, Chapter 8 quantified the impact of observed behaviours on subsequent downstream passage. Results were in agreement with Chapter 7; Pacific salmon smolts exhibited more avoidance responses when navigation with mechanosensory and visual cues was possible. Avoidance had a dramatic effect on subsequent passage, fish were delayed by approximately 8 fold, travelled 3.5 time further, and encountered a higher spatial velocity gradient across the body. These studies highlight the impact variation in response has on subsequent passage, and the potential for multimodal signals to be used in combination to repel fish (e.g. from hydropower turbine intakes). Conversely, by limiting

information available, undesirable delay may be reduced. This research may have direct application to screen and bypass design, and the potential to improve fish survival at hydropower developments. The challenge for the future is to now apply this information to the field and attempt to improve guidance towards preferred passage routes and facilitate more efficient entry into bypass channels. Research of this nature is starting to emerge, for example, using overhead shade in combination with a trash rack, Greenberg *et al.* (2012) improved the guidance of brown trout smolts away from a turbine intake on the River Emån (Sweden). Considering the results from Chapter 7 and 8, it could be that guidance was enhanced due to the detection of hydrodynamics associated with the screen acting in combination with overhead shade. Experimental and applied research of this nature should continue in the future.

Owing to the inherent complexities of studying fish behaviour, a number of additional factors present interesting avenues for future experimental research in downstream fish passage. These were noted in the conclusions of Chapter 8, and are: 1. Do fish habituate to hydrodynamic gradients? 2. What is the influence of more complex ecological interactions on fine-scale behaviour? and, 3. How does behaviour vary between species? Answers to this final question are of key importance in determining the applicability of results presented in Chapters 7 and 8 to other species. Research on this topic is starting to emerge. Russon *et al.* (2011) conducted a series of flume experiments at the ICER experimental facility, where a comparison between brown trout and European eel behaviour was made as they encountered velocity gradients associated with an orifice weir. Results illustrate that while trout react at a similar spatial velocity gradient under different discharge regimes, eels tended to react predominantly to physical structures. This highlights the complication in developing effective bypass facilities for multiple species of fish. Conditions that one species avoid, another may not. Having said this, a more recent study conducted at ICER, using a similar constricted channel setup as that in Chapter 7, found that 34% of European silver eels exhibited an avoidance and retreat response on encountering the accelerating velocity gradient (L. Eakins, pers comm.). Eels are also frequently reported to express oscillatory or milling type behaviours on encountering hydropower intakes under field scenarios (Behrmann-Godel and Eckmann, 2003). Moreover, silver eels are reported to be negatively phototactic (Haddingh *et al.*, 1999) and to avoid certain acoustic stimuli (Sand *et al.*, 2000). Much scope remains for research

into the behaviour of multiple species of fish to the aim of facilitating efficient multi-species fish passage around anthropogenic barriers.

For upstream migrant fish, most fish passes were originally designed to accommodate highly motivated species with strong swimming abilities, such as adult salmonids (Bunt *et al.*, 2012). The need for research into the factors that limit the efficiency of fish passes for non-salmonid species of conservation concern within Europe was highlighted during the literature review (Chapter 2). This was explored during Chapter 6 where the behaviour of upstream migrant adult river lamprey in response to water velocity and turbulence, hydrodynamic features ubiquitous with fish passes, was assessed in a large open channel flume at the ICER experimental facility.

Lamprey volitionally ascended the experimental flume during hours of darkness and selected to pass through either a high or low turbulent zone, dependent on lateral position, under a high or low velocity treatment. Although predicted to avoid turbulence, no evidence of this was found at either a coarse- or fine-scale. It is therefore not possible to suggest the manipulation of turbulence within fish passes for the purposes of enhancing attraction towards and progression through such structures. However, lamprey did increase their swimming speed in response to higher water velocity, an advantageous trait for ensuring minimum delay in fish passes once the fish has located the entrance. However, water velocities should not exceed the maximum speed lampreys are able to maintain for the period of time needed to progress upstream otherwise passage success will remain low. Furthermore, prior research illustrates that as velocity increases above those encountered in Chapter 6, a burst-attach form of locomotion is expressed. The inclusion of suitable attachment sites in the design of fish passes are of importance for enabling the execution of this natural performance enhancing behaviour.

While previous research on the behaviour of non-salmonids (e.g. that of Silva *et al.*, 2011; 2012) found significant correlations with turbulent features, no such evidence was obtained during Chapter 6. However, it could serve to guide future research. The study was well founded, based on the poor efficiency of current fish passes for lampreys, previous observations that turbulence may contribute to poor passage, and on numerous suggestions that lamprey may find turbulent locations challenging environments. The lack of any clear correlation between behaviour and turbulence could relate to a number of factors. It could

be that turbulence, or at least the levels (e.g. of *TKE*) or structure (e.g. periodic vortex shedding in the horizontal plane) of turbulence generated within Chapter 6, did indeed not influence swimming performance or behaviour. Yet, higher levels or more stochastic, three dimensional turbulent environments (likely to be more common in nature) may still impact lamprey behaviour. Furthermore, some of the responses that were indicative of strong avoidance could have been occurring as the fish instantaneously encountered vorticity associated with a single vortex (Webb and Cotel, 2010, and as illustrated in Figure 9.3). While it was not possible to quantify behaviour and hydrodynamics instantaneously, this level of fish / fluid interaction may have taken place (similar to the work of Liao *et al.*, 2003, who found trout to slalom between successive vortices under laboratory conditions). Whether technological advancements will enable the collection of such data in the future is unclear, but would open up some interesting opportunities, particularly for the discipline of “Ecohydraulics” and its potential application to fish passage (See Vowles *et al.*, In press). Finally, water temperature was positively correlated with fish swimming speed in Chapter 6. However, while temperature is known to increase maximum attainable speeds, it also reduces endurance, presenting contrasting challenges for fish passage design. How future changes in river temperature influence the passability of barriers to fish migration and the performance of fish passes may become an increasingly important aspect for future research.



Figure 9.3. Visualisation of the vortex street created during Chapter 6 and a track of a river lampreys head position as it ascended the flume. This illustrates the potential simultaneous interaction that may have occurred between the lamprey and the hydrodynamic conditions created.

9.1. Conclusions

The research reported in this thesis was conducted in pursuit of two aims. The first was to assess the impact of Hydrostatic Pressure Converters on fish behaviour and survival, while the second was to investigate and identify factors that may limit fish pass efficiencies. To realise these aims, six research objectives were identified (see Chapter 3). Conclusions drawn from this body of research in relation to each of objective are presented below.

Objective 1: Identify methods and highlight research trends, biases and gaps in knowledge on the ability of fish to move through hydropower installations and around associated impoundments

A quantitative and narrative literature review in Chapter 2 showed that research relating to fish passage at anthropogenic barriers has continually increased over the past 50 years, and has used a diversity of methods. Despite a wealth of research, fish passage structures generally appear to have low efficiencies for both up and downstream moving fish. The lack of effective downstream guidance and passage structures for juvenile salmonids

despite over 30 years of research is testament to this. Upstream fish pass efficiencies remain low for many non-salmonids which differ greatly in swimming ability and behaviour, in comparison to the more traditionally studied salmonids. Research should strive towards developing fish passes that are suitable for both up- and down-stream movements of a wide variety of fish species, as required under the EU Water Framework Directive.

Objective 2: Develop a numerical blade strike model to predict the probability of a fish striking a HPC blade

A numerical blade strike model (BSM) was developed (Chapter 5) which predicted the probability of a fish striking the leading edge of a HPC blade. The use of blade strike modelling aided the assessment of HPCs, which when combined with empirical data (see objective 3 below) allowed recommendations for river / fisheries management to be made, prior to installation in a field setting.

Objective 3: Estimate injury / mortality associated with downstream passage through a HPC, taking into consideration the behaviour of multiple species of fish

Through the incorporation of empirical data of fish behaviour on approach to a prototype HPC intake in an experimental flume, it was possible to determine the influence of species specific behaviours on the probability of strike. Behavioural data also indicated that multiple fish species would not simply avoid the intake to a HPC, but were highly likely to pass through an unscreened device. Fish sustained severe physical damage when caught in the pinch point between the blade tips and base of the river channel. This damage was deemed to be unrecoverable. An unacceptably high risk to downstream moving fish was illustrated and, in the absence of design alterations, a fish screen and associated bypass channel were recommended to protect the fish fauna within our rivers.

Objective 4: Quantify the behavioural response of upstream migrant non-salmonids to hydrodynamic conditions associated with fish passage facilities

The impact of hydrodynamic variables ubiquitous with fish passage facilities (water velocity and turbulence) on upstream migrant adult river lamprey (Chapter 6) was assessed. Results did not support the hypothesis that lamprey would avoid areas of elevated

turbulence. However, fish swimming speed was correlated with increased water velocity and temperature. Impacts of water velocity and temperature on swimming performance raise some interesting future challenges for fish passage design, particularly considering predicted changes to flow and temperature regimes with future climate (e.g. milder and wetter winters, but hotter and dryer summers; UKCIP, 2002)..

Objective 5: Quantify the behavioural response of downstream migrant fish to conditions associated with HPC and bypass facilities

While multiple species of fish showed no avoidance behaviour on approach to a HPC intake in an experimental flume (Chapter 5), brown trout were observed avoiding accelerating velocity gradients during Chapter 7. This chapter advanced our understanding of how fish respond to velocity gradients (a hydraulic feature ubiquitous to bypass entrances) and illustrated the influence of additional environmental stimuli on fine-scale behaviour. Multimodal stimuli enhanced responsiveness, illustrating that environmental stimuli associated with bypass entrances influence behaviour by acting in combination. The use of multimodal stimuli in influencing fish behaviour to facilitate more efficient downstream fish passage is a valuable area for future research.

Objective 6: Quantify the impact of variable behaviour on subsequent passage at conditions associated with bypass facilities.

Despite numerous experimental investigations into the response of salmonids to velocity gradients, Chapter 8 was the first to quantify the impact of variable behaviour on subsequent downstream passage. This chapter highlighted the significance of behaviour on delay, and supported the findings of Chapter 7 by highlighting the potential for multimodal signals to be used in combination to repel fish; or conversely, the value of limiting information available to fish when attempting to reduce undesirable delay.

9.2. Contributions to existing knowledge and thinking

As a result of this thesis a number of original contributions to existing knowledge and thinking have been made to the field of fish passage and low-head hydropower development:

- In Chapter 2, a critical review of hydropower and fish passage literature outlined flaws in some traditional research approaches. The value of large open channel flumes for obtaining fine-scale behavioural information and creating hydrodynamic environments relevant to fish pass design, were highlighted. Sections of this chapter were incorporated into a publication that outlines the importance of embracing techniques that enable the more realistic quantification of behaviour and hydrodynamic environments, and of a shift in scientific culture towards one that encourages interdisciplinarity. See Vowles, A.S., Eakins, L. R., Piper, A.T., Kerr, J.R. & Kemp, P.S. (In Press). Developing realistic fish passage criteria – An ecohydraulics approach. In Maddock, I., Harby, A., Kemp, P., Wood, P. (eds.). *Ecohydraulics: An integrated approach*. Wiley, Chichester, West Sussex, England.
- The impact of a novel low-head hydropower technology on downstream moving fish, recommendations for management, and suggestions for improving blade strike models in general were made (Chapter 5). This study was the first to incorporate behaviour into BSMs, highlighting that risks to downstream moving fish is variable depended on species specific behaviours rather than simply their physical characteristics. This work will be submitted to the international journal *Ecological Engineering* as Vowles *et al*. The importance of behaviour in predicting the impact of a novel small-scale hydropower device on the survival of downstream moving fish.
- Building on previous research into the behavioural response of salmonids encountering velocity gradients, it was illustrated that reactions occur as a threshold spatial velocity gradient is experienced, that a number of different responses may be elicited, and that multimodal stimuli can reduce response thresholds. This original information is of relevance to those working in fish passage engineering. See Vowles, A.S. & Kemp, P.S. (2012). Effects of light on the behaviour of brown trout (*Salmo trutta*) encountering accelerating flow: Application to downstream fish passage. *Ecological Engineering* **47**: 247-253.
- During my candidature, discussions at two International Leverhulme Trust Network Meetings (titled ‘Bridging the Gap between Fish Behaviour and Hydraulics’) resulted in exploration of Signal Detection Theory, traditionally used in psychological studies, for its applicability to fish passage research. Signal Detection Theory could prove useful in measuring behavioural performance, and

subsequently the development of fish passage facilities, by accounting for individual bias in behaviour and influencing the discriminability of stimuli for fish. For more details see Kemp, P.S., Anderson, J.J. & Vowles, A.S. (2012). Quantifying behaviour of migratory fish: Application of signal detection theory to fisheries engineering. *Ecological Engineering* **41**: 22-31.

Research presented in this thesis highlights the importance of conducting Environmental Impact Assessments on new hydropower technologies, and the complexities involved in developing more efficient fish pass facilities. The challenge for future research is to advance fish passage through development of realistic, multi-species and life-stage design criteria. Studies should be conducted across a range of spatial scales and combine the advantages of both flume and field based techniques. Technological developments in telemetry and hydraulic profiling allow this to take place in the field, while, as illustrated throughout this thesis, the ever advancing techniques employed within flumes enable the direct observation and quantification of behaviour and hydraulic parameters at much finer scales, under conditions in which test variables are manipulated while confounding factors are controlled.

For flume based research, more work is required to verify which hydraulic metrics are most appropriate from a biological perspective (Lacey *et al.*, 2012), and how fish collect, process and respond to environmental stimuli (Liao, 2007; Kemp *et al.*, 2012). Although such research has clear value for fish pass development, examples of successful application remain scarce (but see Moser *et al.*, 2011), with the majority of fish passes still found to be poorly functioning (Bunt *et al.*, 2012; Noonan *et al.*, 2011). Advances in technology will likely facilitate better integration of experimental, modelling and field based approaches, but ultimately the successful application of flume based research is required if they are to be used to improve fish pass efficiencies.

Chapter 10

Closing remarks

Despite the questionably insignificant overall contribution of low-head hydropower to national and European renewable energy targets, it has clear value on a smaller, community scale. Development of low-head hydropower (of which thousands of potential sites exist across the UK) could reduce energy costs and provide a source of income through the sale of surplus electricity (e.g. through the UK Feed-In Tariff scheme) for the energy producer. Furthermore, schemes generating around 50 KW (for example) can power several homes, farms or business units (Environment Agency, 2010b). Hydropower schemes, however small, must be developed in an environmentally acceptable manner. Research presented in this thesis will help development of environmentally acceptable hydropower through recommendations made on a novel low-head technology, and by aiding our understanding of fish behaviour in response to conditions associated with up- and down-stream fish pass facilities.

Many thousand low-head structures currently prevent or limit fish movements in the UK (Environment Agency, 2010a), and globally (e.g. Porto *et al.*, 1999). If hydropower can be developed in an environmentally acceptable way, then maybe we should consider these schemes as an opportunity to improve fish passage and the connectivity of our rivers. For example, by incorporating fish pass facilities into the design of developments at locations that currently restrict fish movements, or by co-locating a new hydropower development with current fish pass facilities, improving attraction efficiency for fish. The continual development of more efficient fish pass criteria through original research, in addition to this shift in thinking with regards to hydropower development, could prove rewarding for all concerned.

In addition to assessing site-specific impacts and improving fish passage and survival at a single hydropower development, the cumulative impact of multiple facilities located within a catchment must also be taken into consideration during the consent and planning process. Even for technologies that have relatively low impacts on downstream moving fish (e.g. the Archimedean Screw Turbine) the cumulative effects of passage through a succession of

installations can be large (Bracken and Lucas, 2012). Prioritising which potential hydropower sites should be developed, which barriers require improvements in fish passage, and those which should be removed, at a catchment wide scale, is a key challenge for river managers and regulators, but vital if the ecological status of our rivers are to meet the required standards.

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