University of Southampton

FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

SCHOOL OF ENGINEERING

DEVELOPING A LOW-COST FISH PASSAGE SOLUTION FOR GAUGING WEIRS

by

DANIELLA MONTALI-ASHWORTH

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

February 2020

University of Southampton

Abstract

FACULTY OF ENGINEERING AND PHYSICAL SCIENCES

SCHOOL OF ENGINEERING

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

DEVELOPING A LOW-COST FISH PASSAGE SOLUTION FOR GAUGING WEIRS

by

Daniella Montali-Ashworth

Fluvial habitat connectivity is essential for the transfer of energy, materials and organisms along rivers. In-river barriers (such as dams and weirs) disrupt the river continuum, causing numerous populations of fish to decline as movement between critical habitats is impeded. Gauging weirs, present worldwide, act as barriers to the upstream movement of some fish due to the unfavourable hydraulic conditions created on the downstream face. Regulations, such as the Water Framework Directive (European Commission, 2010) along with others internationally, requires that these barriers be retrofitted or removed so that fluvial connectivity is increased and habitat connectivity restored. There is a need to develop simple low-cost solutions to enhance multi-species fish passage, while not impacting the ability of these structures to gauge flow or increasing their potential to accumulate debris. In this thesis a staggered array of Cylindrical Bristle Clusters (CBCs) were developed as a novel solution to aid fish passage over gauging weirs. The simplicity and modularity of the design helps improve cost effectiveness and ease of installation. Experiments investigated the use of an array CBCs, mounted on the downstream face of Crump weirs, to improve upstream passage of multiple species of fish while maintaining gauging accuracy. Results showed that the passage efficiency of a Crump weir was increased for roach and chub when retrofitted with CBCs. Swim path analysis indicated fish utilised low velocity zones in the wake of clusters to facilitate passage. Fish exhibited a range of sinuous swimming behaviours while manoeuvring through the CBC array to ascend the weir, the most common of which was zigzagging between two lines of clusters. Time taken to pass the weir and length of the swim path were greatest under the highest cluster density, where manoeuvrability was most constrained. Debris accumulation was minimal during the test period. Passage efficiency, the number of fish that passed as a percentage of those that attempted to do so, was a function of cluster diameter and spacing; efficiency was highest (> 80 %) when the ratio of lateral cluster spacing (centre to centre) (S_c) to diameter was less than 5. Cluster array configurations with the lowest wake overlap (D = 0.03 m, S_d = 0.15 m) produced the highest array drag. Maximum velocity reduction can be obtained when wake overlap is minimised, where low velocity areas no longer extend from one cluster to the next. However, wake overlap has a significant influence on fish passage where increasing the proportion of linking low velocity area is more beneficial for fish. Therefore, a compromise is required between increasing velocity reduction potential and improving fish pass utilisation where increased wake width and overlap are potentially best. Consequently, optimal conditions for fish passage can be obtained through tailoring array layout so that the area of low velocity and spacing between the clusters is maximised whilst increasing the overall flow resistance created by the pass. This body of research highlights the potential for a staggered array of CBCs to improve the upstream passage of multiple species of fish at gauging weirs, common barriers to fish migration, without affecting the accuracy of flow gauging. Placement of clusters close to the weir crest without compromising gauging accuracy is a key benefit of this design for regulatory agencies, ecological engineers, and the operators and managers of river infrastructure tasked with mitigating habitat fragmentation for fish while maintaining the provision of services.

Table of Contents

Table of Contents i

Table of Tables v

Table of Figures vii

List of Accompanying Materials xv

Research Thesis: Declaration of Authorship xix

Acknowledgements xxi

Nomenclature xxii

Chapter 1 Introduction 1

1.1 Overview 1

1.2 Aim and Objectives 5

1.3 Thesis Outline 6

Chapter 2 An Evaluation of Existing Fish Passage Solutions 7

2.1 Introduction 7

2.2 Quantifying Fish Passage Efficiency 10

2.3 Passage Efficiency at Triangular Profile Gauging Weirs 17

2.4 Existing Low-Cost Fish Passage Designs for Gauging Weirs 21

2.5 Conclusions 25

Chapter 3 Design Concept – A Staggered Array of Cylindrical Bristle Clusters 26

3.1 Optimising Hydrodynamic Environment for Fish Passage 26

3.2 Modification of Gauging Weir Hydraulics with Roughness Elements 32

3.3 Hydrodynamic Impacts of Roughness Element Density 34

3.4 Fish – Hydrodynamic Interactions around Cylinders 37

3.5 Application of Theory – Design Proposal 38

3.6 Dimensional Analysis 39

3.7 Conclusions 40

Chapter 4 Adaptation of Eel Bristle Boards for Improving Fish Passage at Gauging Weirs 41

Summary 41

4.1 Introduction 42
4.2 Materials and Methods 43
4.2.1 Experimental Setup 43
4.2.2 Hydrometric, Velocity and Depth Trials 44
4.2.3 Fish Trials 45
4.2.4 Debris Accumulation and Bristle Deformation 46
4.3 Results 49
4.3.1 Hydrometric, Velocity and Depth Trials 49
4.3.2 Fish Trials 52
4.3.3 Debris Accumulation and Bristle Deformation 53
4.4 Discussion 54
4.4.1 Hydrometric, Velocity and Depth trials 54
4.4.2 Fish Trials 55
4.4.3 Debris Accumulation and Bristle Deformation 56
4.5 Conclusions 57

Chapter 5 Use of Cylindrical Bristle Clusters as a Novel Multispecies Fish Pass to Facilitate Upstream Movement at Gauging Weirs 59

Summary 59
5.1 Introduction 60
5.2 Materials and methods 62
5.2.1 Laboratory Fish Passage Trials 62
5.2.2 Field Fish Passage Validation and Debris Monitoring 65
5.2.3 Effect on Gauging 69
5.3 Results 70
5.3.1 Laboratory Fish Passage Trials 70
5.3.2 Field Fish Passage Validation and Debris Monitoring 73
5.3.3 Effect on Gauging 77
5.4 Discussion 79
5.4.1 Laboratory Fish Passage Trials 79
5.4.2 Field Fish Passage Validation and Debris Monitoring 80

5.4.3 Effect on Gauging 82
5.5 Conclusions 83

Chapter 6 Fish – Hydrodynamic Interactions Within a Staggered Array of Cylindrical Clusters 85

Summary 85
6.1 Introduction 86
6.2 Materials and Methods 89
6.2.1 Fish Passage and Swimming Behaviour Trials 89
Experimental Setup 89
Experimental Fish Husbandry 94
Experimental Procedure 94
Fish Behaviour and Statistical Analysis 94
6.2.2 Laboratory Hydraulic Trials 95
Experimental Setup 95
Experimental Protocol 96
Data Analysis 97
6.3 Results 98
6.3.1 Fish Passage and Swimming Behaviour Trials 98
6.3.2 Laboratory Hydraulic Trials 100
6.4 Discussion 103

Chapter 7 General Discussion 106

7.1 Current CBC Installations and Manufacture 106
7.2 Recommendations for Management 113
7.3 Influence of Scaling Parameters 114
7.4 Velocity Measurement 116
7.5 Key Findings and Contribution to Scientific Knowledge 117
7.6 Further Work 121
7.7 Conclusions 124

Appendix A Supplementary Information 125

A.1 Laboratory Fish Passage Trials Documented in Chapter 4 125

A.2 Laboratory Fish Passage Trials Documented in Chapter 5 130

A.3 Field Installation of the CBCs Documented in Chapter 5 134

A.4 Gauging Experiments Documented in Chapter 5 140

A.4.1 Setup 140

A.4.2 Percentage impact on gauging 142

A.4.3 Modular limit 148

A.4.4 Manning's n 149

A.5 Array Arrangements used during Experiments Documented in Chapter 6........... 150

A.6 Pictures of the Experimental Setup used during Fish Passage Trials Documented in Chapter 6.. 153

A.7 Pictures of the Experimental Setup used during Hydraulic Experiments Documented in Chapter 6 158

References 168

Table of Tables

Table 4.1 Water depth upstream (US) (0.5 m from weir crest) and downstream (DS) (30 m from the weir crest) of the flat-V weir, in addition to longitudinal depths down the centre of the weir (0, 0.17, 0.37, 0.57, 0.695 and 0.82 m from the weir crest numbered from 1 to 6), Fr number along the weir face (locations as for depth measurements using average velocities), and Re number for point 5 (near base) before hydraulic jump. Measurements were taken at low (*L*), medium (*M*) and high (*H*) flows for the control (*λ1*), and treatments (*λ2*, *λ3* and *λ4*)................50

Table 5.1 Periods (C = control, T = treatment) over which multispecies fish passage over a Crump gauging weir on the River Adur, West Sussex, UK (50°95'74.63''N, 0°26'58.75"W) were monitored with corresponding tagging dates and the number of fish tagged during each tagging event...68

Table 5.2 Passage efficiency data showing the number of roach that passed, failed and attempted to pass over a Crump weir for the treatments tested..................70

Table 5.3 Detections of PIT tagged fish at loops located at the bottom (loop 1), middle (loop 2) and top (loop 3) of a Crump weir during treatment (T: fish pass installed) and control (C: no fish pass installed) periods. Some of the fish detected during one control or treatment period may have been detected again during another period and were considered as separate fish attempting. NA = not applicable.73

Table 6.1 Configurations tested during experimentation and their spacings (S_d), diameters (*D*), slope (S_o), average water depth (*y*), velocity (*V*), Froude number (*Fr*), percentage of 'low' velocity area within the array (*% LVA*), and dimensionless ratios (fish body amplitude [*BA*], fish body length [*BL*], fish body width [*BW*]).92

Table 6.2 Numbers of fish that passed (P), failed (F), approached and attempted for each of the treatments tested. 98

Table 6.3 Experimental configurations tested and associated Froude values above (1) and within (2) the array and corresponding submergence (y / h_2). 102

Table 7.1 Comparison of different passage efficiency experiments from Chapter 4, 5 and 6. 119

Table of Figures

Figure 1.1 General layout of a typical (a) Crump and (b) flat-V weir (Beach, 1984). Crumps have 1:2 and 1:5 upstream and downstream slopes respectively with flat-V's having a central convergence of flow with slopes varying from 1:10 to 1:40...2

Figure 2.1 A number of fish passage designs including (a) Bottom Baffle Fishway – Lariner Fish Pass (b) Pool and Traverse Fish Pass (c) Vertical Slot Fishway (FAO and DVWK, 2002), (d) bristle passes (Hintermann, 2010), (e) low cost baffle passes (Forty, 2015) and (f) studded eel tiles. 8

Figure 2.2 Mean (±SE) upstream passage efficiency for migration at five types of fish passage facility, for salmonid and non-salmonid fishes (Noonan et al., 2012).11

Figure 2.3 Fish swimming speeds for fish commonly found in the UK, calculated by using SWIMIT v3.3 produced by Jacobs Aquatic (2006) based on work undertaken by Clough and Turnpenny (2001) for average migratory temperatures (11˚C for Grayling (Ovidio et al., 2004, Ingram et al., 1999), 11˚C for Trout (Freyhof, 2013), 13 ˚C for all others [Lucas et al., 1998]) and a range of fish sizes. 13

Figure 2.4 Fish swimming modes (Sfakiotakis et al., 1999) and areas of the body used for propulsion in different fish species. 14

Figure 2.5 Photograph of (a) roach (*Rutilus rutilus*) (Froese and Pauly, 2017) and (b) chub (*Squalius cephalus)* (edited: Supino, 2019). 15

Figure 2.6 Section view of a triangular profile weir illustrating the flow conditions induced at the weir, where flow entering the system goes from sub to supercritical flow down the weir face before transitioning to subcritical flow again as the hydraulic jump forms at the base of the weir. 20

Figure 2.7 A bristle board comprising of conical synthetic bristle clusters fixed onto a plastic board..21

Figure 2.8 Flat-V weir retrofit using low cost baffles on the river Moors at Hurn in Dorset (White and Woods-Ballard, 2003). 22

Figure 2.9 Baffle arrangement on a functioning weir: Brimpton Weir (Servais, 2006)....23

Table of Figures

Figure 3.1 Schematic diagram of velocity profiles in open channel flow of high relative submergence (small roughness) adapted from (Manes et al., 2007) where h_w is the water depth and v is water velocity. 27

Figure 3.2 Schematic diagram of flow through submerged roughness elements showing the representative flow profile for subcritical flows at different spacings (Nepf, 2012). 28

Figure 3.3 Effects of Reynolds numbers on the flow profiles around cylinders (Blevins edited, 1990). 30

Figure 3.4 Flow past a circular cylinder for (a) subcritical Reynolds number and (b) supercritical Reynolds number illustrating where the point of separation occurs around the cylinder and wake formation and shedding (Devenport and Borgoltz, 2016). 31

Figure 3.5 Experimentally determined drag coefficient variation in a fluid around a cylinder for different Reynolds numbers (Tritton, 2007) using a range of different sized cylinders. 31

Figure 3.6 Schematic diagram showing the flow profile created over a Crump gauging weir where roughness elements are mounted to the downstream weir face. 32

Figure 3.7 Schematic diagram of different flow bleed events and their effect of the downstream wake behind the cluster (Taddei et al., 2016). 34

Figure 3.8 (a) Numerically simulated wakes for array densities of 0.0884, 0.1451 and 1, where the colours red and blue denote positive and negative vorticity respectively, with green corresponding to irrotational fluid. The flow is directed from left to right where the Reynolds number for each array was 2100 and (b) experimentally determined wakes and measured velocities (m s^{-1}) behind porous circular clusters of different density in air with an incoming free-stream velocity of 20 m s^{-1} (Nicolle and Eames, 2011; Taddei et al., 2016). 35

Figure 3.9 Location of sensory nodes on *Oncorhynchus mykiss* with small filled circles (arrowed) and large filled circles representing superficial neuromasts and canal pores respectively (Montgomery, 2003). 37

Figure 3.10 Plan view of a section of cylindrical clusters in the flow illustrating the lateral (c/c) spacing between clusters (S_c), lateral spacing and diagonal between clusters (S_c' and S_d respectively) and diameter (D). 38

Figure 4.1 (a) Bristle boards and the flat-V weir in (b) section, (c) elevation and (d) plan, illustrating the unmodified bristle substrate and the weir dimensions used in experimentation (distances shown in mm). 43

Figure 4.2 The model flat-V weir with no bristles i.e. control (*λ1*) (top left), bristles at 0.1 m spacing (*λ2*) (top right), 0.05 m spacing (*λ3*) (bottom left) and the graduated density design (0.02 m to 0.06 m spacing) (*λ4*) (bottom right). 45

Figure 4.3 A photograph of (a) some of the holding tanks used to home the roach at the University experimental facility in Chilworth and (b) the water testing equipment and water sampling undertaken for 4 different tanks used to home the fish.46

Figure 4.4 A sample of the debris that was tested during debris experiments undertaken in the laboratory showing the representative size and type of debris used during experiments. 47

Figure 4.5 Field installation of the bristle boards (*λ2*) on a flat-V weir at Monks Brook, Hampshire, UK. 48

Figure 4.6 Trials undertaken to determine the effects of different densities compared to a control (*λ1*) measuring (a) water levels at the crest of the flat-V weir and (b) the upstream water level relative to the crest, measured 0.5 m from the crest, when boards were placed 0.17, 0.17 and 0.21 m downstream of the crest for *λ2, λ3* and *λ4* respectively. 49

Figure 4.7 Water depth measurements and representative locations of these measurements down the weir face and upstream of the crest corresponding to data presented in table 4.1...51

Figure 4.8 Average percentage velocity reduction observed due to different bristle densities (*λ2*, *λ3* and *λ4*) mounted on the flat-V weir relative to the control for low (*L*), medium (*M*) and high (*H*) flows. 51

Figure 4.9 Fish Passage Efficiency (triangles) and corresponding maximum water velocities (squares) and water depths (diamonds) for low (*L*), medium (*M*) and high (*H*) flows tested. 52

Figure 4.10 Debris accumulation within the bristles over a flat-V weir in (a) laboratory and (b) field conditions. 53

Figure 4.11 Bristle boards (a) just installed on the weir in the experimental facility and (b) reclaimed approximately a year after installation on a flat-V weir at Monks Brook- Stoneham Lane. 54

Figure 5.1 Photograph of the experimental setup showing the blocks used to create the rectangular channel within the flume, fish screens indicating the upper and lower extents of the experimental setup, the weir placed between these screens and the frame created using item bars to hold the camera recording fish movements. The photograph was taken looking downstream before the setup was complete. 63

Figure 5.2 (a) Plan of the experimental setup used to conduct fish passage trials indicating location of the weir and fish release (holding) area, (b) weir cross-section indicating dimensions, and (c) cluster metrics (diameter [*D*] and diagonal and horizontal spacing between the outer edges of the clusters and horizontally from centre to centre [S_d, $S_{c'}$ and S_c] respectively) which were altered to test their influence on fish passage. All units are in mm. 63

Figure 5.3 Fish pass installation on the compound Crump weir at Sakeham where boards were installed in the central channel and water was prevented from going down the weir during installation using 2 wooden boards held in place upstream. 65

Figure 5.4 Site location (black dot on inset map) and plan of the compound Crump weir on the River Adur, West Sussex, UK (50°95'74.63’’N, 0°26'58.75"W) (EA, 2017) on which a novel fish pass was installed. The fish pass consisted of Cylindrical Bristle Clusters mounted onto the downstream weir face in the central channel. Positions of PIT loops 1, 2 and 3 and the weir crest are indicated. 66

Figure 5.5 (a) time to pass for fish that passed over a Crump weir for treatments λb, λc and λd where spacing between clusters was 0.06 m, 0.1 m and 0.15 m, respectively; (b) swim path length (*SPL*) (m) for λb, λc and λd. Box plot of the median (horizontal line), interquartile range (box) and highest and lowest observations (whiskers). 71

Figure 5.6 Examples of fish pathways over the weir through the staggered array of CBCs (circles) for λd, 0 denotes the location of the crest and 1.2 the base of the hydraulic jump, with 1.2 m in the y axis being the distance traversed up the weir and x coordinates denoting the weir width. Video analysis produced pathways created using fish tracking software where the position of the fish head per frame rate was recorded. The dashed and solid arrows denote the flow and fish direction respectively. 72

Figure 5.7 Debris accumulation over the fish pass installed on the compound Crump weir at Sakeham in July 2018....................76

Figure 5.8 Stage-discharge relationship for the control and treatments (0.07 m diameter with 0.1 (λA) and 0.15 (λB) m diagonal spacing and 0.05 m diameter with 0.15 m diagonal spacing (λC) at (a) 0.2, (b) 0.3 and (c) 0.4 m from the crest 78

Figure 6.1 Schematic diagram of the effect of a cylindrical cluster on the downstream wake formation and von Karman street and sketch of the shear layer growth where L_1 is the length of the downstream wake, and the $\delta 1$ is the width of the shear layer (Zong and Nepf, 2012). 86

Figure 6.2 Different wake overlap states (Nicolle, 2009 and Wang et al., 2013). 87

Figure 6.3 (a) Tandem, (b) side by side and (c) staggered cylinder arrangement (Nicolle, 2009)....................87

Figure 6.4 Plan and section view of the experimental setup used to quantify fish passage at, and the hydrodynamic conditions created by, a CBC array showing the weir and extent of the experimental area (dimensions in mm)....................89

Figure 6.5 Photographs of the flume setup looking upstream (left) with the tilting weir and CBCs installed and the fish acclimatisation area within the flume (right).......90

Figure 6.6 Representative water velocity map (m s^{-1}) within the array of clusters (black dots, not representative of cluster size, λv), from the crest (0) to the top of the hydraulic jump. Flow direction denoted by the black arrow. Velocity sampling locations denoted as purple crosses, velocity measurements were only taken in these locations. The colour map was created by interpolating between these points and therefore should not be taken as the actual velocity...................93

Figure 6.7 Photograph of the experimental setup looking upstream showing the CBCs mounted onto the downstream Crump weir face within the flume with water flowing through the clusters and a hydraulic jump at the weir base.............96

Figure 6.8 The theoretical (a) and actual (b) flow conditions induced at a Crump weir when retrofitted with bristle clusters, where flow entering the system goes from subcritical to supercritical flow down the weir face (h_c is critical depth, h_1 and h_2 is the normal depth at (1) and (2) respectively). 98

Figure 6.9 Passage efficiency (%) for the treatments tested as a percentage of those that attempted where S_c is spacing between clusters (c/c) and D is diameter in meters. 99

Figure 6.10 Fish swimming pathways showing behaviour *B1* where fish zigzag between two lines of clusters (a) *B2* where fish swim between the wall and a line of clusters (b) and *B3* where diagonal movement through the array occurs (c). 100

Figure 6.11 Scatter plot of the change in drag coefficient with increasing S_c/D highlighting areas where wake overlap does or does not occur (calculated based on Taddei [2016]). 101

Figure 6.12 Scatter plot of array density and change in velocity where V1 is the approach velocity and V2 is the water velocity within the array. 101

Figure 6.13 Flow around a cylindrical cluster at different levels of submergence. 101

Figure 6.14 Combination of data obtained from separate fish and hydraulic trials showing the relationship between passage efficiency and S_c / D and mean C_D in relation to S_c / D. 102

Figure 7.1 The compound Crump weir at Shermanbury on the river Adur (a) with fish pass in place looking upstream and (b) downstream when clusters were submerged and (c) unsubmerged. The fish pass was installed in the central channel and (d) comprised of boards (all dimensions in mm) which were placed side by side and bolted onto the downstream weir face. 107

Figure 7.2 Fish pass installation at Hatterells gauging weir on the river Adur 108

Figure 7.3 Design drawing for the cylindrical bristle clusters fabricated by Berry and Escott. 110

Figure 7.4 Fish pass installed in March 2019 on the DeLank near Bodmin (EA, 2019). 111

Figure 7.5 Design drawings produced by Mott Macdonald for proposed CBC fish pass installation on a modified bypass channel at Twerton as part of the Bath and Avon Flood Defence Scheme. 112

List of Accompanying Materials

Assigned DOI: https://doi.org/10.5258/SOTON/D1359

The submitted files comprise of data underpinning all of the experimental chapters included in the PhD thesis titled 'Developing a low-cost fish passage solution for gauging weirs'.

Research Thesis: Declaration of Authorship

Print name:	Daniella Montali-Ashworth

Title of thesis:	Developing a low-cost fish passage solution for gauging weirs

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

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 submitted for publishing as:

Montali-Ashworth, D., Vowles, A.S., De Almeida, G. and Kemp, P. (2020). Use of Cylindrical Bristle Clusters as a novel multispecies fish pass to facilitate upstream movement at gauging weirs. Ecological Engineering. 143. 105634. 10.1016/j.ecoleng.2019.105634.

Signature:		Date:	

Acknowledgements

The author would like to acknowledge the project sponsors (EPSRC and the Environment Agency) aswell as a large variety of people who have helped make this work possible. Firstly, this work would not have started without the enthusiasm of the Environment Agency, Dr Costa Manes and Dr Andy Vowles. I would also like to thank my supervisors Prof Paul Kemp, Dr Gustavo deAlmeida and Dr Andrew Vowles for their encouragement and help, especially in pointing out the flaws in my plans and helping me to improve many aspects of experimental design and analysis. Notably, I would like to thank David Potts, Richard Dixon and Joseph Prince for their valuable contribution to this body of work throughout the preliminary phase of this project. I would also like to express how grateful I am for the hard work and financial contributions that members of the Environment Agency, including Perikles Karageorgopoulos, Richard Iredale, David Gilbert, Adrian Fewings, Andy Roberts, John Harwood and many others have put into this project to make it a success. Throughout this project I have been lucky to have had so much help from members of EDMC including Maurice Jones, and the hydraulic technicians at the University of Southampton specifically Toru Tsuzaki and Karl Skammell, your insight into practical aspects of fish passage design and experimentation have been invaluable. All of my friends and members of ICER, including James Wakeling, Anita Laborde, Rob Needham, Helen Currie, Nick Flores-Martin, Jim Kerr, James Miles and many others have been a great help with numerous things including providing advice, helping me make bristle boards for many hours, electrofishing and tagging fish for fish passage trials and volunteering as lone working cover so that I could get my experiments done, you guys are amazing. Finally, I would also like to thank Dr Toru Tsuzaki again because without him I would have given up ages ago and Ashley Rogers who listened to me rant on about my PhD problems for hours, your technical assistance throughout the experimental period and your hydraulic insight and encouragement have been priceless.

Nomenclature

Notation	Unit	Description
A	m^2	area of the obstruction
b	m	weir breadth
C_d	-	coefficient of discharge estimated with the Rehbock formula
C_D	-	drag coefficient
C_{dE}	-	effective coefficient of discharge in the modular range
C_{dr}	-	drowned flow reduction factor
C_s	-	cluster shape
D	m	diameter
d	m	diameter of bristle within the cluster
dM	$kgms^{-2}$	rate of change in momentum
dt	s	change in time
f	-	friction factor
Fr	-	Froude number
F_D	N	drag force
F_f	N	bed friction force
F_{H1}, F_{H2}	N	hydrostatic force at location (1) and (2) respectively
F_{RES}	N	flow resistance
F_w	N	component of weight acting on a slope
g	$m\ s^{-2}$	acceleration due to gravity
h	m	depth of water over weir crest
H_{1e}	m	effective upstream total head relative to the lowest crest elevation
H_c	m	cluster height
h_c	m	critical depth
h_n	m	normal depth
h_{n1}	m	normal depth (no bristles clusters present)
h_{n2}	m	normal depth (bristles clusters present)
h_p	m	separation pocket head
h_w	m	water depth

Notation	Unit	Description
J	Nm	flexural rigidity of the bristle
k_h	-	head correction factor
L_1	m	length of downstream wake
LCB		Low Cost Baffle
l_e	m	effective length
L_p	m	Pass length
m	-	crest cross-slope (1 vertical: m horizontal)
n	-	Manning's n
N	-	number of clusters within array
N_c	-	number of bristle elements within a cluster
p	m	height of the weir
q	$m^2 s^{-1}$	discharge per unit width
Q	$m^3 s^{-1}$	total volumetric discharge
Re	-	Reynolds number (ratio of inertia to viscous forces)
S_b	m	Spacing between elements within the cluster
S_c	m	spacing between clusters (centre to centre)
S_c'	m	lateral spacing between clusters
S_d	m	diagonal spacing between clusters
S_o	-	bed slope
V_f	$m\ s^{-1}$	fish swimming velocity
V_t	$m\ s^{-1}$	target velocity
V_w	$m\ s^{-1}$	water velocity
Z_H	-	shape factor
δ1		width of shear layer
λ	-	array density
μ	Nsm^{-2}	dynamic viscosity
π	-	PI
ρ	$kg\ m^{-3}$	water density
ϕ	-	cluster density

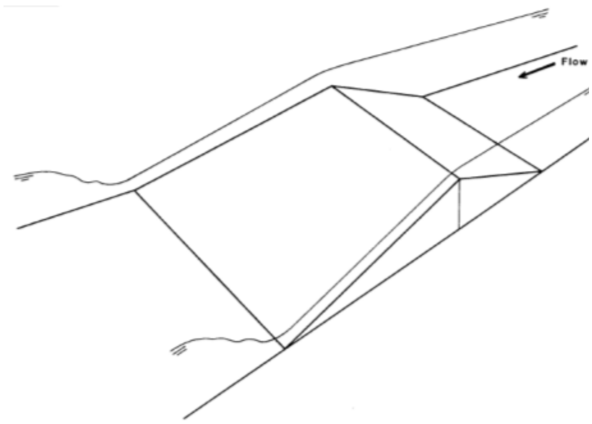
Chapter 1 Introduction

1.1 Overview

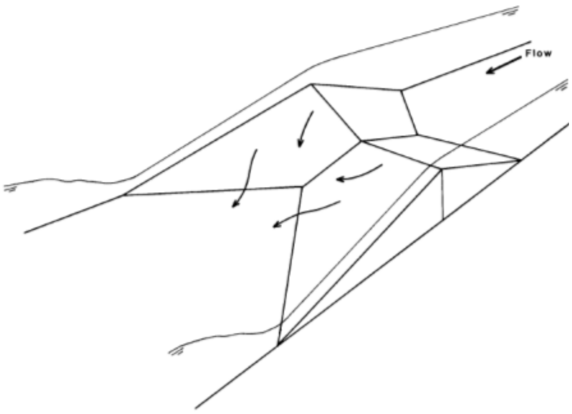
Habitat connectivity allows for the transfer of energy, materials and organisms between different locations along a river (Pringle, 2001). The river continuum concept (Vannote et al., 1980), which encapsulates the different physical conditions created along the reach of a river and the subsequent biotic response, and the serial discontinuity concept detailing the shifts in biotic and abiotic patterns and processes in rivers as a result of dams (Ward and Stanford, 1983), are of significant importance. These concepts outline how river connectivity is imperative if healthy river habitats are to be obtained. This is reduced when in-river barriers such as dams and weirs are present, especially in highly managed river systems where barriers are numerous along a river reach, leading to a higher density than would occur naturally within river systems. There is at least one artificial barrier for every 1.5 km of stream in Great Britain and only 1% of rivers in England, Scotland and Wales are free of artificial barriers (Jones et al., 2019). River flow cannot diverge around the structure, as is often possible at natural barriers, such as beaver dams.

Barriers within rivers have resulted in declining population for numerous fish species as movement between essential habitats is impeded (Lucas and Frear, 1997; Lucas and Baras, 2001; FAO and DVWK, 2002; Rickard et al., 2003; Armstrong et al., 2010; Dibley et al., 2012). Migration is important for aquatic organisms as it allows for movement between habitats with different specific advantageous characteristics for spawning and feeding (Lucas and Baras, 2001). The implications of habitat fragmentation and reduced habitat connectivity is a global issue (Rosenberg et al., 2000). Without mitigating for the impacts that barriers have on fish populations, largescale population decline and genetic fragmentation (Lucas and Baras, 2001) will continue to occur, reducing fish population sustainability and diversity, with great cost both economically and environmentally. As such, a number of policy documents have been created worldwide that seek to outline principles to guide environmental habitat management decisions and achieve rational outcomes that lead to environmental protection and enhancement. These include the NIWA Fish Passage Guidelines (Franklin et al., 2018), Law 4.630, 1998 in Brazil, Fisheries NSW Policy and Guidelines for Fish Habitat Conservation and Management (Fairfull, 2013) and the EU Water Framework Directive 2000/60/EC, which sets targets to raise all European waters to a good condition. To obtain such targets it has stipulated that “the continuity of the river is not disturbed by anthropogenic activities and allows undisturbed migration of aquatic organisms and sediment transport” within European rivers (European Commission, 2010). Following from this, to mitigate for the reduction in fish population sustainability and diversity, there is a need to improve river connectivity at existing barriers worldwide through barrier removal or modification.

Gauging weirs such as the Crump and flat-V weir (figure 1.1) are extensively used internationally to monitor river discharge and are essential for river management practices (Armstrong et al., 2010; Rickard et al., 2003; Wessels and Rooseboom, 2009; Larinier, 2001). Data gathered can be critical, for example, in accounting water use for irrigation and abstraction purposes (Clemmens et al., 2001) or for informing flood prediction and prevention strategies and quantifying the effect of climate change on river flows.



(a)



(b)

Figure 1.1 General layout of a typical (a) Crump and (b) flat-V weir (Beach, 1984). Crumps have 1:2 and 1:5 upstream and downstream slopes respectively with flat-V's having a central convergence of flow with slopes varying from 1:10 to 1:40.

While alternative options exist for monitoring river discharge and related activities, weir removal and replacement are often impractical due to logistical reasons such as cost (EA pers. comm.). Flat-V and Crump weirs are of particular interest, where retrofit is easier when compared to free-overfall type weirs (e.g. sharp or broad crested), they are triangular in profile with a central convergence and uniform flow created over the downstream face for the former and latter respectively. These weirs are common in the UK with over 550 Crump and flat-V weirs operated by the Environment Agency in England alone and function over a wide range of flows and so are frequently employed where accurate gauging of low flow is required (BS ISO 4377, 2012). Triangular profile weirs limit upstream fish passage as they span the width of river channels, and often have shallow water depths at low flows and high velocities at higher flows on their downstream face which may exceed fish swimming capability (e.g. Vowles et al., 2015; Kerr et al., 2015; Lucas & Frear, 1997).

Crump weirs have been recorded impeding the passage of barbel (*Barbus barbus*) (Lucas and Frear, 1997), grayling (Lucas and Bubb, 2005) and European eel (Vowles et al., 2015; Kerr et al., 2015) amongst other species with passage efficiencies of 40, 36 and 0 – 20% recorded respectively for the study site and conditions present. Retrofitting gauging weirs with fish passage solutions can help reconnect habitat for fish (Dodd et al., 2018). Despite evidence that upstream passage of potamodromous non-salmonids is limited by gauging weirs (Lucas & Frear, 1997), with negative impact at the population level (Baras et al., 1994; Welcomme, 1994), only brief attention has been directed towards creating low-cost fish passage solutions that will facilitate their passage over these structures without impacting gauging (but see Servais, 2006).

A recent design of relevance, termed the 'Low Cost Baffle' (LCB), was developed by Servais (2006) and is comprised of rectangular obstructions (baffles), mounted onto the downstream weir face in stepped rows parallel to the weir crest and arranged so that water is funnelled through a central V shaped channel, with side channels to provide refuge areas. The intention is that baffles decrease water velocity and increase water depth to allow upstream passage of fish while not impacting the gauging capabilities of the weir or accumulating debris. However, impact on gauging and debris accumulation was observed under flume and field conditions respectively, as to obtain suitable velocities for fish passage, subcritical flow conditions were induced (Servais, 2006). Field studies assessing the fish passage performance of LCBs shows an overall efficiency of 68% for brown trout (Salmo trutta) at a 7.6 m wide, 6.7 m long Crump weir on the River Ribble (Yorkshire, UK) (Forty et al., 2016) and 24.4 – 46.6% for a range of cyprinid species at a 9 m wide, 2.4 m long low-head gauging weir on the River Hogsmill (Greater London, UK) (Lothian et al., 2019). This is promising; however, the design is limited to certain channel geometries where weirs can often be too narrow for baffles. A more modular design would therefore be advantageous as it would allow for a variety of weirs to be retrofitted. In addition, this design could be improved upon with regards to fish passage efficiency. Further, there is a need for an alternative to LCBs which does not affect gauging when placed close to the crest, accumulate debris and that also creates favourable hydraulic conditions for non-salmonid passage.

Due to the number of weirs present, any design solution that would improve passage efficiency at gauging weirs must be cost effective. Cost effective solutions must be simple to install, therefore retrofit onto the downstream face of the weir is required as opposed to other traditional fish pass solutions. Financial saving can also be made if the design does not require consultant input allowing for practitioners, such as the Environment Agency, to follow simple design rules. Cost is also influenced by the ease and simplicity of instalment therefore something that can simply be bolted to a weir would be extremely advantageous.

Bristle boards, comprised of a staggered arrangement of plastic cylindrical clusters, and studded tiles, comprised of a staggered arrangement of solid cylinders, have been utilised to facilitate eel and lamprey passage over gauging weirs with varying degrees of success (Armstrong et al., 2010; Kerr et al., 2015; Vowles et al., 2015). They provide a climbing substrate for these species with elongated body morphologies and as such are unlikely to be effective for multiple species (including other non-salmonids) which differ in body morphology and behaviour (i.e. exhibit sub-carangiform locomotion and do not climb). However, adapting the design of bristle and studded tile passes could improve non-salmonid subcarangiform fish passage at gauging weirs. Literature on cylindrical clusters suggests that a reduction in water velocities and increase in water depth will occur due to the hydraulic resistance created by the clusters. This can be optimised by: the staggered arrangement which creates the greatest flow resistance compared to other arrangements which may be more navigable for fish (Wang et al., 2013); the cylindrical shape where fish utilization of the hydrodynamics created in the wakes of cylindrical objects has been well documented (Liao, 2007; Hockley et al., 2014) and; the porosity of the cylinders, which create increased drag and a longer low velocity wake downstream of the cylinder compared to a solid cylinder (Taddei et al., 2016), increasing velocity reduction for the same area of space occupied. Given these properties, a staggered array of cylindrical bristle clusters in particular (CBCs) would be beneficial if developed for fish passage.

1.2 Aim and Objectives

The aim of the work presented in this thesis is to develop a low-cost fish passage solution for sloped gauging weirs that enhances the upstream fish passage efficiency for non-salmonid subcarangiform species through the installation of CBCs on the downstream face. The solution must reduce water velocity and increase water depth on the downstream face, allowing for fish passage whilst having a negligible impact on the coefficient of discharge used to measure flow at gauging stations and not accumulate debris. Due to the number of gauging weirs across the UK and internationally, the design must be cost effective and easy to install forming a low-cost fish passage solution that can be easily applied retrospectively as part of an adaptive river management strategy.

To achieve this aim, objectives were set to: 1) assess the impact of different CBC arrays, retrofitted onto a sloped weir, on the passage efficiency and swimming behaviour of roach (*Rutilus rutilus*), a ‘model’ non-salmonid fish species when compared with the performance of a control (unmodified) weir; 2) validate fish passage efficiency of the design under field conditions and monitor debris accumulation; 3) determine the influence of CBC array configurations on gauging and hydrodynamics.

Recommendations for gauging weir retrofit and optimisation of design efficiency, of value to regulatory agencies, ecological engineers, and the operators and managers of river infrastructure tasked with provisioning services while improving ecological status and environmental sustainability, are proposed.

1.3 Thesis Outline

- Chapter 2 reviews the literature on fish passage, in particular at weirs, to gain insight on what might contribute to optimal hydraulic conditions required to improve fish passage over steep slopes characteristic of triangular profile gauging weirs. The hydraulic theory relating to these weirs is also presented.
- Chapter 3 details the design background along with current literature of how fish interact with similar hydraulic environments.
- Chapter 4 presents work undertaken to determine whether an existing solution, eel bristle boards, can be modified to improve multispecies fish passage over a flat-V weir, where the central convergence of flow causes particularly difficult passage conditions for non-salmonids.
- Chapter 5 further develops the concept of using bristle cluster arrays to improve fish passage based on scientific literature collated in Chapter 3 and observations from Chapter 4. Experiments determined if and how fish can utilise an array of cylindrical bristle clusters to aid passage over a Crump weir, passage efficiencies were calculated and compared to a control (no bristle pass) in an experimental flume. The impact of array spacing on fish swimming behaviour was also analysed. Subsequently, results gathered from installation of the design in the field on a Crump gauging weir are presented. In addition, experimental work analysing the effect of a staggered array of bristle clusters on the gauging ability of a Crump weir was undertaken.
- Chapter 6 investigates the influence of wake geometry on fish passage in greater detail, analysing fish swimming behaviour and passage efficiency between different arrangements of cluster spacing and diameter. This was combined with work undertaken to understand the hydraulics created by different densities of staggered arrays, where the relationship between flow resistance and array density is investigated.
- Finally, Chapter 7 provides a discussion of the work undertaken and seeks to highlight the main conclusions gathered, recommendations for regulatory agencies and outline further avenues that could be explored as a result of this body of research.

Chapter 2 An Evaluation of Existing Fish Passage Solutions

2.1 Introduction

Improving the connectivity of rivers has become increasingly important due to the large number of in-river barriers that hamper, or in some cases, totally inhibit fish movement (Baras et al., 1994; Welcomme, 1994). The natural river structure, which once comprised of continuous and discontinuous reaches, has been significantly altered by man-made barriers. They have extremely long lifespans (100+ years), create fast shallow flows when water crests over the structure and are often contained within narrow river sections, preventing the river from finding alternative routes around them (Burchsted et al., 2010). Fish communities can be impacted as movement between river reaches is impeded. For example, numbers of fish moving are typically high during spawning season where fish seek to migrate between different habitats, but it can also occur when fish are seeking food or shelter in tributaries (Lucas et al., 1998). River infrastructure as hindrances to fish migration are an age-old problem, causing delay to migration and increased use of limited energy resources, reducing the probability of successful spawning (Lucas and Frear, 1997; Gowans et al., 2003; Glebe and Leggett, 1981; Castro-Santos and Letcher, 2010). In some cases, passage over barriers is impossible and habitat fragmentation occurs. Habitat fragmentation can have negative impacts on fish populations if the proportion of suitable habitat left is low (Andre'n, 1994). River barriers can also create reduced genetic diversity and species richness (Larinier, 2001).

Numerous solutions have been developed in an attempt to enable fish to surmount barriers to their migration and improve river connectivity (Clay, 1995; Larinier, 2001) as often weir removal and replacement is impractical due to logistical reasons, such as water regulation. Existing fish passes include traditional pool and traverse passes and baffle fish passes (Alaskan A, Plane baffle denil, Larinier super active baffle) along with fish lifts and locks and rock and artificial bristle substrate ramps (e.g. figure 2.1), in addition to numerous others (see Armstrong et al., 2010; FAO and DVWK, 2002). Bristle boards as fish passes have been used for decades as a way of aiding eel (*Anguilla* spp.) migration over gauging weirs by acting as a climbing substrate (Armstrong et al., 2010) and have also been utilised in various forms to aid fish passage around hydropower stations, using a series of shallow sloping ramps with dense bristle clusters attached to the base (Hintermann, 2010).

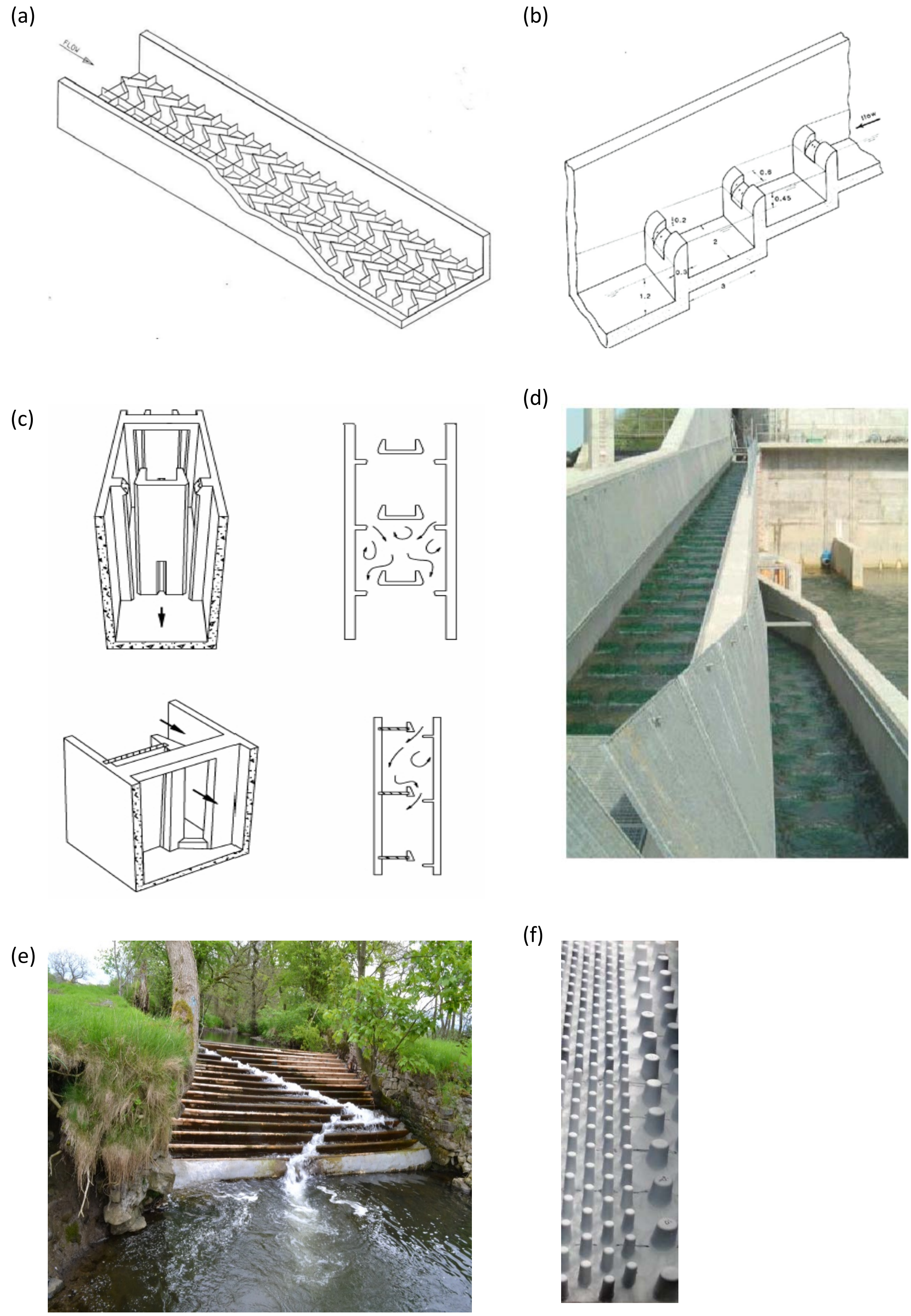


Figure 2.1 A number of fish passage designs including (a) Bottom Baffle Fishway – Lariner Fish Pass (b) Pool and Traverse Fish Pass (c) Vertical Slot Fishway (FAO and DVWK, 2002), (d) bristle passes (Hintermann, 2010), (e) low cost baffle passes (Forty, 2015) and (f) studded eel tiles.

Existing fish passage solutions can be expensive (FAO and DVWK, 2002), with costs varying widely depending on the size of the obstruction, the complexity of design and cost of materials, although actual installation and running costs are not widely documented. For most fish pass solutions, costs are dependent on location, ease of access and river flows. For gauging weir retrofit, the type of weir, gradient and head difference will be key factors determining the suitability of a fish pass solution. The final decision on fish pass selected is not exclusively based on cost but also on functionality, as different designs are required depending on what type of species are present within the river and the height of the barrier, amongst other things.

A fish pass cost comparison (£) from a number of sources (Servais, 2006; Don Catchment Rivers Trust, 2013) provides a glimpse into the magnitude of expenditure required for weir retrofit using pool type passes (£480 – £664 k) and baffle passes (Alaskan A, Plane baffle denil, Larinier super active baffle; £480 – £664 k) along with easements such as rock ramps and pre-barrages (£4 – £15 k) and low-cost baffles (LCB) (£8 – £110 k) in comparison to weir removal (£288 k). As some costs are very generalised, with the scale of the project, type of weir and inclusion of labour costs being unspecified, it is difficult to directly compare pass types.

Each of these pass types have a variety of design configurations depending on the barrier type and size, but the key principle utilised in fish passage design is energy dissipation, where water velocity is reduced through frictional losses due to the flow resistance caused by structures in the water. As a consequence of momentum transfer, the potential energy of the water is converted to kinetic energy causing turbulence, through molecular scale interactions leading to aeration and as heat and sound.

2.2 Quantifying Fish Passage Efficiency

Length, slope, water depth and water velocity in fish passes are characteristics that affect passage efficiency. Fish pass efficiency can be quantified using attraction efficiency, passage efficiency, overall passage efficiency and delay, using telemetry (remote monitoring technology often in the form of tags), where definitions are as follows (taken from Noonan et al., 2012):

- Attraction Efficiency: The percentage of fish detected immediately below the fish pass of a sample of the population released further downstream after being caught and tagged in some way;
- Entrance Efficiency: The percentage of fish attracted to the fish pass that enter into the fish pass;
- Passage Efficiency: The percentage of fish entering the fish pass that succeed in passing;
- Overall passage efficiency: The percentage of fish passing of those tagged;
- Delay: The time between fish entering and successfully exiting the fish pass.

Conditions approaching a barrier to migration can influence the number of fish which attempt to pass (Kemp et al., 2008). A fish is most likely to attempt to pass a structure if it has sufficient flow which indicates a possible swimming route upstream (FAO and DVWK, 2002) and if the turbulent energy fluctuations are small enough that disorientation is prevented (Montgomery et al., 2003). Passage efficiency is also related to individual swimming behaviour and fish health (Pon et al., 2009; Castro-Santos, 2005). Flow, temperature and lighting can also act as stimuli.

Fish pass efficiency can be measured using acoustic, radio or Passive Integrated Transponder (PIT) tags (Bunt et al., 2012). PIT tagging is the most common method used for quantifying passage efficiency. PIT tags work through providing the number of tagged fish that pass through a transponder loop, which can be placed in a choice location such as the exit or entrance of a fish pass and records the number of fish attempting and passing over the fish pass, of the fish that were tagged. Fish pass effectiveness can be defined as “a qualitative concept which consists in checking that the pass is capable of letting all target species through within the range of environmental conditions observed during the migration period” (Larinier, 2001).

Noonan et al. (2012) collated a number of fish passage study data for a variety of pass types and concluded that the most efficient fish passage design based on the available data was the pool and weir design, with fish passage of salmonids being higher than that of non-salmonids due to their superior swimming abilities (Webb, 1975) (figure 2.2). Traditional fish passes are less effective in aiding passage of smaller species with lower swimming capabilities (MacDonald and Davies, 2007; Mallen-Cooper and Brand, 2007).

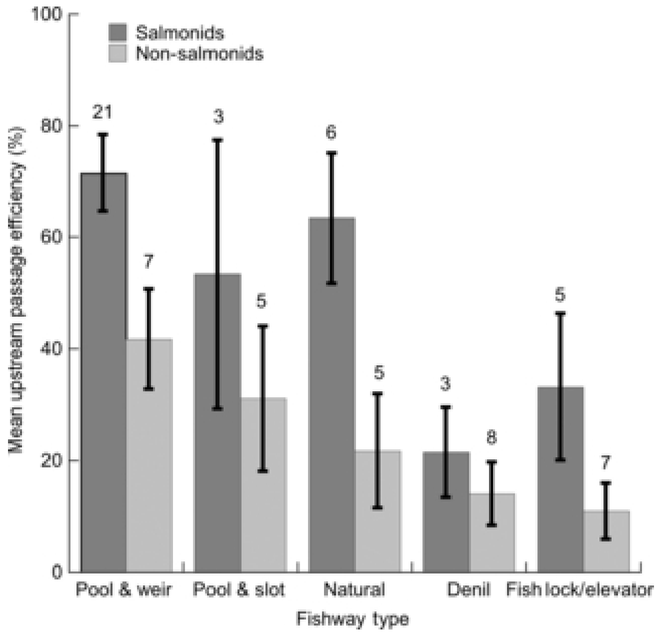


Figure 2.2 Mean (±SE) upstream passage efficiency for migration at five types of fish passage facility, for salmonid and non-salmonid fishes (Noonan et al., 2012).

A large number of fish passes were initially designed to aid in salmonid passage as it was believed that the majority of non-salmonid species did not migrate (Lucas et al., 1998); this has since been refuted (Lucas et al., 2000; Lucas et al., 1998). Specification of a target fish species is important as different fish species have different swimming preferences (e.g. benthic or pelagic) and abilities, and these parameters can be used to determine which fish pass is most suitable for which species of fish.

Unfortunately, due to the differing techniques used for measurement of fish passage efficiencies it is hard to compare results accurately (Bunt et al., 2012). A standard procedure for fish pass efficiency measurements is therefore required (EA pers. comm., 2016). It is well established that fish pass efficiency can be quantified as the number of fish that pass that want to do so. Unfortunately, it is difficult to ascertain fish motivation and differing methods are used to characterise passage attempts. Many people use approaching into the vicinity of the pass as proof of this, others that a fish makes a clear attempt to surmount the high velocity flow on the face of the fish pass. Once a standard for fish passage efficiency measurements is set, results from different fish passage experiments can then be compared to determine which fish passes allow for passage of which species. It will also enable determination of problems regarding different aspects of poorly performing fish passes for future improvement. The conclusions drawn by various papers are dependent on the dataset being analysed and therefore it is difficult to obtain any firm conclusions on fish passage rates of different fish passes.

Further insight gained from analysing the efficiencies of existing fish passes is that they are currently quite low, with mean upstream passage efficiency of 41.7% for salmonids and 21.1% for non-salmonids (Noonan et al., 2012). It is hypothesised that 90 – 100% passage efficiency is required to mitigate the ecological effects of impoundments and restore habitat connectivity (Noonan et al., 2012) as, if the maximum number of fish can pass over the obstruction, the likelihood of species survival is increased (Ferguson et al., 2002; Lucas and Baras, 2001; Williams et al., 2012). It is debatable whether such high fish passage efficiencies are really required as many populations have still survived with reduced numbers as there is less competition for food resources (Minto et al., 2008). In some cases, fish populations have been severely impacted with significant reduction in fish numbers (Gowans et al., 2003) due to cumulative effects of reduced passage over barriers and on occasion fish species elimination from a river basin has occurred, therefore impacts can be site specific (Williams et al., 2012). Even when fish passes are installed, habitat fragmentation may still occur as fish may lack motivation to pass over the barrier, especially if there is already suitable habitat located downstream (Roscoe and Hinch, 2010).

Fish passes need to be designed with a biodiversity protection mind-set rather than focussing on the most economically important fish species which are most often more capable swimmers (Oldani et al., 2007) and therefore it is recommended that they be modified to have lower velocities (approx. 1 m s^{-1}) (Szalay, 1967; Armstrong et al., 2010). This is commonly undertaken by creating milder slopes and passage facilities across the whole depth of the water column so that both benthic and pelagic fish species can migrate. Reduction in water velocity is desirable to reduce energy expenditure of fish and increase the effectiveness of fish passage designs. This being said, if the velocity is too low, fish may not be able to detect the fish pass entrance thus reducing the effectiveness of the fish pass (Haro and Castro-Santos, 2012). Separate attraction flow can be provided to mitigate for this (FAO and DVWK, 2002) but this is not always possible. Ultimately, an optimal velocity must be determined which can be defined as the target velocity where in its simplest form a balance is required between velocity reduction and pass attraction to optimise fish passage (Armstrong et al., 2010; Williams et al., 2012).

Fish swimming is generally categorised as either cruising, sustained or burst swimming activity (Larinier, 2002). Burst speeds are most often observed during fish passage over barriers that generate higher velocities such as weirs (Servais, 2006) and are defined as speeds that can only be maintained for seconds or tens of seconds (Knaepkens et al., 2007). Therefore, a good fish pass must take a short amount of time to swim through or have resting areas so that a critical threshold for successful fish passage is achieved (Vowles et al., 2015); otherwise fish will fatigue and fail to ascend the fish pass.

Average burst swim speeds of a number of roach (*Rutilus rutilus*), bream (*Abramis brama*), chub (*Squalius cephalus*), dace (*Leuciscus leuciscus*), grayling (*Thymallus thymallus*) and brown trout (*Salmo trutta*) found in British rivers range between 0.7 and 1.6 m s^{-1} (figure 2.3; Clough and Turnpenny [2001]) where fish swim speeds vary depending on species, length and age. This is low compared to swim speeds of Atlantic salmon (*Salmo salar*), for example, for which swim speeds of approximately 4 m s^{-1} have been recorded (Colavecchia et al., 1998).

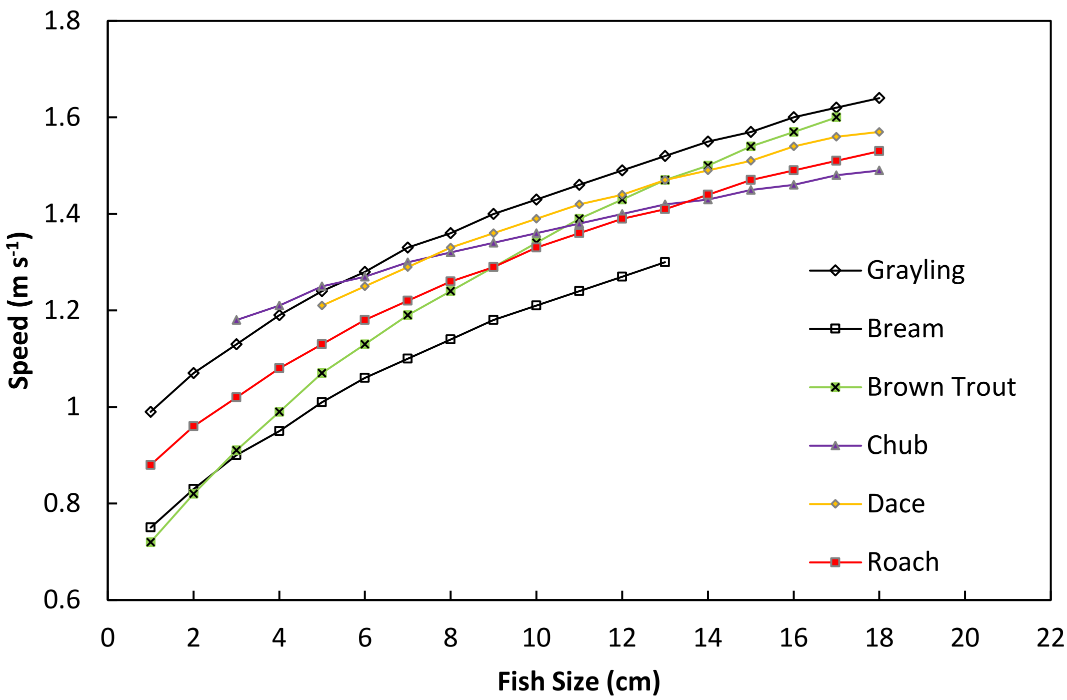


Figure 2.3 Fish swimming speeds for fish commonly found in the UK, calculated by using SWIMIT v3.3 produced by Jacobs Aquatic (2006) based on work undertaken by Clough and Turnpenny (2001) for average migratory temperatures (11˚C for Grayling (Ovidio et al., 2004, Ingram et al., 1999), 11˚C for Trout (Freyhof, 2013), 13 ˚C for all others [Lucas et al., 1998]) and a range of fish sizes.

Benthic (bottom feeding) fish utilising low velocity zones caused by low shear near wall boundaries at the bed of the river, are more likely to be slower swimmers and struggle to surmount barriers due to the large amount of red muscle (aerobic) as opposed to white muscle (anaerobic) (Videler, 1993). Other types of fish (pelagic) are better adapted to fast moving water due to their habitat and feeding preference, where they utilise the mid channel areas within a river (Videler, 1993). Fish morphology influences their ability to pass over obstacles and the rate of energy expenditure can be related to the drag force created by a fish (McElroy et al., 2012).

Fish have different drag coefficients due to their body morphology (influencing streamlining) and size and therefore some would require more energy than others to surmount a barrier (see Sagnes and Statzner, 2009). Drag coefficient also varies depending on Reynolds number (Re) (ratio of inertia to viscous forces), with the lowest drag coefficients observed at higher Reynolds numbers. Fish size can also have a significant impact when surmounting barriers with limited water depth, as larger fish may not always be fully submerged, increasing the amount of energy expenditure required for fish passage due to reduced buoyancy effects as fish are lighter in water than air (Sfakiotakis et al., 1999).

Generally, fish create propulsion through movement of their body, where propulsion can vary dependent on body morphology, and thrust is generated differently dependent on fin locations (figure 2.4) (Webb, 1986; Ojanguren and Brana, 2003). Sub-carangiform fish form the largest proportion of non-salmonid fish species.

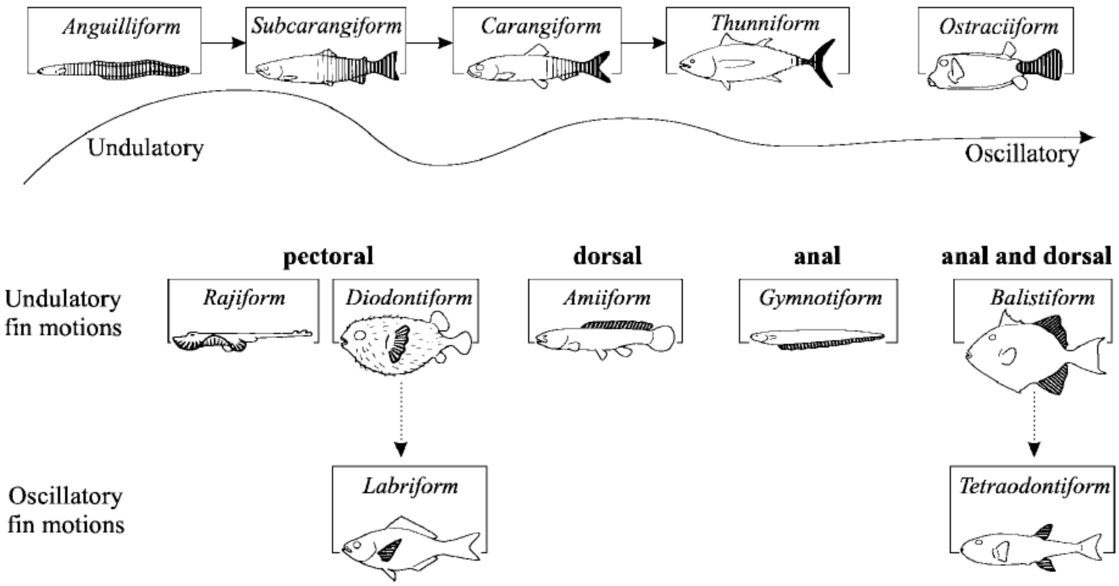


Figure 2.4 Fish swimming modes (Sfakiotakis et al., 1999) and areas of the body used for propulsion in different fish species.

Body morphology can vary greatly, dependent on species adaptations applicable for survival in different habitats, where different water velocities are prevalent or where turning manoeuvres and rapid acceleration are required to avoid predators (Sfakiotakis et al., 1999). The speed that a fish can generate is approximately proportional to the frequency of their body undulations. This frequency is limited by the length of the fish but also by their use of anaerobic muscles. Anaerobic muscle use is very sensitive to temperature and so fish swimming speed and endurance is particularly determined by fish length and water temperature (Larinier, 2002), with increasing temperature generally increasing swimming speed up to a point.

Fish swimming is complex, where swim speeds vary depending on fish length, morphology, water temperature and muscle type, where the ratio of red or white muscle contributes to whether a fish can maintain speeds for a long period of time (red) or perform rapid movements such as bursting but soon fatigue (white) (FAO and DVWK, 2002). The fish species that require greater assistance, as they have the most difficulty surmounting barriers, are those with lower swimming capacity in comparison to those with higher swimming ability such as salmon (White and Woods-Ballard, 2003; Larinier, 2002). The maturity of a fish when it migrates is also of interest, with more mature and often subsequently larger fish having a higher swimming capability.

Roach (figure 2.5a) and chub (figure 2.5b) are good example of a 'weaker' swimming freshwater fish species. Both are potamodromous cyprinids with swim speeds and morphological makeup typical of other non-salmonids, making them a good model species for fish passage studies. With sub-carangiform swimming motion, they swim at a range of depths within the water column, performing short spawning migrations when reaching sexual maturity. Roach have been documented as a shoaling fish, with a capability to survive in moderately polluted waters (Kottelat and Freyhof, 2007). They reach sexual maturity at 2 – 3 (males) and 3 – 4 (females) years old (approx. 0.14 m long), spawning in spring (often April – May) when temperatures rise above 12 ˚C. They range in size between 0.02 – 0.5 m (Kottelat and Freyhof, 2007) with average lengths of 0.25 m and have burst swim speeds ranging from 0.8 to 1.41 m s^{-1} for body lengths between 0.05 – 0.18 m at 13 ˚C (Clough and Turnpenny, 2001). Chub are pelagic freshwater fish, migrating within the breeding season and spawning between May and August when water temperatures rise above 12 ˚C. They have a typical size range of 0.07 – 0.30 m, with males reaching sexual maturity at 2 – 4 years while females do so between 4 – 6 years (Kottelat and Freyhof, 2007) with swim speeds of 1.18 – 1.42 m s^{-1} for body lengths between 0.08 – 0.18 m at 13 ˚C (Clough and Turnpenny, 2001).

(a) (b)

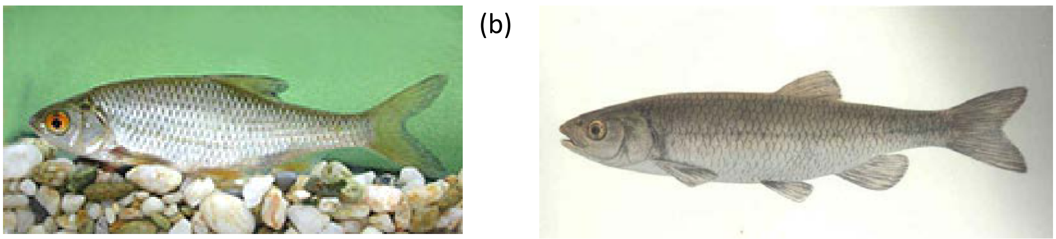


Figure 2.5 Photograph of (a) roach (*Rutilus rutilus*) (Froese and Pauly, 2017) and (b) chub (*Squalius cephalus)* (edited: Supino, 2019).

Different fish species have different migration patterns and migrate at different times of the year, for example, brown trout (*Salmo trutta*) normally migrate between late October and March, often with a peak in November – December (Freyhof, 2013). Non-salmonids such as cyprinids typically begin migrating at 9 – 10 ˚C (Lucas et al., 1998) and move upstream to spawn in spring. Glass eels and elvers also migrate upstream during the spring period. Downstream migration of silver eels occurs in late summer/ early autumn. A window of flow rates and temperatures will be associated with the time of migration. This is important when considering pass operation times and corresponding flow regimes to predict flows that the pass will be required to work under (Armstrong et al., 2010). The majority of spawning occurs during the spring and summer months (Lucas et al., 1998). Even so, it is hard to pinpoint any specific time of year that migration up and down rivers will occur as this varies between species and between individuals within species, with peaks during certain months dependent on the flows and temperatures which occur. This also varies between years. Therefore, as different species migrate at different times of the year, a fish pass that functions well for multiple species should operate year-round. This would allow for creation of a holistic fish pass which would fulfil the requirements of the WFD, where passage for all species and life stages is preferred.

2.3 Passage Efficiency at Triangular Profile Gauging Weirs

A small but significant contribution to habitat fragmentation is created by gauging weirs which produce a combination of high velocity and shallow water depths at low modular flows, with depth and velocity greater for higher modular flows. Two common gauging weir designs are Crump and flat-V weirs, with over 550 currently used by the Environment Agency in England alone (White et al., 2006), and many more in river systems worldwide (Winter and Densen, 2001; Wessels and Rooseboom, 2009; Rooney et al., 2015). Crump weirs have been recorded impeding the passage of barbel (*Barbus barbus*) (Lucas and Frear, 1997) and grayling (Lucas and Bubb, 2005) amongst others, with passage efficiencies of 40 and 36% recorded, respectively. These weirs are triangular in profile; with upstream and downstream face slopes of 1 (vertically): 2 (horizontally) and 1:5 respectively. Flat-V weirs have a central convergence (with slopes varying from 1:10 to 1:40 [table 1 BS ISO 4377, 2012]) resulting in increased accuracy (in comparison to Crump weirs) in measuring discharge at both high and low flows.

Flat-V and Crump weirs, subsequently referred to as triangular profile weirs, are specifically of interest for retrofitting, the former having central convergence of flow and the latter having uniform flow over its downstream face. Flat-V weirs are better at measuring low flows and therefore operate more accurately over a wider range of flows in comparison to Crump weirs (BS ISO 4377, 2012). In open channel flow, energy and momentum balance are of great importance. Conservation of energy, where the potential and kinetic energy going into the system (for example, at a weir) is equal to the potential and kinetic energy going out of the system plus any energy losses as heat and sound due to friction, holds true for all conditions over a weir. In addition, gradually varied flow occurs (apart from at the crest of the weir), where depth varies gradually along the length of the channel (Chow, 1959).

Triangular profile weirs can be used to calculate flow by measuring upstream head (for modular conditions). For flat-V weirs this can be done using equations 2.1 and 2.2 (BS ISO 4377, 2012).

Modular
$$Q = 0.8C_{dE}\sqrt{g}mZ_H {H_{1e}}^{\frac{5}{2}} \quad (2.1)$$

Un-modular
$$Q = 0.8C_{dE}C_{dr}\sqrt{g}mZ_H {H_{1e}}^{\frac{5}{2}} \quad (2.2)$$

Where *Q* is the total volumetric discharge, C_{dE} is the effective coefficient of discharge in the modular range, *m* is the crest cross-slope (1 vertical: m horizontal), Z_H is the shape factor and H_{1e} is the effective upstream total head relative to the lowest crest elevation. C_{dr} is the drowned flow reduction factor and is defined by:

$$C_{dr} = 1.078\left[0.909 - \left(\frac{h_{pe}}{H_{1e}}\right)^{\frac{3}{2}}\right]^{0.183}$$

h_{pe} is effective separation pocket head relative to lowest crest elevation and is defined by:

$$h_{pe} = h_p - k_h$$

Where h_p= separation pocket head, k_h= head correction factor

For Crump weirs, the discharge can be calculated as (Chadwick et al., 2004; British Standards Institution, 1986):

$$Q = \frac{2}{3}C_d\sqrt{g}bh^{3/2} \tag{2.3}$$

Where *b* is the weir breadth, *h* is the depth of water over the weir crest, C_d is the coefficient of discharge estimated with the Rehbock formula

$$C_d = 0.602 + 0.083 \times \frac{h}{p}$$

Where *p* is the height of the weir.

At a weir, the water normally changes flow regime twice, transitioning from subcritical to supercritical and then back again at the base of the weir. The Froude number (Fr) (ratio of inertia to gravitational forces), is used to characterise whether flow is super or subcritical, where if the flow is supercritical, inertial forces become dominant. Flow is supercritical if Fr > 1, critical when Fr = 1, and subcritical when Fr < 1.

$$\mathrm{Fr} = \frac{V_w}{\sqrt{gh_w}} \tag{2.4}$$

Where V_w is water velocity, *g* is the acceleration due to gravity and h_w is the water depth.

As the water approaches the weir it is flowing under subcritical conditions (figure 2.6) where the normal depth (h_n) is greater than the critical depth (h_c) (referred to as an M1 flow profile) until the water hits the weir and the bed slope becomes adverse. The change in height at a weir quickly converts the potential energy of the flow into kinetic energy, increasing the flow velocity where an A2 profile forms and the water depth becomes equal to critical depth. All weirs operate by forcing critical depth close to the weir crest, the exact location varies dependent on energy losses and occurs a distance downstream of the crest which varies dependent on discharge (Henderson, 1966). Following this an S2 profile can be seen just downstream of the weir crest where the surface profile must pass through critical depth, which can be identified as the point of inversion of curvature in the water surface close to the weir crest. Water acceleration occurs as the water passes over the crest, where the force imposed by the bed resistance on the flow reduces for flow over a steep slope (S_o). This acceleration causes a gradual drawdown in water surface profile where flow transitions from a depth upstream, through critical depth, to a new depth which is present over the face of the weir, where the depth is smaller than the critical depth (S2 profile) and reaches supercritical normal depth (h_n) providing sufficient weir length. Downstream of the point where critical depth forms the flow is characterised as supercritical, which will transition to subcritical flow again at the hydraulic jump. This can occur at the bottom of a weir but varies depending on downstream water levels. At a hydraulic jump the potential energy of the flow reduces due to a shallower bed slope and momentum transfer occurs as shallow supercritical water collides with deeper subcritical water downstream. Physically, there is a jump in water depth, known as a hydraulic jump where energy losses occur.

Once flow passes through critical depth, upstream conditions are no longer affected by downstream conditions (modular flow) as waves on the water surface travel slower than the flow velocity. Therefore, downstream disturbances cannot change the flow characteristics upstream of a region of supercritical flow unless the weir becomes drowned (i.e. supercritical flow is supressed completely by the downstream conditions), in which case the upstream flow becomes a function of both upstream and downstream water depth (un-modular flow) (BS ISO 4377, 2012; Rickard et al., 2003). Flow depth increases over the weir length depending on the location of the hydraulic jump downstream and river discharge.

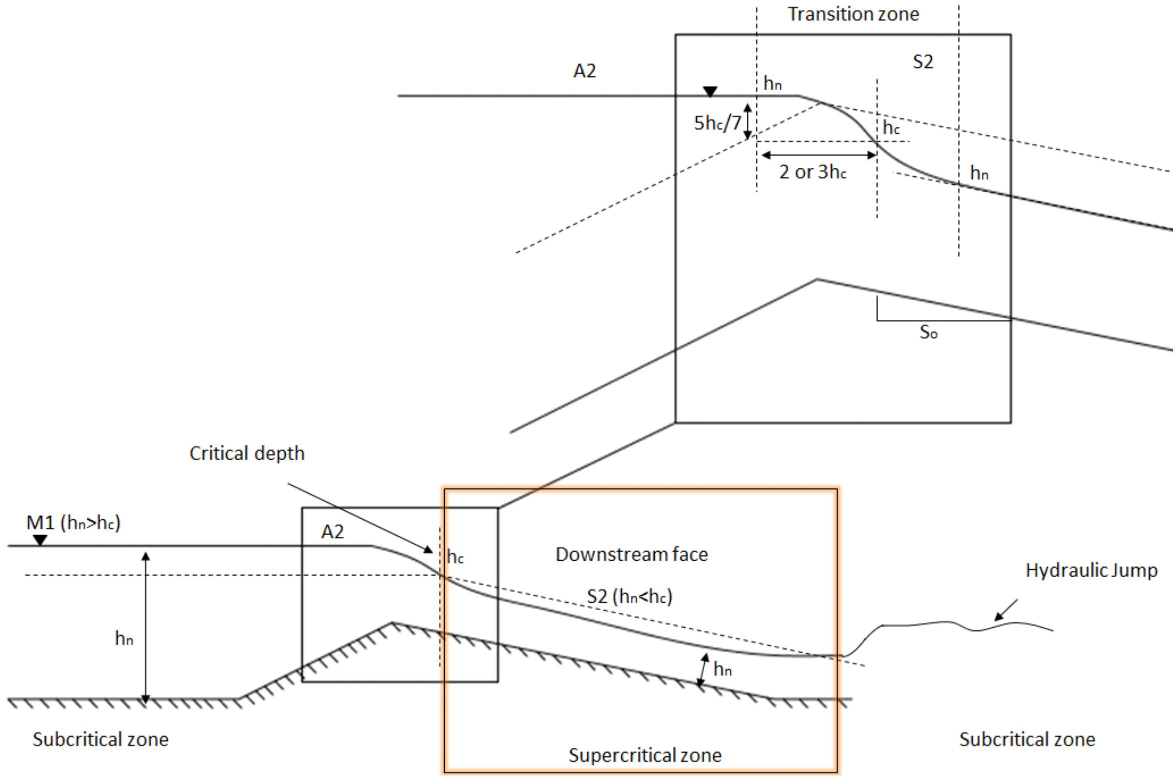


Figure 2.6 Section view of a triangular profile weir illustrating the flow conditions induced at the weir, where flow entering the system goes from sub to supercritical flow down the weir face before transitioning to subcritical flow again as the hydraulic jump forms at the base of the weir.

For accurate water depth measurement at gauging weirs, the Environment Agency stipulates that the coefficient of discharge must not be effected by more than 3%, otherwise recalibration of the stage-discharge curve (which shows the relationship between water depth and flow) would be required and due to additional errors inherent in the measurement of flow at gauging stations such as the location, quality and maintenance of the structure, condition and the maintenance of both the upstream and downstream channels, the zeroing of the water level gauge and the accuracy of the water level recording apparatus, flow measurement accuracy could be compromised by up to 10% (White and Woods-Ballard, 2003). This is undesirable, therefore a design which does not affect gauging is required.

2.4 Existing Low-Cost Fish Passage Designs for Gauging Weirs

Gauging weir retrofit requires that the fish pass be placed on the downstream face of the weir where slopes characterised as hydraulically steep are present. Unfortunately, unlike other fish passage solutions, those for sloping weir retrofit cannot have shallower gradients to ensure low water velocities.

Weirs are commonly retrofitted with bristle boards for eel passage by bolting the boards to the sides or face of the weir (Solomon and Beach, 2004). Studded tiles are a similar design that has also recently been deployed to the same aim (Tummers et al., 2018). Bristle boards are comprised of a number of bristle clusters (figure 2.7) which function in a similar manner to mats of vegetation, creating hydraulic resistance that reduces water velocities whilst allowing for eel to wriggle through the dense clusters. This is specifically designed for the anguilliform eel due to their body morphology which differs to most other species of fish (e.g. sub-carangiforms). Work has been undertaken to determine the efficiacy of these designs for passage of eel (Kerr, 2015; Vowles et al., 2015; Vowles et al., 2017) with notable improvements seen compared to an unmodified weir. These boards are low-cost at approx. £100 per board, dimensions: 1 x 0.4 m.

Figure 2.7 A bristle board comprising of conical synthetic bristle clusters fixed onto a plastic board.

Past work has also been undertaken to retrofit a flat-V weir at Hurn, along the river Moors, Dorset, for non-anguilliform fish. This weir was retrofitted using a baffled fish pass system mounted onto the downstream face of the weir (White and Woods-Ballard, 2003, figure 2.8). The baffles functioned as energy dissipators, distributing flow laterally and substantially reducing water velocities over the weir (White and Woods-Ballard, 2003).

Figure 2.8 Flat-V weir retrofit using low cost baffles on the river Moors at Hurn in Dorset (White and Woods-Ballard, 2003).

Servais (2006) further developed the low-cost baffled fish pass solution for Crump weirs (figure 2.9). The baffles are created using recycled plastic and moulded into shape using a custom-built mould to create beams. These beams are bolted to the face of the weir, perpendicular to the flow direction and arranged so that a notch is present running diagonally up the weir. The selected arrangement allows for channels of deeper water to form within the notched zone along with areas within the pass where fish can rest. LCB's reduce water velocities and increase water depth over the weir face which inherently creates conditions that can impact gauging. Servais (2006) noted the importance of positioning the baffle at an optimal distance from the crest of the weir. If the baffle was placed too close to the crest it would interfere with the upstream water depth, consequently altering the stage-discharge relationship of the weir (determined by using the upstream water depth) and therefore the weirs gauging ability. This is undesirable as the effect on the stage-discharge relationship must be minimal so that the coefficient of discharge is not altered and weir recalibration is not required. Guidelines stipulate that the effect on the coefficient of discharge should not be greater than 3% (White and Woods-Ballard, 2003). Therefore, both the height of the first baffle and its distance from the crest must be optimised to ensure that there is no change in gauging ability. The height of the first baffle when placed downstream of the crest on the weir face was made equal to the height of the crest. LCBs have been placed approximately 0.74 m from the crest (Lothian et al., 2019) with this varying depending on baffle height, as the first baffle causes the water to back up, potentially influencing gauging if the baffles are placed too close to the crest. The baffles also create a blockage across the majority of the weir width which increases the backwater effect created by the design compared to something that would not block the majority of the weir width.

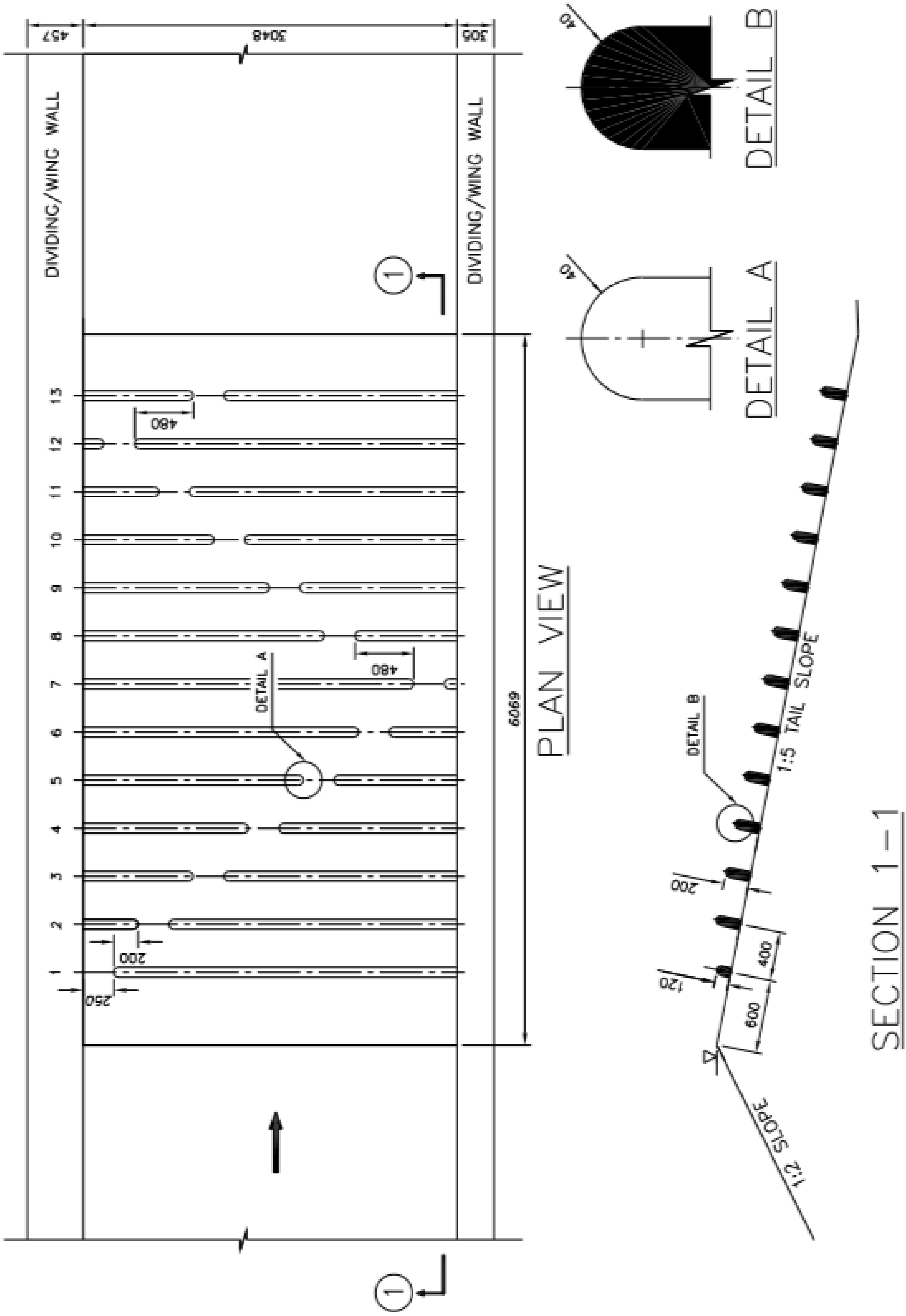


Figure 2.9 Baffle arrangement on a functioning weir: Brimpton Weir (Servais, 2006).

Servais (2006) also theorised that the shorter the distance fish are required to burst between the crest and the first baffle downstream from the crest, the smaller the expenditure of energy allowing for more successful migration of fish upstream. Depending on life history, certain migratory species stop feeding during spawning migration, so have finite energy reserves to migrate and spawn; therefore, if they expend a significant proportion of this energy traversing up the weir, the rate of successful spawning can be reduced (Armstrong et al., 2010). Additionally, the burst distance could be so great that fish may be unable to traverse it at all due to the higher velocities experienced in this region of the pass. Fish have been reported sitting within the baffles as they struggle to surmount the distance from the fish pass to the crest of the weir increasing their vulnerability to predators (EA pers. comm., 2019).

Servais (2006) found that one of the disadvantages of the baffle design was sediment build up and debris accumulation behind the first line of baffles, where impact on gauging is greatest. Siltation within the baffles has also been documented in rivers where sediment transport of bed load is high making the pass less effective unless maintained regularly (EA pers. comm., 2019).

A clear advantage of the design is its low cost where costing of the low-cost baffles (LCBs) came to < £30 per baffle unit using a baffle mould (EA pers. comm., 2015) but even with their relative low cost, baffle installation can be limited by weir width or require cranage. The arrangement of LCBs that can improve fish passage often requires design input, especially because the width of weirs vary between sites, a factor that also increases cost. The entirety of the weir must be dewatered so that the baffles can be installed. This could be overcome with a more modular design as only part of the weir would need to be dewatered reducing the need for overpumping during construction.

Fish passage studies with trout > 0.08 m (Forty et al., 2016) and barbel, chub, dace and roach > 0.14 m (Lothian et al., 2019) to quantify the effect of the design on passage efficiency appear promising. Even so, weirs vary in geometry and in some cases are too narrow for baffles, necessitating something more modular in design that will fit on any sized weir. In addition, as a variety of flow regimes and a range of fish species and sizes need to be accommodated it is difficult to determine whether the results from Dodd et al. (2018) and Lothian et al. (2019) are transferrable, especially in the case where weir slopes are very long, water velocities high and fish swimming speeds comparatively low. Fish passage is not guaranteed and there is evidence to suggest that the efficiencies of LCBs could be improved on for weaker swimming fish (Lothian et al., 2019) with design improvements suggested.

2.5 Conclusions

Analysis of the literature suggests that river connectivity is of critical importance as it allows fish to migrate between different life-stage specific habitats (Lucas and Frear, 1997; Williams et al., 2012). Gauging weirs can impede river connectivity as they act as barriers to fish movements because of the shallow water depths and/ or high velocities present on the downstream weir face (White and Woods-Ballard, 2003; Turnpenny et al., 2002; Russon et al., 2011; Vowles et al., 2015; Kerr et al., 2015). Of particular interest is the passage of non-salmonid fish, particularly potamodromous species, as they have been largely neglected where fish passage design is concerned (Lucas et al., 1998), with many designs tailored only to salmoniformes with higher swimming capability (Lucas et al., 1998). Consideration for weaker swimming non-salmonids is required to produce successful fish passes for a broader range of fish species and age classes (Forty et al., 2016).

Fish passes exist which can reduce the impact of gauging weirs on riverine habitat (Servais, 2008). These fish passes function through using the principle of energy dissipation to reduce flow velocities and increase water depths on the downstream weir face. However, high levels of debris accumulation and effects on gauging (unless placed a considerable distance from the crest) are clear design limitations.

The high cost and unfeasibility of using standard solutions to retrofit gauging weirs (Larinier, pool and weir, rock ramp etc.) and detrimental impact of specialised fish passage solutions (LCBs) on gauging capabilities suggests that a more effective fish pass is required. This fish pass, must reduce water velocity and increase water depth on the downstream weir face, not compromise the coefficient of discharge used to measure flow by more than 3% and not accumulate debris on gauging weirs. Due to the high number of gauging weirs across the UK and internationally, the design must also be cost effective and easy to install.

Chapter 3 Design Concept – A Staggered Array of Cylindrical Bristle Clusters

Analysis of existing literature has revealed that successful fish passage designs require sufficient energy loss so that water velocities are reduced to levels lower than maximum fish swimming speeds. This can be achieved by increasing bed roughness. Attempts to create increased bed roughness, so that a reduction in velocity is obtained, have been documented through the use of bristle boards (Armstrong et al., 2010) or can come in the form of vegetation (Nepf, 1999), baffles used in culverts (Newbold et al., 2014) and cylinder arrays used to dissipate wind energy (Gu, 1996) amongst others.

It is necessary to understand the combination of elements which could create increased roughness on the downstream face of a sloped weir, increasing energy loss and reducing velocities in a manner beneficial for fish passage, without effecting gauging. Increasing bed roughness for sloped weir retrofit, where changes in slope are not possible, increases water depths for the same flow, increasing the probability of impacting gauging. To minimise impact on gauging and to allow the design to be placed closer to the weir crest, thereby increasing the chance of fish successfully passing, a design that functions at velocities greater than those typically selected in fish passage designs, thus creating a smaller influence on depth, is required. This could be accomplished through utilising advantageous fish-hydrodynamic interactions created by certain objects.

This requires a combination of knowledge with regards to hydraulic characteristics of obstructions within the water column, the swimming behaviour of fish, and the interaction between the two. The use of cylinders as a roughness element is focussed on due to the wealth of literature on the hydrodynamic conditions they create (Taddei et al., 2016; Zdravkovich, 1997; Zong and Nepf, 2010) and because they can create favourable conditions for fish to swim under some scenarios (see Liao, 2007).

3.1 Optimising Hydrodynamic Environment for Fish Passage

In rivers, open channel flow conditions are present where the bed roughness has an effect on the overall velocity distribution, which is smallest when water depths are large relative to bed roughness height, creating energy loss within the water column. When analysing the velocity profile distribution in open channels, the bed roughness effects cause a logarithmic flow profile where shear stresses at the bed reduce the velocity in the inner flow layer. In simplest terms, as the distance from the bed increases, the effect of bed roughness decreases and a log layer and then outer layer are apparent (figure 3.1). Bed roughness has this impact on the flow profile because shear stresses created by the interaction between the channel bed and water interface create eddies which break down, dissipating energy and subsequently reducing water velocities. Creating a bed roughness that occupies the entirety of the flow depth produces conditions which are more desirable for fish passage as energy loss is increased hence water velocity is reduced and water depth is increased.

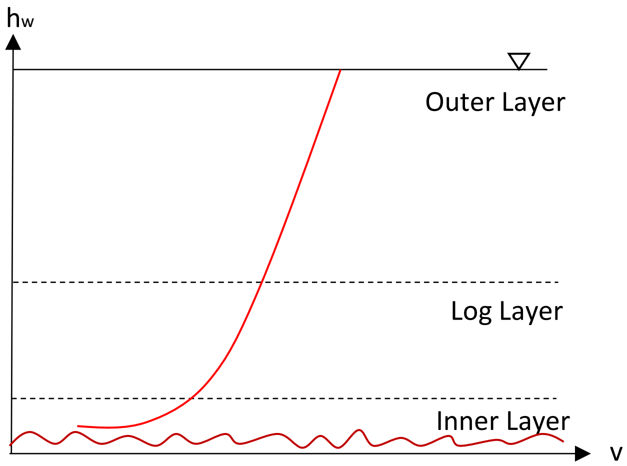


Figure 3.1 Schematic diagram of velocity profiles in open channel flow of high relative submergence (small roughness) adapted from (Manes et al., 2007) where h_w is the water depth and v is water velocity.

To optimise the hydraulic environment for fish passage, the effects of roughness element distribution and density can be tailored accordingly. For example, consider a bed of vegetation within a river, such as an array of infinite width and length (Nepf, 1999) (figure 3.2). Within an array of vegetation of infinite width and length, in submerged flow, where the arrangement is characterised as dense, there are two distinct velocity regions (Nepf, 2012). Firstly, a layer of fast-moving fluid has been identified in past studies above the roughness elements, called the surface layer (figure 3.2). This will be capable of carrying large amounts of flow given reasonable water depth above the elements as there is comparatively little resistance at this level. The flow is idealised as that over a rough solid bed (Huai et al., 2009a, 2009b). As the flow velocity in the roughness layer is non-zero, the velocity profile of the surface layer must be superimposed on a non-zero-base velocity. The velocity profile for submerged subcritical flows, with sparsely distributed roughness elements, is logarithmic in nature with velocity within the roughness region decreasing monotonically with increasing cluster density (where density is the proportion of area occupied by the roughness elements) (Nepf, 2012).

Dense arrangements of vegetation produce undesirably high flow resistance where subcritical flow conditions are created. In addition, a dense arrangement of cylinders (represented as vegetation in this case) would be undesirable with regards to fish passage as fish require space between the elements so that they can navigate through their environment successfully (Bainbridge, 1958).

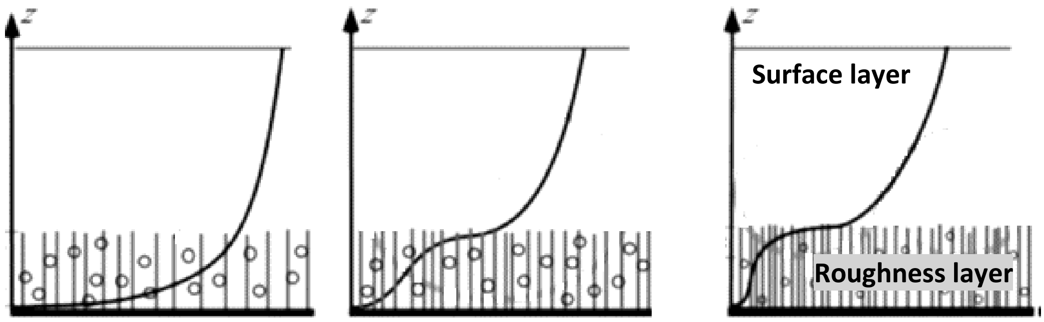


Figure 3.2 Schematic diagram of flow through submerged roughness elements showing the representative flow profile for subcritical flows at different spacings (Nepf, 2012).

Roughness elements, which can come in the form of clusters of bristles, cylinders, vegetation etc. effect water velocities and depths due to the flow resistance induced which reduces the total energy of the water. Depending on whether the roughness elements are unsubmerged or submerged, stiff (Nepf, 2012) or flexible (Marjoribanks et al., 2014; Nepf, 2012; Wu et al., 1999; Baptist et al., 2007), on mild (Aberle and Järvelä, 2013; Graf and Yulistiyanto, 1998) or steep slopes (Wu et al., 1999; Ishikawa et al., 2000) with different diameters, spacings and porosities (Zong and Nepf, 2012; Taddei et al., 2016) the magnitude of the flow resistance and subsequent velocity reduction varies.

These roughness elements generate flow resistance which can be calculated as a drag force (Etminan et al., 2017), where drag force can be calculated as:

$$F_D = \frac{1}{2} C_D \rho A {V_w}^2 \tag{3.1}$$

where C_D is the drag coefficient, ρ is the density of water, A is the area of the obstruction and V_w is the water velocity.

The calculation of hydraulic resistance using drag force in this way is different to conventional methods for calculating hydraulic resistance such as using Manning's n to characterise the approximate roughness coefficient (Guardo and Tomasello, 1995; Wu et al., 1999; Huthoff et al., 2013) or a friction factor (*f*) (Cheng, 2015). Although these approaches can be useful, attributing energy losses to the drag force created by the roughness elements provides a better representation of the cluster-flow interaction (e.g. Marjoribanks et al., 2014; Luhar and Nepf, 2013; Ishikawa et al., 2000; Kothyari et al., 2009; Auel et al., 2014). The time-averaged drag force on canopy elements (F_D) can be related to the roughness element diameter (D) and height (H_c), the fluid density (ρ), and velocity (V_w).

To calculate drag force F_D, an empirical parameter (drag coefficient C_D) is required. Estimation of the drag coefficient can be complex and many studies assume a value of $C_D \approx 1$ for cylinders (Nepf, 2012). In practice, this assumption can be inaccurate as energy losses occur which are not accounted for and their effect would need to be represented by modifying the drag coefficient. Therefore, the drag coefficient needs to be determined through experimentation. Skin friction drag, between the roughness element and the flow, and form/pressure drag created by the shape of the roughness element and the pressure difference, created around the front and back of the roughness element, are experienced around an object and contribute to the overall drag force induced on the water, reducing water velocities (Tritton, 2007). The magnitude of skin friction, form or pressure drag varies depending on the obstruction geometry, roughness, flexibility and turbulence effects, which consequently can influence the value of C_D. For cylinders, form/pressure drag is dominant over drag generated by skin friction.

Extensive work has been undertaken on flow created by circular cylinders (e.g. Zdravkovich, 1997; Sumer and Fredsoe, 2006) where the magnitude of the flow resistance created by the cylinder (which can be quantified by calculating the drag force), has been recorded to vary depending on the Reynolds number and object size and shape, which determines whether streamlining or turbulent effects occur and cannot be quantified simply (Cheng, 2015, figure 3.3). Reynolds number reflects whether molecular viscosity or internal mixing patterns are dominant. Wake shedding, separation, boundary layer formation and drag coefficient varies dependent on Reynolds number (figure 3.3, 3.4 and 3.5) where the drag coefficient reduces at critical Reynolds numbers which occur between $3x10^5$ and $3.5x10^5$ and then changes again at supercritical Reynolds numbers which occur between $3.5x10^5$ and $1.5x10^6$ (figure 3.5). The arrangement of the roughness elements can also affect the average velocity, as some elements upstream could create a sheltering effect, diminishing impact velocities on those downstream (Nepf, 1999). The array density (λ), a function of spacing and diameter (variable for flexible elements which bend under increasing flow velocity), and roughness element density (φ) also affects the drag force (Kothyari et al., 2009; Taddei et al., 2016), where roughness element density influences the magnitude of flow bleed through the element, changing the magnitude of the drag force on the flow. Therefore, to maximise velocity reduction and predictably influence flow characteristics one can modify the size and shape of the obstruction in addition to its density.

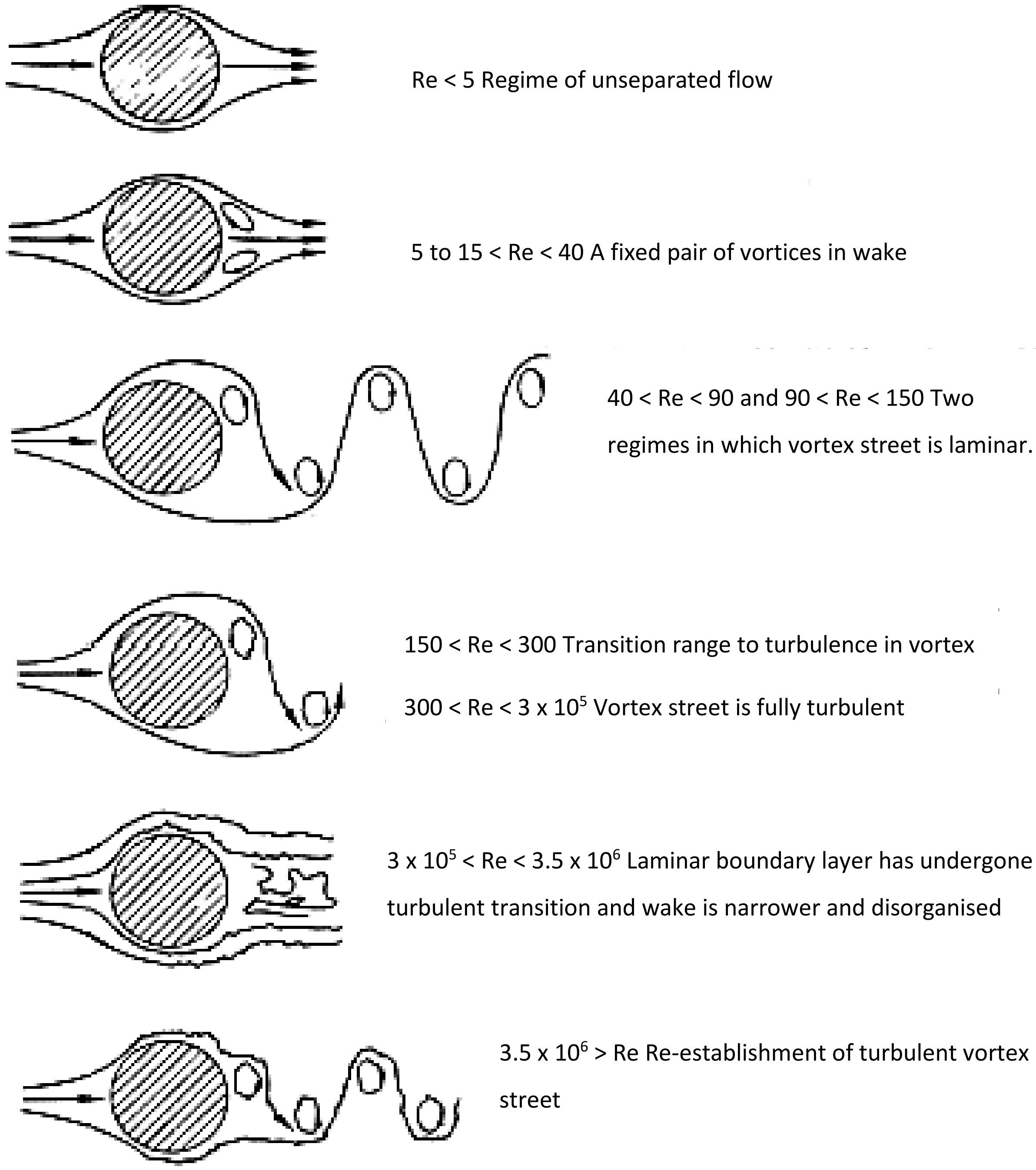
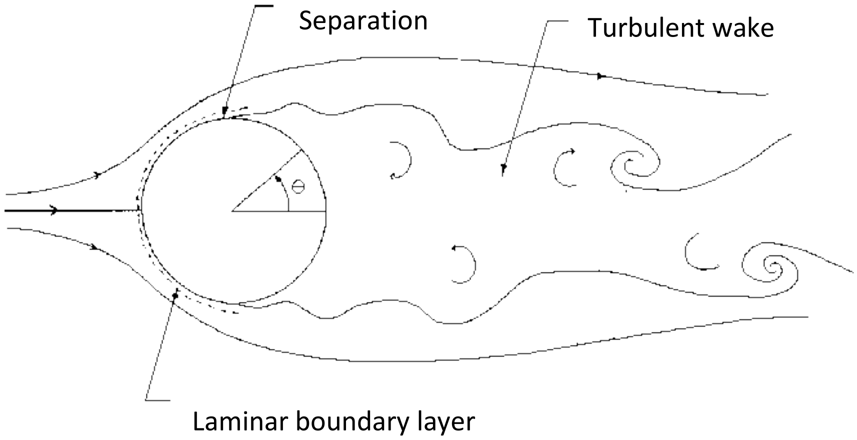
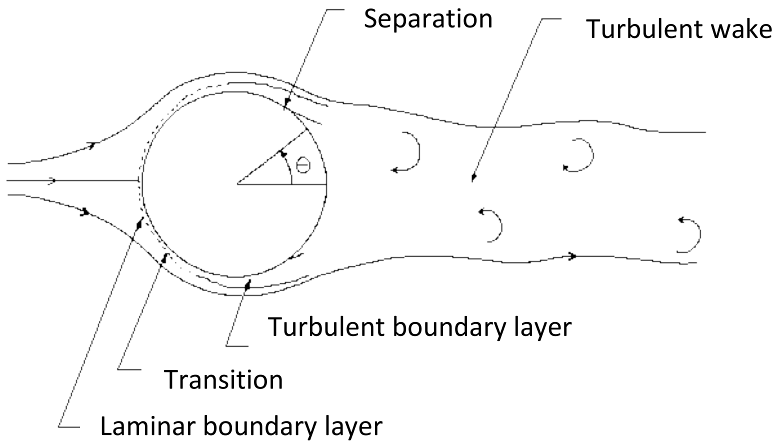


Figure 3.3 Effects of Reynolds numbers on the flow profiles around cylinders (Blevins edited, 1990).



(a) Subcritical Reynolds number



(b) Supercritical Reynolds number

Figure 3.4 Flow past a circular cylinder for (a) subcritical Reynolds number and (b) supercritical Reynolds number illustrating where the point of separation occurs around the cylinder and wake formation and shedding (Devenport and Borgoltz, 2016).

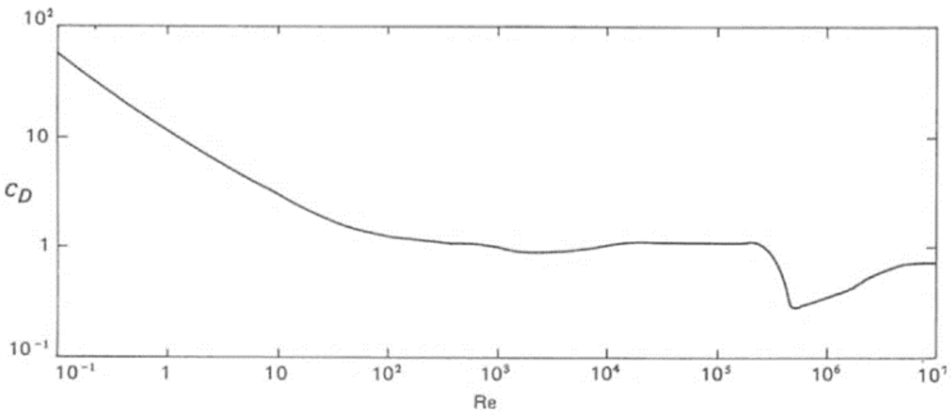


Figure 3.5 Experimentally determined drag coefficient variation in a fluid around a cylinder for different Reynolds numbers (Tritton, 2007) using a range of different sized cylinders.

3.2 Modification of Gauging Weir Hydraulics with Roughness Elements

Gauging weir retrofit for fish passage requires modification of the flow characteristics on the downstream weir face. This modification can affect gauging accuracy if upstream and crest tapping water level measurements, used to provide a stage-discharge relationship, are affected. No impact on gauging accuracy can be obtained through ensuring supercritical flow conditions even with the design in place, or by placing the design at a sufficient distance from the crest where the flow can transition from sub to supercritical before encountering the area of flow modified by the fish pass.

It is assumed that when roughness elements are placed onto the downstream face of a gauging weir the flow profile is modified, where within a control volume (section 1 and 2 denoted in figure 3.6), a number of changes occur compared to flow over an unmodified triangular profile weir. Within the roughness elements the hydrostatic force (F_{H1}) and forces created due to water acceleration and weight component on a slope (F_w) are counteracted by the drag forces (F_D) created by roughness elements and a downstream hydrostatic force (F_{H2}) (figure 3.6). Immediately upstream of the elements the water backs up as the flow resistance created will slow down the water velocity and an increase in water depth occurs (figure 3.6). Within the elements, a higher normal depth is present (h_{n2}). The difference between the critical depth (h_c) and this new normal depth (h_{n2}) is smaller than between h_{n1} and h_c. If this new normal depth is greater than the critical depth due to the flow resistance created by the elements, an effect on gauging could be observed depending on the extent of the backwater effect created by this increase in water depth. Therefore, if subcritical flow is induced on the downstream weir face due to a high density of roughness elements, gauging can theoretically be affected depending on the distance the elements are placed from the crest, as such the design would need to be placed downstream of a transition zone in which supercritical flow could develop.

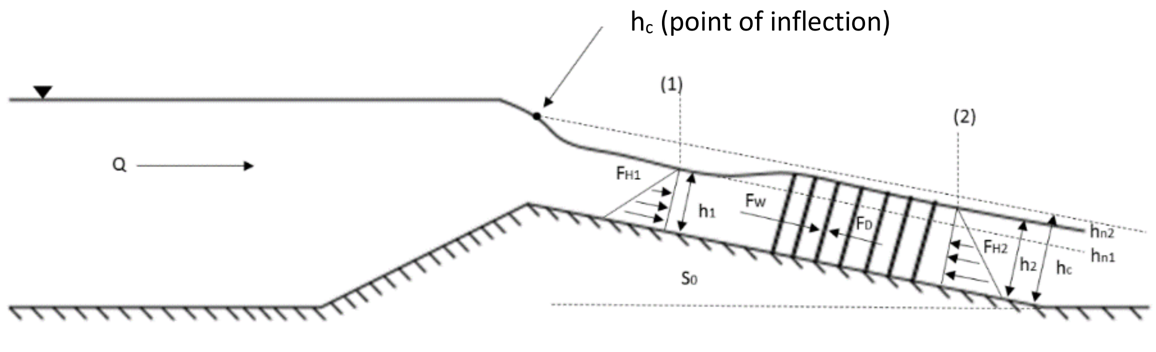
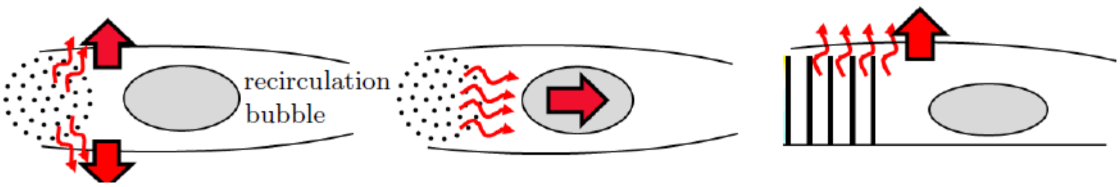


Figure 3.6 Schematic diagram showing the flow profile created over a Crump gauging weir where roughness elements are mounted to the downstream weir face.

In addition to upstream water depths, downstream water depths can also be used to gauge flow, although this is much less common (EA pers. comm., 2019), therefore the impact of the design on downstream water depths is also of interest. It is hypothesised that when downstream water levels increase to the point that the weir will become drowned, the clusters will be fully submerged and will act more like a small surface roughness. At this point energy losses from interaction of upstream and downstream water levels will be much greater than any effect of the clusters on the water level and as such can be considered negligible. When modular conditions are present over the weir face, the impact of the fish pass on downstream water depth will be dependent on the drag force created by the roughness elements on the flow. This should be minimal if advantageous fish-hydrodynamic interactions created by certain objects are built upon, reducing the drag reduction required and therefore impact on downstream water depth. In the majority of cases, upstream water levels are used for gauging flows within rivers at weirs but in some cases both the upstream and downstream water levels will be collected depending on the quality of the gauging site. If downstream water depths are used, the accuracy of the measurements are dubious because of the large fluctuation in water depth due to the turbulent conditions present in the vicinity of a hydraulic jump. Therefore, any small influence on water depth would be unlikely to be detected. The effect of the fish pass on the modular limit will be quantified in further work once an optimal array configuration is determined (see Appendix A.4.3).

3.3 Hydrodynamic Impacts of Roughness Element Density

Roughness element density affects the magnitude of flow bleed through the roughness element which when porous forms a cluster of elements (Taddei et al., 2016) (figure 3.7). Lateral, trailing edge and vertical flow bleeding can occur through cylindrical clusters which cause energy dissipation. It is hypothesised that the drag force of a cluster should be greater than that of a solid cylinder as the separation point for clusters occurs slightly further upstream than for solid cylinders. In addition, the summation of energy losses in each individual internal cylinder within a bristle cluster may simply be greater than that associated with a large, solid cylinder.



(a) Lateral bleeding (b) Trailing edge bleeding (c) Vertical bleeding

Figure 3.7 Schematic diagram of different flow bleed events and their effect of the downstream wake behind the cluster (Taddei et al., 2016).

Cluster density has been used to characterise the effects of different cylinder arrangements on the flow. The cluster density φ (Eq 3.2) can be defined as the ratio between the area occupied by all the individual cylinders within the cluster $(N_C\pi d^2)/4$ and the base area of the cluster $\pi d^2/4$ (Taddei et al., 2016).

$$\varphi = (d^2\, N_c\,)/D^2 \qquad (3.2)$$

Where N_C is the number of individual cylindrical elements within the cluster, *d* is the diameter of the individual elements and *D* the diameter of the cluster.

When φ is less than 0.05 no vortex street forms (Taddei et al., 2016) because, as cluster density increases, the length of vortices within the street decreases (Zong and Nepf, 2012). At φ values between 0.05 and 0.15, a low velocity zone is present behind the cluster and the vortex street forms some distance downstream of the cluster. At φ values greater than 0.15, the wake produced is similar to that of a solid cylinder (Nicolle and Eames, 2011) (figure 3.8). Some experimental work has been undertaken (Chen et al., 2012; Zong and Nepf, 2012; Folkard, 2005; Taddei et al., 2016) but further work is required to determine whether the observed relationship between cluster density and drag is applicable for an array of porous cylindrical clusters.

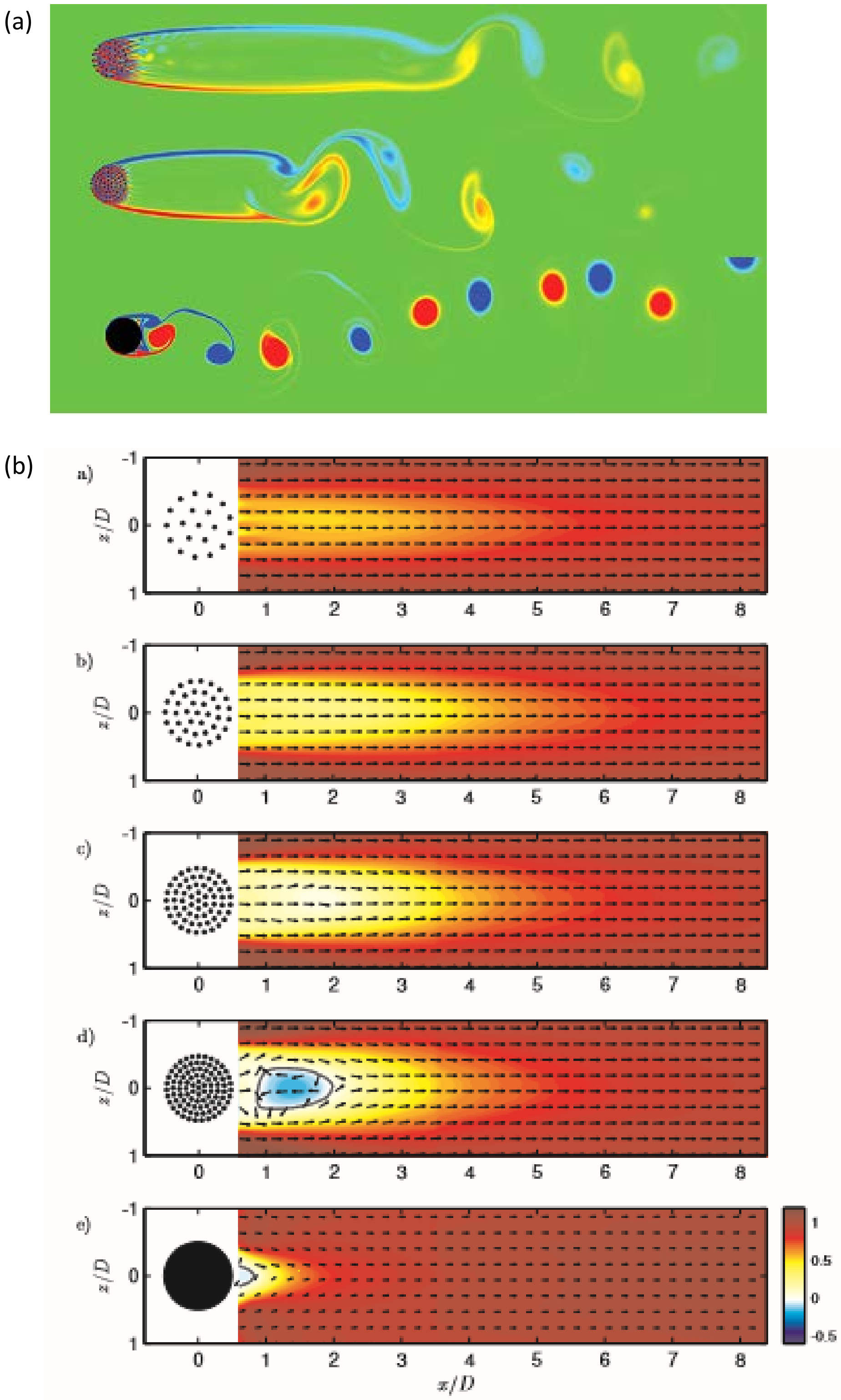


Figure 3.8 (a) Numerically simulated wakes for array densities of 0.0884, 0.1451 and 1, where the colours red and blue denote positive and negative vorticity respectively, with green corresponding to irrotational fluid. The flow is directed from left to right where the Reynolds number for each array was 2100 and (b) experimentally determined wakes and measured velocities (m s^{-1}) behind porous circular clusters of different density in air with an incoming free-stream velocity of 20 m s^{-1} (Nicolle and Eames, 2011; Taddei et al., 2016).

Compared to solid cylinders, cylindrical clusters create steady wakes of increased length downstream, where the flow resistance and downstream wake created by the cluster can vary depending on cluster density (Grant and Nickling, 1998; Nicolle, 2009; Nicolle and Eames, 2011; Taddei et al., 2016). Flow resistance in the form of a drag coefficient is reported to increase with increasing cluster density until the solid cylinder case, where drag coefficient decreases (Taddei et al., 2016). This means that greater areas of lower velocity can be created for the same array footprint, using a specific array density and cluster density, which could aid fish passage.

The effect of wall proximity of elements to each other within a cluster is important as, if the density is high more flow will be forced around the cluster than through it and the angle of separation will be affected. Zdravkovich (2003) states that for a certain cylinder spacing the external and internal eddy shedding will be absent resulting in a minimum value of drag coefficient. Therefore, depending on the porosity, one can get internal, none or external eddy shedding. In addition, the higher the density the more intense the top shear layer which results in greater wake entrainment and momentum transfer induced by the wake (Taddei, 2016). Free end effects on wake development are not as strong for porous patches as they are for solid obstacles so conditions for fish swimming could be more favourable as the strength of the vortices generated by the object is reduced. The strength of vortices has been shown to cause fish buffeting and displacement (Tritico and Cotel, 2010). Porous patches have a wake which resembles the wake generated behind a long aspect ratio square cylinder where the separation point of the flow along the sides of the patches is fixed by the lateral bleeding at the most external cylinder where the shear layers grow with a linear trend (Taddei, 2016).

Cluster arrangement can have an impact on the overall flow resistance created (Meire et al., 2014) with the staggered arrangement creating the greatest flow resistance (Wang et al., 2013). Cluster arrangement could also influence flow interaction between clusters which could affect the velocity profile within the array. According to Meire et al. (2014), neighbouring clusters act independently of each other with the exception of very dense, closely spaced clusters. Therefore, the velocity profile behind each wake will be independent of eddies produced by the clusters on either side. This does not mean that upstream cluster wakes will have no impact on the velocities experienced by downstream clusters.

3.4 Fish – Hydrodynamic Interactions around Cylinders

The interaction of fish with their hydrodynamic environment is a broadly studied topic (Liao, 2007 and references within). Fish are highly sensitive creatures capable of sensing hydrodynamic cues within a riverine system, using their lateral line (figure 3.9) to successfully navigate through complex environments containing woody debris, large boulders and other structures (Montgomery, 2003).

Fish swimming around cylinders has been a topic of particular interest with strong evidence to suggest that fish can utilise the hydrodynamic environment to improve swimming performance (Liao, 2007). Experimental work has been undertaken around solid cylinders where entraining, Karman gaiting, bow waking and free stream swimming were observed (Liao, 2007). Entrainment involves fish holding position behind an object such as a cylinder whilst expending minimal energy, as they orient their body based on spatial flow patterns so that the effect of hydrodynamic forces on their bodies are reduced (Przybilla et al., 2010). Displacement downstream can also occur where vortices created within the flow disorientate and buffet the fish respectively (Montgomery, 2003). Fish displacement is recorded to occur when the size of the vortices or eddies created within the flow is equal to the fish length as the force of the eddy impacting the fish is at its greatest (Cotel and Webb, 2015).

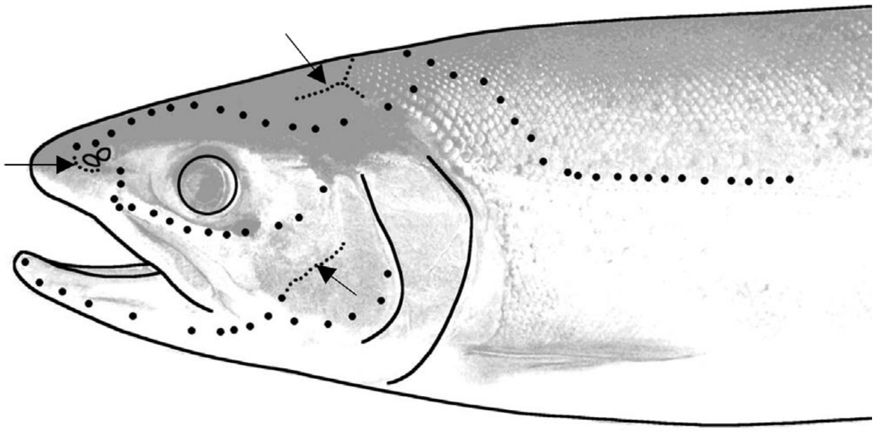


Figure 3.9 Location of sensory nodes on *Oncorhynchus mykiss* with small filled circles (arrowed) and large filled circles representing superficial neuromasts and canal pores respectively (Montgomery, 2003).

Evidence of fish use of the hydrodynamic environment created by cylinders suggests that utilising them to aid in fish passage over barriers is possible. As yet no work has been undertaken to determine whether a fish pass created of a number of porous cylinders would create hydraulic conditions favourable for fish passage and how fish would interact with that environment.

3.5 Application of Theory – Design Proposal

Based on evidence provided in the literature, a staggered array of cylindrical clusters (CBCs) has the potential to increase passage efficiency at gauging weirs when retrofitted to the downstream face. This staggered array is comprised of clusters with diameter *D* and spacing S_c between each cluster (figure 3.10), these length scales are critical in defining the array density. The array density can be defined, based on work by Nepf (2012) amongst others, as

$$\lambda = \frac{\pi D^2}{4{S_c}^2} \tag{3.5}$$

Where S_c is the spacing (c/c) between adjacent clusters and *D* is the cluster diameter (figure 3.10).

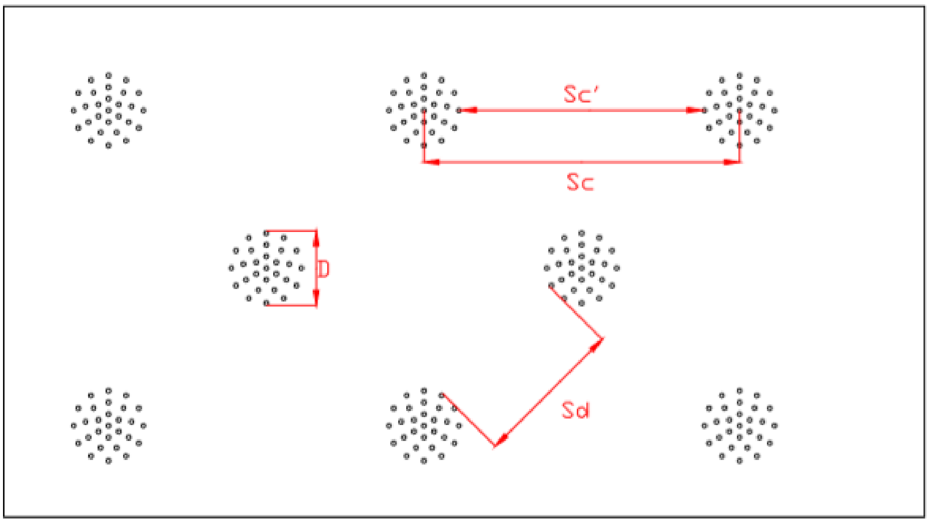


Figure 3.10 Plan view of a section of cylindrical clusters in the flow illustrating the lateral (c/c) spacing between clusters (S_c), lateral spacing and diagonal between clusters (S_c' and S_d respectively) and diameter (*D*).

A cylindrical cluster shape was chosen based on literature illustrating that fish readily use the wakes of cylinders (Kerr et al., 2015). Cylinders produce a predictable flow resistance and have been well studied in the past with a large volume of literature on the topic (Zdravkovich, 1997; Taddei et al., 2016; Nicolle, 2009; Zong and Nepf, 2012). Cylindrical bristle clusters are a logical choice with regards to cluster shape as weaker recirculation occurs downstream of the cluster (compared to the solid cylinder case (Taddei, 2016). As fish can also be displaced by the buffeting of vortices shed from solid cylinders (Cotel and Webb, 2015), reduced vorticity could be beneficial for fish passage. Destabilisation is most likely to occur when the diameter of vortices created within the wakes are equal to the fish length as the force impacting the fish is at its greatest (Cotel and Webb, 2015). Based on this it is hypothesised that reduced fish destabilisation would occur within a staggered array of cylindrical clusters.

3.6 Dimensional Analysis

To determine which dimensionless parameters influence the flow resistance, and therefore determine which variables should be systematically analysed experimentally, a dimensional analysis was undertaken using the Buckingham pi method. The flow resistance (F_{RES}) of force per unit area is a function of both cluster and flow properties (Eq 3.6)

$$F_{RES} = f(D, d, S_b, H_c, S_c, C_s, J, \rho, \mu, V_w, h_w, g) \tag{3.6}$$

Where D is the cluster diameter, d the diameter of bristles within the cluster, S_b the spacing within the bristles in the cluster, H_c is the cluster height, S_c the spacing between clusters, C_s the cluster shape, J the flexural rigidity of the bristle, ρ is water density, μ is dynamic viscosity, V_w is water velocity (upstream) and h_w is water depth (upstream).

Using the Buckingham pi method where V_w, D and ρ are repeating variables, the non-dimensional variables that need to be investigated can be determined:

$$\frac{F_{RES}}{{V_w}^2 D^2 \rho} = f\left(\frac{d}{D}, \frac{H_c}{D}, \frac{S_b}{D}, \frac{S_c}{D}, \frac{h_w}{D}, C_s, \frac{JD^4}{\rho {V_w}^2}, R_e, F_r\right) \tag{3.7}$$

Dimensional analysis reveals that flow resistance is dependent on: Reynolds number (Re) (ratio of inertia to viscous forces); Froude number (Fr) (ratio of inertia to gravitational forces); flow conditions (which effect the magnitude of relative submergence of each bristle) and array density (λ) which varies dependent on the cluster diameter, cluster density (φ) and spacing between each cluster (S_c). In the derivation of non-dimensional parameters, bed friction is neglected as side and bed friction effects can be assumed negligible in comparison to cluster effects (Cheng and Nguyen, 2011).

Of particular interest in this body of work is the effect of spacing and diameter on flow resistance and fish passage. Other parameters effecting flow resistance either can be assumed negligible or should be kept constant (Re, Fr, submergence and aspect ratio) so that these effects can be analysed. For example, some terms can be assumed negligible or unchanging during experiments, for instance, a significant amount of knowledge can be obtained from current literature on the effects of cluster shape and flexural rigidity on flow resistance (Aberle and Järvelä, 2013; Marjoribanks et al., 2014; Nepf, 2012; Wu et al., 1999; Baptist et al., 2007). Where the deflection of the elements creating the cluster is negligible, the flexural rigidity term can be ignored (Fenzl, 1962; Kouwen and Unny, 1973; Fathi-Maghadam and Kouwen, 1997) as there is no appreciable difference between the actual height of the cluster and its height when under loading (where the cluster would deflect and therefore its effective height would decrease).

3.7 Conclusions

Retrofitting cylindrical bristle cluster (CBC) arrays onto the downstream face of gauging weirs to improve upstream fish passage is suggested based on sound hydraulic theory and evidence of fish behaviour and swimming performance and, when installed, should provide opportunity for fish to surmount previously impassable barriers. Requirements of the design are that it will not affect gauging, but will decrease velocities on the weir face and increase water depths. These should be fulfilled as, with respect to hydrometrics, optimal conditions can be obtained through attaining supercritical flow conditions before the first line of CBCs, where upstream water depths are not affected by downstream flow disturbances. Therefore, compromising the hydrometric properties of the weir can be avoided, whilst reducing the velocity (and increasing water depth).

Chapter 3 concludes that the optimal array arrangement, quantified by S_c / D, will depend on size and swimming ability of the target species / life stage. There is a requirement to maximise spacing to allow fish adequate room for manoeuvrability and not effect gauging, create a larger proportion of low velocity zones within the array (which can be manipulated by varying S_c / D) and create wakes that are attractive to fish so that they can be utilised for pass navigation. Therefore, only a small range of S_C / D will work for a particular species / life stage, too small and it will constrain fish, too large and it will not impact the hydraulic conditions present over gauging weirs sufficiently to increase passage efficiency. Experimental work is required to optimise the S_C / D ratio to maximise fish passage.

Chapter 4 Adaptation of Eel Bristle Boards for Improving Fish Passage at Gauging Weirs

Summary

A novel and low-cost method of modifying flow on the downstream face of triangular profile gauging weirs to facilitate fish passage is presented. Utilising a staggered array of bristle clusters in the form of modified eel bristle boards at various densities, the impact on gauging hydrometrics, velocity and water depth were recorded. Fish passage studies were also undertaken to determine the impact of the different modified eel bristle densities on passage efficiency. Debris accumulation trials were also undertaken and the material robustness analysed under field conditions. The hydrometric properties of the weir were weakly impacted by the presence of bristles even when mounted close to the weir crest and at high density. Average water velocities were reduced by approximately 50% (from 1.4 to 0.7 m s^{-1}) to levels suitable for passage of a wide range of fish species and sizes. Fish passage efficiency increased by up to 40%, depending on flow and density, compared to the control. Large debris accumulation was low due to the self-cleaning nature of the bristles when submerged, however some of the bristles deformed in the flow. This design is a comparatively low-cost fish passage solution and is easy to retrofit onto gauging weirs and hence represents a promising method of aiding fish passage over these structures. The results presented provide a solid basis for further research into the optimisation of this fish passage design and may prove to be a viable solution for gauging weirs and other similar barriers to fish migration.

4.1 Introduction

Flat-V gauging weirs are common in the UK, but their design makes them particularly challenging for fish to ascend due to high water velocities on the downstream face, which often exceed fish swimming capabilities, and shallow water depths. Studies have shown that flat-V weirs can be a major barrier to fish passage (White and Hartley, 1966; Turnpenny et al., 2002) with widespread distribution as a barrier to longitudinal river connectivity throughout the river network (White and Woods-Ballard, 2003). There is a particular need for this weir type to be retrofitted based on anecdotal evidence of low fish passage efficiencies when retrofitted with low-cost baffles (EA pers. comm, 2015) and the unsuitability of other conventional fish passage designs due to cost or impact on gauging, amongst other reasons.

Bristle passes are a low-cost fish passage solution commonly employed to aid eel passage over riverine barriers. Eels have anguilliform swimming motion and utilise the passes by crawling between the high density clusters. In aquatic habitats, a range of other non-salmonid fish species are also present that require passage over structures to reach alternative habitats (Lucas et al., 2000). These include roach (*Rutilus rutilus*), dace (*Leuciscus leuciscus*) and chub (*Squalius cephalus*) which all exhibit a subcarangiform swimming motion. Fish utilising subcarangiform swimming motion have a larger swim footprint than eels and are therefore unable to pass through bristle passes currently designed for eels. However, modifying eel bristle passes for subcarangiform species, by increasing the spacing between bristle clusters, could provide a low-cost fish passage solution for a wide range of fish species found in riverine environments. This could improve passage over a multitude of barriers and be utilised at fish ramps aswell as weirs.

In this study, a fish pass solution is tested which can be used to retrofit gauging weirs, such as flat-V weirs. The fish pass solution comprises of modified eel bristle boards, which act as a staggered array of clusters. The density of the bristle boards was varied in an attempt to ensure the design did not compromise the coefficient of discharge used to determine flow by more than 3% (White and Woods-Ballard, 2003). The design was also required to decrease water velocity and increase water depth to facilitate fish passage and not accumulate debris.

The aim of this study was to determine whether modified eel bristles are a viable and low-cost solution for improving subcarangiform fish passage at flat-V gauging weirs. The effectiveness of this design was tested through investigating; 1) the impact of bristle density on the hydrometric properties of a model flat-V weir, 2) the impact of bristle density on water depth and velocity on the downstream face of the weir, and the performance of the design 3) with regards to upstream passage of roach (*Rutilus rutilus*), 4) under debris loading, and 5) regarding bristle deformation after installation in the field.

4.2 Materials and Methods

4.2.1 Experimental Setup

A flat-V weir (figure 4.1) was constructed in an external hydraulic flume with trapezoidal channel (50 m long, 2.1 m wide at the base, approx. 3 m wide at the top and 0.5 m deep) at the International Centre for Ecohydraulics Research (ICER) Hydraulics Laboratory, Chilworth Science Park, University of Southampton (UK).

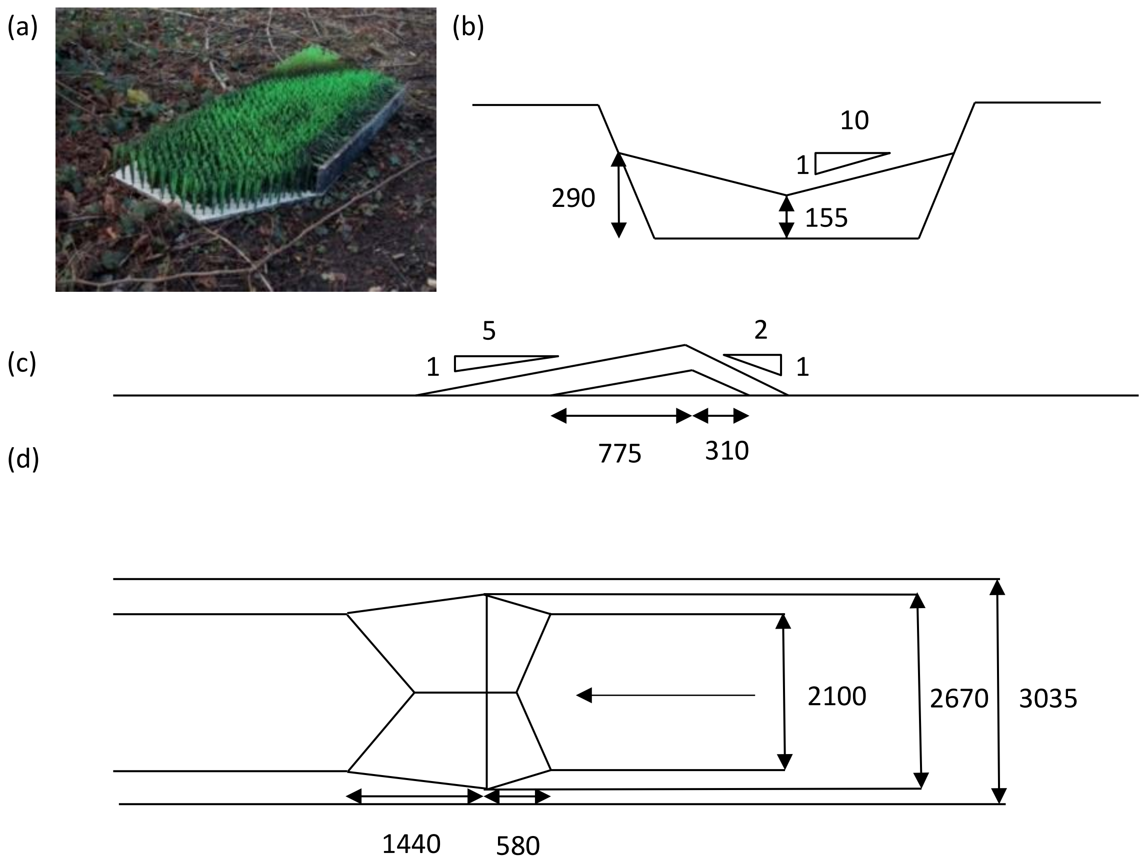


Figure 4.1 (a) Bristle boards and the flat-V weir in (b) section, (c) elevation and (d) plan, illustrating the unmodified bristle substrate and the weir dimensions used in experimentation (distances shown in mm).

The bristles (mounted on 0.01 m thick polypropylene boards) were placed on the downstream face of the weir and consisted of a staggered array of synthetic bristle clusters (figure 4.2), 0.07 m in length and 0.005 m in diameter. An unmodified model weir was used as a control (*λ1*). A range of different bristle spacings measured diagonally from centre to centre; 0.05 m (*λ2*), 0.1 m (*λ3*), and a graduated density design (0.02 m to 0.06 m) (*λ4*) were trialled (table 4.1) (figure 4.2) and compared to the control to understand the impact of different densities on the hydrometric properties of the weir and fish passage, these are characterised as 3 different treatments. The chosen spacings, adequate for the fish sizes tested in this study, reflect the estimated distance that fish of differing size ranges (0.07 – 0.15 m) require for manoeuvrability between the bristles (Servais, 2006). A graduated density (*λ4*) was tested as it was hypothesised that smaller spacing on the sides could be utilised by weaker swimming, smaller fish where velocity reduction would be greater. Uniform densities were tested as if the majority of fish, regardless of size and swimming ability, could pass up the weir assisted by a greater spacing, design simplicity and efficiency could be obtained. Experiments were carried out using a number of discharges (*Q*) denoted as low (*L*) (0.01 m^3s^{-1}), medium (*M*) (0.04 m^3s^{-1}) and high (*H*) (0.1 m^3s^{-1}) (table 4.1).

4.2.2 Hydrometric, Velocity and Depth Trials

Water depth and velocity measurements were undertaken for all flow conditions, to within an accuracy of ± 0.5% at six locations down the centreline of the weir face (0, 0.17, 0.37, 0.57, 0.695 and 0.82 m from the weir crest, denoted as measurements 1 – 6 in table 4.1, figure 4.7) with and without bristles, in addition to upstream (US) (0.5 m from the weir crest) and downstream (DS) (approx. 30 m from the weir crest). Measurements were recorded 0.5 m upstream of the weir crest according to guidelines stipulated in BS ISO 4377 (2012). Velocities were recorded at 50% of the bristle height and halfway between the water surface and the bristle top when the bristles were submerged. Reynolds (Re) numbers were also computed to determine flow conditions present. A point gauge and a flat head electromagnetic flow meter (Valeport Model 801), were used to measure water depth and velocity respectively. The flow meter has a cylindrical sampling range 10 mm above the electromagnetic heads, samples data at a frequency of 2 Hz, digitally filtered from raw 96 Hz data (Valeport Limited, 1999).

To determine whether the bristle clusters would impact the gauging ability of the weir, the modified eel bristle boards [altered so that bristle spacings measured diagonally from centre to centre were 0.05 m (*λ2*), 0.1 m (*λ3*), and 0.02 m to 0.06 m (*λ4*)] were mounted onto the downstream weir face and the first bristle line was incrementally moved further from the crest. For each incremental movement, the water depth at the crest and 0.5 m upstream of the weir crest line were measured over a range of flows and a stage-discharge relationship was obtained. A point gauge at the crest and upstream measured the water depth to within an accuracy of ± 0.005 m.

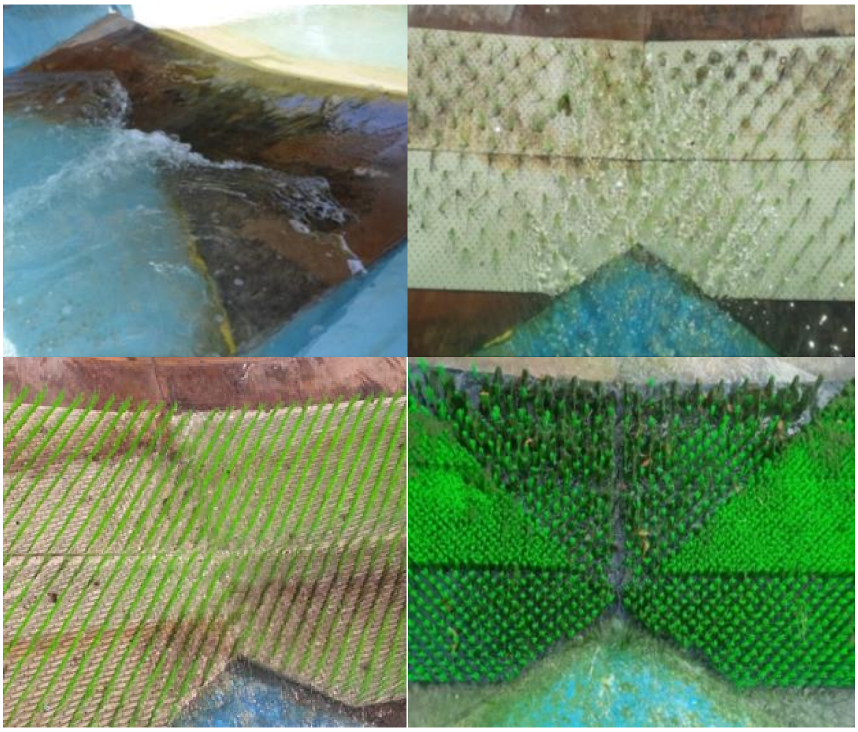


Figure 4.2 The model flat-V weir with no bristles i.e. control (*λ1*) (top left), bristles at 0.1 m spacing (*λ2*) (top right), 0.05 m spacing (*λ3*) (bottom left) and the graduated density design (0.02 m to 0.06 m spacing) (*λ4*) (bottom right).

4.2.3 Fish Trials

Fish passage trials, for each flow and density, were conducted using roach (mean total length ± SD of 0.095 m ± 0.0233) over a period of 4 weeks (1/07/15 – 31/07/15) between 09:00 and 20:00 hours. Roach were chosen based on their wide distribution in the UK, their suitability as 'model' non-salmonid fish species due to their swim speeds being lower or similar to those of other non-salmonid fish (Clough and Turnpenny, 2001) and generic body morphology. Fish were sourced from the Environment Agency hatchery in Nottingham and transported to holding tanks at the ICER Hydraulics Laboratory in oxygenated water containers. Fish were kept in 1200 L holding tanks (figure 4.3a) (17 ± 3 °C) where water quality (ammonia, nitrite, and nitrate) was monitored (figure 4.3b) using a freshwater test kit (API) (figure 4.3b) and maintained within suitable levels for fish health through the use of biological filtration and part (typically 50%) water changes. Refuges were used to provide an element of habitat complexity within the holding tanks and help reduce stress. Fish were fed daily.

(a) (b)

Figure 4.3 A photograph of (a) some of the holding tanks used to home the roach at the University experimental facility in Chilworth and (b) the water testing equipment and water sampling undertaken for 4 different tanks used to home the fish.

Individual roach were only used once to avoid result bias due to learned behaviour. Twenty repeats were undertaken for each experimental flow-density combination. The experimental areas, sectioned off with nets, consisted of the flume area 2 m upstream of the weir crest and 2 m downstream of the weir base. Acclimatisation for at least 1 hour prior to trial initiation was undertaken in a perforated barrel downstream of the experimental area. On initiation of each trial the roach were released in an area of low velocity 2 m downstream of the weir base. Trials terminated after successful passage over the weir crest or a period of 1 hour had elapsed. Fish passage was monitored visually. Passage attempts were calculated as the number of fish approaching the weir (0.5 m from the weir base) of the percent of those that were released. Passage efficiency was calculated as the number of fish passing the weir as a percent of those that attempted.

4.2.4 Debris Accumulation and Bristle Deformation

To determine levels of debris accumulation, leaves and woody debris (ranging from 0.005 – 0.03 m in diameter and up to 1 m in length, figure 4.4) were introduced into to the water approximately 3 m upstream of the flat-V weir. The proportion of debris successfully passing the weir was recorded under *L*, *M* and *H* flow for bristle density *λ2* placed 0.17 m from the weir crest as this configuration was the most successful at fulfilling previous hydrometric requirements, preventing a compromise in gauging accuracy by more than 3%.

(a)

(b)

Figure 4.4 A sample of the debris that was tested during debris experiments undertaken in the laboratory showing the representative size and type of debris used during experiments.

Field tests were also undertaken where bristles were mounted onto a flat-V weir at Monks Brook-Stoneham Lane SU442174 (Hampshire, UK) (figure 4.5) and monitored periodically to observe the performance of bristles in real riverine conditions under debris loading. The boards were attached directly onto the weir face by drilling into the concrete using a cordless drill and using screws and raw plugs for the fixings. The boards were installed at low flows by hand, being held in place whilst the fixings were inserted. The installation was simple and quick, lasting less than an hour. The experiments allowed for monitoring of debris accumulation every few months over approximately a year under a range of flow conditions. Any bristle deformation was also monitored visually to check for durability of the proposed solution.

Figure 4.5 Field installation of the bristle boards ($\lambda 2$) on a flat-V weir at Monks Brook, Hampshire, UK.

The weir in the field was on a small river with mean flows of 0.294 m^3s^{-1}, a 95% exceedance of 0.03 $m^3s^{-1}$and 5% exceedance of 1.127 m^3s^{-1}. The lower range of flows are comparable to those tested in the laboratory (low: 0.01 m^3s^{-1}, medium: 0.04 $m^3s^{-1}$and high: 0.1 m^3s^{-1}).

4.3 Results

4.3.1 Hydrometric, Velocity and Depth Trials

As bristles were placed closer to the weir crest, the stage-discharge relationship became increasingly compromised. At a distance of 0.17 m, the stage-discharge curves overlap with the control curve (within experimental error of ± 0.001 m), for all the investigated bristle densities (figure 4.6). The *λ2* (0.05 m c/c) configuration of bristle clusters, placed 0.17 m from the crest, had little to no effect on gauging, with depth measurements closely matching those measured during the control (figure 4.6a). *λ3* also had negligible effect on upstream water levels. *λ4* (placed 0.21 m away from the crest) caused a slight impact on water depth at the crest within the margin of error (± 5 mm) (figure 4.6a), with minimal effect upstream (figure 4.6b).

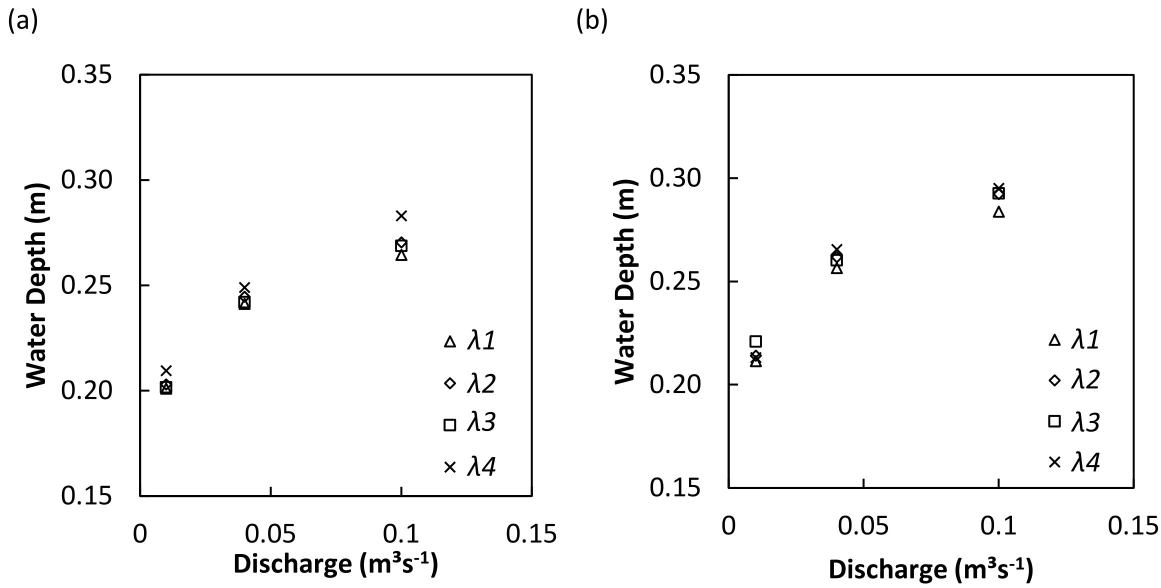


Figure 4.6 Trials undertaken to determine the effects of different densities compared to a control (*λ1*) measuring (a) water levels at the crest of the flat-V weir and (b) the upstream water level relative to the crest, measured 0.5 m from the crest, when boards were placed 0.17, 0.17 and 0.21 m downstream of the crest for *λ2, λ3* and *λ4* respectively.

Table 4.1 Water depth upstream (US) (0.5 m from weir crest) and downstream (DS) (30 m from the weir crest) of the flat-V weir, in addition to longitudinal depths down the centre of the weir (0, 0.17, 0.37, 0.57, 0.695 and 0.82 m from the weir crest numbered from 1 to 6), Fr number along the weir face (locations as for depth measurements using average velocities), and Re number for point 5 (near base) before hydraulic jump. Measurements were taken at low (*L*), medium (*M*) and high (*H*) flows for the control (*λ1*), and treatments (*λ2*, *λ3* and *λ4*).

		Density											
		λ1			*λ2*			*λ3*			*λ4*		
		L	M	H	L	M	H	L	M	H	L	M	H
	Q ($m^3 s^{-1}$)	0.01	0.04	0.10	0.01	0.04	0.10	0.01	0.04	0.10	0.01	0.04	0.10
Depth (m)	US	0.21	0.26	0.28	0.21	0.26	0.29	0.22	0.26	0.29	0.21	0.27	0.30
	1	0.06	0.09	0.12	0.06	0.10	0.13	0.06	0.10	0.13	0.06	0.10	0.14
	2	0.04	0.08	0.10	0.04	0.08	0.11	0.06	0.08	0.11	0.06	0.12	0.15
	3	0.04	0.06	0.09	0.05	0.08	0.10	0.05	0.10	0.13	0.08	0.12	0.16
	4	0.03	0.06	0.07	0.04	0.07	0.10	0.04	0.09	0.12	0.08	0.13	0.15
	5	0.03	0.05	0.07	0.04	0.07	0.09	0.05	0.09	0.11	0.08	0.13	0.15
	6	0.03	0.05	0.08	0.03	0.07	0.10	0.05	0.10	0.12	0.08	0.13	0.15
	DS	0.05	0.10	0.14	0.05	0.01	0.14	0.05	0.10	0.14	0.05	0.10	0.14
Fr	1	0.83	0.83	0.84	0.75	0.75	0.71	0.68	0.69	0.62	0.70	0.60	0.53
	2	1.57	1.24	1.14	1.22	1.08	1.00	0.62	0.75	0.77	0.60	0.50	0.51
	3	2.01	1.69	1.51	1.27	1.01	1.12	0.99	0.86	0.74	0.84	0.67	0.65
	4	2.63	2.06	1.92	1.77	1.35	1.13	0.96	0.98	0.83	0.86	0.64	0.66
	5	3.01	2.18	2.04	1.55	1.45	1.41	1.07	0.98	0.83	0.84	0.70	0.69
	6	3.14	2.09	1.98	2.06	1.52	1.33	1.07	1.07	0.92	1.28	0.95	0.98
Re	($x10^5$)	4.4	8.4	12	3.4	7.5	11	2.8	6.7	8.0	3.8	6.4	9.0

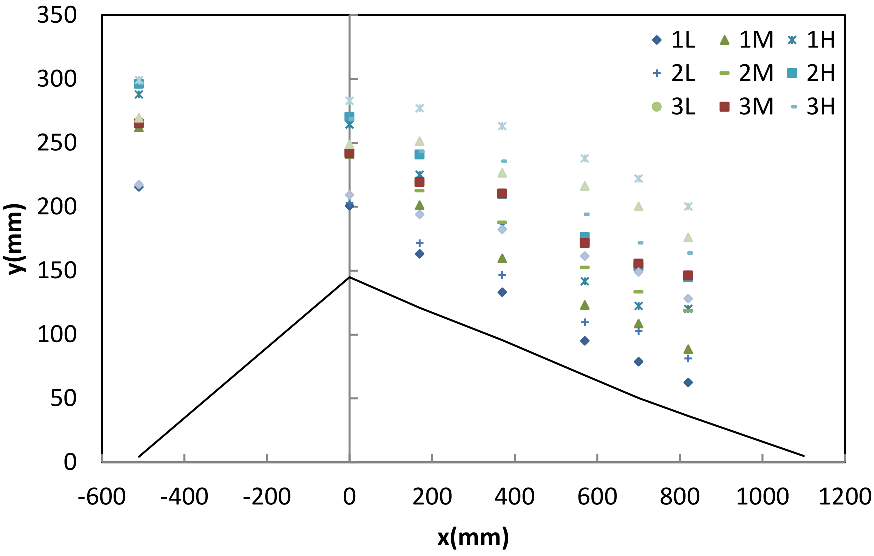


Figure 4.7 Water depth measurements and representative locations of these measurements down the weir face and upstream of the crest corresponding to data presented in table 4.1.

As expected, bristles reduced water velocity on the downstream face at all tested flows (figure 4.8) with greater velocity reduction recorded for increasing density. Reynolds number for all the treatments were in the range of $3x10^5$ to $1x10^6$. Froude numbers ranged from 0.5 to 3, where higher densities e.g. the graduated density (*λ4*) reduced Froude numbers below 1 resulting in subcritical flow conditions. Acceleration occurred down the face of the weir due to gravity therefore velocities were higher at the base of the weir than at the crest. Water acceleration was reduced when bristles were installed on the downstream weir face.

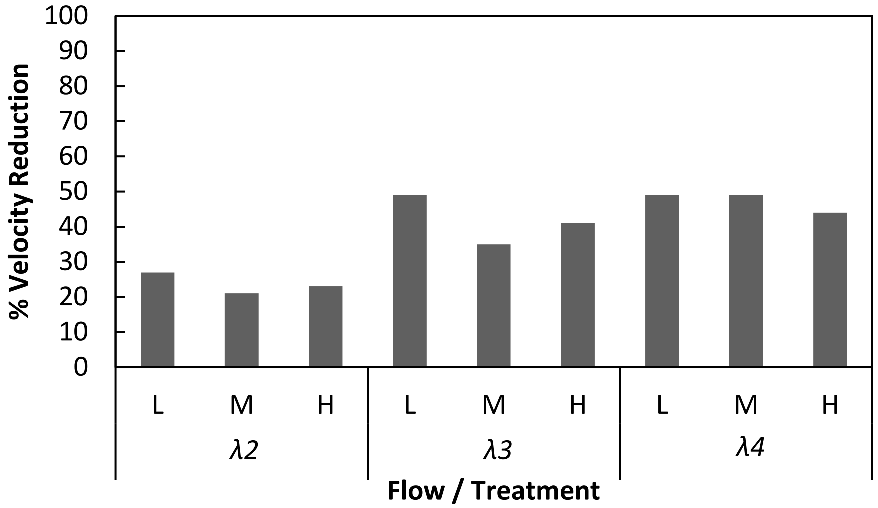


Figure 4.8 Average percentage velocity reduction observed due to different bristle densities (*λ2*, *λ3* and *λ4*) mounted on the flat-V weir relative to the control for low (*L*), medium (*M*) and high (*H*) flows.

4.3.2 Fish Trials

Roach showed very strong positive rheotaxis (attraction toward a current of water), with all roach attempting to ascend the weir. Fish attempted to swim up the centre of the weir in the majority of cases but when unable to ascend, they attempted to swim up the sides. This was prevented for the graduated density due to spacing constraints. A range of fish sizes (0.07 – 0.16 m) were recorded passing the weir. Fish passage was not prevented for the control at low flows (30% passage efficiency) increasing at medium flow (50%) (figure 4.9). Higher flows had reduced passage efficiency due to greater velocities even though depth was greater than the body height of the fish tested (35%) (figure 4.9). For *λ2*, passage improved compared to the control from 35 – 50% and 50 – 75% for low and medium flow respectively. At higher flow, passage was very low (5%). For *λ3* and *λ4*, all flows show fish passage improvement with passage efficiencies of 80 and 85% for *λ3* at low and medium flows and 75 and 80% for *λ4* at low and medium flows. The least improvement was seen for the higher flows (53 and 70% for *λ3* and *λ4* respectively) (figure 4.9). Some fish impingement, where fish become stuck on a bristle, was observed for *λ3* and *λ4*.

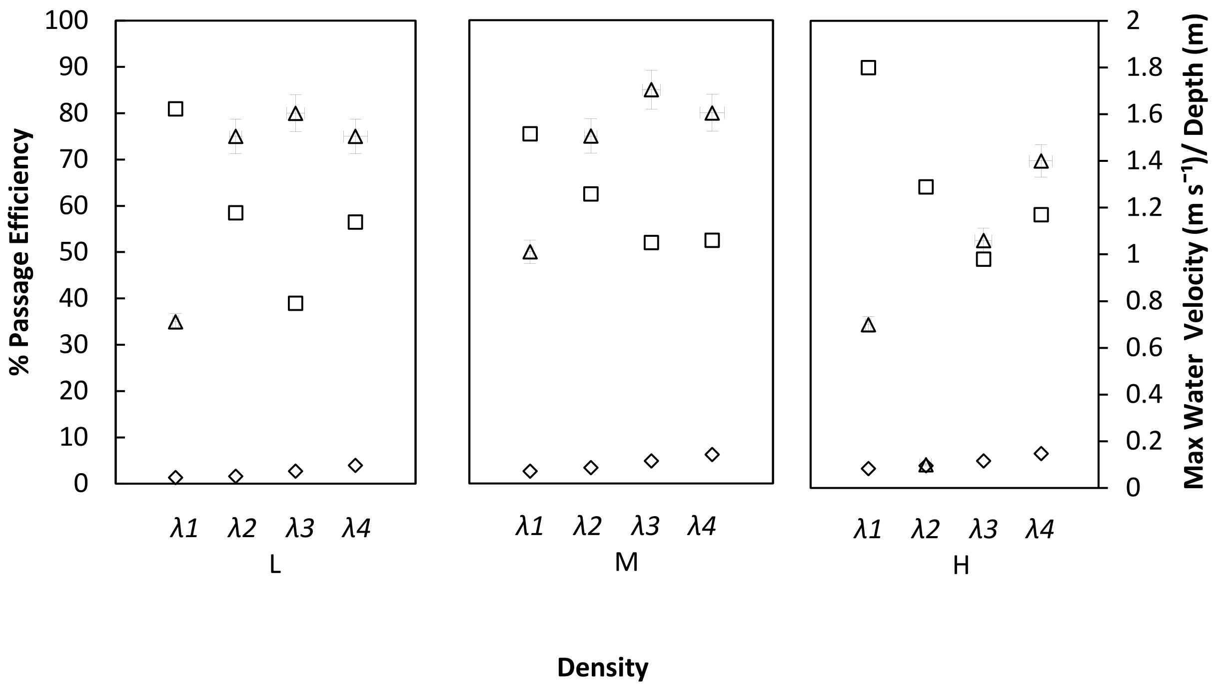


Figure 4.9 Fish Passage Efficiency (triangles) and corresponding maximum water velocities (squares) and water depths (diamonds) for low (*L*), medium (*M*) and high (*H*) flows tested.

4.3.3 Debris Accumulation and Bristle Deformation

During flume studies, twigs and leaves accumulated at the crest of the weir when bristles were unsubmerged for all densities tested (Figure 4.10a) and did not dislodge until higher flows were experienced. The proportion of woody debris passing at low flows was 0%, however the majority of leaves did pass. As discharge increased, large debris dislodged as the bristles became submerged. Field observations for *λ2* (0.05 m spacing), reinforced laboratory tests, as only small leaf accumulation was observed over a 1 year period (Figure 4.10b) where flows were experienced that submerged the bristles, such as the high flow scenario tested in experimental trials. Bristle deformation was observed (Figure 4.11) after being subjected to a range of natural flows and speculated additional loading from vehicles using it as a ford (EA pers. comm., 2014).

(a) (b)

Figure 4.10 Debris accumulation within the bristles over a flat-V weir in (a) laboratory and (b) field conditions.

(a) (b)

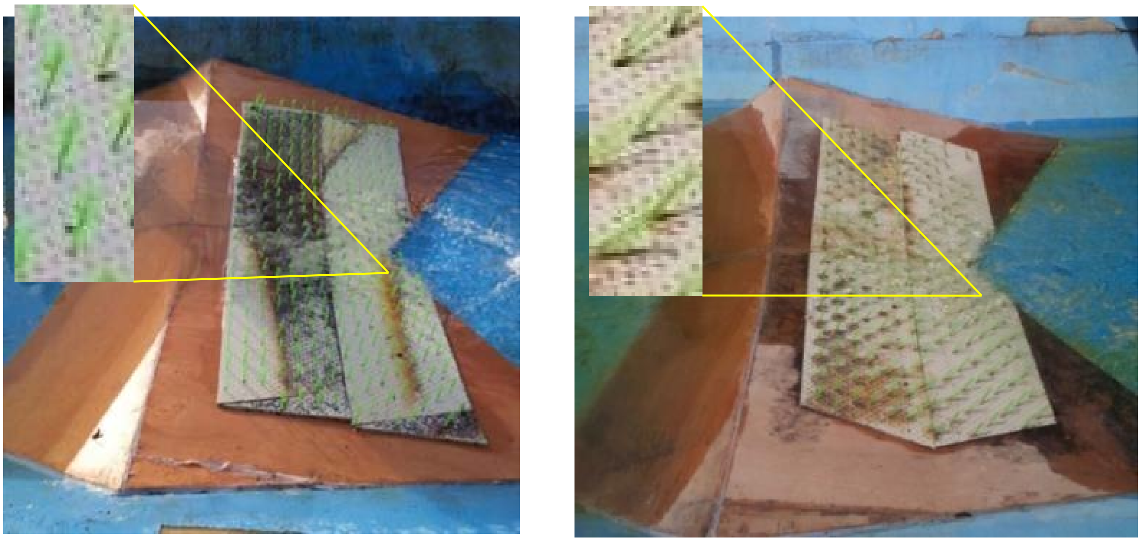


Figure 4.11 Bristle boards (a) just installed on the weir in the experimental facility and (b) reclaimed approximately a year after installation on a flat-V weir at Monks Brook-Stoneham Lane.

4.4 Discussion

4.4.1 Hydrometric, Velocity and Depth trials

The stage-discharge relationship was compromised when clusters were closer to the crest and when subcritical flow conditions were present, corresponding with theoretical predictions. Subcritical flow conditions, created where the spacing between the clusters was small and bristle density was high, as obtained for *λ4*, effected gauging but also produced the greatest velocity reduction and depth increase as they induce a large flow resistance. For *λ4*, a greater velocity reduction was recorded for the lower discharges tested, as the higher the discharge the smaller the effect of bristles on the average velocity profile as the bristles became submerged. When these conditions are present the bristles occupy a smaller proportion of the water column and a surface layer forms above the clusters where there is comparatively less flow resistance (Nepf, 2012).

In this study, modified eel bristle boards with small diameter bristle clusters (0.005 m in diameter) were utilised to improve fish passage. Although advantageous as they are low-cost (approx. £100 per board, dimensions: 1 x 0.4 m), their impact on velocity reduction could be improved, this would especially be required if larger weirs than that tested were to be retrofitted. It is possible that a staggered array of larger cylindrical clusters, as opposed to the bristles utilised in this study, would be more advantageous. This is because, depending on the cylinder diameter the area of low velocity downstream will vary and fish may be able to voluntarily entrain behind the cylinder (Webb, 1998). Entrainment occurs when fish hold position behind an object such as a cylinder whilst expending minimal energy, as they orient their body based on spatial flow patterns so that the effect of hydrodynamic forces on their bodies are reduced (Przybilla et al., 2010). It is hypothesised that similar fish behaviour will be observed behind a large cylindrical bristle cluster, with fish reacting to hydrodynamic cues within the flow. Combining multiple cylindrical bristle clusters into a staggered array with overlapping wake regions may provide micro-habitat that aids fish passage.

4.4.2 Fish Trials

Although passage efficiencies increased for the species and sizes tested, weaker swimming fish such as bream (*Abramis brama*) may not succeed in passing the same barrier as this is dependent on the magnitude of velocity reduction. Maximum velocities recorded in this study were 1.3 m s^{-1} for the most efficient densities tested ($\lambda 3$ and $\lambda 4$) compared to 2 m s^{-1} and 1.5 m s^{-1} for $\lambda 1$ and $\lambda 2$ respectively. For $\lambda 1$ and $\lambda 2$ passage efficiencies were lower as velocities were greater than predicted average burst swim speeds for the size of roach tested (based on Clough and Turnpenny, 2001). Roach are a good model species as their swimming speeds and mode is representative of other subcarangiform, non-salmonids which should also be able to pass such as dace and chub. In this study, hatchery fish were used during experimentation as it was not possible to source an adequate number of wild fish of a specific size. While this also helps reduce the impact of these studies on wild populations, hatchery fish may have weaker swimming performance compared with their wild counterparts, and so results may be conservative.

Observations during the experimental period suggest that spacings ≤ 0.05 m cause some (although minimal) fish impingement therefore, varied spacing for different sized fish or larger overall spacing is required to allow for passage of a range of fish sizes. Selecting a configuration which produces relatively high flow resistance such as $\lambda 3$ requires relatively small spacings, possibly compromising fish manoeuvrability as sufficient space for their body width and swimming motion is required. Spacing between the bristles is an important aspect of the design as if this is too small, fish impingement can be observed. An understanding of the fish swimming mechanics and the area required for a fish to manoeuvre through an array of obstacles is important. There is evidence to suggest that larger fish require a greater area for manoeuvrability due to a larger amplitude of its body while swimming (Bainbridge, 1958). Studies show that is more difficult for larger fish to manoeuvre compared to smaller fish as their turn radius is larger

(Fish, 2002; Walker, 2000). This might suggest why some fish became impinged within the bristles for the denser configurations tested. Investigation into the effect of bristle density on the size of European eel (*Anguilla anguilla*) passing through a bristle pass found that denser substrates exclude larger individuals (Legault, 1992). Legault (1992) suggested that bristle spacing be adjusted according to the size distribution of eels at a particular site. Similarly, such site-specific refinements should be considered for future bristle arrays.

4.4.3 Debris Accumulation and Bristle Deformation

Observations showed that debris accumulated at the crest of the weir when bristles were unsubmerged for all densities tested and did not dislodge until higher flows were experienced. This strongly suggests that the height of the clusters should be minimised as much as possible to reduce the impact of the design on debris accumulation when unsubmerged. It is suggested that the height of the clusters should be no greater than the depth of the fish the pass is designed to accommodate to minimise debris accumulation. Testing to analyse debris accumulation suggests that the design is self-cleaning when the water depth surpasses that of the bristle height but further work is required to corroborate this in a large-scale field setting. Investigation should be undertaken into whether maintenance costs for this fish passage solution could be greatly reduced compared to other fish passage designs due to reduced debris accumulation and the cheapness of the bristle boards, which can be changed easily if damaged due to extreme weather or unexpected events. Suitable improvements on bristle properties are required to prevent bristle deformation so that flow resistance is not reduced over time and pass performance is not impacted.

4.5 Conclusions

Water velocities were reduced by approximately 50% when modified eel bristle arrays were installed on the downstream face of a flat-V weir, when compared to a control (unmodified weir). The velocity reduction was sufficient for some roach (0.07 – 0.16 m) to pass upstream over the weir. Large debris accumulation was low due to the self-cleaning nature of the bristles when submerged, however some of the bristles deformed in the flow. With respect to economics, this design is a comparatively low-cost fish passage solution and is easy to retrofit onto the downstream face of a flat-V gauging weir, making it a potential solution for improving fish passage over weirs and other sloped obstacles including fish ramps. However, design improvements are required to optimise fish passage efficiency. Potential fish impingement must be prevented through use of a more informed spacing. Determination of a more appropriate spacing will provide further detail into how fish utilise this array to ascend barriers to their migration and whether array spacing and diameter influences pass utilisation. In addition, a suitable, flexible and robust alternative to the bristles tested is required that allows for design longevity with minimal maintenance as pass durability is important.

A staggered array of cylindrical clusters should be tested with respect to passage efficiency of non-salmonids on a Crump weir with uniform flow conditions on the downstream face. The transition from flat-V to Crump allowing for more detailed understanding of fish-flow interactions through the array as flow will be 2D. Larger cluster diameters should be selected so that larger wakes and therefore low velocity zones are created, which are likely to be beneficial for fish passage. Investigation of whether fish can utilise this modified design and their swimming behaviour as a function of cluster spacing should be undertaken to analyse the effects of space available for swimming on fish passage efficiency. An understanding of the hydraulics created by this fish pass with respect to flow resistance and velocity reduction potential should also be investigated. Further, testing of an optimised design in the field should be undertaken to validate experimental work.

Chapter 5 Use of Cylindrical Bristle Clusters as a Novel Multispecies Fish Pass to Facilitate Upstream Movement at Gauging Weirs

Summary

Gauging weirs act as barriers to the upstream movement of some fish due to the unfavourable hydraulic conditions created on the downstream face. There is a need to develop simple low-cost solutions to enhance multi-species fish passage, while not impacting the ability of these structures to gauge flow or increasing their potential to accumulate debris. This study investigated the use of an array of Cylindrical Bristle Clusters (CBCs), mounted on the downstream face of Crump weirs, to improve upstream passage of multiple species of fish while maintaining gauging accuracy. Laboratory tests with roach (*Rutilus rutilus*) showed that the passage efficiency of a Crump weir was increased from 0% (control) to ≈30% when retrofitted with CBCs. Swim path analysis indicated fish utilised low velocity zones in the wake of clusters to facilitate passage. Time taken to pass the weir and length of the swim path were greatest under the highest cluster density, where manoeuvrability was most constrained. Following these promising experimental results, the fish pass efficiency of a weir retrofitted with a staggered array of CBCs, was evaluated in the field. Upstream passage of a number of non-salmonid fish, including chub (*Squalius cephalus*) and roach, was monitored using Passive Integrated Transponder telemetry at a 7 m long, 1.2 m wide, Crump weir with a 1:5 downstream slope. Overall passage efficiency considering all species increased from 2% to 14% when the fish pass was installed (chub efficiency increased from 0 to 52%). Debris accumulation was minimal during the test period. Assessment of the impact of a variety of CBC array densities on gauging was also undertaken. Results confirmed the theoretical expectation that when arrays are placed downstream of the point where the flow regime changes from sub to supercritical no effect on gauging occurs. This study highlights the potential for a staggered array of CBCs to improve the upstream passage of multiple species of fish at gauging weirs, common barriers to fish migration, without affecting the accuracy of flow gauging.

5.1 Introduction

Fluvial habitat connectivity is essential for the transfer of energy, materials and organisms along rivers (Pringle, 2001). In-river barriers (such as dams and weirs) disrupt the river continuum, causing numerous populations of fish to decline as movement between critical habitats is impeded (Lucas and Baras, 2001; Dibley et al., 2012). While the impact of large-scale structures, such as some hydropower dams, have gained much interest (Larinier, 2001), small-scale infrastructure is often overlooked. However, in many countries their impacts are substantial because of their high density as a consequence of a long historic legacy of river development. Gauging weirs are small structures commonly installed to measure river discharge, and are essential for flood monitoring and river management practices (Armstrong et al., 2010; Rickard et al., 2003; Wessels and Rooseboom, 2009; Larinier, 2001). Long-term records of river flow data from gauging weirs enable, for example, the analysis of the potential effects of climate change on river flows, accounting water use for irrigation and abstraction purposes, and informing flood prediction and prevention strategies. Gauging weirs such as the flat-V and Crump design are commonly employed internationally. They span the width of the channels in which they are installed, and have a triangular longitudinal profile with either a central convergence (flat-V) or a uniform distribution of flow along the crest (Crump). As with many low-head barriers, these gauging weirs can limit upstream fish passage as they produce a combination of high velocity and shallow water depths at low modular flows, with depth and velocity greater for higher modular flows. Passage is limited if there is insufficient depth for fish to attain adequate swimming propulsion over the face, or if the velocities experienced exceed burst swimming capabilities (e.g. Vowles et al., 2015; Kerr et al., 2015; Lucas & Frear, 1997). Therefore, with increasing river development globally, there is a requirement to develop efficient methods to mitigate environmental impacts created by these structures.

The impacts of gauging weirs on fish passage has been investigated in relation to several species, including the diadromous anguilliform river lamprey (*Lampetra fluviatilis*) (Russon et al., 2011) and European eel (*Anguilla anguilla*) (Vowles et al., 2017), and potamodromous fishes, such as barbel (*Barbus barbus*) and grayling (*Thymallus thymallus*) (Lucas and Frear, 1997; Lucas and Bubb, 2005). Such studies indicate that gauging weirs can substantially impede the movement of fish, and ultimately impact population viability over the long-term. Provision of fish passage at gauging weirs can help re-establish habitat connectivity (Dodd et al., 2018), and examples of designs used include a ‘Low Cost Baffle’ (LCB) pass (Servais, 2006) and ‘tiles’ (Tummers et al., 2018). The LCB pass is made up of rectangular baffles that are mounted onto the downstream weir face in stepped rows parallel to the crest and arranged so that water is funnelled through a central V shaped channel. The baffles reduce water velocity and increase depth, and are intended to facilitate upstream passage without reducing the gauging capabilities of the weir, or increasing the potential to accumulate debris. Unfortunately, failure to meet both of these design criteria is observed under experimental and field settings if the baffles are placed too close to the crest. To improve gauging, the baffle must be placed at such a distance from the crest that fish passage can be compromised (Servais, 2006). Alternatively, ‘tiles’ of a variety of designs, such as those with projections of bristles, solid cylinders, or conical shaped studs, are installed on the face of weirs to increase roughness and facilitate the upstream movement of fish that are able to climb or swim through them. These low-cost fish passage solutions are typically designed to help the passage of eel, and to a lesser extent lamprey, and have achieved varying degrees of success (Armstrong et al., 2010; Kerr et al., 2015; Vowles et al., 2017; Watz et al., 2019). They are considered to be species-specific, providing a climbing substrate for eel, but are likely to be ineffective for other species that do not have an anguilliform body morphology or exhibit climbing behaviour.

A logical extension of the development of tiles is to broaden the design remit to include a wider range of target species. Here we propose the adaptation of tiles through incorporating Cylindrical Bristle Clusters (CBCs) arranged in a staggered array to facilitate upstream movement of fish, and potentially other aquatic organisms. In an advance of the solid cylindrical design commonly used (Baker and Boubée, 2006; Vowles et al., 2017), which provide heterogeneity of flow as a result of the wakes created (Kerr et al., 2016), CBCs were used in this study as their higher porosity ensures the wakes are longer (Nicolle, 2009) and drag is greater (Taddei et al., 2016). When applied to fish passes, CBCs can result in lower impedance of flow than other designs, reducing impacts on gauging, increasing space available for fish to swim while still reducing water velocity and increasing depth. The staggered arrangement was chosen because, for the same density, the greatest flow resistance is created compared to other arrangements (Wang et al., 2013).

In this study, the potential to enhance the upstream fish passage efficiency of Crump weirs was investigated for multiple species through the installation of CBCs on the downstream face. To achieve this aim, four objectives were set to: 1) determine whether a staggered array of clusters improves fish passage for a cyprinid fish species when compared with the performance of a control (unmodified) weir; 2) test the influence of different CBC spacings on the movement of fish in a flume; 3) validate fish passage efficiency of the design under field conditions and monitor debris accumulation; and 4) determine the influence of CBC array configurations on gauging. Recommendations for gauging weir retrofit and optimisation of design efficiency, of value to regulatory agencies, ecological engineers, and the operators and managers of river infrastructure tasked with provisioning services while improving ecological status and environmental sustainability are proposed.

5.2 Materials and methods

5.2.1 Laboratory Fish Passage Trials

Experiments were conducted using a model Crump weir installed in a trapezoidal open channel flume (60 m long, 2.1 m and 3 m wide at the base and top respectively and 0.5 m deep) at the International Centre for Ecohydraulics Research (ICER) Laboratory, Chilworth Science Park, University of Southampton (UK). Inside the trapezoidal flume a rectangular channel (1.38 m wide and 9 m long) was constructed and into which the weir was placed (figure 5.1 and 5.2). The channel entrance was tapered to avoid flow separation. Further photographs of the experimental setup can be found in Appendix A.2.

Trials were undertaken with (treatment) and without (control) CBCs. Cylindrical bristles, made from Polybutylene terephthalate (Cottam Brush, UK), were used to create the clusters. The material properties were expected to reduce the probability of permanent deformation induced by water and debris loading. When installed, the staggered array of cylindrical clusters covered the entirety of the downstream weir face (2 m^2) with the exception of a distance of 0.17 m between the weir crest and the first line of CBCs (figure 5.2). This gap was deliberately included in the design to allow the flow to transition from sub to supercritical before encountering the first line of clusters. The region of supercritical flow between the crest and the first row of bristles aims to ensure that the increased depths produced by the CBC will not drown the weir, therefore in theory guaranteeing that gauging accuracy is unaffected. In addition to the control (subsequently referred to as λa), three different treatments were tested which consisted of minimum spacing between clusters of 0.06, 0.1 and 0.15 m (subsequently referred to as λb, λc and λd, respectively). Spacings were selected based on UK National Guidelines for the width required between baffles to allow small (0.10 – 0.14 m fish length), medium (0.14 – 0.17 m) and large (> 0.17 m) fish to ascend baffled fishways (Armstrong et al., 2010).

A CBC diameter of 0.03 m was tested to create a series of low velocity zones extending from behind one cluster to the next (Nicolle, 2009). The bristles within the clusters were equally spaced and resulted in a density (φ) of 0.1 (defined as $N_c\, d^2 / D^2$, where N_c is the number of elements within the cluster, d is the internal diameter of individual bristle elements and D is the cluster diameter) where the wake is longest without creating recirculation behind the cluster (Taddei et al., 2016). A bristle height of 0.1 m was used as this was greater than the fish body depth.

Figure 5.1 Photograph of the experimental setup showing the blocks used to create the rectangular channel within the flume, fish screens indicating the upper and lower extents of the experimental setup, the weir placed between these screens and the frame created using item bars to hold the camera recording fish movements. The photograph was taken looking downstream before the setup was complete.

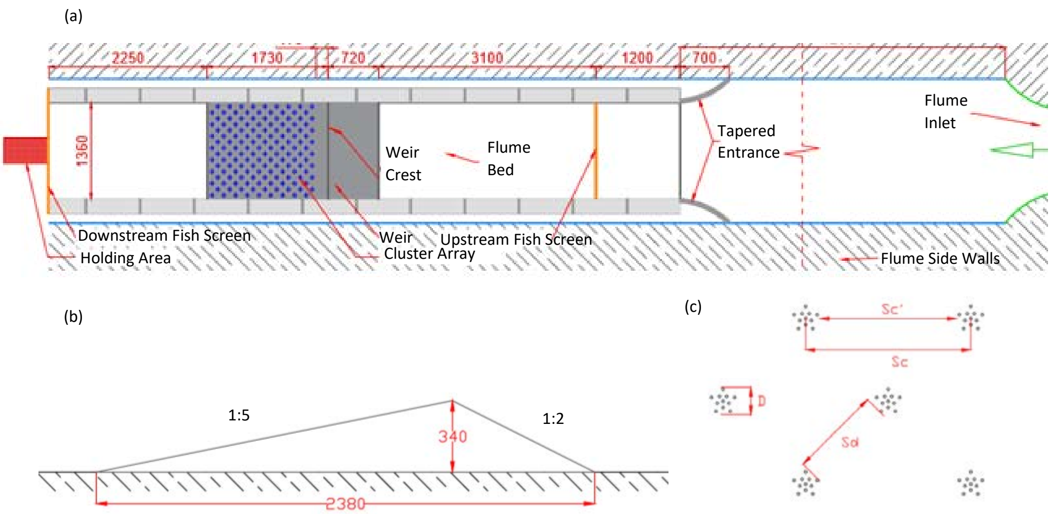


Figure 5.2 (a) Plan of the experimental setup used to conduct fish passage trials indicating location of the weir and fish release (holding) area, (b) weir cross-section indicating dimensions, and (c) cluster metrics (diameter [*D*] and diagonal and horizontal spacing between the outer edges of the clusters and horizontally from centre to centre [S_d, $S_{c'}$ and S_c] respectively) which were altered to test their influence on fish passage. All units are in mm.

An upward looking ADCP (Sontek IQ, San Diego, CA, USA) placed on the bottom of the flume 6 m upstream of the weir was used to measure flow rate and water depths. An average flow of 0.08 $m^3 s^{-1}$ was used for all treatments, with approach depths of 0.4 m recorded. This translates into a discharge per unit width (q) of 0.06 $m^2 s^{-1}$. Mean ± SD temperature recorded during the trials was 15.1 ± 0.9 °C. Time averaged velocities and depths down the weir face were measured at the crest, 0.075 m from the crest and every 0.1 m along from this point to the base of the weir using a velocimeter (Valeport Model 801) and point gauge, respectively, for each of the treatments, in between the CBCs (not in the wakes of the clusters). Mean and maximum velocities down the weir face (time and space averaged over the length of the weir) were respectively 1.86 ± 0.53 and 2.5 m s^{-1} for λa, 1.38 ± 0.26 and 1.7 m s^{-1} for λb, 1.66 ± 0.38 and 2.1 m s^{-1} for λc, and 1.74 ± 0.4 and 2.2 m s^{-1} for λd. Reynolds numbers around the clusters (calculated using the water velocity and depth at each point down the weir face) ranged from $6x10^4 – 1.2 x10^5$.

Roach (*Rutilus rutilus*) were chosen as the model species due to their wide UK distribution and burst swim speeds that are representative of other potamodromous non-salmonids (Clough and Turnpenny, 2001). Trials were conducted using individual fish sourced from a lake in Caddington (Bedfordshire, UK) 3 weeks prior to experimentation. Fish were kept in 1200 L holding tanks (15.0 °C ± 7.4) where water quality (ammonia, nitrite, nitrate) was monitored and maintained within suitable levels for fish health (nitrite < 1 mg L^{-1} and nitrate < 50 mg L^{-1}) through daily part (typically 50%) exchange with dechlorinated water. Sixty trials where conducted for each treatment and the control (mean length (m) ± SD (m) λa: 0.16 ± 0.04, λb: 0.16 ± 0.36, λc: 0.16 ± 0.03, λd: 0.15 ± 0.03) over a period of 2 weeks (14th May 2016 – 31st May 2016) between dawn (04:00) and dusk (22:00 hours).

Acclimatisation to the flume water temperature occurred for at least one hour prior to the start of each trial. Fish were held in a perforated barrel placed downstream of the experimental area, defined by two wire mesh screens placed approximately 2 m downstream of the weir base and 2 m upstream of the weir crest. On initiation of each trial a single fish was released at the furthest downstream extent of the experimental area (approximately 2 m downstream of the foot of the weir). Each trial lasted until the fish successfully ascended over the weir crest or after 30 minutes had elapsed. Time of attempt (where fish entered onto the downstream weir face) and time of successful passage, at which the whole body of a fish passes over the weir crest, were documented during trials. Fish swim paths were recorded using videography (30 fps) and post processed using tracking software (Logger Pro v3.8.2, Vernier Software, Beaverton, OR, USA) that recorded the head position in each video frame. Two-dimensional (x, y) co-ordinates were produced and subsequently used to calculate the swim path length (i.e. distance travelled on the downstream weir face as fish ascended upstream) and time taken to pass the weir.

Passage efficiency was calculated for each treatment as the number of fish passing the weir as a percentage of those that attempted. A chi-square test was used to test for a difference in passage efficiency between treatments. As data relating to swim path length and time to pass was non-parametric (Shapiro-Wilk test), Kruskal-Wallis tests were used to determine whether the metrics differed with treatment. Dunn tests were carried out *post hoc* to determine where significant differences occurred between treatments.

5.2.2 Field Fish Passage Validation and Debris Monitoring

To validate efficiency under a field scenario, the CBC bristle pass was installed on a compound Crump weir at Shermanbury Place Estate on the River Adur, West Sussex, UK (50°95'74.63’’N, 0°26'58.75"W) (figure 5.3 and 5.4). The weir has a central channel (1.2 m wide and 7 m long) and two channels on either side (both 2 m wide). The central weir crest is 0.45 m lower than those at the side, which only overflow during high flow events > 2.75 $m^3 s^{-1}$. This weir was selected for the tests as the fish community is dominated by non-salmonids, particularly roach (*Rutilus rutilus*) and chub (*Squalius cephalus*), and is known to present a barrier to fish movement (EA pers. comm.).

Figure 5.3 Fish pass installation on the compound Crump weir at Sakeham where boards were installed in the central channel and water was prevented from going down the weir during installation using 2 wooden boards held in place upstream.

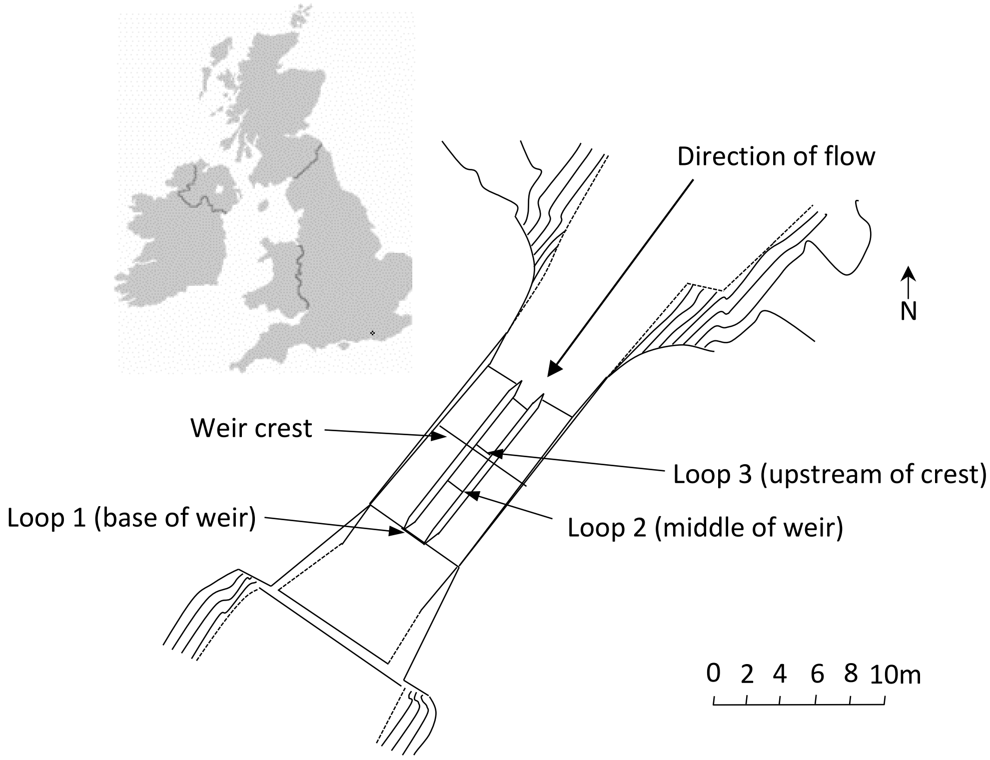


Figure 5.4 Site location (black dot on inset map) and plan of the compound Crump weir on the River Adur, West Sussex, UK (50°95'74.63''N, 0°26'58.75"W) (EA, 2017) on which a novel fish pass was installed. The fish pass consisted of Cylindrical Bristle Clusters mounted onto the downstream weir face in the central channel. Positions of PIT loops 1, 2 and 3 and the weir crest are indicated.

The bristle pass comprised of a staggered array of CBCs spaced a minimum of 0.17 m apart with a diameter of 0.05 m, height of 0.15 m and cluster density of 0.05 (due to manufacturing constraints). Compared to the flume studies, a larger spacing and diameter was tested in the field to facilitate passage of larger fish and increase the area of low velocity behind the clusters. The pass was installed 0.2 m below the weir crest to minimise any backwater effect created. Further photographs of the fish pass installation can be found in appendix A.3.

Passive Integrated Transponder (PIT) telemetry was used to quantify fish passage performance at the weir. Three rectangular PIT loops were installed; the first at the base of the weir adjacent to the wing-walls, the second on the weir face 3 m upstream from the base, and the third 0.3 m upstream of the weir crest (figure 5.4). The loops were connected to tuning boxes linked to multiplex Half Duplex readers (Wyre Microdesign, UK) and data loggers housed securely on the river bank and powered by three 110 aH leisure batteries connected in series.

The detection range was measured by passing PIT tags of 12 mm and 23 mm through the PIT loops. Tags were secured to a pole and moved towards the centre, left and right of the loops at different angles, monitoring the reader output to determine at what distance/ position the tag was detected. At all loops, the detection range was 0.2 m and 0.3 m for 12 mm and 23 mm tags, respectively. The detection range for 32 mm tags was assumed to be greater than 0.3 m. Detection efficiency was quantified as the number of times the PIT tag was detected divided by 100 (the number of times the PIT tag was passed through the loop). All tags were detected when the detection efficiency was measured at a discharge of 0.6 $m^3 s^{-1}$.

River water temperature was recorded every hour using multiple submerged temperature loggers (Hobo Temp/Light Pendant, Onset Computer Corporation, MA, USA) attached to each PIT loop. Multiple loggers were deployed in case of equipment failure or loss. Discharge data was monitored every 15 minutes by the Environment Agency.

Fish passage was monitored at the weir with (treatment) and without (control) the bristle pass installed during the months of April, May and June 2017. Control and treatments were tested for approximately half of each month (table 5.1). Electrofishing (pulsed DC with a single anode) was conducted from a boat over an approximately 300 m stretch of river upstream and downstream of the weir. Captured fish were anaesthetised (0.3 ml L^{-1} 2-phenoxyethanol), identified to species, measured (fork length, with the exception of eel which were measured as total length) and weighed. A 12 mm, 23 mm or 32 mm HDX PIT tag (Wyre Micro), was inserted into the peritoneal cavity (tag burden did not exceed approx. 2% of fish mass). Tags were sterilised in ethanol, rinsed in purified water and inserted through a 5 mm incision made immediately anterior to the pelvic girdle. Once recovered in aerated river water, all fish were released in a low velocity area downstream of the weir, approximately 10 m below loop 1.

Fish passage performance was monitored for chub (number (n) = 70, mean ± SD length = 0.274 ± 0.133 m:), dace (*Leuciscus leuciscus*) (n = 22, length = 0.151 ± 0.220 m), roach (n = 124, length = 0.124 ± 0.230 m), gudgeon (*Gobio gobio*) (n = 6, length = 0.113 ± 0.063 m), pike (*Esox lucius*) (n = 16, length = 0.392 ± 0.151 m), bream (*Abramis brama*) (n = 15, length = 0.369 ± 0.121 m), brown trout (*Salmo trutta*) (n = 3, length = 0.192 ± 0.013 m), rudd (*Scardinius erythrophthalmus*) (n = 5, length = 0.134 ± 0.020 m), perch (*Perca fluviatilis*) (n = 17, length = 0.174 ± 0.058 m) and eel (*Anguilla anguilla*) (n = 12, length = 0.489 ± 0.225 mm). Detections at loops 1, 2 and 3 determined the number of fish that attempted to ascend the weir, those able to ascend half the weir face, and the number that successfully passed, respectively. Attraction efficiency was defined as the number of fish detected at the foot of the weir (loop 1), and assumed to be attempting to ascend, as a percentage of those tagged and released downstream. Passage efficiency was defined as the number of fish that successfully ascended the fish pass (detected at loop 3) as a percentage of those that attempted (detected at loop 1).

Table 5.1 Periods (C = control, T = treatment) over which multispecies fish passage over a Crump gauging weir on the River Adur, West Sussex, UK (50°95'74.63’’N, 0°26'58.75"W) were monitored with corresponding tagging dates and the number of fish tagged during each tagging event.

Treatment	Date (2017)	Tagging	N° Tagged
C1	27th March – 12th April	27th March	163
T1	13th April – 26th April		
C2	27th April – 15th May		
T2	16th May – 31st May	16th May	127
C3	31st May – 14th June		
T3	14th June – 3rd July		

To determine factors influencing fish passage, further analysis was conducted on data collected for chub, the only species with a sufficiently large data set. A binomial regression model was created to identify whether pass installation, flow, temperature, time of day, number of days since tagging, change in flow per unit of time (15 mins), fish length and/ or weight were predictors of successful passage. The most parsimonious model was determined by AIC value comparison. The time variant predictors (as opposed to length or weight) used in the model were data recorded nearest to the time a fish was last detected at loop 1 (i.e. attempting to pass, which may or may not have been successful). Observations remained “independent” of one another, avoiding violation of the assumptions required for statistical analysis i.e. “repeat measures” as the last attempt (if not successful) or the attempt immediately prior to the first successful passage was included, irrespective of treatment. Passage success was assumed when the fish was subsequently detected at loop 3 within a time interval t < 30 mins after being detected at loop 1 or 2. Fish that were detected at loop 3 without being recently detected at loop 1 or 2 were not counted as having passed as during periods of high flow fish had an alternative passage route. Debris accumulation within the fish pass was monitored using a wireless camera (Ltl Acorn Ltl-6210M) and periodically by EA operational staff (April 2017 – April 2018).

5.2.3 Effect on Gauging

Gauging experiments were undertaken in a rectangular open channel flume (13 m long, 0.6 m wide and 0.8 m deep) at the ICER Hydraulics Laboratory, Boldrewood Innovation Campus, University of Southampton (UK). Analysis of the effect of three arrangements of spacing and diameter (0.07 m diameter with 0.1 [λA] and 0.15 [λB] m diagonal spacing, and 0.05 m diameter with 0.15 m diagonal spacing [λC]) on gauging at a Crump weir with 1:5 downstream slope, 1:2 upstream slope and 0.4 m crest height was undertaken for free-flowing conditions (hydraulic jump forming downstream of the array). Control measurements of water depth (*C*) were taken using a point gauge $2h_{max}$ upstream of the weir crest (approx. 0.3 m, as for BS ISO 204360 (2008) where h_{max} is the maximum gauged head relative to the crest level), at the weir crest and 1 m downstream of the weir base. Measurements were undertaken for 10 flows ranging from 0.032 to 0.12 $m^3 s^{-1}$ increasing in equal intervals. Data was collected in the same manner for the different array arrangements. Stage-discharge relationships were determined using this data for each of the different treatments. Tests were undertaken when the array was mounted at a distance from the crest of 0.17, 0.20, 0.25, 0.30, 0.35 and 0.40 m. Velocities were measured for the configuration mounted 0.40 m from the crest. Four velocity measurements were taken along transects located immediately downstream of the last line of clusters, 2 directly in the wake of the clusters, and 2 in the middle laterally in between the clusters, 1.9 m downstream of the weir crest, using an electromagnetic open channel flow meter (Valeport Model 801). Average water depths were also measured at these locations and used to determine the Froude number at this location only. However, flow in the bristle section was highly turbulent, aerated and displayed large variations of depth in time and space. For this reason, although the values of averaged quantities are reported in this chapter, these figures should be interpreted within the context of a very complex flow. Further experiments were undertaken to determine the influence of these array configurations on the modular limit (see appendix A.4).

5.3 Results

5.3.1 Laboratory Fish Passage Trials

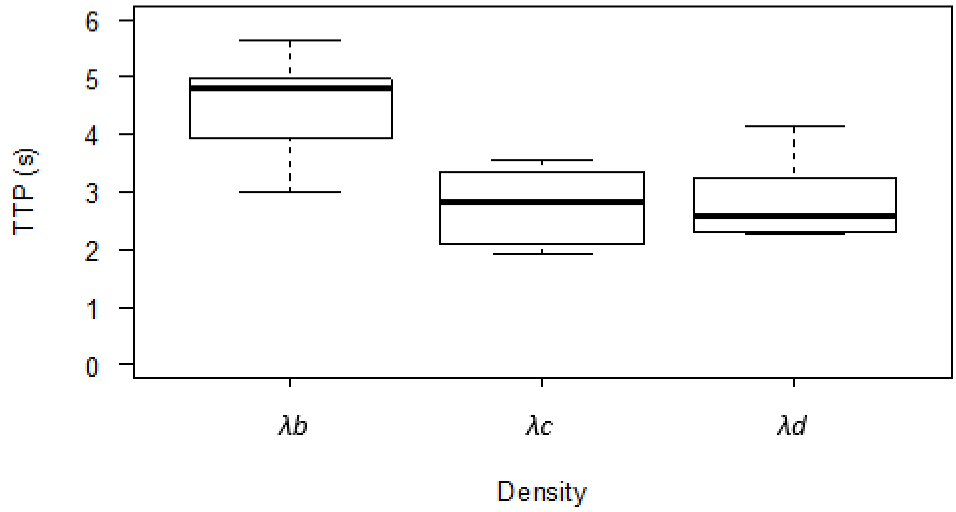
Attempts varied between treatments being 45, 43 and 38% for λb, λc and λd respectively. Fish passage efficiency was higher for all treatments than the control (table 5.2), under which movement was blocked. Passage efficiency did not differ between λb, λc and λd (X^2 = 0.552, df = 2, p = 0.75; table 5.2). Time to pass (TTP in figure 5.5a) differed with CBC density (X^2 = 8.822, df = 2, p < 0.05), being greater under λb than λc (P < 0.05) and λd (P < 0.05) (figure 5.5a). There was no difference in time to pass between λc and λd (P = 1.00; figure 5.5a).

As fish ascended the weir during treatments, they manoeuvred between CBCs within the array (figure 5.6, additional figures in appendix A.2). This occurred under all CBC densities and resulted in sinuous swim paths. Despite this common pattern of movement, swim path length differed with CBC density (X^2 = 6.674 df = 2, p < 0.05), being longer under λb than λd (P < 0.05) (figure 5.5b). Swim path length (SPL in figure 5.5b) did not differ between any other densities (figure 5.5b).

Table 5.2 Passage efficiency data showing the number of roach that passed, failed and attempted to pass over a Crump weir for the treatments tested.

Treatment	Pass	Fail	Attempts	Passage Efficiency
λa (Control)	0	18	18	0
λb (S_d = 0.06)	7	20	27	26
λc (S_d = 0.10)	7	19	26	27
λd (S_d = 0.15)	8	15	23	35

(a)



(b)

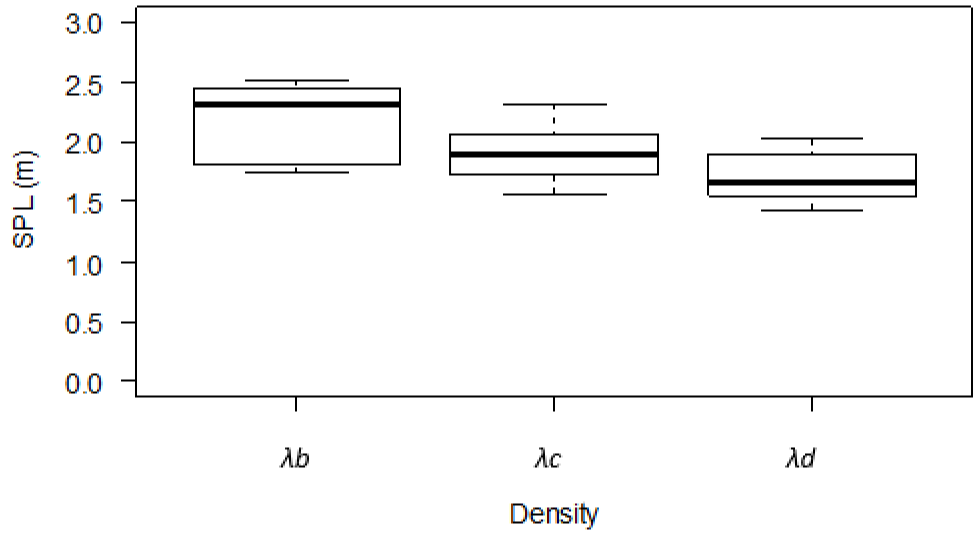


Figure 5.5 (a) time to pass for fish that passed over a Crump weir for treatments *λb*, *λc* and *λd* where spacing between clusters was 0.06 m, 0.1 m and 0.15 m, respectively; (b) swim path length (*SPL*) (m) for *λb*, *λc* and *λd*. Box plot of the median (horizontal line), interquartile range (box) and highest and lowest observations (whiskers).

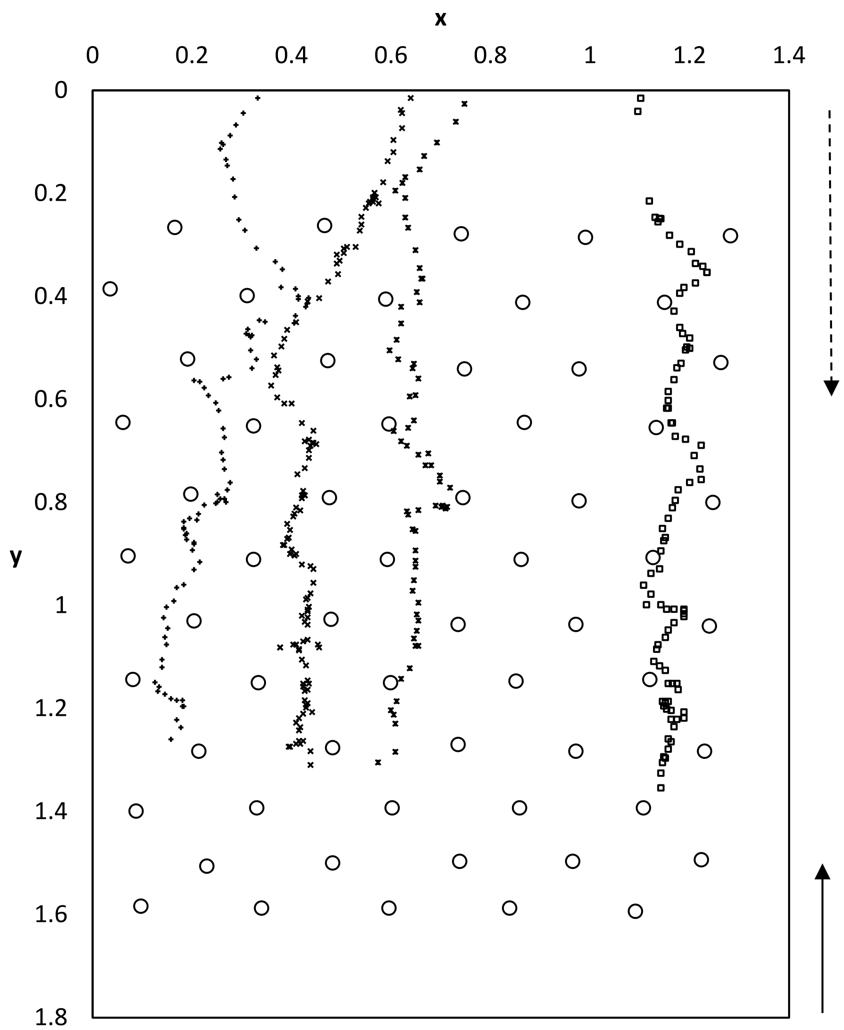


Figure 5.6 Examples of fish pathways over the weir through the staggered array of CBCs (circles) for *λd*, 0 denotes the location of the crest and 1.2 the base of the hydraulic jump, with 1.2 m in the y axis being the distance traversed up the weir and x coordinates denoting the weir width. Video analysis produced pathways created using fish tracking software where the position of the fish head per frame rate was recorded. The dashed and solid arrows denote the flow and fish direction respectively.

5.3.2 Field Fish Passage Validation and Debris Monitoring

Average attraction efficiency did not differ when the fish pass was installed compared to the control (table 5.3). Attraction was higher during the 2 weeks immediately after tagging and release under both the control and treatment periods.

Table 5.3 Detections of PIT tagged fish at loops located at the bottom (loop 1), middle (loop 2) and top (loop 3) of a Crump weir during treatment (T: fish pass installed) and control (C: no fish pass installed) periods. Some of the fish detected during one control or treatment period may have been detected again during another period and were considered as separate fish attempting. NA = not applicable.

	Loop 1	**Loop 2**	**Loop 3**	**% Att**	**Species Numbers**
C1	31	NA	0	18.8	14 roach, 6 chub, 4 eel, 3 dace, 3 perch, 1 gudgeon
T1	20	NA	0	12.1	11 roach, 3 perch, 2 chub, 2 dace, 1 gudgeon, 1 pike
C2	24	0	0	14.5	12 roach, 4 chub, 4 perch, 1 dace, 1 eel, 1 gudgeon, 1 pike
T2	68	23	10	23	31 roach, 18 chub, 7 perch, 4 bream, 3 eel, 2 dace, 1 gudgeon, 1 pike, 1 rudd
C3	10	2	0	3.5	5 roach, 3 perch, 1 eel, 1 pike
T3	22	8	2	7.8	13 roach, 5 perch, 2 chub, 1 eel, 1 bream

A range of fish species and sizes attempted to pass the weir in the field during both control and treatment periods (table 5.3). Roach (length = 0.12 m ± 0.012 m), perch (length = 0.18 ± 0.024), eel (length = 0.33 m), pike (length = 0.60 m) and chub (length = 0.22 ± 0.099) were detected at the middle loop, representing 30% of those that were detected at the base of the weir.

When data for all species was aggregated, passage efficiency was 14% and 2% during treatment and control periods, respectively. One pike (0.60 m) passed over the weir during the control. Chub were the only species that passed the weir when the fish pass was installed, achieving a passage efficiency of 52%. No other species successfully passed the weir (i.e. detected at loop 3).

Despite experiencing similar discharge regimes (0.39 ± 0.37 $m^3 s^{-1}$ and 0.49 ± 0.7 $m^3 s^{-1}$ for the control and treatment periods, respectively) chub attempted under a greater range of flows when the pass was installed (range = 0.29 – 5.56 $m^3 s^{-1}$ with mean ± SD = 2.56 ± 1.50 $m^3 s^{-1}$) compared to the control (range = 0.29 – 0.50 $m^3 s^{-1}$ with mean ± SD = 0.39 ± 0.07 $m^3 s^{-1}$) with all bar one of those that passed doing so below the 10% exceedance flow (i.e. values of *Q* that were exceeded for 10% of the study period) (range = 0.40 – 4.31 $m^3 s^{-1}$ with mean ± SD = 2.18 ± 0.99 $m^3 s^{-1}$).

Although all chub passed when the CBCs were installed, the best performing binomial logistic regression model was where length (coeff: 1.076e-02 ± SE 5.488e-03, $p < 0.05$) and fish pass installation (coeff: 1.957e+01 ± SE 3.600e+03, $p = 0.996$) were considered in combination. The best model for passage included two of the predictor variables: “treatment” and “fish length”. The mean ± SD fish length of those that passed was 0.37 ± 0.09 m compared to 0.22 ± 0.12 m for those that attempted and failed.

Debris accumulation was also monitored where debris accumulation was minimal during the test period (figures 5.7a, b and c). Some algal growth occurred over the monitoring period but maintenance did not increase compared to existing levels previously undertaken for unmodified weirs. Occasional debris accumulation in the form of leaves and weed did occur but washed away upon cluster submergence. Larger debris accumulation was not recorded, with logs and other woody debris passing through the fish pass easily with the flow.

Debris accumulation at Sakeham was monitored over a period of 18 months and varied dependent on flow conditions and respective cluster submergence. Debris accumulation only occurred when the clusters were unsubmerged with little to no accumulation at the first line of clusters (figure 5.7a). The reduced proportion of debris accumulating at the crest is advantageous with respects to gauging. Boards coloured up with algae and naturalised.

(a)

(b)

(c)

Figure 5.7 Debris accumulation over the fish pass installed on the compound Crump weir at Sakeham in July 2018.

5.3.3 Effect on Gauging

Rating curves were obtained for the unmodified and retrofitted weirs (figure 5.8) collating data from separate tests in which the CBCs were positioned at distances of 0.2, 0.3 and 0.4 m from the crest of the weir (5.5a, 5.5b, 5.5c, respectively). When the CBCs were placed close to the crest of the weir, flow gauging was affected over a wide range of discharges (figure 5.8a). The difference between stage-discharge curves was observed to increase with the density of the cluster (i.e., in 5.8a *λA* deviates more from *C* than *λB*), as expected from the higher energy losses produced by the denser cluster. However, as the array is moved further from the crest the extent of the impact on gauging is considerably reduced, only being significant for the higher range of discharges (figure 5.8b). At 0.4 m from the crest (figure 5.8c), none of the configurations tested affected gauging significantly (i.e. maximum difference in the measured water depth between treatment and control was less than 3% of the control water depth, see Appendix A.4.2). *λA*, *B* and *C* reduced water velocities immediately downstream of the last line of clusters furthest away from the crest on average by 51, 35 and 29% compared to the control. Froude numbers in this location were supercritical for all treatments and flows (minimum observed was Fr = 1.3). Further analysis of the gauging results can be found in Appendix A.4.

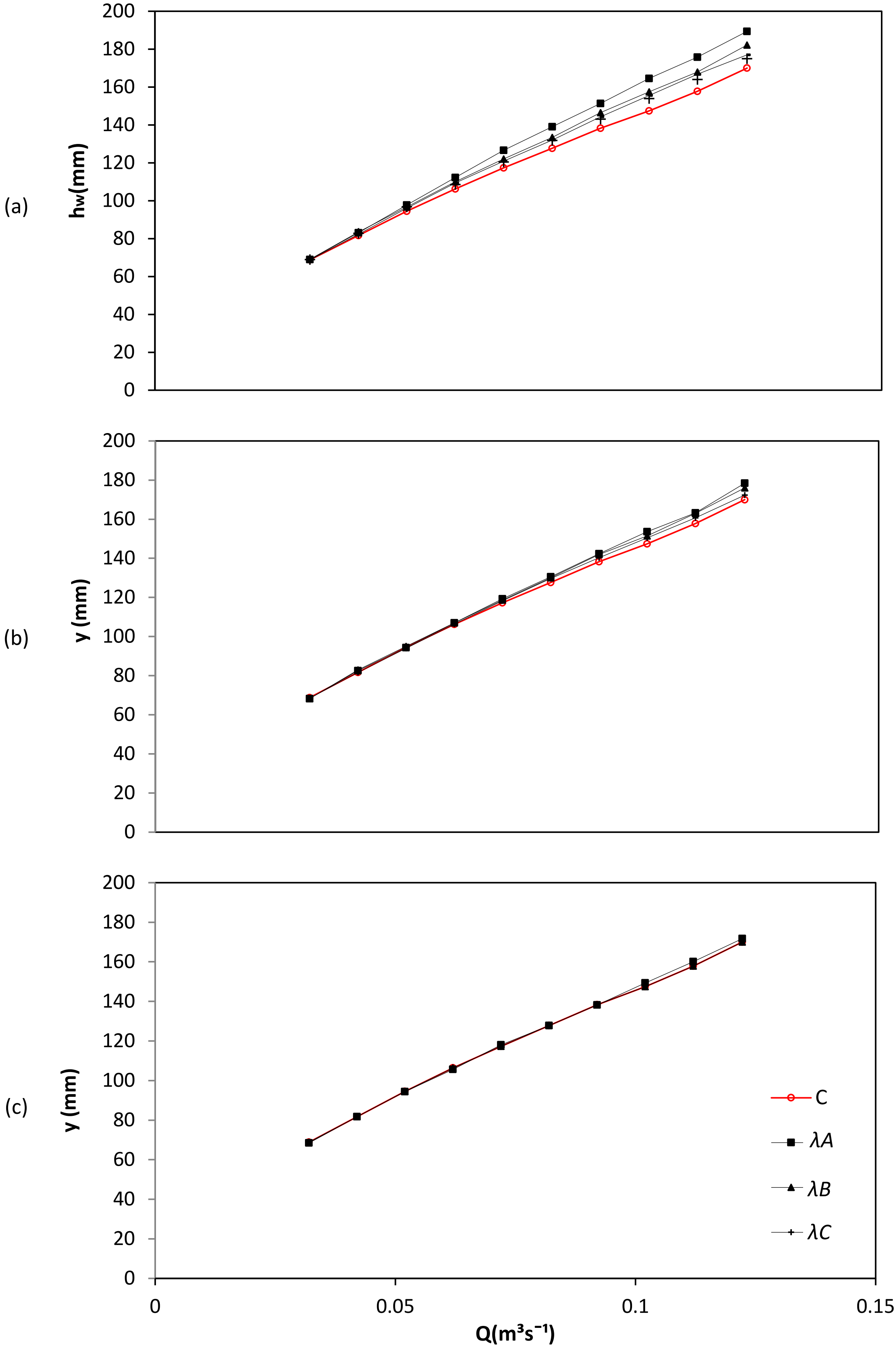


Figure 5.8 Stage-discharge relationship for the control and treatments (0.07 m diameter with 0.1 (λA) and 0.15 (λB) m diagonal spacing and 0.05 m diameter with 0.15 m diagonal spacing (λC) at (a) 0.2, (b) 0.3 and (c) 0.4 m from the crest

5.4 Discussion

5.4.1 Laboratory Fish Passage Trials

The passage efficiency for roach at an unmodified model Crump weir in an open channel flume was 0%. Only two fish progressed past the hydraulic jump, a region characterised by high levels of aeration and turbulence which likely increased energetic cost of swimming (Enders et al., 2003) and destabilised fish (Tritico and Cotel, 2010). For those that did progress beyond the hydraulic jump, passage was impeded by high water velocity (max 2.5 m s^{-1}).

The passage efficiency of roach improved to approx. 30% when CBCs were installed on the downstream face of the weir. Passage was likely facilitated by fish utilising low velocity zones/ shear in the wake of CBCs and/ or because bulk velocity decreased. Indeed, the sinuous paths taken as the fish navigated the weir highlighted the importance of the hydrodynamic heterogeneity created due to the provision of low velocity zones in the wake of the clusters. Future designs may be adjusted to maximise the length of the low velocity zone behind the CBCs to further improve fish passage.

Passage efficiencies did not significantly differ between the high (λb), medium (λc) and low (λd) density arrays tested, possibly because the mean water velocities were similar between the treatments, and/ or the space available was not sufficiently different to effect manoeuvrability. Any of the configurations tested when placed on a gauging weir would be sufficient to improve passage efficiency provided the water velocity remained below the maximum burst speed for the subject fish. For this to be the case over a large range of flows, a higher hydraulic resistance created by the clusters would be required to prevent the velocity through the bristles increasing (as for sparse vegetation arrangement; Nepf, 2012) to a point at which fish passage was prevented. This could, however, have a potential negative impact on gauging accuracy. To prevent this, alternative configurations that continue to enable fish to utilise the heterogeneous hydrodynamic environment created by the clusters while maintaining gauging efficiency over a wider range of flows should be investigated. It is possible that increased cluster diameter would have greater benefit for passage as the larger wakes and wake overlap created may increase the area available for fish to rest. In addition, larger clusters (and spacings) could create increased velocity reduction for the same density therefore improving passage without impacting gauging

The time taken to pass the weir was shorter when cluster density was low. This was a function of the ratio of cluster spacing to body length, which can be approximated by understanding that the distance travelled by a fish per tail beat is greater for a larger tail amplitude (Bainbridge, 1958). Greater passage would be expected if manoeuvrability was not hampered because fish could swim further for the same number of tail beats, reducing passage time. Alternatively, when cluster spacing was smaller, time to pass would increase as fish adopt more tortuous paths to navigate denser clusters to progress upstream. This puts into question the spacings recommended for baffles for fish > 0.17 m as the recommended spacing of 0.15 m would be too narrow and therefore larger spacings would be desirable.

There was no difference in time to pass between the two lowest density treatments (λc and λd). This suggested neither treatments constrained fish movement and that both spacings were sufficient to facilitate passage without hampering manoeuvrability. Similarly, the lack of difference in swim path length between λc and λd indicated that spacing was not a constraint for the size of fish tested. The variation in swim path length between λb and λd could also be attributed to spacing constraints as, for the fish tested, the body amplitude would need to be between 0.02 and 0.07 m for swimming to remain uninhibited (Bainbridge, 1958). Fish movement would become increasingly inhibited as swim path length increases when fish must manoeuvre around the clusters to successfully navigate the array.

5.4.2 Field Fish Passage Validation and Debris Monitoring

When fish passage was assessed at a Crump weir in the field, it was observed to pose a barrier to upstream fish movements. The installation of CBCs enabled some fish to ascend the weir, but overall efficiency remained low (14%). Under the control, passage was likely limited by a combination of factors, including a relatively long weir face (7 m), high velocity and shallow depth. Such conditions have previously been shown to limit the passage of non-salmonids (Barbel and Grayling) (Lucas and Frear, 1997; Lucas and Bubb, 2005) with similar swim speeds to chub that attempted to pass the weir in this study.

Chub approached under a greater range of flows when the fish pass was installed compared to the control ($0.238 - 5.56\ m^3\ s^{-1}$ and $0.238 - 0.499\ m^3\ s^{-1}$). This may be explained by more favourable approach conditions being formed at the base of the weir when the clusters reduced the bulk velocity, resulting in a reduction in the magnitude of the hydraulic jump (Chadwick et al., 2004), and less turbulence and aeration (Resch and Leutheusser, 1972) as a result. In agreement with the observation of others (e.g. Forty et al., 2016), attraction efficiency under both control and treatment conditions was highest immediately after the release of tagged fish.

Overall, 73% of fish did not attempt to ascend the weir, possibly indicating a lack of motivation to move upstream and/ or sufficient availability of suitable habitat downstream. However, a range of species (bream, perch, gudgeon, rudd, roach, dace, perch, eel, pike and chub) attempted to ascend the weir (i.e. detected at the downstream and middle PIT loop), with some individuals attempting to pass multiple times, resulting in successful passage for only a limited number of chub and pike. This suggested that, even with the installation of CBCs, this weir remained a complete barrier to most species, and partial barrier to others. This indicates that the suitability of the design tested is variable, providing a feasible solution for low head weirs, but becoming increasingly limited for higher head structures. It is possible that the design may be limited to shorter weirs for smaller fish species such as roach compared to chub as fish are unable to traverse longer lengths at the swim speeds necessary to counteract the water velocities experienced within the pass. Further design optimisation and monitoring of field installations is needed to understand design limitations, and decisions to employ this fish passage solution will depend on the specific goals set.

Passage of chub was influenced by fish length (mean ± SD of those that passed was 0.37 ± 0.09 m compared to 0.22 ± 0.12 m for those that attempted and failed). Swimming performance is known to be positively related to fish size, so it was expected that larger chub were more likely to pass the modified structure provided there was sufficient room between the clusters to facilitate manoeuvrability. All chub that passed did so when the CBCs were installed, although this finding was limited by the extent of data, with only four fish attempting to do so under the control (compared to 21 during the treatment). Passage occurred under relatively high flows, but while the weir remained unsubmerged. Under the highest flows, the hydraulic jump was raised to the middle loop reducing the distance fish had to traverse the barrier from 7 m to 3 m.

Although passage efficiency was 52% for chub, two fish were detected moving back downstream within 30 seconds of passing the weir. These may have been volitional movements or could have resulted from fatigue and associated fallback. If the latter, it would imply that the fish pass requires modification so that water velocities are further reduced, and/ or more effective resting areas are provided at the top of the pass to enable recovery.

Only 30% of the roach that attempted reached the middle of the weir and none successfully passed the crest. It is possible that the weir was excessively long to allow passage for this species, as burst swimming through the arrays can only be maintained for short periods of time (Knaepkens et al., 2007). Even if the water velocity was below the maximum burst swimming speed, passage will be unsuccessful if the fish fatigues before reaching the weir crest. Therefore, metrics such as distance of ascent (Castro Santos et al., 2009; Amaral et al., 2019) in addition to burst swimming capability should be considered when developing design criteria. For longer weirs, a fish must either increase its swim speed to pass before fatigue or maintain the same speed for longer. The difficulty in balancing swim speed, distance of ascent and time to fatigue remains an important challenge in fish passage design, and better understanding of the interaction between the factors requires further research.

5.4.3 Effect on Gauging

The effect of CBCs on the gauging accuracy of a model Crump weir in an open channel flume was greatest when the array density was high and placed close to the crest. CBC arrays increase and decrease water depth and velocity respectively, on the downstream weir face. When this occurred close to the crest, the hydrodynamic alterations caused by the CBC array likely propagated upstream, impeding the transition from sub to supercritical flow through the point of critical depth (Rickard et al., 2003). The extent of any impacts to gauging will depend on the degree to which water depth increases as well as the Froude number between the crest and the first cluster line (Chadwick at al., 2012). As the exact location where critical depth occurs is difficult to predict, so too is the precise location that CBC arrays can be placed without impacting gauging. When CBC arrays were placed 0.4 m from the weir crest, gauging accuracy did not differ between any of the densities tested and the control (unmodified weir). This is because a zone is maintained between the crest and cluster array where flow can transition from sub to supercritical. Being able to place CBC arrays relatively close to the crest of gauging weirs without compromising hydrometric standards provides a potential advantage over alternative (baffled) designs. For example, to prevent interference with the gauged level of the River Hogsmill (a tributary of the River Thames), a LCB pass was placed 0.74 m below the weir crest, resulting in high water velocity and low depth remaining above the most upstream baffle (Lothian et al., 2019). These conditions, even over a distance of 0.74 m, may have been difficult for fish to pass.

5.5 Conclusions

Fish utilised a staggered array of Cylindrical Bristle Clusters (CBCs) to surmount a Crump gauging weir; passage efficiency improved from 0 to 30% for roach under experimental conditions, and from 0 to 52% for chub in the field. Under experimental conditions, lower array densities provided greater space for fish to manoeuvre to regions of low velocity in the wake of clusters, reducing swim path length during ascents and the time taken to pass. Further design optimisation may be achieved by increasing the cluster diameter to increase wake width and length, thus providing a greater proportion of low velocity areas that fish utilise during weir passage. Debris accumulation was minimal, effectively allowing for the design to be low maintenance, beneficial from a cost, gauging and fish passage perspective.

Gauging accuracy of the modified Crump weir will not be compromised if a zone is maintained between the crest and cluster array where flow can transition from sub to supercritical. The length of this “buffer zone” in which supercritical flow is achieved is dependent on array density and discharge. A buffer zone with a maximum distance of 0.4 m between the crest and the most upstream line of bristles did not impact gauging under the highest array density and discharge tested, with upstream water depth remaining uninfluenced by downstream flow disturbance. Placement of clusters close to the weir crest without compromising gauging accuracy is a key benefit of this design for regulatory agencies, ecological engineers, and the operators and managers of river infrastructure tasked with mitigating habitat fragmentation for fish while maintaining the provision of services.

Chapter 6 Fish – Hydrodynamic Interactions Within a Staggered Array of Cylindrical Clusters

Summary

Anthropogenic barriers in rivers (e.g. culverts, dams and weirs) can block fish movements and negatively impact fish communities. Recent tests (Montali-Ashworth et al., 2020) have shown that fish passage at such barriers can be improved through the use of cylindrical bristle cluster (CBC) arrays. To better understand the mechanisms that cause improved fish passage through CBC arrays, there is a need to investigate the interaction between fish swimming and their hydrodynamic environment. In this study, the relationship between passage efficiency, swimming behaviour of roach (*Rutilus rutilus*) and the hydrodynamic environment created by different CBC array geometries was investigated. On a sloping weir in an open channel flume, six treatments were tested which consisted of 3 cluster diameters (D) (0.03, 0.05 and 0.07 m) and 2 spacings (S_d) between clusters (0.10 and 0.15 m). Passage efficiency, the number of fish that passed as a percentage of those that attempted to do so, was a function of cluster diameter and spacing; efficiency was highest (> 80%) when the ratio of lateral cluster spacing (centre to centre) (S_c) to diameter was less than 5. Fish exhibited a range of sinuous swimming behaviours while manoeuvring through the CBC array to ascend the weir, the most common of which was zigzagging between two lines of clusters. Additional tests to characterise the hydrodynamics created by CBC arrays with respect to the flow resistance was undertaken for a range of D (0.03, 0.05 and 0.07 m) and S_d (0.05, 0.10 and 0.15 m). Cluster array configurations with the lowest wake overlap (D = 0.03 m, S_d = 0.15 m) produced the highest bulk drag coefficient (as defined in the main text). This study revealed that a CBC array with a S_c / D ratio less than 5 has potential to improve the upstream passage of weak swimming non-salmonid fish, such as roach, if retrofitted to gauging weirs. Fish passage efficiency can be improved by increasing the size of the wake behind bristle clusters and the overall hydraulic resistance created within the array while ensuring sufficient space is available for fish to manoeuvre. Additionally, fish utilise lower velocity areas when swimming through a CBC array, often combining different swimming behaviours to successfully navigate at burst speeds.

6.1 Introduction

Improving the connectivity of rivers has become increasingly important due to the large number of barriers, such as low-head gauging weirs, which hamper, or in some cases, totally inhibit fish movement (Baras et al., 1994; Welcomme, 1994). Recently, a staggered array of cylindrical bristle clusters (CBCs) has been used to aid fish passage over low-head gauging weirs (Montali-Ashworth et al., 2020). The CBC array reduces average flow velocity and increases water depth with literature showing that localised areas of lower velocity are generated in the wake of individual clusters within the array (figure 6.1; Zong and Nepf, 2012). These low velocity wakes vary in width and length depending on cluster diameter (*D*) and spacing (S_c) (Zong and Nepf, 2012; figure 6.2 and 6.3). Consequently, the hydrodynamic environment within the CBC array is linked to the dimensionless parameter S_c/D (Nicolle, 2009).

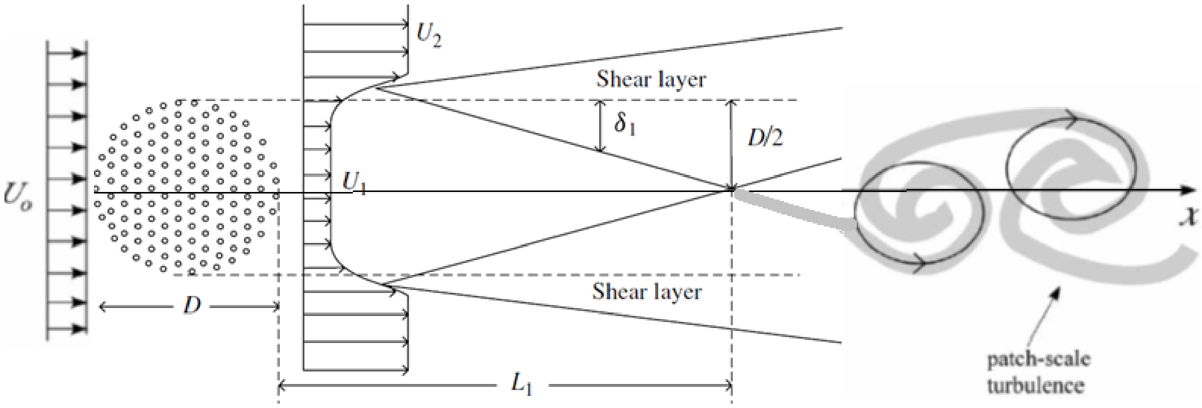


Figure 6.1 Schematic diagram of the effect of a cylindrical cluster on the downstream wake formation and von Karman street and sketch of the shear layer growth where L_1 is the length of the downstream wake, and the *δ1* is the width of the shear layer (Zong and Nepf, 2012).

The majority of studies for solid cylinders to date have observed that when $S_c/D > 4$, the wakes produced by the cylinders do not interact (Nicolle, 2009; Wang et al., 2013). When $3 < S_c/D < 4$, the shear layer which forms due to flow separation around the upstream cylinder, attaches to the boundary layer around the downstream cylinder. When $S_c/D < 3$, the wake created by the upstream cylinder overlaps with that produced by the one downstream (Nicolle, 2009). When cylinders are parallel and $S_c/D < 1.2$, they form a single bluff body. For patches of vegetation or porous clusters, the ratio of S_c/D which produces wake overlap differs to that of solid cylinders because they generate longer wakes for the same diameter (Nepf, 1999; Taddei, 2016). Taddei (2016) found that wake length varied depending on porosity, with near wake velocity dissipation occurring when S_c/D was greater than 5, suggesting that wake overlap could occur for ratios smaller than this if two cylinders were studied in tandem. While our understanding of the hydrodynamics around porous cylinder clusters has advanced in recent years, studies on arrays of these porous cylinder clusters and our understanding how fish interact with such hydrodynamic environments remains limited. Specifically, there is no information on how the ratio of S_c/D influences the swimming behaviour of fish or their passage over sloped weirs retrofitted with CBC arrays.

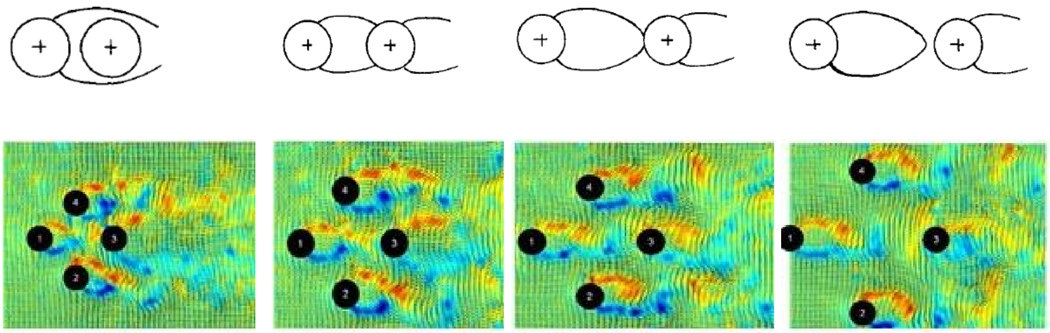


Figure 6.2 Different wake overlap states (Nicolle, 2009 and Wang et al., 2013).

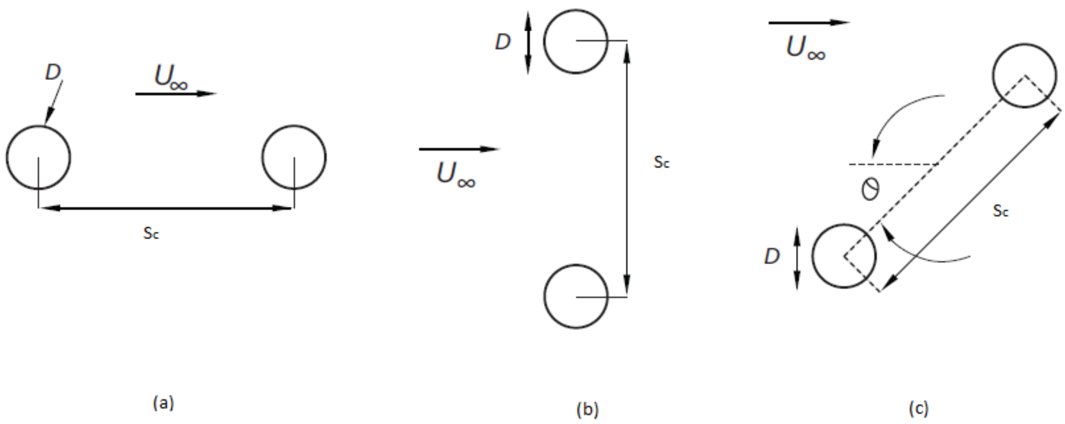


Figure 6.3 (a) Tandem, (b) side by side and (c) staggered cylinder arrangement (Nicolle, 2009).

The interaction of fish with their hydrodynamic environment is a topic that has generated interest in recent years (Montgomery, 2003; Liao, 2007; Cotel and Webb, 2015; Kerr et al., 2016). Fish are highly sensitive organisms capable of detecting hydrodynamic cues within aquatic systems using their lateral line. The lateral line is comprised of sensory receptors called neuromasts, which are distributed across the head and body, both on the skin (superficial neuromasts) and within sub-dermal canals (canal neuromasts), allowing fish to navigate through complex hydrodynamic environments occupied by woody debris, large boulders and other structures (Montgomery, 2003).

Understanding fish swimming in complex hydrodynamic environments has been a topic of particular interest. For example, trout swimming around cylinders can, under certain conditions, utilise the hydrodynamics created to reduce energetic costs (Liao et al, 2003; Kerr et al, 2016). Swimming behaviours that facilitate this include entrainment, where fish hold position behind a cylinder and orientate their body based on spatial flow patterns so that the effect of hydrodynamic forces are reduced (Przybilla et al., 2010). Fish can also be displaced by the buffeting of vortices shed from solid cylinders (Cotel and Webb, 2015). This is most likely to occur when the diameter of vortices created within the wakes are equal to the fish length as the force impacting the fish is at its greatest (Cotel and Webb, 2015). Evidence of fish use of the hydrodynamics created by cylinders, if appropriate conditions (e.g. that do not destabilise fish) are present, suggests that they may be beneficial to fish attempting to ascend upstream through an array of CBCs.

This study assessed the impact of different CBC arrays, retrofitted onto a sloped weir, on the passage efficiency and swimming behaviour of roach (*Rutilus rutilus*), and hydrodynamics. This was achieved by: 1) determining if passage efficiency is influenced by wake width and length by varying the spacing and diameter of clusters to alter wake overlap and the area of low water velocity; 2) quantifying fish swimming behaviour when navigating through CBC arrays; and 3) investigating the relationship between S_c / D and the resulting flow resistance created for CBC arrays.

6.2 Materials and Methods

6.2.1 Fish Passage and Swimming Behaviour Trials

Experimental Setup

To determine if passage efficiency was influenced by spacing and diameter which predominantly influences wake width and length and to quantify the swimming behaviour of roach when navigating through CBC arrays, experiments were conducted using a weir in a rectangular open channel flume (16 m long, 0.6 m wide and 0.8 m deep) at the International Centre for Ecohydraulics Research (ICER) Laboratory, Boldrewood Campus, University of Southampton (UK) (figure 6.4 and 6.5). A staggered array of cylindrical clusters attached to a base board (figure 6.4), was mounted on the downstream face of the weir, the slope of which could be varied. The cylindrical clusters comprised of individual cylindrical elements 0.003 m in diameter (*d*).

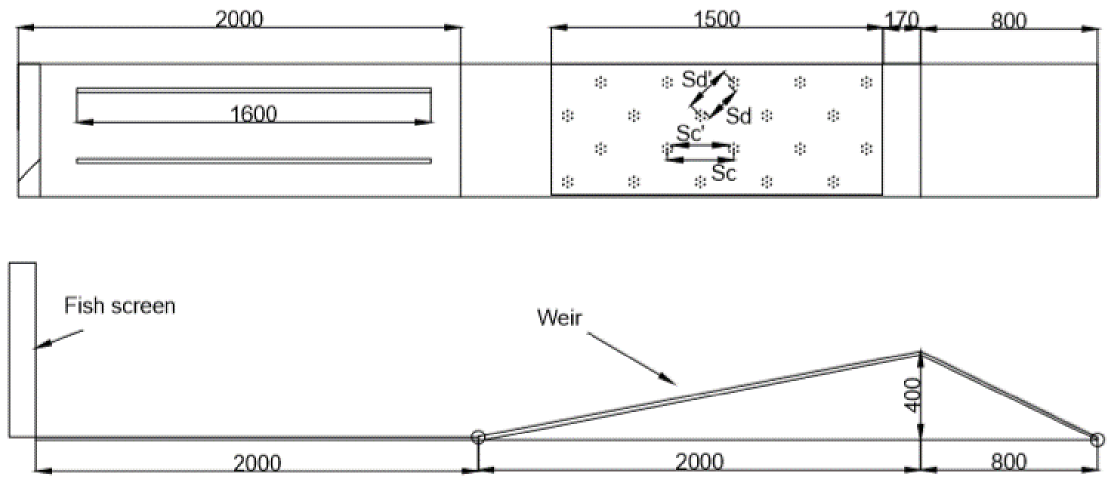


Figure 6.4 Plan and section view of the experimental setup used to quantify fish passage at, and the hydrodynamic conditions created by, a CBC array showing the weir and extent of the experimental area (dimensions in mm).

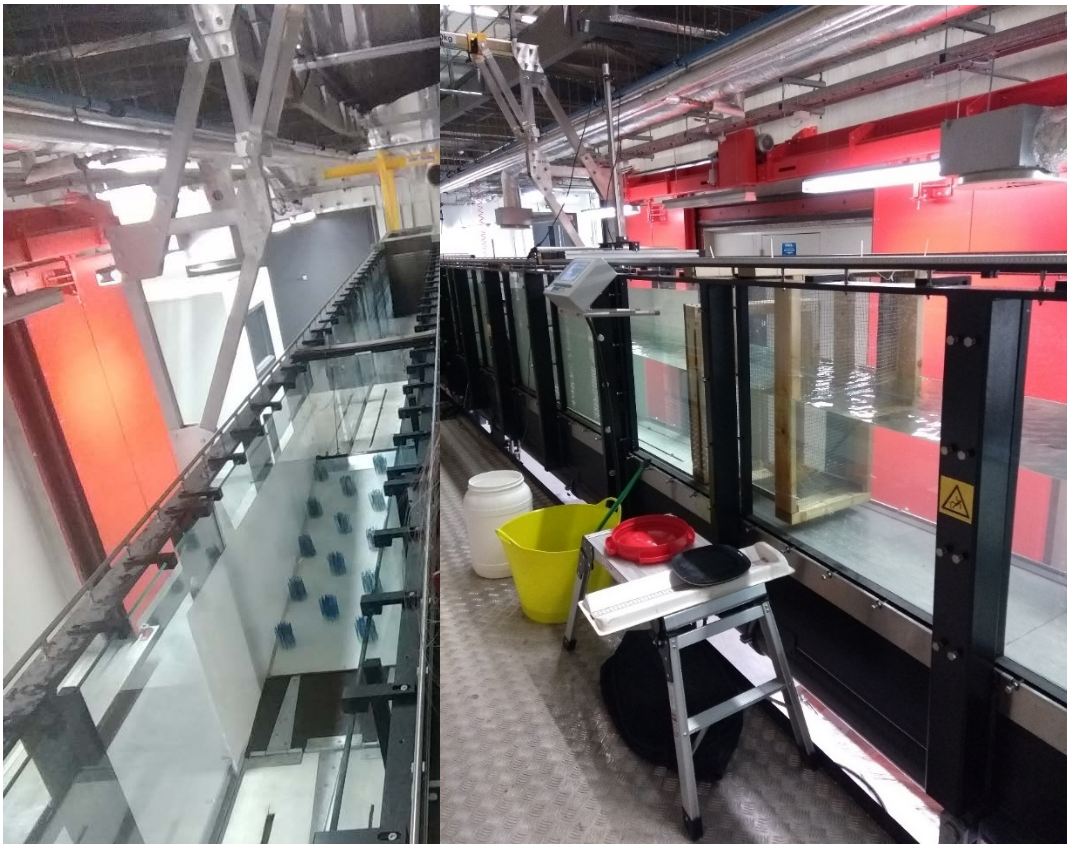


Figure 6.5 Photographs of the flume setup looking upstream (left) with the tilting weir and CBCs installed and the fish acclimatisation area within the flume (right).

We postulate that fish passage through a CBC array installed on a sloped weir is a function of the traverse length, water depth, water velocity (average and fluctuation in velocity), spacing between clusters (S_c), cluster diameter (D), cluster porosity and weir slope. To quantify the impact of S_c / D and size of the wakes created on fish swimming, only S_c and D varied between treatments. Other key parameters that may influence fish passage (traverse length, water depth and velocity, cluster porosity) remained constant (table 6.1). Temperature differed between some treatments (λi: 16.94 ± 1.02, λii: 17.94 ± 0.77, λiii: 19.31 ± 0.50, λiv: 19.01 ± 0.38, λv: 17.74 ± 0.73, λvi: 18.26 ± 0.55). Fish length (mean ± S.D: 0.146 ± 0.006 m, $F = 0.99$, $df = 5$, $p = 0.423$) and weight (mean ± S.D: 47 ± 9 g, $X^2 = 8.12$, $df = 5$, $p = 0.150$) did not differ between treatments. Average Froude numbers, calculated using average water depths and velocities, were greater than or equal to unity for all experiments (table 6.1, variables defined later in the text).

A tilting gate located approx. 8 m downstream of the weir crest was adjusted to ensure the distance fish were required to swim remained consistent (1.67 m) between treatments. A cluster density (φ) of 0.1 was used (defined as $N_c\, d^2 / D^2$, where N_c is the number of elements within the cluster, d is the internal diameter of individual bristle elements and D is the cluster diameter) where the wake is longest without creating recirculation behind the cluster and an alternate vortex street of the far wake will be present (Taddei et al., 2016). A bristle height of 0.1 m was used for all experiments.

Experiments were undertaken with the same spacing and different diameters in addition to the same diameter and differing spacings, resulting in 6 treatments (table 6.1). The space between clusters was greater than the body amplitude of the fish to ensure manoeuvrability was not hampered. Incoming flow discharge, measured using magnetic flow meters located within the recirculating flume pipes, was maintained constant (0.06 ± 0.0005 $m^3 s^{-1}$).

Velocity mapping in the CBC array was undertaken using an electromagnetic flow meter (Valeport Model 801) at 2/3 of the depth measured from the weir bed. The flow meter has a cylindrical sampling range 10 mm above the electromagnetic heads, samples data at a frequency of 2 Hz, digitally filtered from raw 96 Hz data (Valeport Limited, 1999). Velocity was measured in the locations shown in figure 6.6, directly in the wake of each of the clusters and in line with these positions in the middle laterally in-between the clusters, as well as in between the clusters throughout the array. Water depths were measured using a point gauge at the same location as for the velocity recording. To ensure that water depth (and therefore averaged velocity) remained constant between different treatments, the weir slope was modified for each test. To assess whether the change in slope could have an effect on the fish passage (by reducing the work done by the gravitational force exerted on the fish as it moves from downstream to the crest), the ratio between the work of the drag and gravity forces for different slopes was estimated. Such a ratio was found to be very large (>20x) for all tests, so that changes in the slope were assumed to have a negligible effect on the passage efficiency. Mean water velocity within the array, and more specifically in the wake and in-between the clusters, was calculated. Mean velocity throughout the array did not differ between treatments (1.21 ± 0.03 $m^3 s^{-1}$, $F = 2.13$, $df = 5$, $p = 0.06$). However, velocity did differ when comparing between treatments using data only from within the wake ($F = 3.95$, $df = 5$, $p < 0.01$; differences between λvi and λii aswell as λiii and λii) or in-between clusters ($F = 20.93$, $df = 5$, $p < 0.001$; differences were between λvi and all other treatments). For all treatments, the mean velocity in the wake of clusters was lower than those in-between (figure 6.6). Therefore, the areas behind and in-between clusters are subsequently defined as ‘low’ and ‘high’ velocity, respectively

Table 6.1 Configurations tested during experimentation and their spacings (S_d), diameters (D), slope (S_o), average water depth (y), velocity (V), Froude number (Fr), percentage of 'low' velocity area within the array (*% LVA*), and dimensionless ratios (fish body amplitude [*BA*], fish body length [*BL*], fish body width [*BW*]).

	(λ*i*)	**(λ*ii*)**	**(λ*iii*)**	**(λ*iv*)**	**(λ*v*)**	**(λ*vi*)**
S_d	0.10	0.10	0.10	0.15	0.15	0.15
D	0.07	0.05	0.03	0.07	0.05	0.03
S_o	0.25	0.22	0.19	0.17	0.17	0.17
y (± SD)	0.08 ± 0.01	0.07 ± 0.01	0.07 ± 0.01	0.08 ± 0.01	0.07 ± 0.01	0.07 ± 0.01
V_w (± SD)	1.18 ± 0.15	1.23 ± 0.14	1.24 ± 0.19	1.2 ± 0.22	1.24 ± 0.24	1.28 ± 0.27
Fr	1.37	1.54	1.56	1.36	1.54	1.60
%LVA	57.00	49.00	29.00	45.00	32.00	24.00
S_c / D	3.40	4.20	6.10	4.60	6.00	8.30
S_d / BA	1.66	1.66	1.66	2.60	2.60	2.50
S_c' / BL	1.16	1.10	1.03	1.80	1.70	1.50
D / BW	4.10	2.90	1.80	4.10	2.90	1.80
D / BL	0.48	0.34	0.21	0.48	0.34	0.21

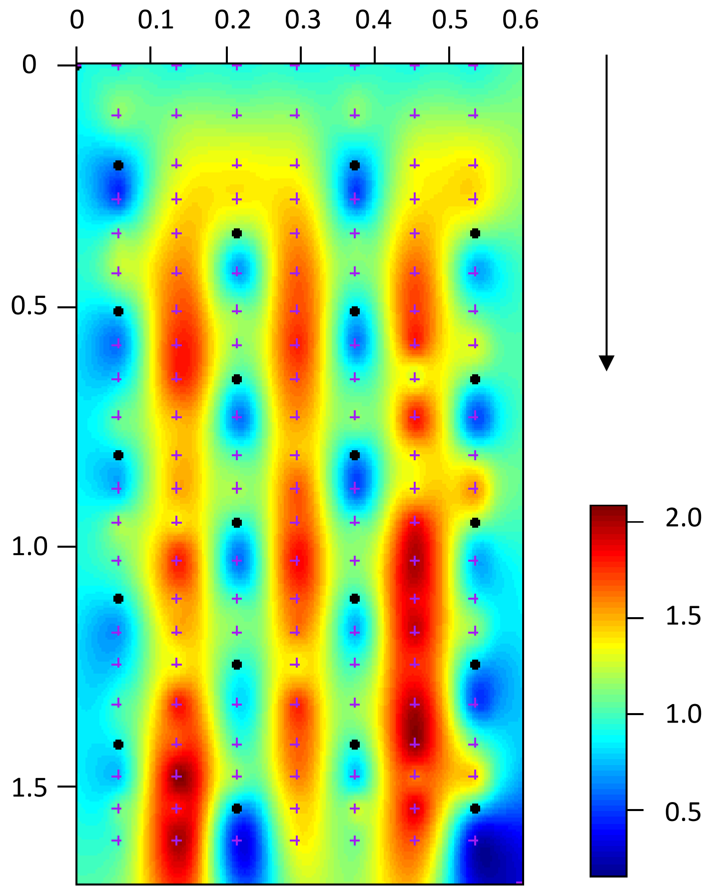


Figure 6.6 Representative water velocity map (m s^{-1}) within the array of clusters (black dots, not representative of cluster size, λv), from the crest (0) to the top of the hydraulic jump. Flow direction denoted by the black arrow. Velocity sampling locations denoted as purple crosses, velocity measurements were only taken in these locations. The colour map was created by interpolating between these points and therefore should not be taken as the actual velocity.

Experimental Fish Husbandry

Roach were selected for this study because they are a common easily sourced non-salmonid species found in British rivers with swim speeds representative of other cyprinid fishes. Fish were sourced on 27 March, 10 days prior to experimentation, from a lake at Manor Farm, Caddington (Bedfordshire, UK) and housed in 1200 L holding tanks in the ICER experimental facility. Water quality was maintained, monitored for ammonia, nitrite and nitrate and kept within suitable levels for fish health (nitrite < 1 mg L^{-1} and nitrate < 50 mg L^{-1}) through regular part (typically 50%) exchange with dechlorinated water. Holding tank temperatures were 12.5 ± 0.37 °C.

Experimental Procedure

Experiments were undertaken from the 6 April to 4 May 2018 between 08:00 and 23:00 using individual fish. Thirty trials were undertaken for each treatment. Acclimatisation of fish to the water temperature of the flume (17.7 ± 0.82 °C) was carried out for at least 1 hour prior to trial initiation using a holding area upstream of the weir. On initiation of each trial one fish was released at the furthest extent of the experimental area (approximately 2 m downstream of the weir). Swimming through the array was recorded using an overhead Logitech webcam. Trials terminated once the fish passed the weir or after a period of one hour had elapsed. External lighting remained at a constant ambient level with visual cues minimised through the use of a blackout screen installed around the flume. At the end of a trial, fish were removed from the flume before being measured and weighed.

Fish Behaviour and Statistical Analysis

The time of release, weir approach (moving upstream from the location of release), attempt (when the whole body-length of the fish passed upstream of the hydraulic jump, see figure 6.7 and 6.8 for hydraulic jump illustration) and pass (when the whole body-length of the fish passed the weir crest) was recorded. Passage efficiency was calculated for each treatment as the number of fish that passed the weir as a percentage of those that attempted. A chi-squared test was used to determine whether observed passage efficiency differed from expected. Fish navigation through the CBC array was quantified in relation to length of fish swim path, time to pass and swimming behaviour using videography post processed using tracking software (Logger Pro). Swim paths were produced by recording the position of the fish's head each frame, generating two-dimensional (x, y) co-ordinates. These were subsequently used to determine the time taken to navigate the weir face (from the hydraulic jump to crest), swim path length, and space use within the array relative to the velocity field experienced. Swim path length was calculated as $\sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2)}$ where x/y_1 and x/y_2 are swim path co-ordinates along the x and y axes at time t_1 and time t_2. Data of swim path length and time to pass for all the fish that passed under the different treatments was tested for normality using a Shapiro-Wilk test. As data violated the assumption of normality and could not be corrected through transformation, treatments were compared using a Kruskal-Wallis test. Position co-ordinates of each fish within the array were used to identify swimming behaviours exhibited when navigating the array. The movement of fish as they ascended the weir can be broadly defined as “zigzagging” (B1), “localised wall association” (B2) or “lateral traversing” (B3) or combinations of these (e.g. where a fish traverses laterally to another cluster before returning to zigzagging). The percentage of time (seconds) spent behind and in-between the clusters while exhibiting each behaviour was calculated.

6.2.2 Laboratory Hydraulic Trials

Experimental Setup

To investigate the relationship between S_c / D and the resulting flow resistance created, experiments were undertaken in a rectangular open channel flume (22 m long, 1.38 m wide and 0.6 m deep) at the ICER Hydraulics Laboratory, Chilworth Science Park, University of Southampton (UK). Various CBC arrays were attached to a board and mounted on the downstream face of a Crump weir (triangular in cross-section with a 1:2 and 1:5 upstream and downstream slope, respectively). The individual bristle elements (0.003 m in diameter) were arranged in 0.03, 0.05 and 0.07 m diameter clusters (D) at a fixed density (φ = 0.1), with spacings of 0.05, 0.1 and 0.15 m. Two discharge values were tested (Q = 0.07 $m^3 s^{-1}$ and 0.2 $m^3 s^{-1}$) creating varying levels of submergence (not all configurations were unsubmerged for the lower flow and the water depth varied between treatments).

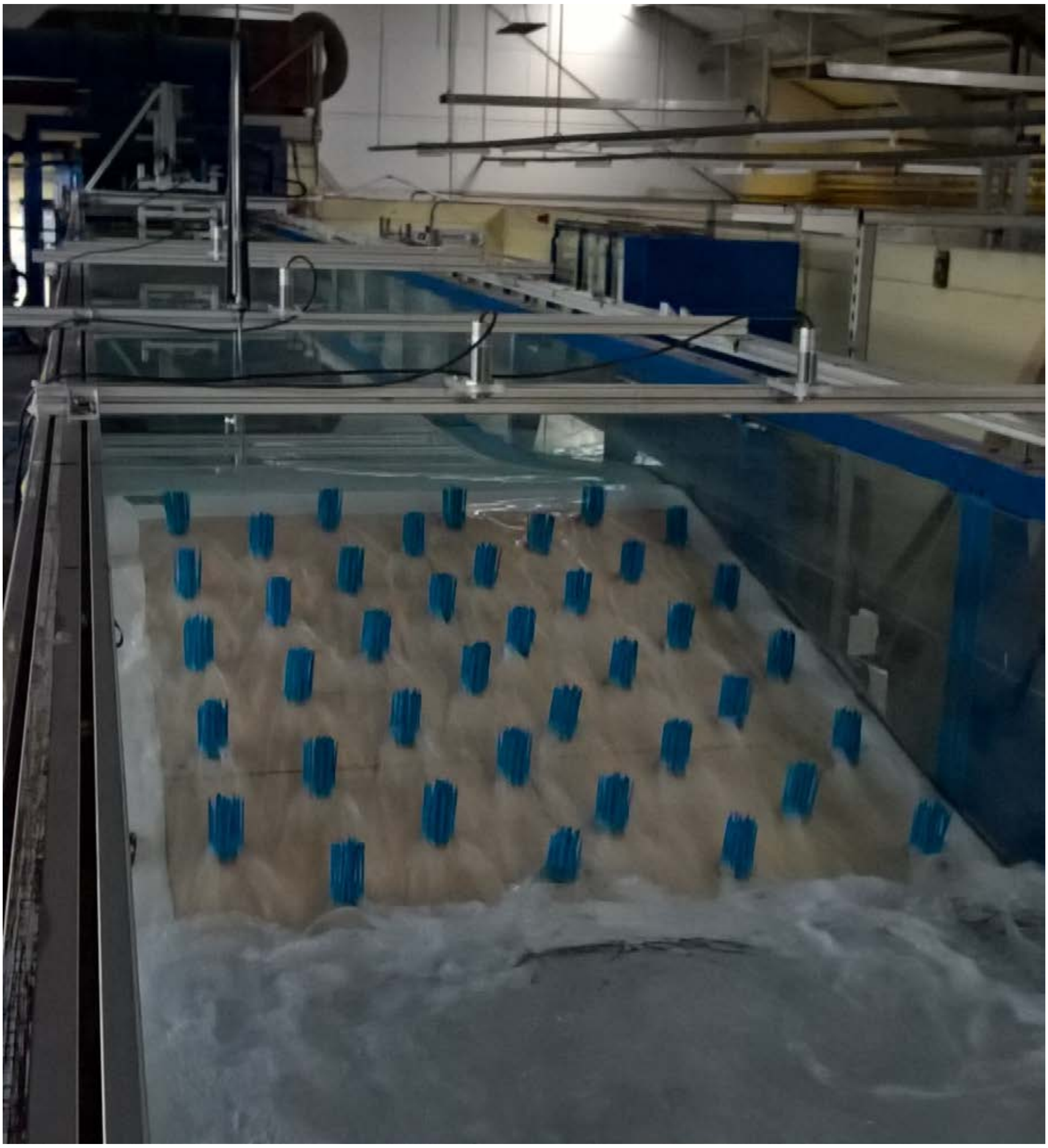


Figure 6.7 Photograph of the experimental setup looking upstream showing the CBCs mounted onto the downstream Crump weir face within the flume with water flowing through the clusters and a hydraulic jump at the weir base.

Experimental Protocol

The discharge and water depth downstream and between the clusters were measured using an ADCP (Sontek IQ, San Diego, CA, USA) placed 10 m upstream of the weir and ultrasonic meter (Senix Toughsonic 14) which measures the distance from the sensor to the free surface of the water, respectively. Water depth was recorded 0.05 m upstream of the first bristle line and within the array, in the wake and non-wake regions downstream of every cluster, just upstream of the hydraulic jump which was located at the base of the weir during all treatments, allowing the influence of the whole array on the flow to be quantified. Water depths were sampled over 5 minutes with a calibrated ultrasonic depth meter. The ultrasonic depth and ADCP flow readings were time averaged. Downstream ultrasonic readings, measured at 2 positions in the wake and non-wake regions within the array, were also spatially averaged. Subsequently, the raw ultrasonic output was transformed with adjustments made to account for the effect of weir slope.

Data Analysis

To calculate the overall drag force created by the cluster array during each treatment, the principle of conservation of momentum was applied to the control volume between two prismatic sections (figure 6.8), assuming a predominantly 1D flow:

$$\frac{dM}{dt} = F_{H1} - F_{H2} + F_w - F_D - F_f \tag{6.1}$$

where dM/dt is the rate of change in momentum of the fluid within the control volume; F_{H1} and F_{H2} are the hydrostatic forces exerted on the upstream and downstream boundaries of the control volume, respectively; F_w is the component of the weight of water in the direction of the flow; F_D is the drag force exerted by the bristles on the fluid; and F_f is the friction force between the fluid and the boundaries of the flume (figure 6.8). Considering only the convective component of the fluid acceleration, assuming that F_f is negligible compared to F_D ($F_D >> F_f$) and substituting the corresponding relations for each of the forces on the RHS of Eq. 6.1 and rearranging yields:

$$C_D = \frac{B\left(\left(g{h_1}^2 - g{h_2}^2\right) + 2g\bar{h}sin\theta L - 2\left(q(V_2 - V_1)\right)\right)}{{V_1}^2 l_e N D} \tag{6.2}$$

Where V_1 and V_2 are the average velocities at sections 1 and 2; h_1 and h_2 are upstream and downstream water depths respectively; $\bar{h}$ is the average water depth using h_1 and h_2; L is the distance between sections 1 and 2; q is the incoming flow discharge per unit width; l_e is the effective height of the cluster (equal to the water depth or actual cluster height when emerged and submerged, respectively); N is the number of clusters within the array; B is the width of the channel and D is the diameter of the cluster.

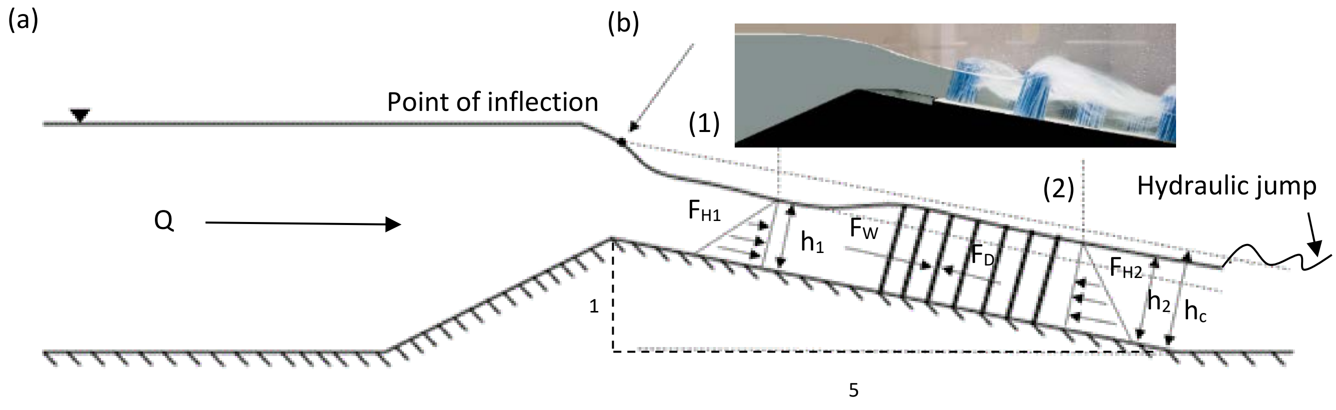


Figure 6.8 The theoretical (a) and actual (b) flow conditions induced at a Crump weir when retrofitted with bristle clusters, where flow entering the system goes from subcritical to supercritical flow down the weir face (h_c is critical depth, h_1 and h_2 is the normal depth at (1) and (2) respectively).

6.3 Results

6.3.1 Fish Passage and Swimming Behaviour Trials

While the percentage of fish that attempted to pass was highest during treatment *λi*, there was no statistical difference between treatments (X^2 = 4.32, df = 5, p = 0.503) (table 6.2). Passage efficiency differed between treatments (X^2 = 22.07, df = 5, p < 0.001) and was highest under treatment *λi*, when the area of 'low' water velocity was greatest and S_c / *D* was lowest (figure 6.9).

Table 6.2 Numbers of fish that passed (P), failed (F), approached and attempted for each of the treatments tested.

Treatment	P	F	Approach	Attempts	% Approach that attempt
S_c = 0.10, *D* = 0.07 (*λi*)	11	2	24	13	54.2
S_c = 0.10, *D* = 0.05 (*λii*)	9	4	29	13	44.8
S_c = 0.10, *D* = 0.03 (λiii)	2	3	27	5	18.5
S_c = 0.15, *D* = 0.07 (*λiv*)	5	2	17	7	41.2
S_c = 0.15, *D* = 0.05 (*λv*)	1	7	21	8	38.1
S_c = 0.15, D = 0.03 (*λvi*)	0	4	15	4	26.7

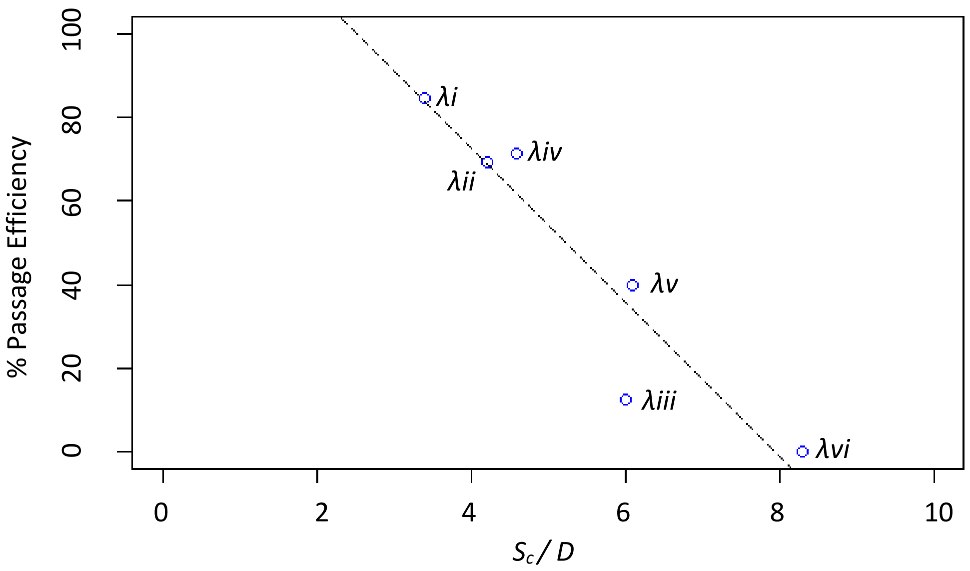


Figure 6.9 Passage efficiency (%) for the treatments tested as a percentage of those that attempted where S_c is spacing between clusters (c/c) and *D* is diameter in meters.

Time to pass and swim path length did not differ between treatments (Kruskal-Wallis X^2 = 8.48, df = 4, p = 0.075 and Kruskal-Wallis X^2 = 5.93, df = 4, p = 0.205, respectively). Swimming behaviour varied between individual fish with the majority (55%) exhibiting *B1*, where they zigzagged between two lines of clusters when passing through the array (figure 6.10a). Seven percent of fish that passed only used the route between the side wall and the first line of bristles (*B2*). Lateral traverse of the pass at some point during ascent (*B3*) was more frequent for the array configurations with the larger spacing (0.15 m). During passage, 38% of fish exhibited combinations of swimming behaviours in which they swam diagonally from cluster to cluster, laterally traversing the entirety of the pass (*B3*, figure 6.10c) before reaching the edge of the flume and localised wall association (*B2*, figure 6.10b). Fish spent approximately 65, 100, and 75% of their time utilising low velocity regions when zigzagging, localised wall association and laterally traversing, respectively. For fish that passed the *λi* treatment (for which the most data was available) the percentage of time spent in low velocity zones ranged from 40 – 79%. As insufficient numbers of fish passed under the other treatments, the time spent in different velocity zones were not categorised.

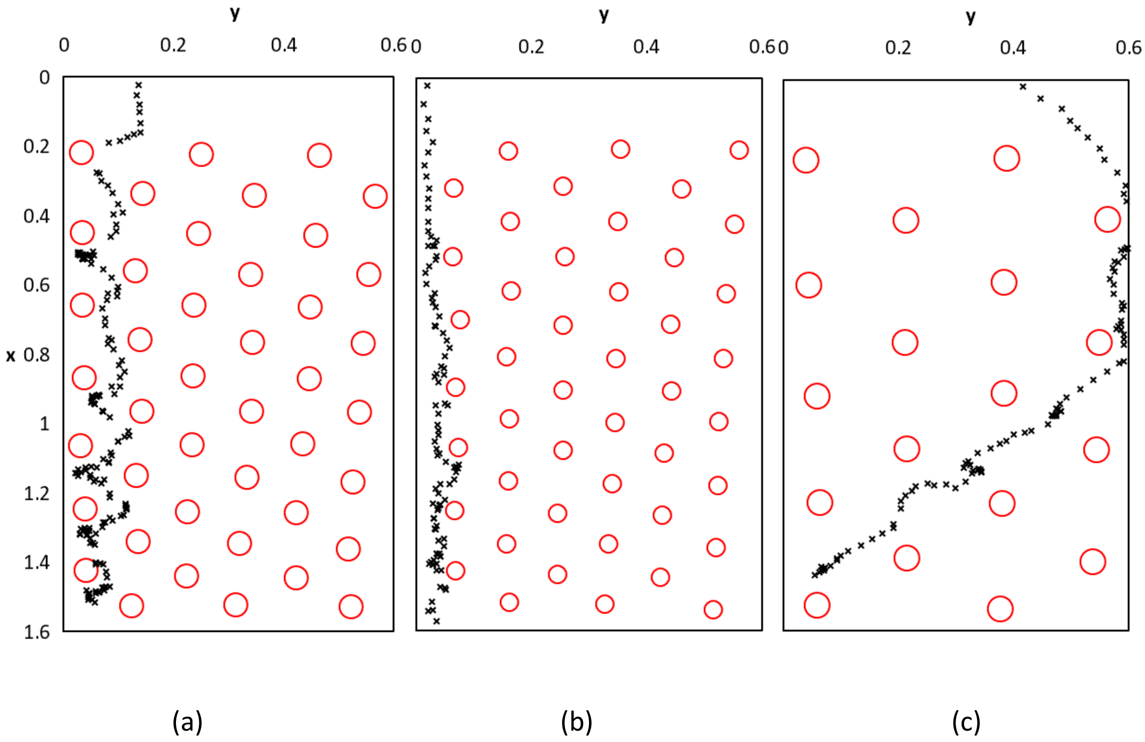


Figure 6.10 Fish swimming pathways showing behaviour *B1* where fish zigzag between two lines of clusters (a) *B2* where fish swim between the wall and a line of clusters (b) and *B3* where diagonal movement through the array occurs (c).

6.3.2 Laboratory Hydraulic Trials

As the density of the array increased and the S_c / D ratio decreased, the drag coefficient decreased up to a point after which no obvious relationship could be ascertained (figure 6.11). There was no relationship between specific diameter or spacings and drag coefficient. No trend was observed between the ratio of approach velocity and velocity within the array and array density (Correlation coefficient = -0.15, t = -0.63, df = 16, p-value = 0.539) (figure 6.12). Reynolds numbers were approximately $1.1\text{x}10^5$ for the experiments undertaken where degree of submergence and Froude number varied between treatments (table 6.3). Immediately behind the clusters water backed up (figure 6.13). The configuration most optimal for fish passage was likely where the wake created by the preceding cluster converged on the succeeding cluster (Figure 6.14).

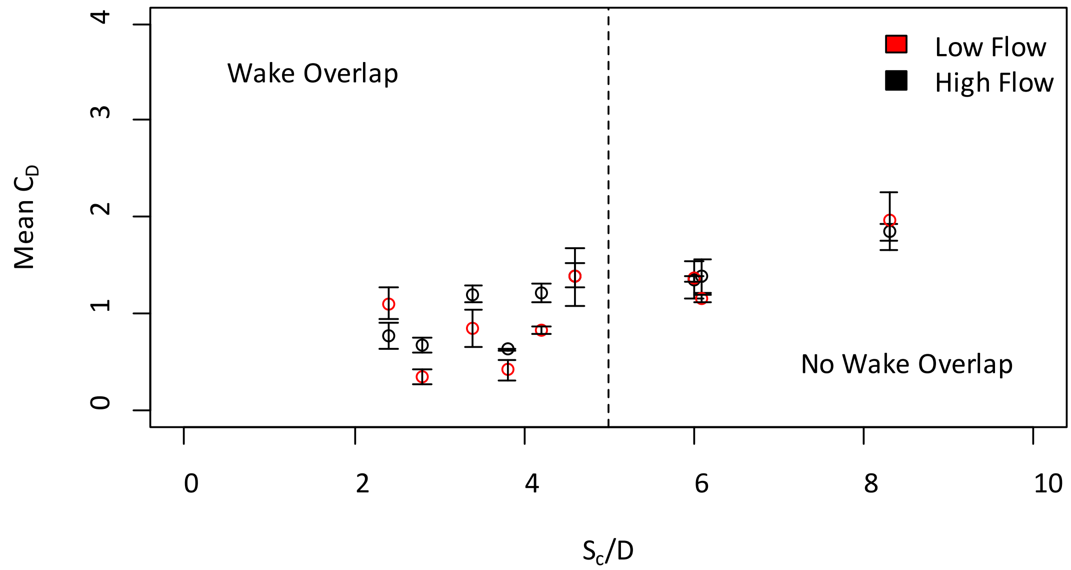


Figure 6.11 Scatter plot of the change in drag coefficient with increasing S_c/D highlighting areas where wake overlap does or does not occur (calculated based on Taddei [2016]).

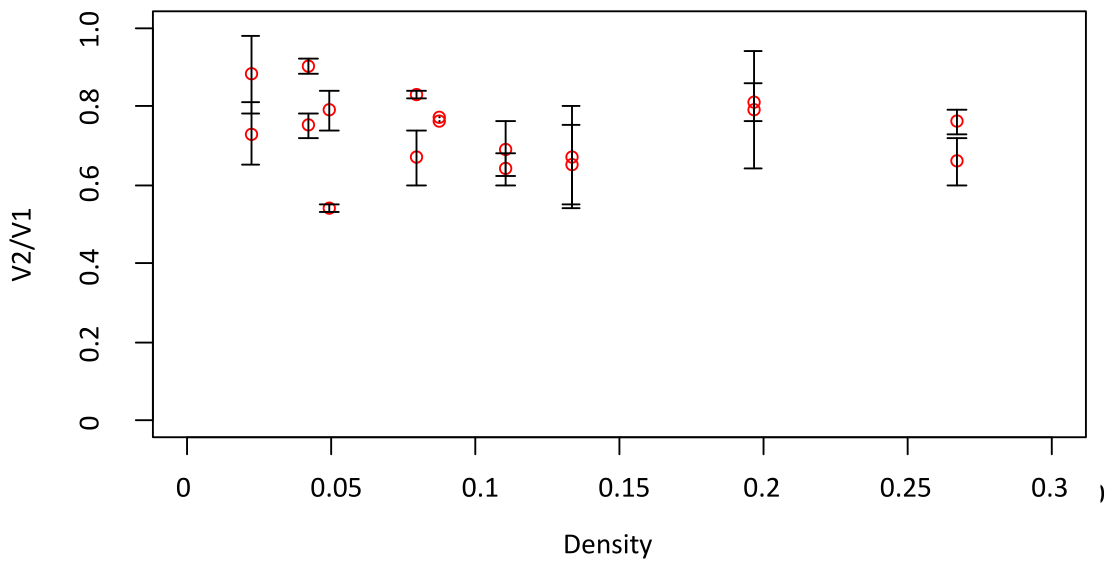


Figure 6.12 Scatter plot of array density and change in velocity where V1 is the approach velocity and V2 is the water velocity within the array.

Figure 6.13 Flow around a cylindrical cluster at different levels of submergence.

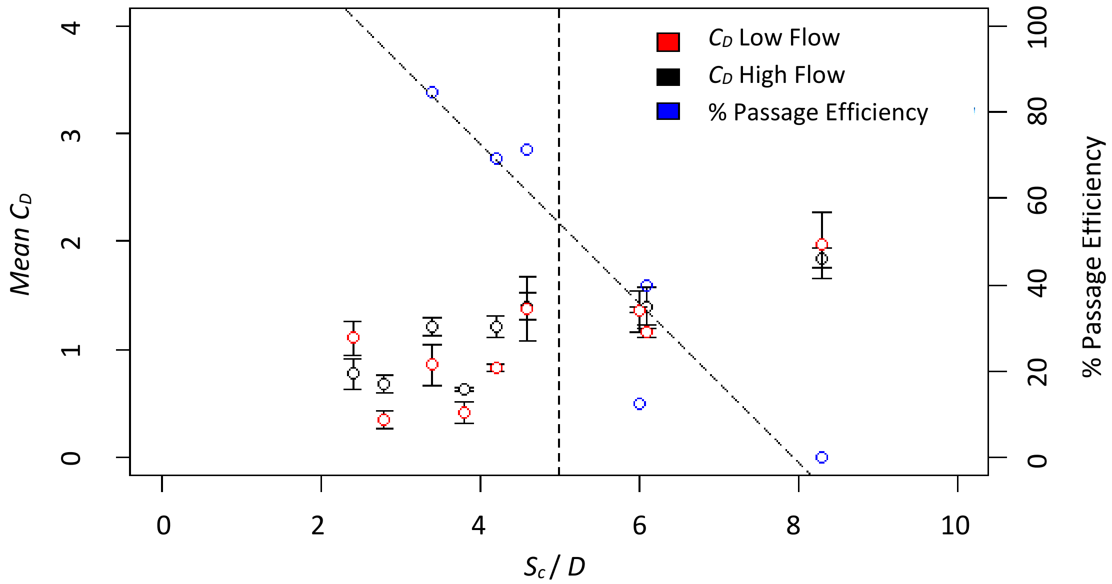


Figure 6.14 Combination of data obtained from separate fish and hydraulic trials showing the relationship between passage efficiency and S_c / D and mean C_D in relation to S_c / D.

Table 6.3 Experimental configurations tested and associated Froude values above (1) and within (2) the array and corresponding submergence (y / h_2).

λ	***Q***	***S_c / D***	***D***	***S_d***	***Fr (2)***	***Fr (1)***	***y / h₂***
0.080	0.07	4.6	0.07	0.15	0.92	1.72	1.51
0.080	0.19	4.6	0.07	0.15	0.94	1.24	0.75
0.133	0.07	3.4	0.07	0.1	0.59	1.42	1.11
0.133	0.19	3.4	0.07	0.1	0.66	1.00	0.59
0.267	0.07	2.4	0.07	0.05	0.39	0.73	0.83
0.267	0.19	2.4	0.07	0.05	0.57	0.86	0.54
0.022	0.07	8.3	0.03	0.15	1.40	1.82	1.82
0.022	0.20	8.3	0.03	0.15	1.14	1.33	0.84
0.042	0.07	6.1	0.03	0.10	0.89	1.77	1.48
0.042	0.19	6.1	0.03	0.10	0.83	1.20	0.70
0.110	0.07	3.8	0.03	0.05	0.58	1.47	1.08
0.110	0.20	3.8	0.03	0.05	0.66	0.98	0.59
0.049	0.07	6.1	0.05	0.15	1.20	1.79	1.58
0.049	0.20	6.1	0.05	0.15	1.08	1.34	0.82
0.087	0.07	4.2	0.05	0.10	0.78	1.76	1.33
0.087	0.19	4.2	0.05	0.10	0.78	1.11	0.66
0.196	0.07	2.8	0.05	0.05	0.47	1.48	0.95
0.196	0.20	2.8	0.05	0.05	0.62	0.91	0.56

6.4 Discussion

Larger wakes produced by CBC arrays improved passage efficiency of roach at a low-head experimental weir. Maximising the proportion of low velocity areas appeared to help fish pass the hydraulic jump, an area characterised by high energy / turbulent flow, contributing to improving overall passage efficiency. Under treatments $\lambda i - \lambda vi$, fish were able to pass over the hydraulic jump and therefore increasing their chances of ascending the weir. Once on the weir, fish utilised low velocity zones when ascending through the CBC array.

Passage efficiency was highest for the 0.07 m diameter clusters (the largest tested) regardless of how far apart they were spaced, suggesting that the larger wakes produced facilitated upstream fish passage. Passage efficiency was lower for the 0.05 m diameter clusters (the medium size tested), with a marked improvement when they were spaced 0.1 m apart, rather than 0.15 m. It could be that the cylinder wakes did not overlap for the larger spacings (see Taddei, 2016) and therefore near wake velocity dissipation occurred, where the flow velocity increased before colliding with the next cluster. Under such a scenario, less low velocity space would be available for fish to exploit, meaning they would encounter higher average water velocities downstream the clusters during their ascent, possibly causing the lower passage observed (λiv). Of the fish that passed the hydraulic jump, no fish passed through the CBC array when clusters were 0.03 m in diameter (the lowest tested) and spaced 0.15 m apart, even though the average array velocity was comparable to the other treatments. As the wake width and, therefore, area of low velocity created was lowest under this treatment, the conditions may have been difficult for fish to ascend with chances of encountering patches of higher velocity being greater.

Montali-Ashworth et al. (2020) indicate that as the density of CBC arrays increase, passage can become compromised as fish manoeuvrability is impacted. In this study, higher densities improved passage as the ratio between CBC spacing and fish body length remained greater than 1, and so fish manoeuvrability was not hampered during weir ascent. This suggests there is an optimal design between high and low CBC density that facilitates passage of roach at small gauging weirs. Above or below these densities, passage is compromised as fish cannot manoeuvre between the clusters or there is insufficient lower velocity regions to reduce energy expenditure and overall water velocity.

The behaviour where fish moved laterally through the cluster array was uncommon. The majority of individuals that successfully ascended the weir did so by zigzagging between two lines of clusters; the most direct route to ascend the weir. The uniform nature of the array, with equal spacing between clusters of equal diameter, creates a coherent hydraulic environment on the weir face, allowing fish to better anticipate the conditions and navigate without becoming disorientated. This hypothesis is based on literature where it has been shown that fish prefer simpler environments when swimming at speed (Ashraf et al., 2017). Fish that ascended next to the flume wall (*B2*) were able to take advantage of the lower water velocity and shear towards the boundary (as for Johnson et al., 2019). This is likely beneficial from a fish passage perspective as less energy would be required to swim through this region. Fish exhibiting behaviour *B3* could have ascended the weir by actively swimming through the low velocity regions in the wake of bristle clusters, and then moving laterally to behind the next cluster, where it continued to ascend. Regardless of which behaviour was exhibited, pathways suggest that fish were seeking areas of low velocity and/or shear when swimming through the CBC array.

The majority of paths were sinuous, with some fish spending a large proportion of time positioned behind the clusters with the variation in time spent in lower velocity zones likely dependent on fish swimming ability and the combination of modes used to navigate the array. The suggestion that fish use the wakes is reasonable as they seek to reduce their energy expenditure in a way that is similar to entraining behind cylinders, which has been observed as a strategy to minimise energy expenditure during upstream movement (Beal et al., 2006). In this case, fish do not entrain behind the clusters as their movement through the array is rapid. Entrainment occurs when fish hold position behind an object such as a cylinder whilst expending minimal energy, as they orient their body based on spatial flow patterns so that the effect of hydrodynamic forces on their bodies are reduced (Przybilla et al., 2010). Although entrainment does not occur, fish paths recorded suggest a similar energy saving behaviour. Combining multiple cylindrical bristle clusters into a staggered array with overlapping wake regions may provide micro-habitat that aids fish passage. Accounting for proportion of different areas available to sample, fish typically spend an equal amount of time in-between and downstream clusters when navigating through the array using behaviour *B1*. This could be attributed to the need for fish to pass areas of higher velocity to reach the next region of low velocity. Fish speed up when traversing through high velocity areas as their rate of upstream progress is maintained relative to the ground as they ascend the CBC array. Therefore, to minimise energetic costs during ascent through CBC arrays, minimising areas of high velocity are recommended, providing that there is sufficient space for fish to manoeuvre.

When characterising the hydrodynamics it was found that CBC arrays with the least wake overlap produced the greatest drag (e.g. treatment λvi with D = 0.03 and S_d = 0.15 produced the maximum drag coefficient [C_D] of 2). When wakes do not overlap, as for the lowest density tested in this study (treatment λvi), C_D is highest and the hydrodynamics more closely replicate the behaviour of flow through porous vegetation (Nepf, 1999). This is because the proportion of flow diverging around the CBC array was minimal as flow was constrained within the flume. This is in contrast to single porous cylinders (Taddei, 2016), where flow diverged around the cluster. Therefore, the relationship between array density and drag for CBC arrays tested in this thesis is more similar to that of flow through vegetated channels (Nepf, 1999). The sheltering effect is more prevalent at lower densities as increasing wake overlap reduces the cumulative energy loss (Nepf, 1999), increasing C_D. For the denser arrays tested here, greater blockage of the flow caused wakes to overlap. As a consequence, the influence of the sheltering effect on C_D is less prevalent.

Submergence varied between treatments, with drag expected to be greater when the clusters were fully submerged under the high flow regime. As water flows over the top of a cluster, there is an increased energy loss due to top shear effects and vertical bleeding, increasing the flow resistance created (Taddei et al., 2016). As cluster submergence increases, the proportion of the flow occupied by the clusters decreases, lowering the drag coefficient (Huthoff et al., 2013). Nevertheless, water velocity reduction in between the bed and cluster top is not compromised during submergence. Instead, C_D incorporates both drag in the zone above the clusters where velocity remains high, as well as drag between the cluster top and the channel bed. At submerged barriers, longer clusters will be less important as fish will be able to utilise the lower velocity high shear area between the cluster tops and the bed, provided it is sufficiently deep to ensure the fish’s body remains submerged.

Although increasing S_c / D increases drag (up to a point) because of the influence of sheltering and blockage effects, a large S_c / D (> 5) is undesirable as a result of the relationship between wake overlap and fish passage efficiency. Therefore, sufficient wake overlap is a requirement for successful fish passage as long as there is available area for fish to manoeuvre through the pass. It is proposed that a large cluster with a large spacing where $S_c / D < 5$ would be ideal for fish passage. Wakes are proposed to overlap when $S_c / D < 5$ (Taddei, 2016) as near wake velocity dissipation occurs this is supported by Nepf (1999), where sparse vegetation where no wake overlap occurs can be characterised as vegetation with density ad < 0.1, where ad is the dimensionless population density (Nepf, 1999), this translates to a S_c / D ratio > 3.16. Therefore, to improve passage efficiency, it is recommended that the S_c / D ratio is tailored to allow increased availability of low velocity areas created by wake overlap behind each cluster, while also reducing velocity in the array and allowing space for fish manoeuvre.

Chapter 7 General Discussion

7.1 Current CBC Installations and Manufacture

The potential for CBC arrays to mitigate habitat fragmentation for some fish at gauging weirs has been demonstrated in this thesis. As a result of this work, the design has been installed at 4 sites in southern England. Three are on compound Crump weirs; on the River Adur (Sussex) at Sakeham (figure 7.1) and Hatterells (figure 7.2), and on the DeLank River near Bodmin (Cornwall) (figure 7.4). The fourth is on a flat-V weir on the River Wallington at North Fareham (Hampshire). All pass installations are being monitored for longevity and debris accumulation. Further work is needed to monitor the fish passage efficiency at these installations.

The fish pass at Hatterells (figure 7.2) was manufactured by Widdops and installed by the Environment Agency in July 2018 for the Ouse and Adur Rivers Trust (OART). Details of the installation were published in the OART Summer 2018 Newsletter. Other installations (figure 7.4) come in the form of individual clusters which, along with the modular nature of the design, can aid in design flexibility for a range of weir geometries (figure 7.3). To date, future installations are planned at Twerton on the River Avon in Somerset (figure 7.5), Waightshale flat-V gauging station on Wroxhall Stream, Isle of Wight and Carisbrooke on Lukely Brook, Isle of Wight (EA pers. comm., 2019) amongst others.

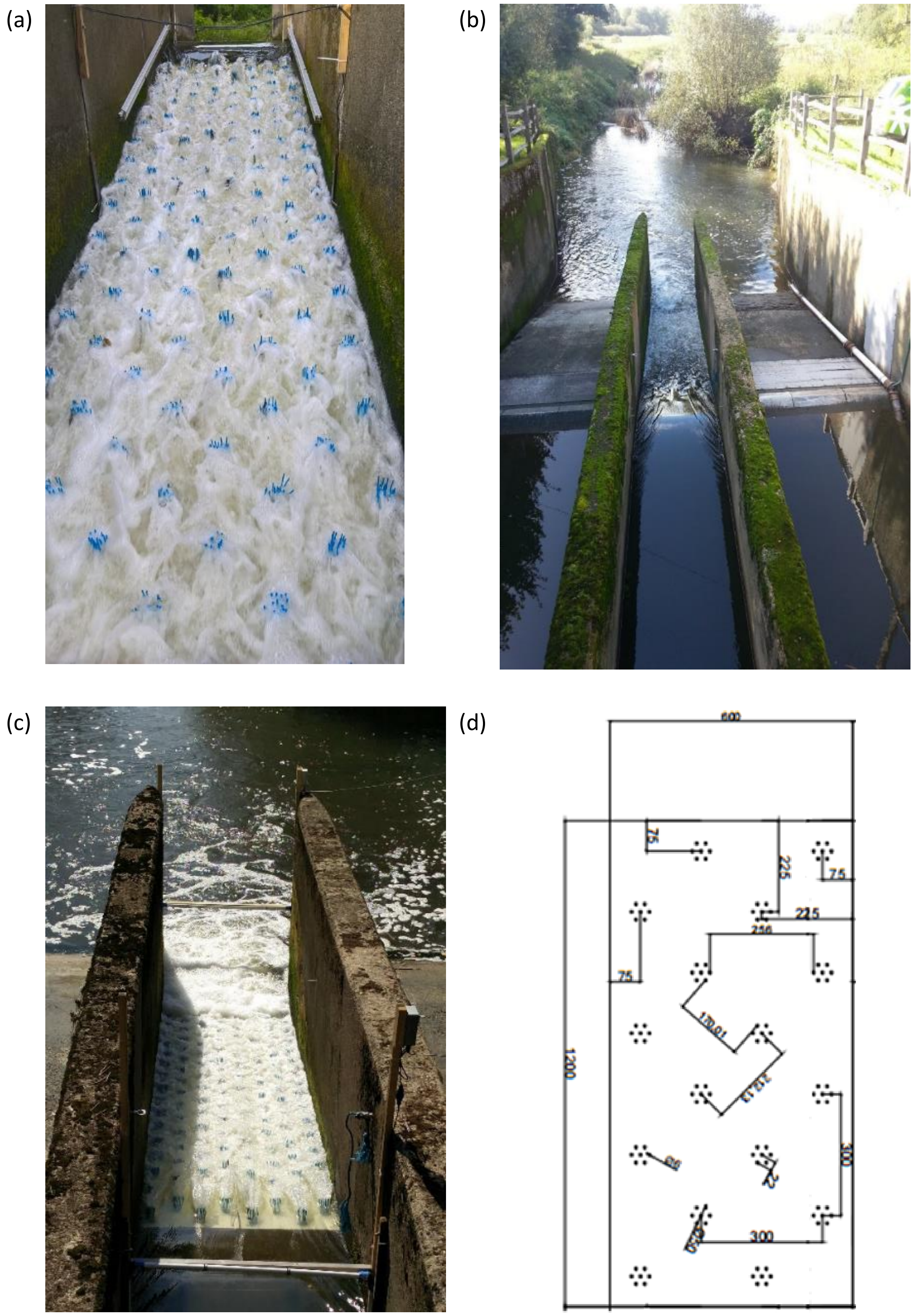


Figure 7.1 The compound Crump weir at Shermanbury on the river Adur (a) with fish pass in place looking upstream and (b) downstream when clusters were submerged and (c) unsubmerged. The fish pass was installed in the central channel and (d) comprised of boards (all dimensions in mm) which were placed side by side and bolted onto the downstream weir face.

Figure 7.2 Fish pass installation at Hatterells gauging weir on the river Adur.

Important aims when developing the CBC fish pass was to ensure the solution was cost effective and easy to install. This has been achieved, as evidenced by the commercial manufacture of the CBCs by Berry and Escott Ltd. (figure 7.3) for £31.85 per cluster. The modular design ensures flexibility in the configuration, dependent on weir geometry and the guidelines outlined in this thesis. A CBC fish pass is a fraction of the cost of traditional fishways. As detailed in Chapter 2, existing fish passage solutions can be expensive (FAO and DVWK, 2002), with costs varying widely depending on the size of the obstruction, the complexity of design and cost of materials, although actual installation and running costs are not widely documented. For most fish pass solutions, costs are dependent on location, ease of access and river flows. A fish pass cost comparison (£) from a number of sources (Servais, 2006; Don Catchment Rivers Trust, 2013) provides a glimpse into the magnitude of expenditure required for weir retrofit using pool type passes (£480 – £664 k) and baffle passes (Alaskan A, Plane baffle denil, Larinier super active baffle; £480 – £664 k) along with easements such as rock ramps and pre-barrages (£4 – £15 k) and low-cost baffles (LCB) (£8 – £110 k) in comparison to weir removal (£288 k). As some costs are very generalised, with the scale of the project, type of weir and inclusion of labour costs being unspecified, it is difficult to directly compare pass types. The CBC's are versatile allowing for application on a range of weirs of different sizes. The pass is simple to design and install by attaching the clusters to the concrete on the downstream weir face with self-fixing bolts. Such an approach is appealing as the different elements work together to create a low-cost fish passage solution that can be easily applied retrospectively as part of an adaptive river management strategy.

The type of material used for the bristles may need to be adapted in future. There is concern that plastic placed in a high energy environment may degrade due to UV and attrition in hydraulically turbulent conditions. Although this is less likely for the material used during prototype tests (PBT) due to its material properties, it is possible that a better bristle material alternative exists. Therefore, it is recommended that further work is undertaken by the manufacturer to find a more suitable alternative material, considering concerns related to plastic pollution.

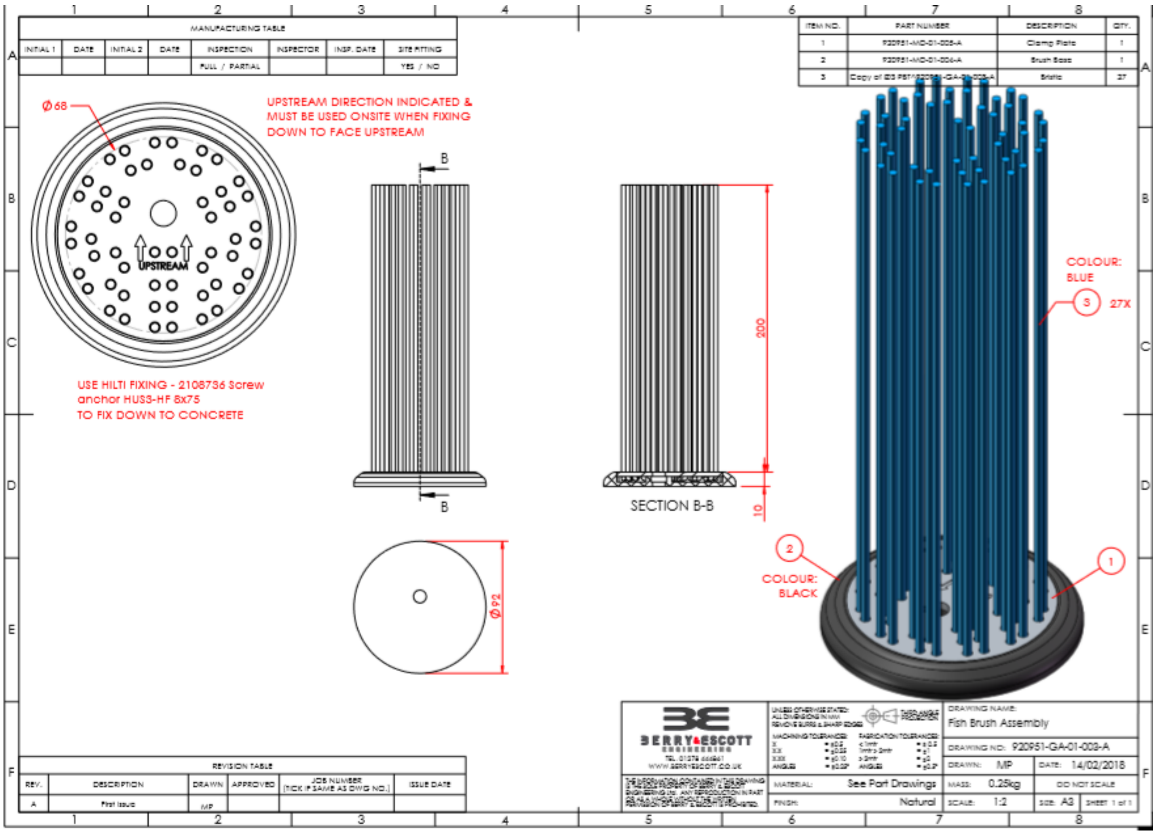


Figure 7.3 Design drawing for the cylindrical bristle clusters fabricated by Berry and Escott.

Figure 7.4 Fish pass installed in March 2019 on the DeLank near Bodmin (EA, 2019).

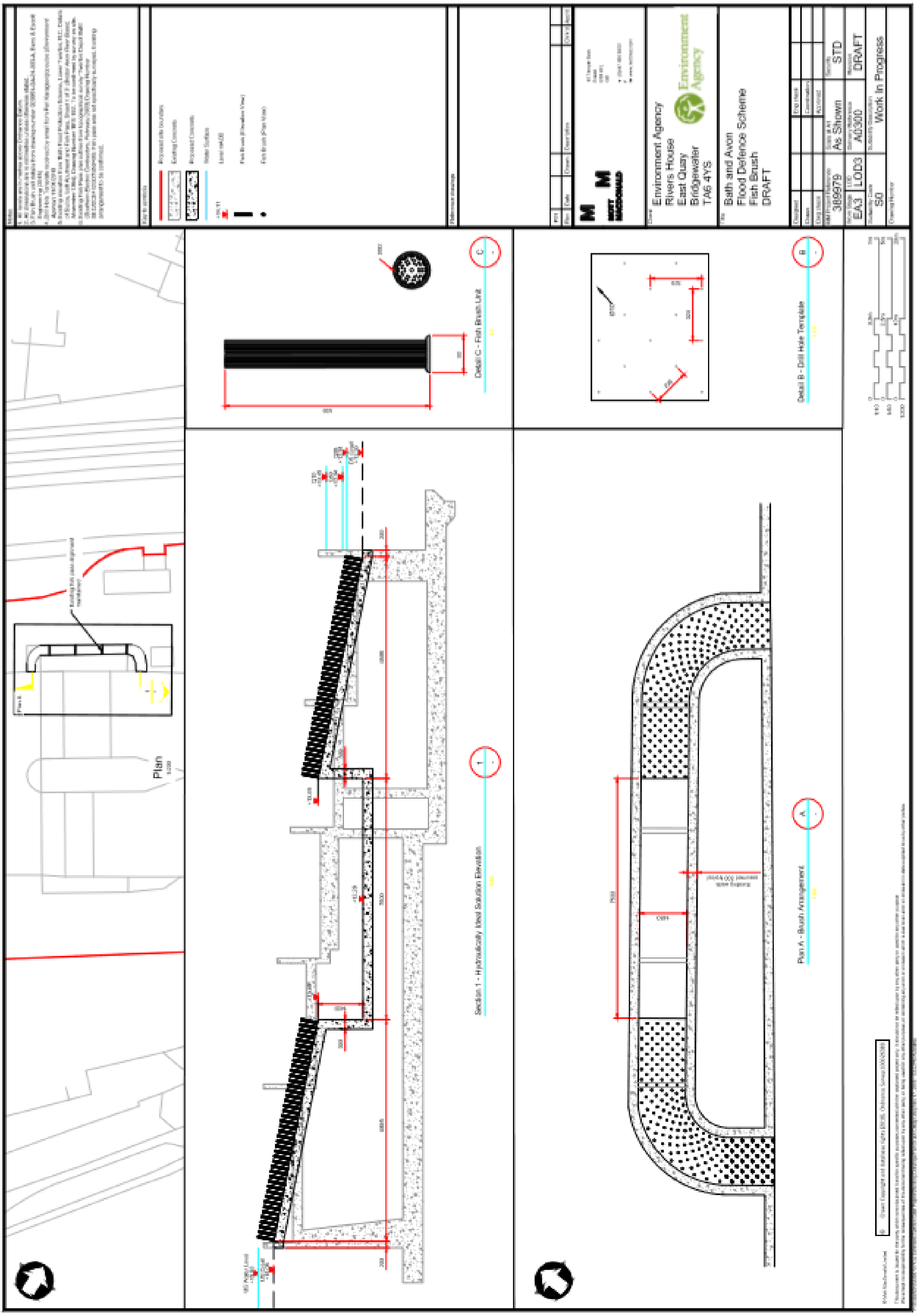


Figure 7.5 Design drawings produced by Mott Macdonald for proposed CBC fish pass installation on a modified bypass channel at Twerton as part of the Bath and Avon Flood Defence Scheme.

7.2 Recommendations for Management

An advantage of taking an experimental approach to this research is that design rules can be developed to enable better implementation of CBC arrays by practitioners. These rules are as follows:

- $S_d > BA$ (Fish body amplitude)
- $S_c > BL$ (Fish body length)
- $D > BW$ (Fish body width)
- $1:2 > D / BL > 1:12$
- $S_c / D \leq 5$

Whereby, if the above rules are adhered to there will be sufficient space available to allow fish to manoeuvre through the pass, with clusters providing sufficient low velocity areas. The magnitude of the hydraulic jump will also be reduced, increasing attempt rate and subsequent success. Extending the CBC array to below the location of the hydraulic jump may further improve passage efficiency as the strength of the hydraulic jump will be reduced, making it easier for fish to progress onto the weir face. Adequate distance between the weir wall and the first parallel line of bristles, greater than the body width of a fish, should also be considered as fish have been shown to utilise this area to navigate through the fish pass. As the most common swimming behaviour was zigzagging between two lines of clusters it is recommended that at least 2 columns of clusters are used when installing a fish pass on a weir.

Based on the work conducted to date, configuration *λB* and *λiv* (both having $S_d = 0.15$, $D = 0.07$), tested in Chapter 5 with respect to gauging and in Chapter 6 with respect to fish passage efficiency, is recommended for installation in the field. It will provide enough space between the clusters for manoeuvrability of larger fish than those tested in Chapter 6 (> 0.15 m), which is likely to be the case under some field scenarios. Where the maximum length of fish that could be accommodated for is approx. 0.17 m taking into account the width of a fish and assuming the body amplitude of a fish is approx. 4 times less than the length of the fish (Bainbridge, 1957). Although $S_d = 0.1$, $D = 0.07$ performed best in the lab study, the spacing could be insufficient for fish longer than those tested in this study with a larger body amplitude that will not fit between the clusters, thus constraining their movement. Of the arrays tested with the largest spacing (S_d = 0.15 m), the largest diameter performed best from both hydraulic (35% reduction in water velocity) and biological (70% passage efficiency for roach) perspectives. Larger diameters than that proposed could be disadvantageous from a cost and space perspective, limiting the design to a certain width of channel.

It is recognised that variable arrays, where the spacing changes across the width of the fish pass, may be advantageous for multi-species passage, as the different spacings can accommodate different sized fish and create a larger range of velocities that could allow for better accommodation for anguilliform swimming on one hand and sub-carangiform swimming on the other. This approach is not recommended and a uniform array is suggested as the best option for fish passage. This is because, in a uniform array, flow conditions are simpler where fish disorientation and displacement are likely to be minimised compared to an array comprised of a number of different diameters as fish prefer simpler environments when swimming at speed (Ashraf et al., 2017). In addition, a variable array could be more complex to design and install, adding to the cost of any fish pass. Uniform densities are preffered as, if the majority of fish, regardless of size and swimming ability, could pass up the weir assisted by a greater spacing, design simplicity and efficiency can be obtained.

7.3 Influence of Scaling Parameters

As this design has the potential to be installed on a number of weirs with varying lengths and flow regimes it is important to consider the applicability of the results and whether they can be scaled. For larger weirs it may be necessary to consider scaling effects of the design with regards to aeration. Interpretation of results from model to field scale can lead to discrepancies between results obtained during modelling and those obtained in reality, as was observed for Walters (1996).

Aeration and turbulent energy fluctuations can occur around a staggered array of cylindrical bristle clusters and therefore its effect should be considered when analysing fish and flow interaction within the pass. Aeration can be considered as the reason for passage failure (White and Woods Ballard, 2003) because aeration can be a product of turbulent flows, where severe fluctuations in turbulent energy occur. Turbulent energy fluctuations can cause fish disorientation (Montgomery et al., 2003) but fish can respond in different ways to turbulent flows. The influence of turbulence on fish has been studied extensively (Lupandin, 2005; Enders et al., 2003; Pavlov et al., 2000; Lacey et al., 2012; Wilkes et al., 2013; Haro and Kynard, 1997; Silva et al., 2012; Foulds and Lucas, 2013). It was observed that turbulent flows can be very costly for fish with regards to energy expended when attempting to navigate these flows (Liao, 2007). The effects of turbulence have been described through measurements of turbulent kinetic energy (TKE), turbulence intensity (TI), relative turbulence intensity (k), turbulent length scale (TLS), or Reynolds shear stresses (τ) but it is debatable whether these approaches are really effective in quantifying space use by fish (Kerr et al, 2016). Instead it has been proposed that a drag metric might be more appropriate (Kerr et al, 2016).

As there is conflicting evidence as to whether aeration does hamper fish passage and a large amount of evidence to suggest that turbulence plays a significant part in how fish navigate in their surroundings, it would be realistic to quantify fish response with some form of turbulence metric, rather than an aeration metric (such as the Weber number which describes the relationship between inertia and surface tension). For example, denil passes have a large amount of aeration but fish passage has still been documented through these (Noonan et al, 2012). This being said, aeration as a deterrent to fish swimming has been strongly proposed in the form of bubble screens suggesting that air bubbles can disorient fish and can be undesirable for fish passage. Therefore, there is conflicting evidence surrounding the extent that aeration plays in deterring fish from successfully surmounting barriers such as triangular profile weirs. As such, it is advisable that aeration is reduced as much as is reasonably practicable. Care should be taken to avoid aeration effects such as those encountered by White and Woods-Ballard (2003) as it should be noted that aeration content does effect drag and therefore drag experienced in the field could be different to drag measured in the laboratory at smaller scales. Even though at times (depending on the flow conditions and subsequent bristle submergence) the fish pass had high levels of air entrainment it could be said that a predictable spatiotemporal component was present within the flow and therefore it should be seen to attract fish (Beal et al., 2006).

Scaling effects were observed between flume and field scale (Hurn baffle installation, White and Woods-Ballard [2003]), and as such was considered when designing the proposed fish pass to ensure that results obtained in the flume are transferable to field conditions. Scale effects can be avoided if appropriate threshold values for different non-dimensional numbers, specifically Froude (Fr) describing the ratio of inertia to gravitational forces, Reynolds (Re) quantifying the ratio of inertia to viscous forces and Weber number (We) which is the ratio of inertial to viscous forces, were adhered to at model scale. Depending on the scaling factor, aeration (quantified by We) can be reasonably scaled if its square root is greater than 140 (Chanson and Gonzalez, 2005); for scale factors of about 2, with Froude and Reynolds numbers exceeding 5 and $2x10^5$ respectively. Unfortunately, these conditions are not met and therefore scale effects would be present in the field, the severity of which is dependent on the relative difference between laboratory and field scales. As the fish pass dimensions used in the laboratory studies are field scale (per unit width) results are applicable for the flows tested and weir length, but different effects could be experienced for longer weirs and higher flows. Unfortunately, the range of flows tested were limited due to hydraulic flume constraints. In the field, a large range of weir widths and heights can be encountered (but with the same slope as that tested during experimentation). Therefore, experimental results per unit width are transferable assuming that the arrangement of cylinders within the clusters does not affect the bulk drag created by the clusters if the density of the clusters is still the same and that the Reynolds numbers experienced during experimentation were high enough that the effects of Reynolds numbers on drag is low.

7.4 Velocity Measurement

The aeration caused by the CBC arrays meant that standard methods for measuring water velocity using ADV probes were inadequate because of the air content in the water. This produced unreliable data, even after filtering techniques were applied. For the case of ADV's aeration can affect the correlation and accuracy of the velocity measurements collected. This is because ADV's measure velocity using the Doppler shift effect where a short acoustic pulse at a set frequency is emitted from a probe at the head of the ADV. This pulse bounces off the particles in the water and returns waves at a different frequency to the receiver probes. Sound travels through air at a different speed than through water. When an ADV transmits a sound wave through a mixed medium of air and water the speed of the wave changes dependent on the air-water mix. Therefore, collected data can contain spikes where the change in medium density has effected the change in speed of the pulse when it returns through the medium. These spikes can be removed using a de-spiking method however it is difficult to determine whether the spikes are the anomalous reading and which average velocity reading is the most representative of the actual water velocity. The air content changes the frequency with which the sound waves are returned to the receivers on average and does not just create random spikes. Signal phase data (radians) is collected by the receiver probes and is used to calculate the phase velocity. Nortek ADV's function where phase data from successive coherent acoustic returns are converted into velocity estimates using a pulse-pair processing technique. Phase data is then converted to speed using the Doppler relation. Higher void fractions modify the phase velocity, increasing the residence time of the transmitted signal as it takes longer to return, therefore reducing the frequency of the returning pulse as well as the signal phase. Ultrasound celerity is not affected by air content/bubbles when bubble volume fraction is less than 0.1 and carrier frequency is far from the resonance of the bubbles (Longo, 2006). Birkhofer et al. (2016) used bubbles to increase the bounce back of ultrasound within the water producing better velocity data as the field is more even. Therefore, for some cases, more bubbles and an even distribution can be advantageous and does not compromise measurements. Mori et al. (2007) states that spike noise filtering is inadequate for aerated flow where ADV measurements were only valid for void fractions between 1 – 3%.

7.5 Key Findings and Contribution to Scientific Knowledge

The work presented in this thesis fulfils the aim of developing a low-cost fish passage solution for sloped gauging weirs. The solution, an array of cylindrical bristle clusters, is founded on hydraulic theory, and has been shown to enhance the upstream passage efficiency for multiple native European fish species. The research has been undertaken experimentally, testing the design compared to a control in both laboratory and field scenarios (Chapter 5 and 6). Key findings revealed the potential for CBC arrays to improve passage efficiency over gauging weirs while having minimal impact on the measurement capabilities of the weir.

Data collected in Chapter 6 provided novel scientific knowledge on the behaviour of fish navigating hydrodynamically complex environments. A range of swimming behaviours that a sub-carangiform species exhibits to enable passage through a CBC array were identified. This information can be used as a platform for future research into modes of swimming adopted by weak swimming fishes to pass through hydrodynamically complex environments, such as those created in fish passes. The sinuosity of fish swim pathways could be investigated, aswell as tailbeat frequency and swim speeds relative to water velocity when navigating 'low' and 'high' velocity zones. Although a number of swimming behaviours were observed, the most common was zigzagging between two lines of bristle clusters. Literature has shown that fish swimming in a shoal allows for fish to save or expend less energy, improving passage success (Marras et al., 2015). It is reasonable to assume that fish swimming through the array, where fish readily use the hydraulics created, swimming in a zigzag pattern from one lower velocity area to another, to aid in passage, is similar to fish swimming within a shoal where vortices are created and utilised by fish to aid in passage. A combination of swimming between the flume wall and a line of clusters and swimming laterally between clusters, was also observed. For fish that navigated to the edge of the flume, upstream progress was subsequently made by swimming between the flume wall and the closest line of clusters, suggesting that fish take advantage of lower velocities towards the boundaries. Sinuous pathways were evident for all fish attempting to pass through the CBC arrays tested in Chapter 6. Studies in Chapter 4 and 5 suggest that a zigzagging swimming behaviour is not exhibited when fish manoeuvre over an unmodified Crump weir. Therefore, it is logical that swimming pathways were in a response to the hydraulic characteristics created by the clusters.

Design optimisation based on hydraulic and fish movement studies revealed the importance of array density, which effects the overall velocity reduction and localised velocity reduction behind the clusters, on passage efficiency. Analysis of the impact of array density on overall flow resistance revealed the importance of wake overlap and the occurrence of a sheltering and blockage effect when clusters are placed closer together (Chapter 6) reducing overall drag of the array. This result is supported by other studies (Nepf, 1999). However, a clear trend between array density and flow resistance (drag) could not be obtained for this study and additional data is required (e.g. at lower array densities than those tested in Chapter 6) to better determine the nature of this relationship for an array of CBCs. Further work should attempt to directly measure the hydrodynamic forces within the array using an alternative method to calculating momentum balance using the water depths upstream and downstream of the array, as this may improve the accuracy of any results obtained. At present there is no standardised method for measuring the drag coefficient, with a multitude of different methods utilised (Sonnenwald et al., 2018). However, the direct measurement of hydrodynamic forces within the array using a force sensor as in Tinoco & Cowen (2013) could prove effective.

A range of experiments were undertaken for this research where different passage efficiencies were recorded depending on the experiment undertaken (table 7.1). Analysis of the results shows that, even though passage efficiency may have been higher overall for the experiments undertaken on the flat-V weir compared to the Crump weir under laboratory conditions, passage efficiencies were actually very similar (analysing maximum increase in percentage passage efficiency). Passage efficiency experiments undertaken in the lab are at a reduced scale compared to some weirs that are present in rivers such as the one that was retrofitted for field work in Chapter 5. Comparing lab and field studies it is unclear which factor contributes the most to passage.

Although it is uncertain whether, for the hydraulic conditions tested in this thesis, porous clusters have discrete wakes let alone being able to calculate their size, it should be noted that fish displacement downstream is possible when large eddy formation occurs downstream of an object (e.g. Tritico and Cotel, 2010). Displacement could occur for different fish species and sizes not tested in this body of work or with alternative cluster diameters, flows or other scaling related variables (see section 7.3). Turbulent flows, where velocity fluctuations can be large and unpredictable, may repel fishes (Cotel et al., 2006; Liao, 2007). At present, it is hypothesised that outside a certain ratio of cylinder diameter to body length (D / BL) of 1: 12 and 1: 2 fish displacement is likely (Liao, 2007 based on work by Liao et al., 2003 and Webb, 1998). For the experiments undertaken in Chapter 6 the mean ratio of cylinder diameter to body length was 0.48, 0.34 and 0.21 for the 0.07, 0.05 and 0.03 m diameter cylinder respectively. This is within the range outlined above and therefore fish displacement downstream was minimised if approximating the wake effects of solid cylinders to those of porous clusters. This may explain the lack of difference between failed attempts in Chapter 6, suggesting that that any vortices shed from the clusters were not of a size or vorticity to destabilise the fish (Lupandin, 2005; Tritico and Cotel, 2010).

Table 7.1 Comparison of different passage efficiency experiments from Chapter 4, 5 and 6.

Variable	Chpt 4 lab	Chpt 5 lab	Chpt 5 field	Chpt 6
Fish length (m)	0.07 – 0.15	0.16	0.2 – 0.4	0.14
Q (m^3s^{-1})	0.01, 0.04, 0.1	0.08	0.29 – 5.56	0.06
B (m)	2.1	1.36	1.2	0.6
S_d (m)	0.05, 0.1, 0.02 - 0.06	0.06, 0.1, 0.15	0.17	0.1, 0.15
D (m)	0.005	0.03	0.05	0.03, 0.05, 0.07
ϕ	-	0.1	0.05	0.1
Trial length	1 hr	30 mins	-	1 hr
Species	Roach	Roach	Chub	Roach
Traverse distance	0.775 m	0.73 m	7 m	1.67 m
Re	$3x10^5 – 1x10^6$	$6x10^4 – 1.2x10^5$	-	$8.4 x10^4 – 1.5 x 10^5$
Fr	0.5 – 3	-	-	1.6 – 1.36
Control %P	30%	0%	0	0
Max increase %P	40	35	52	80
V_{wmax} ($m s^{-1}$)	2 – 1.3	2.5 – 1.7	-	2.1- 1.8
V_{wav} ($m s^{-1}$)	1.4 – 0.7	1.86 – 1.38	-	1.21

Information gathered from the study undertaken to determine the impact of the clusters on hydraulic resistance suggests that sparser densities have a more beneficial impact on velocity reduction (Chapter 6). This is likely due to the reduced sheltering and blockage effect created by the clusters. Both the ability of fish to navigate past the hydraulic jump and up the weir face were improved as width and length of low velocity zones increased (Chapter 6). This may be explained by the larger proportion of the fish pass being occupied by localised lower velocity zones (areas behind the clusters). This hints at the possibility that overlapping areas of localised low velocity zones plays a larger factor for fish passage through CBCs, rather than overall drag reduction.

Optimal conditions for fish passage could theoretically be created if the sheltering effect were reduced so that velocity reduction could be maximised, maximising overall drag created by the array whilst also increasing the area available for fish to manoeuvre and maintaining sufficient linked lower velocity areas. The importance of linking lower velocity areas for fish passage, which relates to the S_c / D ratio, is illustrated in Chapter 6, where λi (S_d = 0.10, D = 0.07), the configuration with the lowest S_c / D ratio where wakes overlapped creating linking lower velocity areas, was the best performing array configuration for roach with regards to passage efficiency. Therefore, to obtain optimal passage conditions for a range of flows and fish species S_c / D should be approximately 5 as near wake velocity dissipation occurs (Taddei, 2016). Wake overlap would be experienced for values below this which would be undesirable from an overall velocity reduction perspective as maximum velocity reduction can be obtained when wake overlap is minimised, where low velocity areas no longer extend from one cluster to the next. Consequently, optimal conditions for fish passage can be obtained through tailoring array layout so that the area of low velocity and spacing between the clusters is maximised whilst increasing the overall flow resistance created by the pass. Further increases in passage efficiency could be obtained through the use of larger diameter clusters to maximise the magnitude of low velocity areas behind the clusters.

The recommended design will have a low effect on gauging accuracy because it does not back up the flow and increase water depth as much as existing fish passage solutions (such as the low-cost baffles). Instead it relies on fish utilising the lower velocity areas created in the heterogeneous flow to successfully surmount the weir in combination with the overall velocity reduction created. Therefore, maintaining a water level above some minimum threshold required for fish passage, regardless of flow within the pass, will not be possible. As such, there may be occasions when water depth is too shallow for fish passage

7.6 Further Work

A staggered array of CBCs improves fish passage efficiency, reduces water velocities, increases water depth, and does not affect gauging when placed downstream of a transition zone where flow changes from sub to supercritical. At gauging weirs, CBC arrays can be placed closer to the crest (approx. 0.4 m) than alternative designs (e.g. the low-cost baffles: 0.74 m [Lothian et al., 2019]). At structures that are not used for gauging, CBCs can be placed up to the crest, which is likely to further improve fish passage efficiency. Although CBCs have been proven to be an effective method for improving the passability of gauging weirs for weak swimming non-salmonids, a number of areas would benefit from further work:

- Determine the influence of weir length and distance of CBCs from the crest on passage efficiency and design performance. The difficulty in balancing swim speed, distance of ascent and time to fatigue remains an important challenge in fish passage design, and better understanding of the interaction between the factors building on research such as that undertaken by Amaral et al. (2019) is required. Currently, fish are required to ascend a weir through the CBC array in a single burst. Burst swimming can typically only be sustained for up to 20 seconds (Knaepkens et al., 2007). Therefore, for long weirs, resting pools may be required. Research to identify the relationship between passage efficiency and weir length (and subsequently pass length) as well as passage efficiency and distance of the fish pass from the crest would allow practitioners to determine how long a CBC array could be before a resting area is required. It would also provide guidance on how far a fish pass can be placed from the crest before passage efficiency is significantly compromised. Unfortunately, the influence of weir length and distance of the pass from the crest on fish passage efficiency were not studied in this thesis. Nevertheless, they are important and should be investigated as they can significantly impact fish passage success.

- Determine the effect of debris on passage efficiency. This would be best undertaken as a field study, in realistic conditions, where the porosity of the clusters could change as debris accumulates and then sheds around them, changing the hydraulic environment created within the array. A number of different bristle stiffness’s could also be tested to determine what flexibility/ robustness configuration is optimal with regards to debris clearing ability and pass longevity.

- Determine whether the effectiveness of CBC arrays are flow dependent. For some flows (whether the weir is unmodified or not), water velocities (V_w) may be greater than fish swimming speeds (V_f). Maximum water velocities experienced during the experiments were much greater than predicted swim speeds. Even so, the significance of the lower velocity areas behind the clusters on fish passage when average water velocities are higher than burst swimming velocities (well above typical free swimming velocity), is unknown. The bulk water velocities encountered during experiments undertaken in this thesis were not significantly greater than the theoretical maximum burst swim speeds of the fish tested when the weir was modified. Therefore, the design may not work when flows create bulk water velocities that are greater than burst swim speeds limiting whether the fish pass can operate year-round and function within a range of flows from Q_{99} to Q_{10} as specified in the fish pass manual (Armstrong et al., 2010). It is possible that, even when the bulk velocity is higher than maximum fish swim speeds, fish can utilise the overlapping localised low velocity areas created by the clusters to pass upstream. If they are unable to utilise the low velocity regions, then upstream passage will not be possible. This hypothesis would need to be tested when bulk velocity on the weir face is greater than the burst swimming speed of the fish by varying the flow conditions and comparing passage efficiency at low, medium and high flows where high creates bulk velocities greater than the swim speed of the fish being monitored.

- Undertake detailed hydraulic mapping of CBC arrays to determine exact wake lengths and widths, comparing with theoretical predictions. Detailed hydraulic mapping of CBC arrays was not conducted during this thesis because average velocity readings behind and in-between the clusters were sufficient for fulfilling the aim of the study. Collection of more detailed measurements was considered; however, this proved a challenge due to the high levels of aeration caused by the array. Further detail would allow a greater understanding of the fish-hydrodynamic interaction. While this was beyond the scope of this thesis, it could be the focus of future PhD or Postdoctoral research, with studies similar to those undertaken by Wang et al. (2013) and Zdravkovich (1987) with solid cylinders repeated for CBCs. The vertical velocity profile at different flows should be measured and compared to existing studies to determine whether CBCs have a similar hydraulic performance to that documented in vegetated flows or flows through arrays of solid cylinders. Results could then be analysed to determine a friction coefficient which can be used by practicioners to simply calculate the water velocity within the CBCs for different flows that will be experienced within a river system.

- Determine if the same levels of passage success are sustained if the S_c / D ratio of < 5 is maintained but larger clusters and spacings are used. It is unknown whether the hypothesis that the same rate of passage success will be maintained if larger clusters and spacings are used and the S_c / D remains ≤ 5. The design may need to be tailored to accommodate salmon as well as the smaller weaker swimming species tested in this study. For this to occur the spacing in between the clusters and diameter of the clusters would need to be increased based on the aforementioned rules maximising velocity reduction, allowing for near wakes to overlap and creating low velocity areas for smaller fish to pass. Therefore, experiments with larger clusters and spacings and a greater number of fish species and sizes could be undertaken to validate this hypothesis. Larger cluster diameters could create larger low velocity zones downstream of the clusters and increase the possibility of areas within the pass where less energy expenditure would be required sitting behind the clusters, a feature that is attractive when catering for a wider range of fish sizes and species. A lack of such areas would likely result in the need for fish to burst swim the full length of the fish pass. Therefore, incorporating these design alterations would be more beneficial for a wider range of fish species.

- The work undertaken in this thesis focussed specifically on the upstream movement of fish through rivers. Downstream passability of structures is also an important component of river connectivity. Some downstream movement of fish was documented during field trials suggesting that passage in this direction is not hindered however further work should be undertaken to determine how easily fish can pass downstream through the CBCs when motivated, and whether there are any negative consequences of doing so (e.g. physical abrasion / damage caused by the bristle tips).

- Investigate the use of CBCs as a selective fish pass and whether they can facilitate the passage of native species while not improving passage for non-natives. In instances where non-native species have lower swimming abilities than native species, CBCs could be tailored to selectively allow for passage of native species only.

7.7 Conclusions

Anthropogenic barriers within rivers have resulted in population declines for numerous fish species as movement between essential habitats is impeded (Lucas and Baras, 2001). Regulations, such as the Water Framework Directive (European Commission, 2010) along with others internationally, requires that these barriers be retrofitted or removed so that fluvial connectivity is increased and habitat connectivity restored. Low-head barriers, such as gauging weirs, are numerous and often impede fish movements and as such their retrofit is required so that fish can pass up- / down-stream. Gauging weir retrofit requires a reduction in water velocities and increase in water depth to levels passable for fish, without affecting the gauging capabilities of the weir. Previous work to mitigate the effects of gauging weirs on fish passage is limited, where current options are costly, effect gauging and/or accumulate debris. This thesis presents a low-cost fish pass solution which can easily be mounted onto the downstream face of steeply sloping surfaces, reducing water velocities, increasing water depth and improving passage efficiency for some native European fishes without effecting gauging and with minimal debris accumulation. The simplicity and modularity of the design helps improve cost effectiveness and ease of installation. The results presented in this thesis indicate that passage efficiency is improved relative to a control for non-salmonid cyprinid species at flat-V, Crump and compound Crump weirs when retrofitted with a staggered array of cylindrical clusters. These bristle clusters generate flow resistance and can be manipulated so that the maximum distribution of low velocity areas can be achieved due to the formation of low velocity wakes behind the clusters. This is hypothesised to help fish burst between wakes, with spacing being optimised to allow for sufficient manoeuvrability through the pass. Based on work undertaken in this thesis it is recommended that a staggered array of CBCs, with $S_c / D < 5$, $S_d > BA$, $S_c' > BL$, $D > BW$ and $1:2 > D / BL > 1:12$, be installed on gauging weirs. The array should be placed downstream of the transition zone where flow becomes supercritical, reducing the impact of barriers on fish population sustainability and diversity whilst not effecting gauging, allowing rivers to comply to policy changes under the Water Framework Directive, where waters are raised to a 'good' condition. Implementation of this solution on gauging weirs and other sloping surfaces will aid regulatory agencies, ecological engineers, and operators and managers of river infrastructure tasked with provisioning services while improving ecological status and environmental sustainability. Indeed, the design has already been implemented on 4 weirs with additional installations proposed and further funding (£25,000) obtained to investigate areas requiring further work. It is important that these installations are monitored to ensure that they are functioning effectively and fulfilling their primary role of reconnecting river habitat for fish.

Appendix A Supplementary Information

A.1 Laboratory Fish Passage Trials Documented in Chapter 4

Figure A.1.1 Experimental setup showing the flume with the flat-V weir inserted looking downstream.

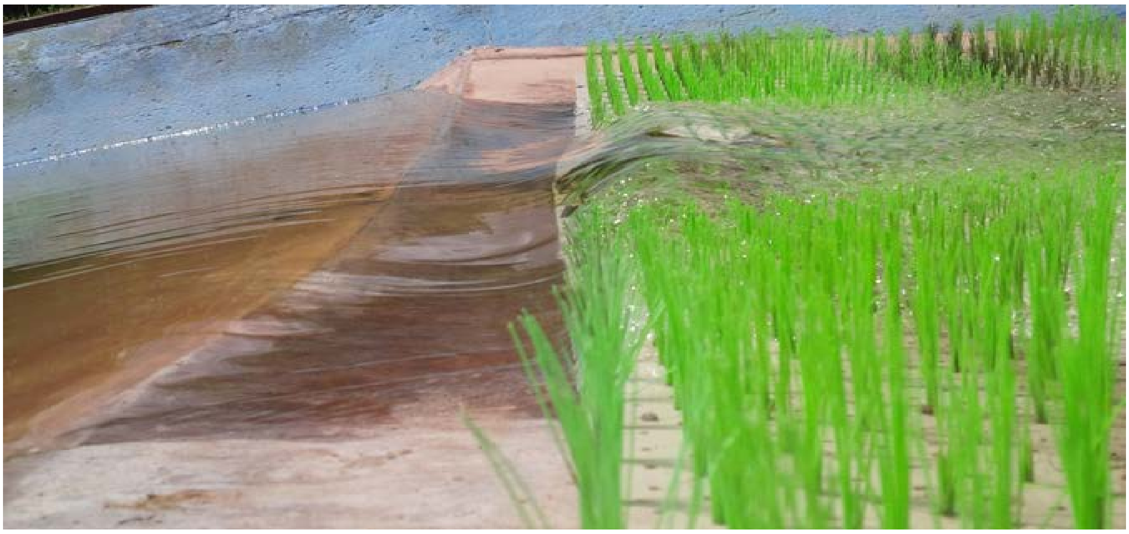


Figure A.1.2 Photograph of the weir crest and interaction between the water and the bristles at this location.

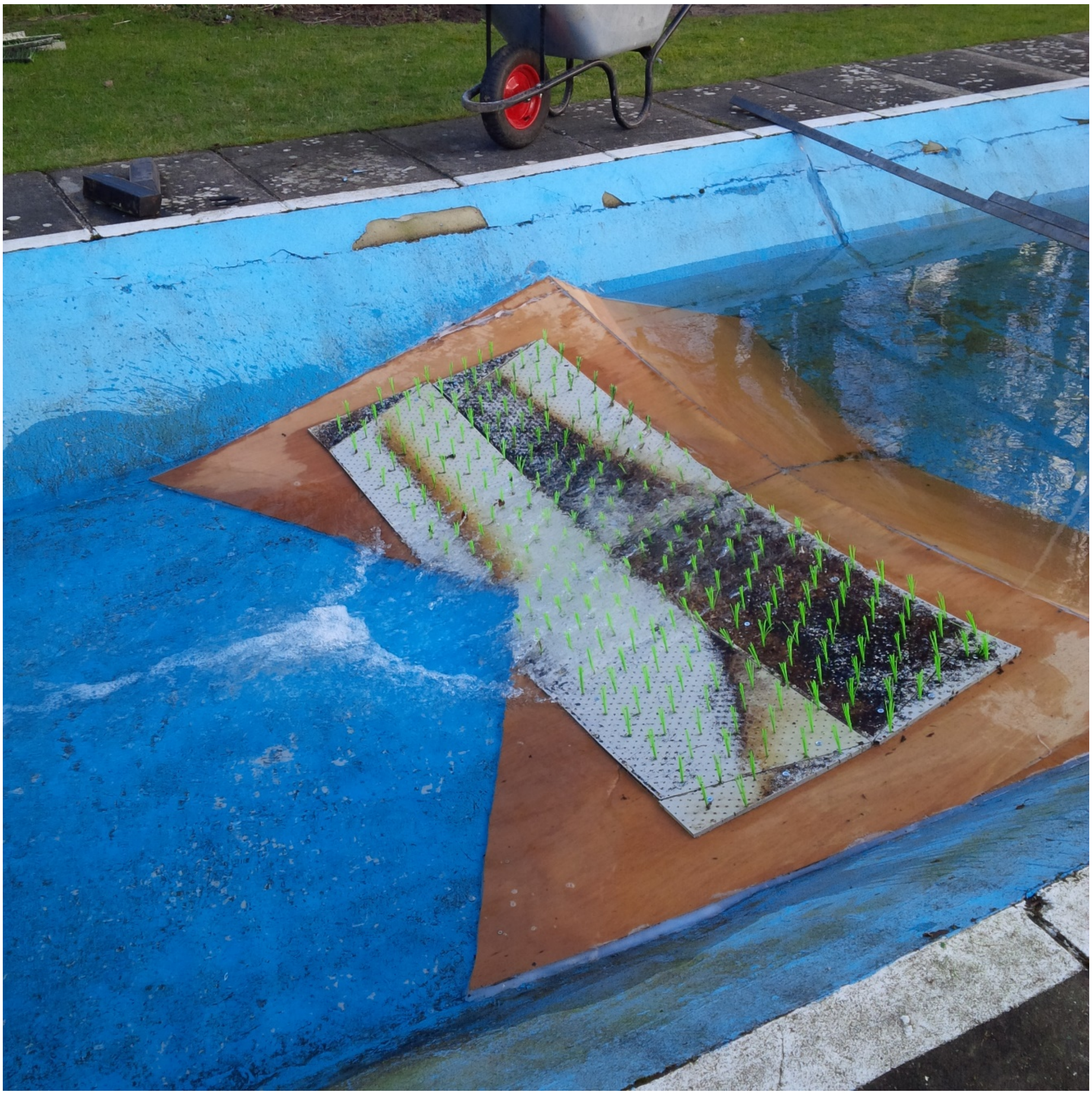


Figure A.1.3 Photograph of the flat-V weir installed in the flume with the bristle boards mounted onto the downstream face.

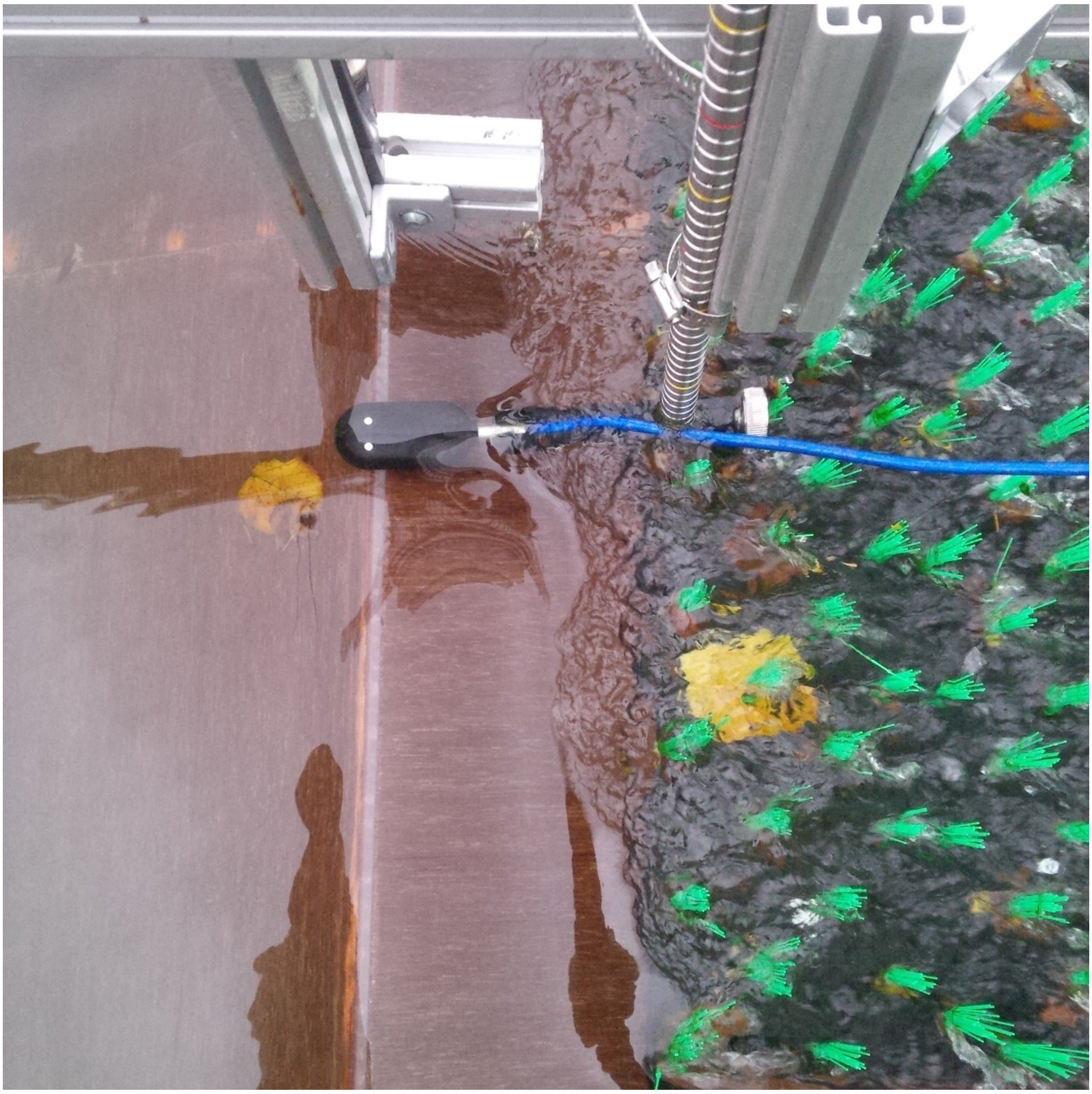


Figure A.1.4 Photograph of the velocimeter used to measure water velocities measuring water velocity at the weir crest upstream of the clusters.

(a)

(b)

Figure A.1.5 Photograph of debris accumulation during field installation of the bristle boards (a) close up and (b) showing the whole installation.

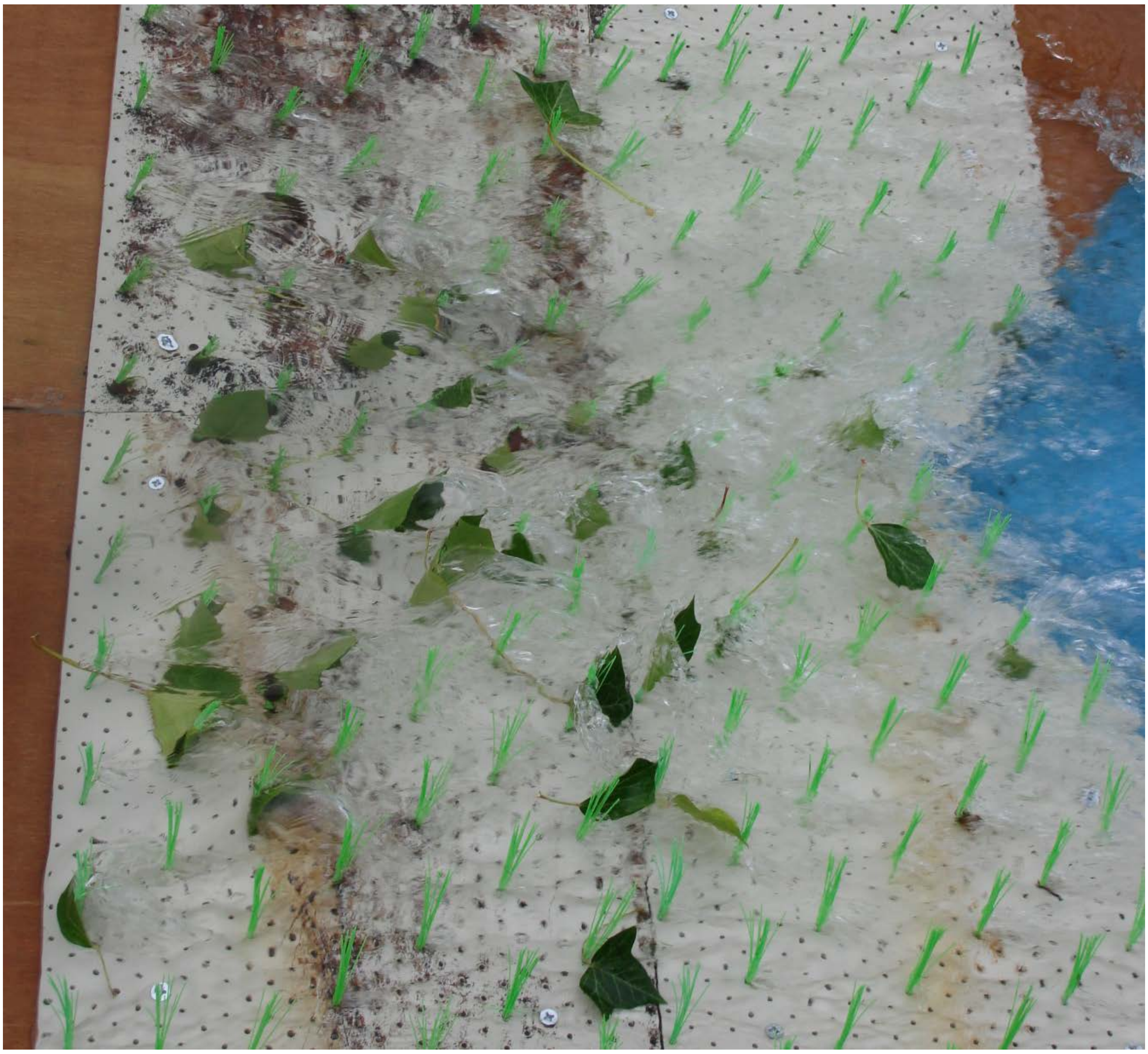


Figure A.1.6 Photograph showing debris accumulation of leaves through the bristles.

A.2 Laboratory Fish Passage Trials Documented in Chapter 5

Figure A.2.1 CBC installation on the downstream face of the Crump weir used during experimental trials.

Figure A.2.2 Fish release area downstream of the weir.

Figure A.2.3 View from above of the CBCs mounted onto the weir with water flowing from top to bottom of the photograph.

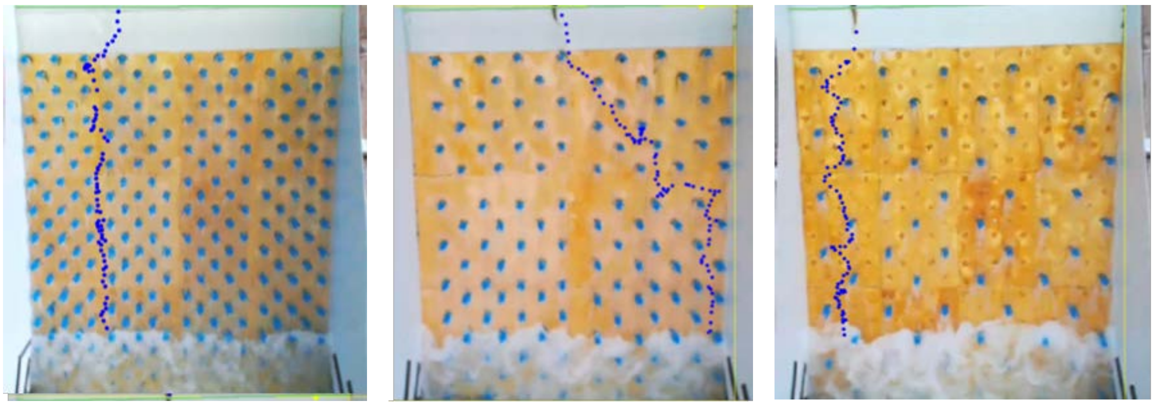
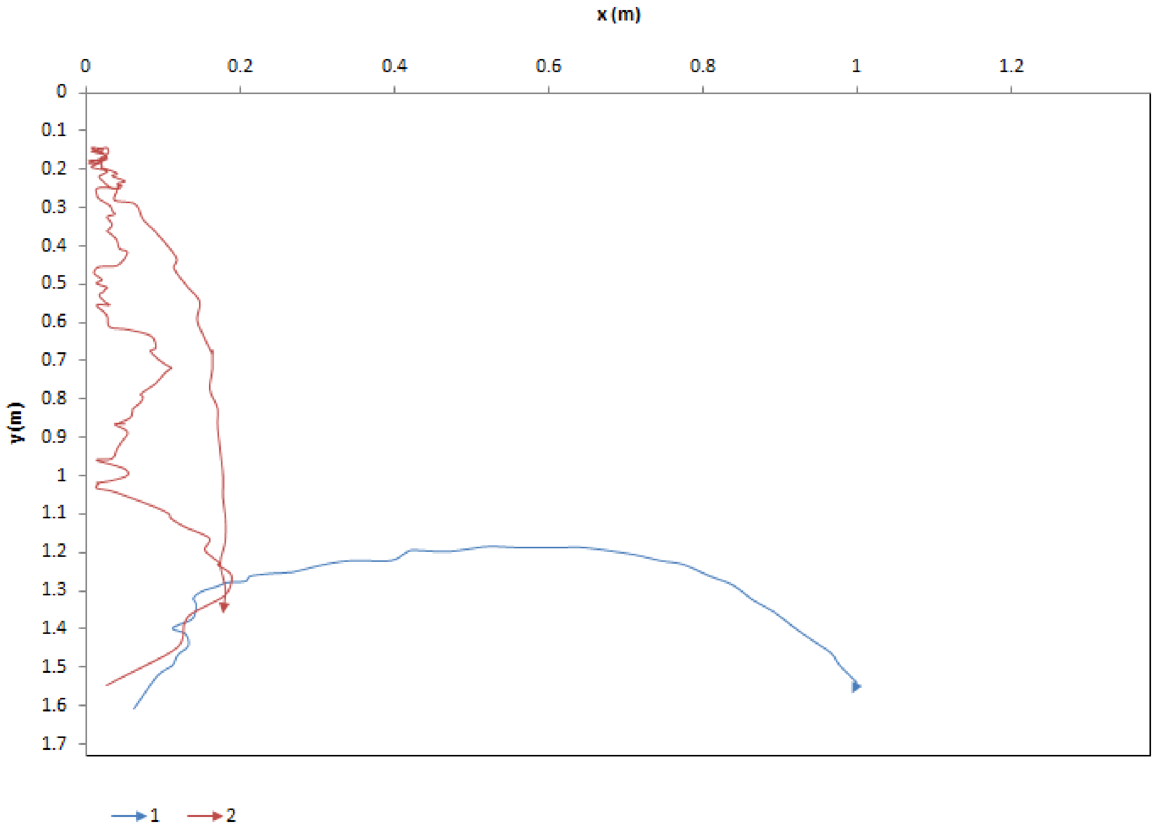
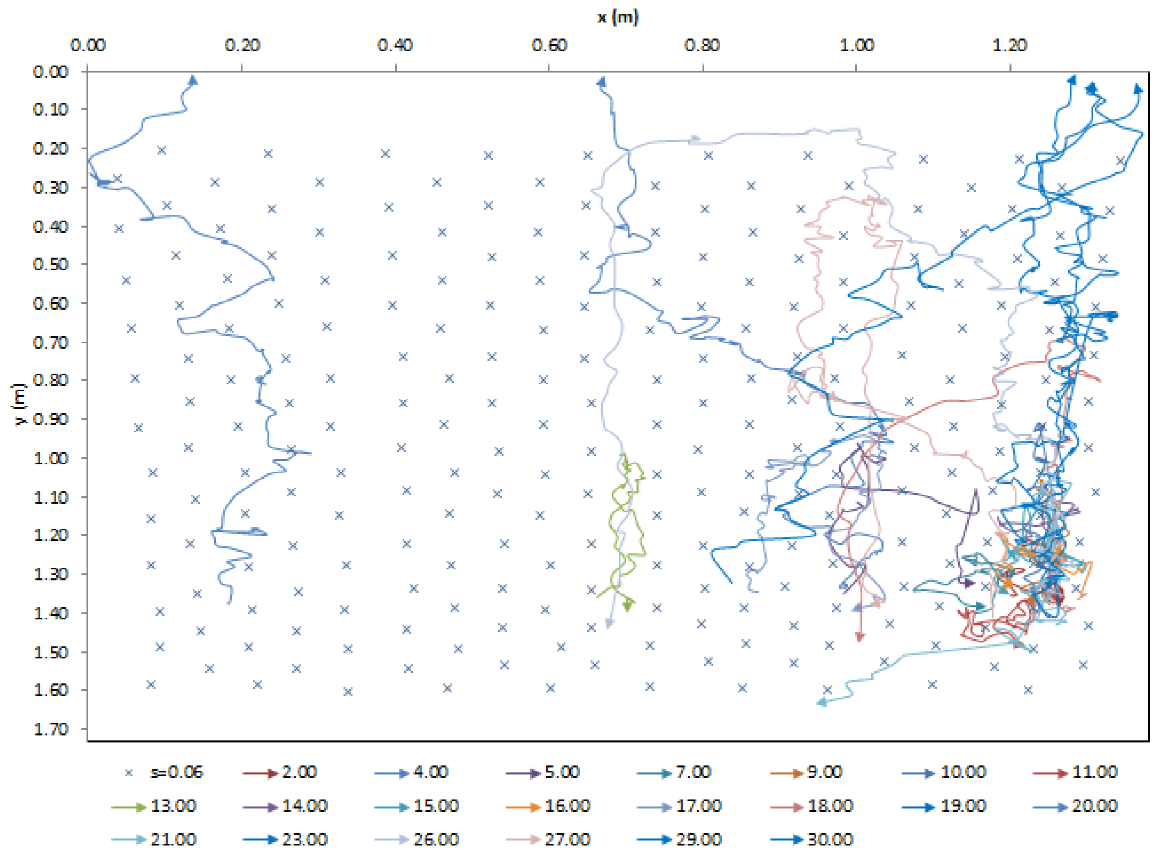


Figure A.2.4 Outputs of some fish pathways produced using Logger Pro for the different cluster arrangements trialled.

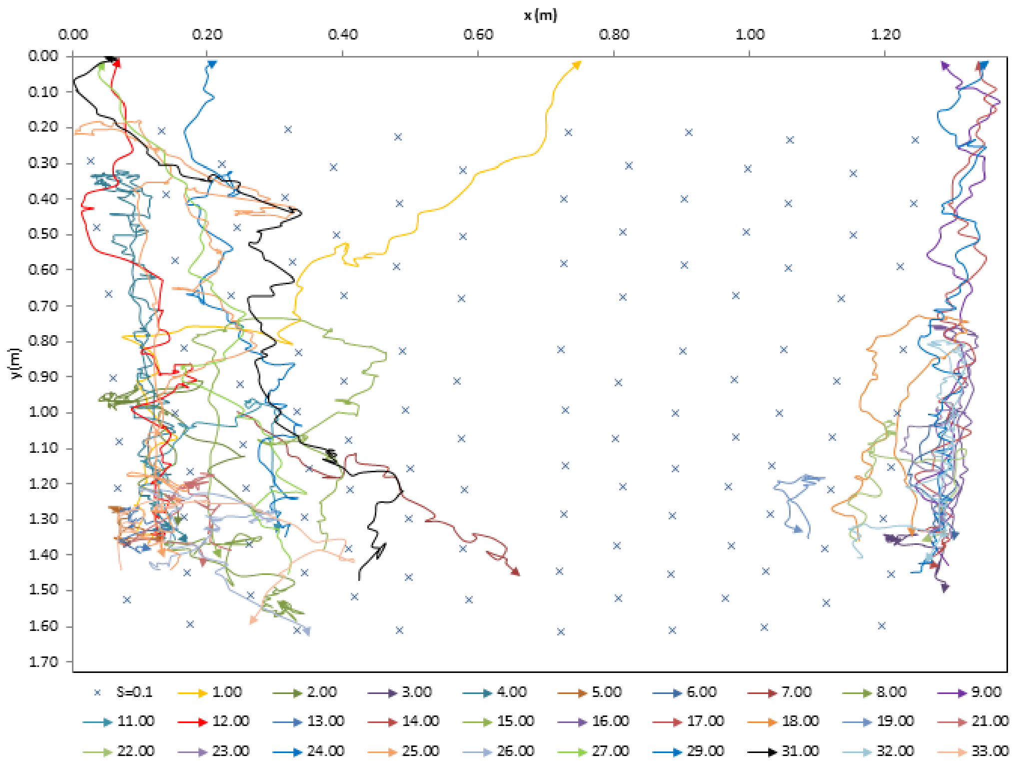
(a)


x (m)
0
0.2
0.4
0.6
0.8
1
1.2
y (m)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1
2

(b)


x (m)
0.00
0.20
0.40
0.60
0.80
1.00
1.20
y (m)
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80
0.90
1.00
1.10
1.20
1.30
1.40
1.50
1.60
1.70
s=0.06
2.00
4.00
5.00
7.00
9.00
10.00
11.00
13.00
14.00
15.00
16.00
17.00
18.00
19.00
20.00
21.00
23.00
26.00
27.00
29.00
30.00

(c)



(d)

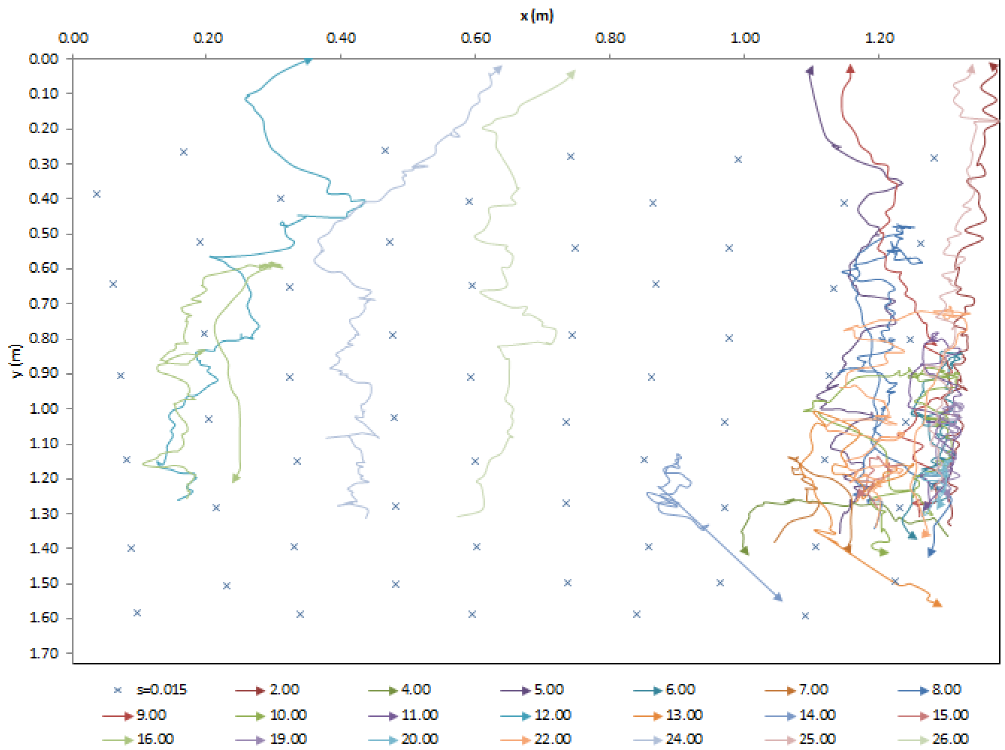


Figure A.2.5 Plot of fish pathways on the weir face for (a) (control), (b) (S_c= 0.06), (c) (S_c= 0.1) and (d) (S_c= 0.15); where the crest is located at y = 0 and the hydraulic jump at the base of the weir and weir side walls (as observed by the camera), are shown as dashed lines.

A.3 Field Installation of the CBCs Documented in Chapter 5

Figure A.3.1 Photograph of the CBCs being installed in the field on a compound Crump weir in the central channel.

Figure A.3.2 CBCs being bolted onto the weir face.

(a)

(b)

Figure A.3.3 Flow through the CBCs looking (a) upstream when the clusters were unsubmerged and (b) downstream when the clusters were only just submerged.

Figure A.3.4 Photograph of the weir at the highest flow experienced during the experimental period.

(a)

(b)

Figure A.3.5 Photograph of (a) the data logging setup and (b) equipment which was connected to the PIT loops installed on the weir

Figure A.3.6 Photograph of Perikles Karageorgopoulos and Jim Kerr with one of the fish caught when electrofishing near the weir. The pike was released without being tagged back into the area it was caught from.

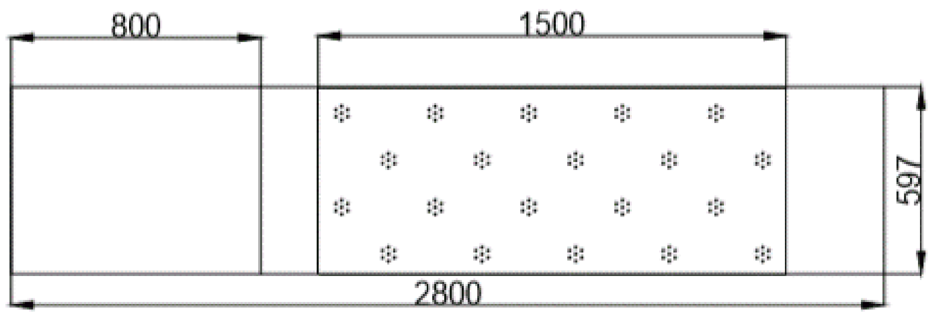
 

Figure A.3.7 Photograph of Andrew Vowles and Paul Franklin with some of the fish caught whilst electrofishing near the weir. These fish were tagged and released just downstream of the weir.

A.4 Gauging Experiments Documented in Chapter 5

A.4.1 Setup

(a)



(b)

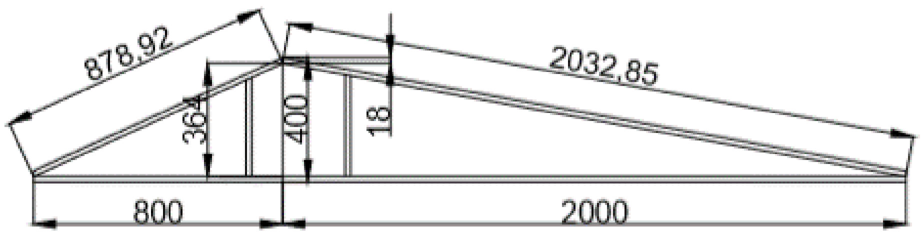
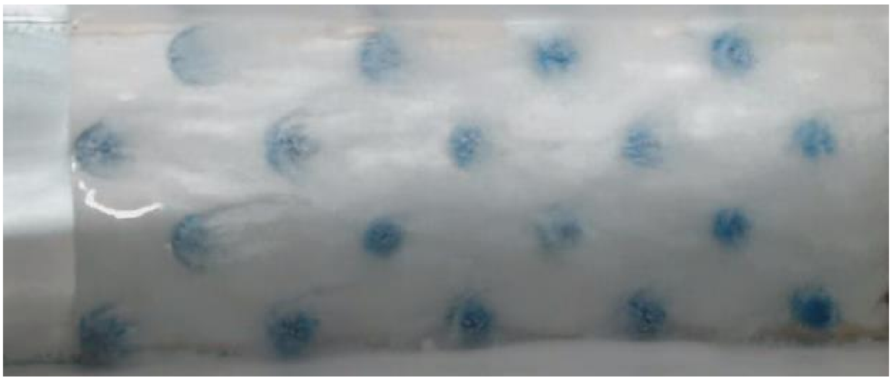
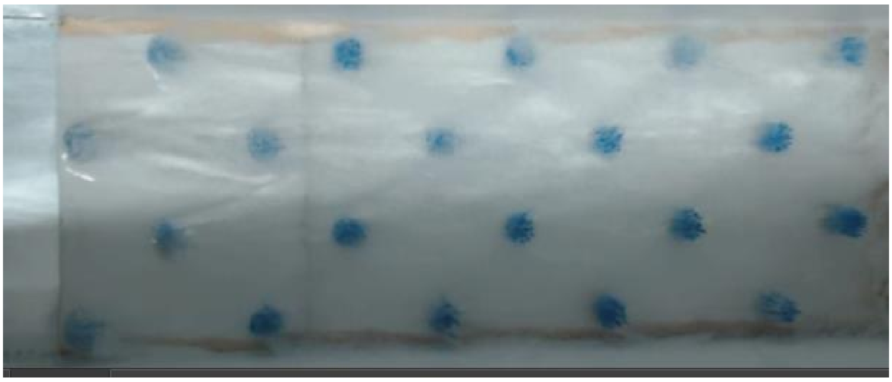


Figure A.4.1 (a) Plan and (b) section view of the weir used during gauging experiments and the associated dimensions (mm).

(a)



(b)



(c)

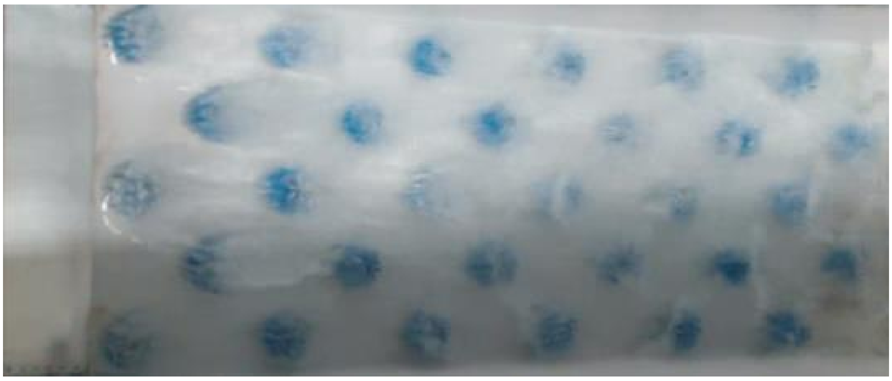


Figure A.4.2 Photographs from plan view of cluster layouts tested during laboratory gauging trials (a) *λA: D* = 0.07, S_d = 0.1; (b) *λB*: *D* = 0.07, S_d = 0.15; (c) *λC*: *D* = 0.05, S_d = 0.15.

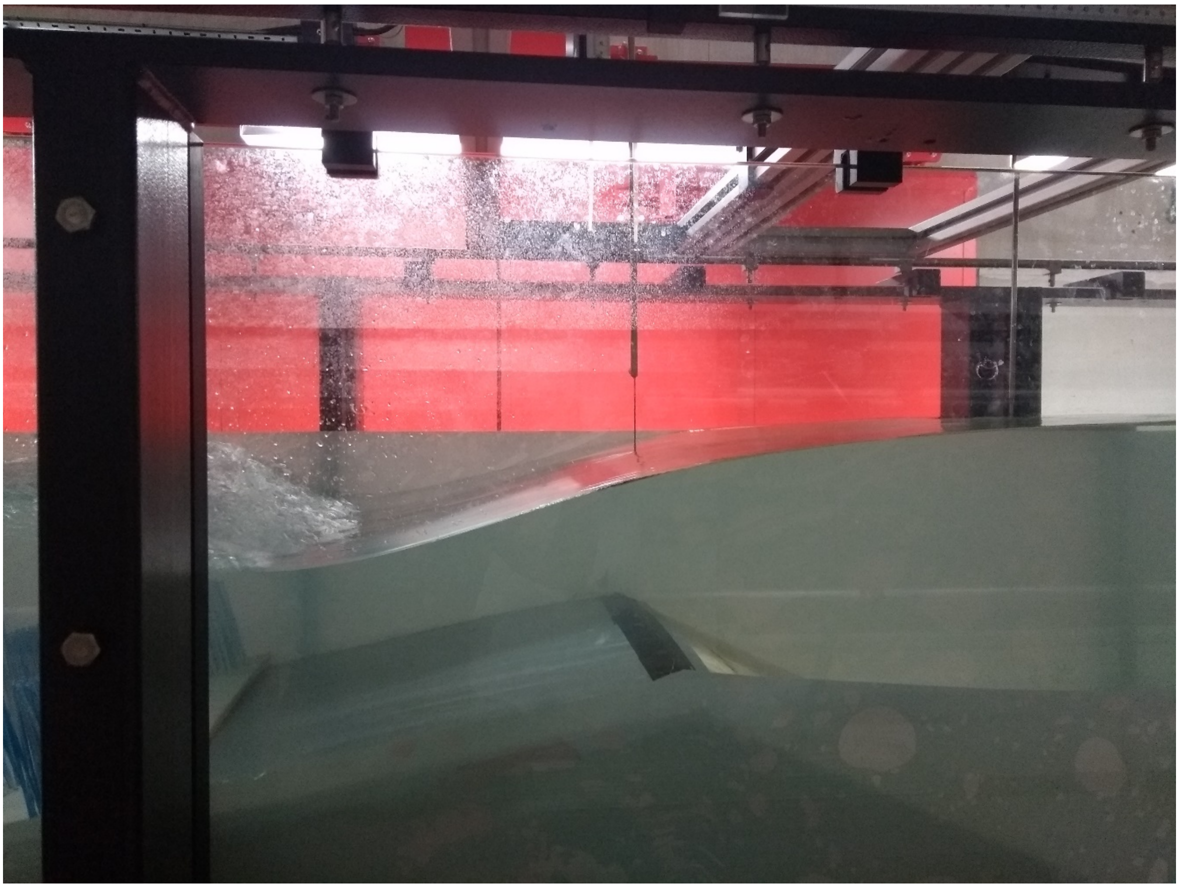
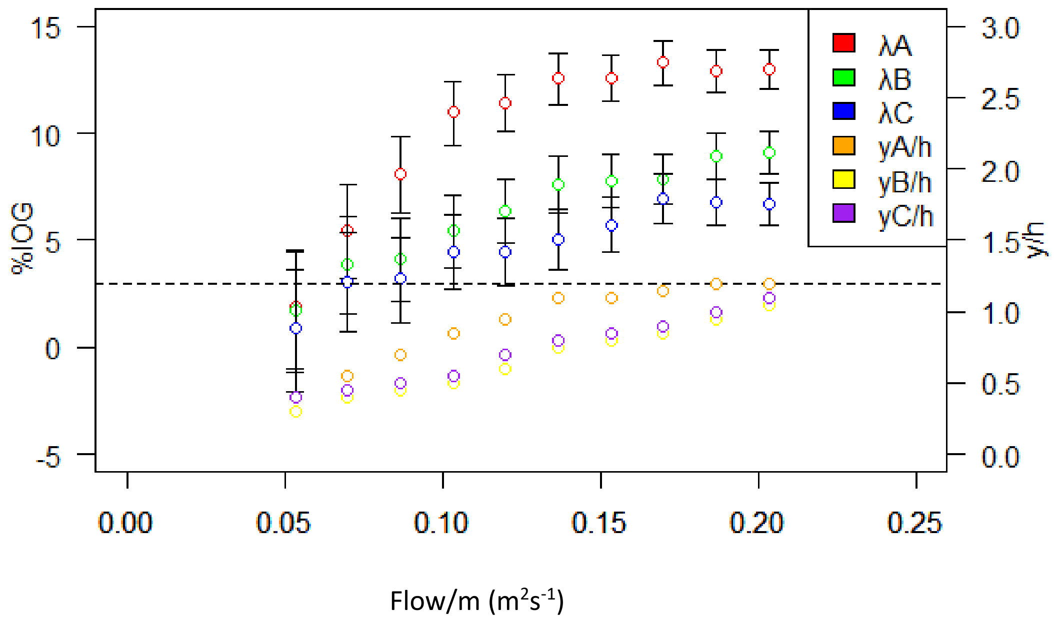


Figure A.4.3 Photograh of the weir crest and water surface profile over the crest when the tailwater level was raised sufficiently that the hydraulic jump formed just prior to the first line of clusters.

A.4.2 Percentage impact on gauging

(a)



(b)

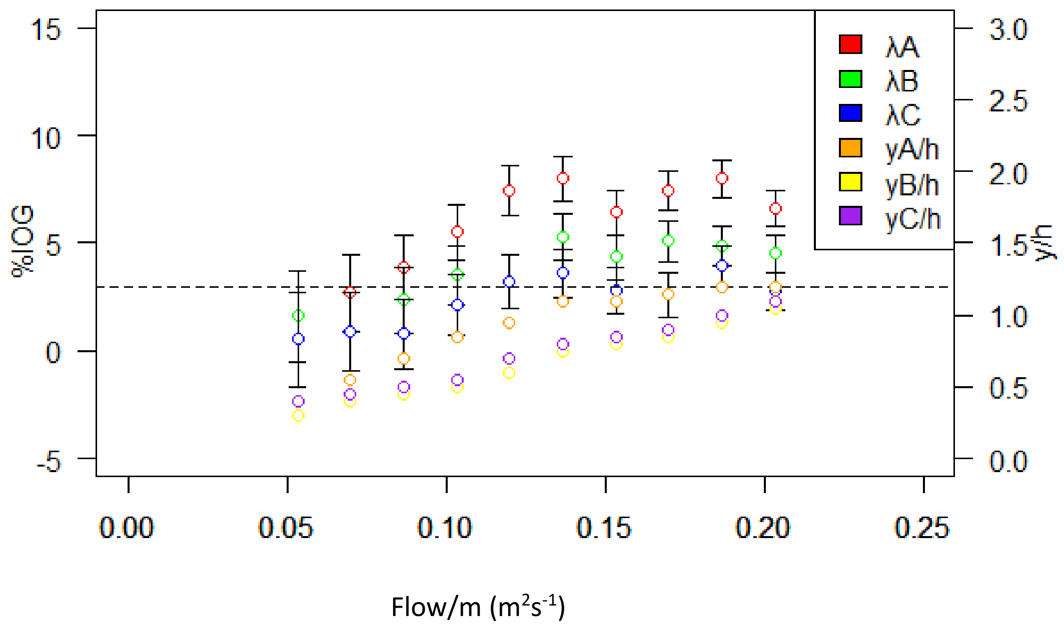
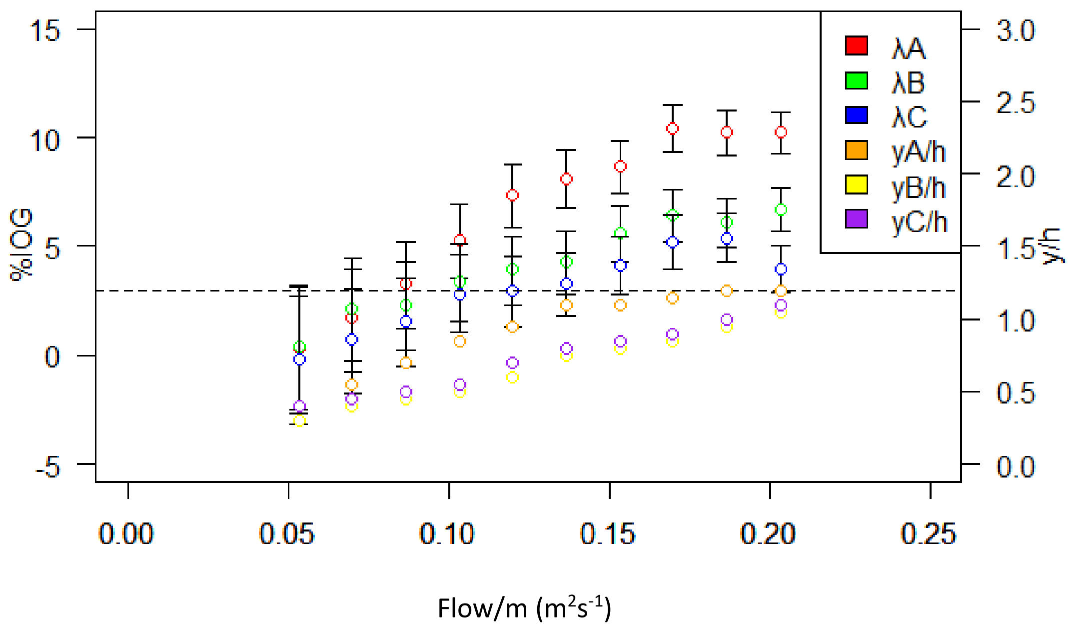


Figure A.4.4 Percentage impact on gauging (% IOG) of the clusters when placed 0.16 m from the weir crest with increasing flow per meter (Flow/m) along with relative submergence (*y/h*) for the corresponding cluster densities (*λA*, *B* and *C*) using (a) crest water levels and (b) upstream water levels to calculate impact on gauging (IOG).

(a)



(b)

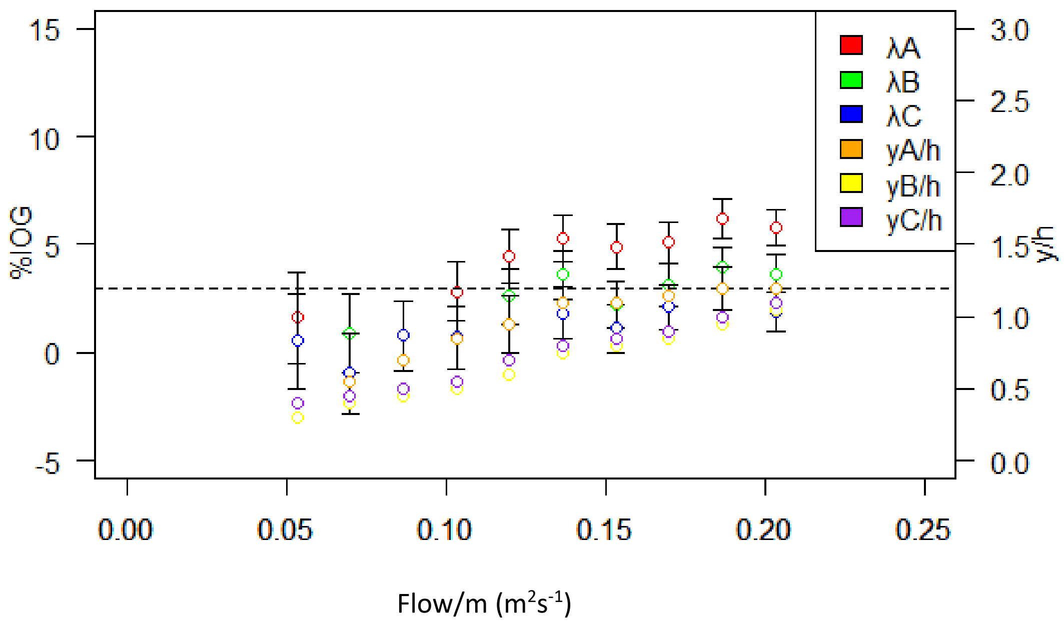
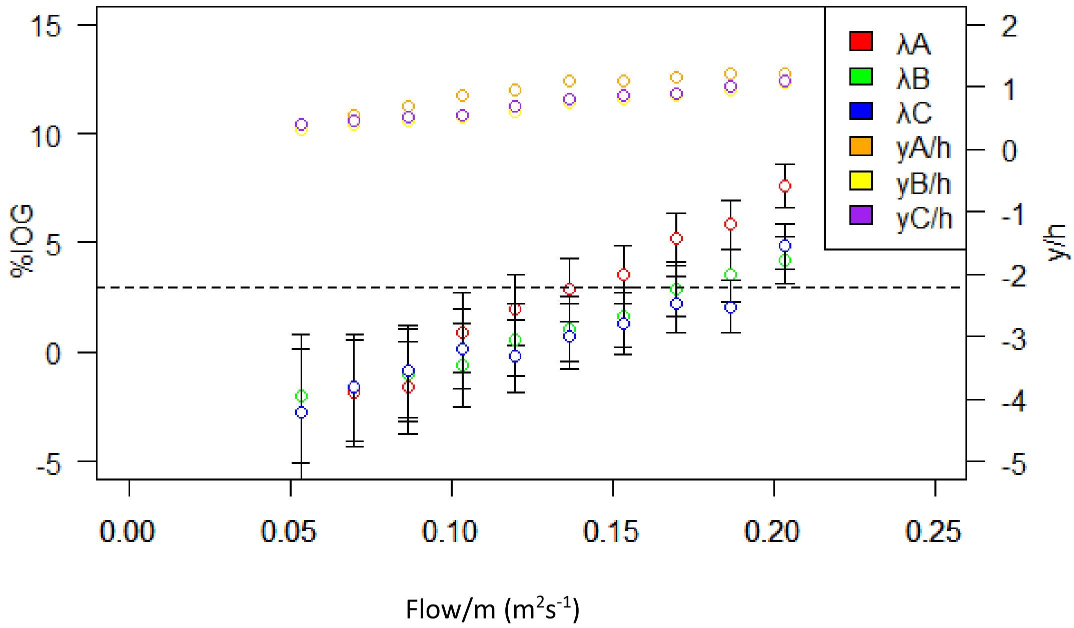


Figure A.4.5 Percentage impact on gauging (% IOG) of the clusters when placed 0.2 m from the weir crest with increasing flow per meter (Flow/m) along with relative submergence (*y/h*) for the corresponding cluster densities (*λA*, *B* and *C*) using (a) crest water levels and (b) upstream water levels to calculate impact on gauging (IOG).

(a)



(b)

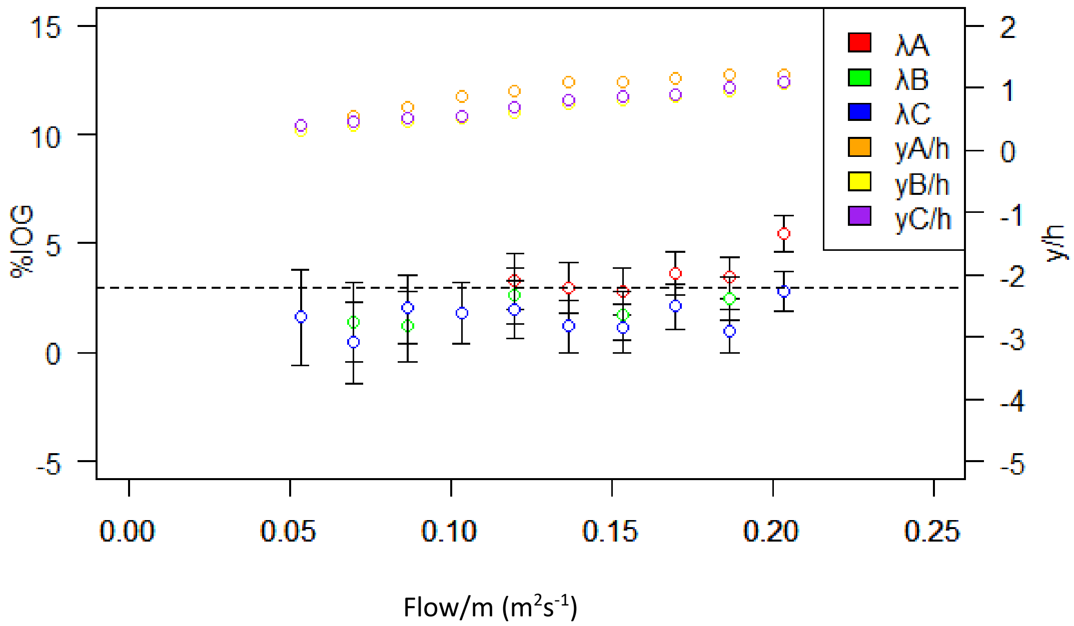
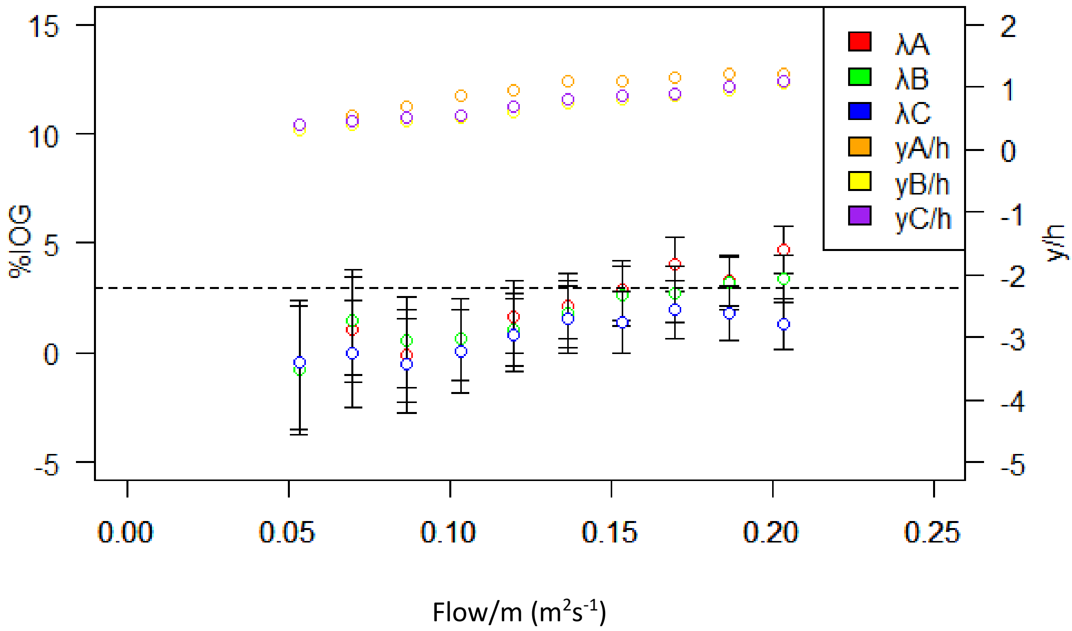


Figure A.4.6 Percentage impact on gauging (% IOG) of the clusters when placed 0.25 m from the weir crest with increasing flow per meter (Flow/m) along with relative submergence (*y/h*) for the corresponding cluster densities (*λA*, *B* and *C*) using (a) crest water levels and (b) upstream water levels to calculate impact on gauging (IOG).

(a)



(b)

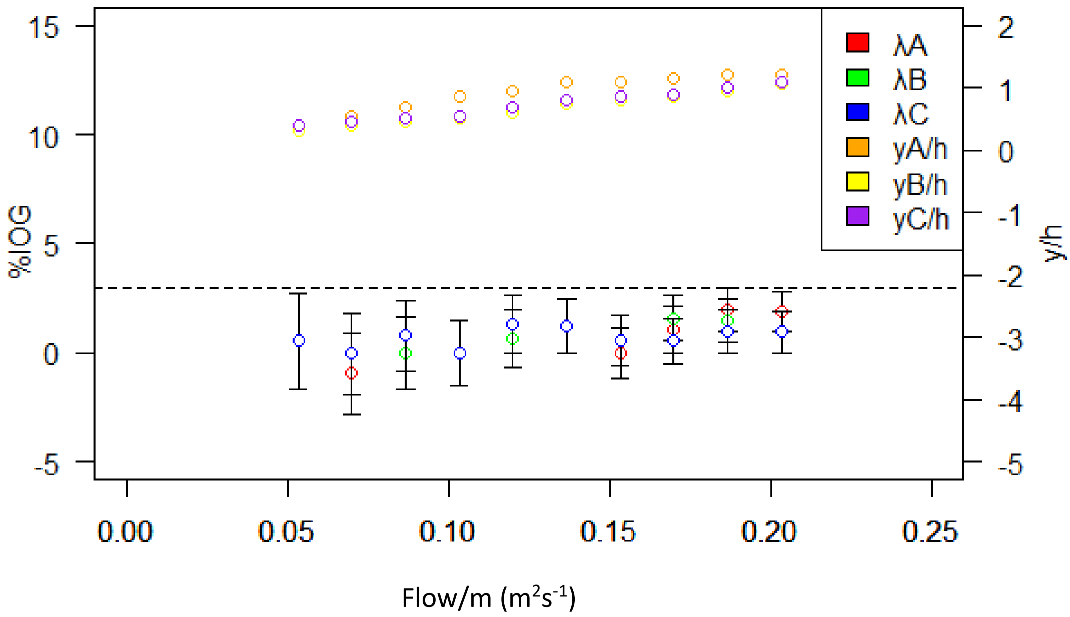
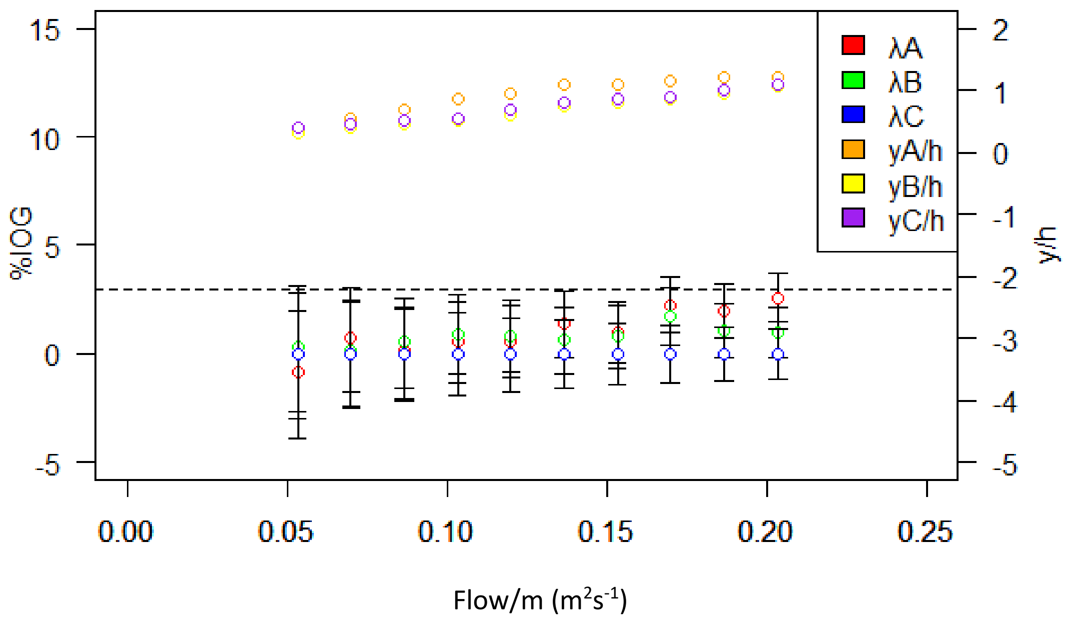


Figure A.4.7 Percentage impact on gauging (% IOG) of the clusters when placed 0.3 m from the weir crest with increasing flow per meter (Flow/m) along with relative submergence (*y/h*) for the corresponding cluster densities (*λA*, *B* and *C*) using (a) crest water levels and (b) upstream water levels to calculate impact on gauging (IOG).

(a)



(b)

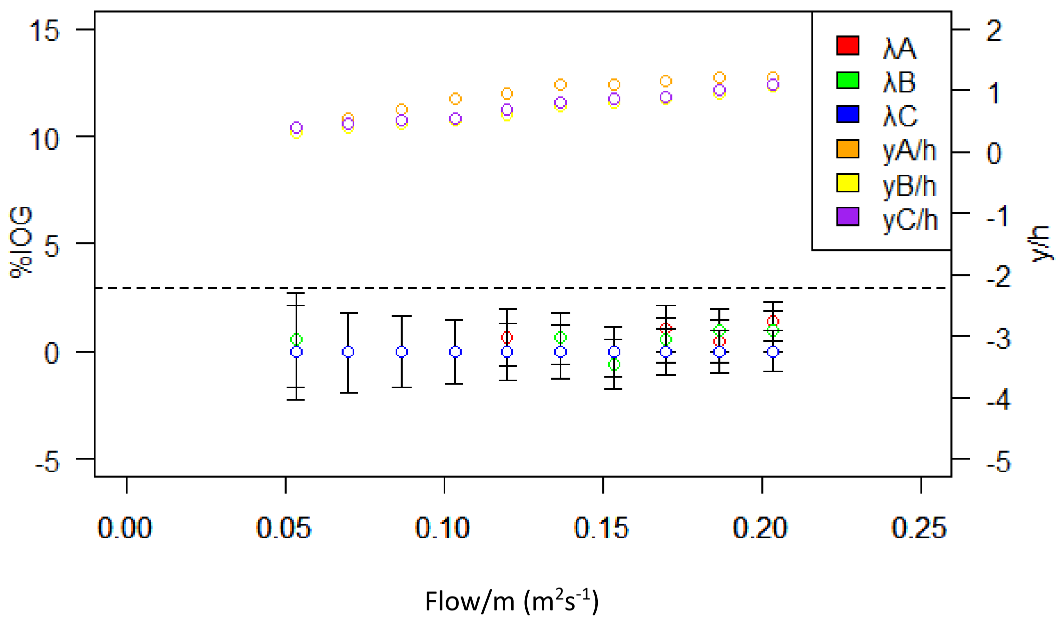
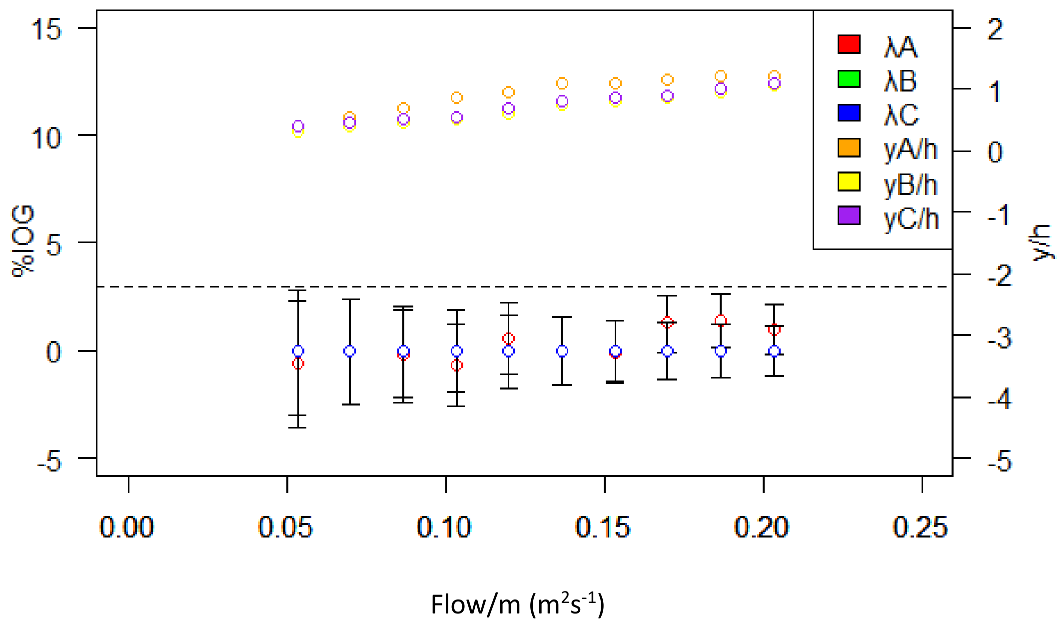


Figure A.4.8 Percentage impact on gauging (% IOG) of the clusters when placed 0.35 m from the weir crest with increasing flow per meter (Flow/m) along with relative submergence (*y/h*) for the corresponding cluster densities (*λA*, *B* and *C*) using (a) crest water levels and (b) upstream water levels to calculate impact on gauging (IOG).

(a)



(b)

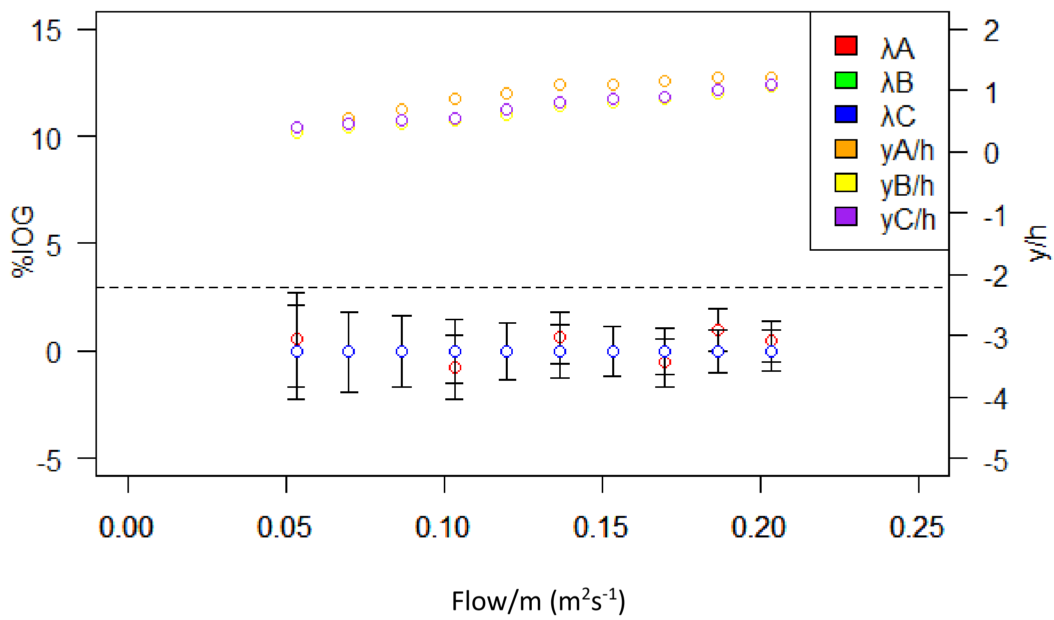
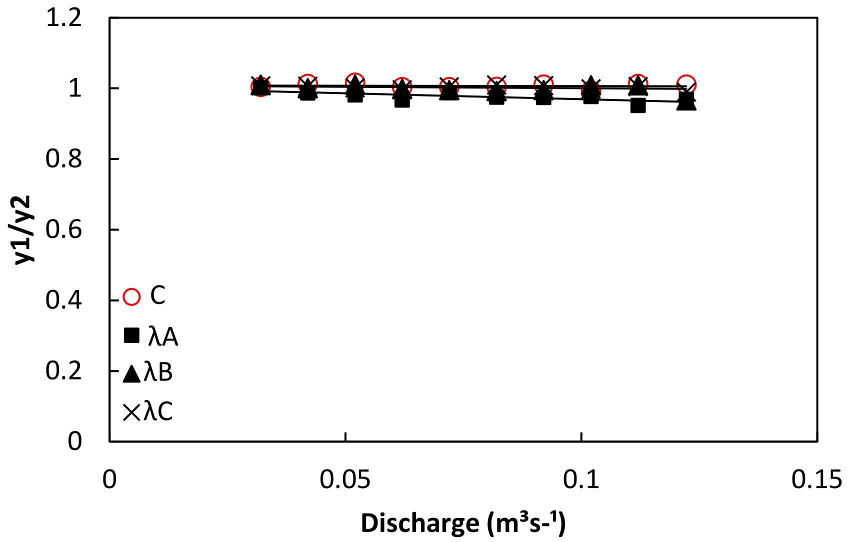


Figure A.4.9 Percentage impact on gauging (% IOG) of the clusters when placed 0.4 m from the weir crest with increasing flow per meter (Flow/m) along with relative submergence (*y/h*) for the corresponding cluster densities (*λA*, *B* and *C*) using (a) crest water levels and (b) upstream water levels to calculate impact on gauging (IOG).

A.4.3 Modular limit

The drowning ratio/modular limit was tested at the distance determined with which the array arrangement did not affect gauging. For each discharge a weir at the end of the flume was raised until drowning occurred (where upstream water levels (*y1*) were affected by downstream water levels (*y2*) by 1mm) at which point the downstream water depth was re-measured. Unfortunately, fluctuations in water level downstream (*y2*) for the different densities increased the measurement error therefore making it difficult to draw a reliable conclusion from the data. As the density increases, the ratio at which the water depth at the crest is influenced by 1 mm decreases, this is because a greater increase in downstream water level occurs for higher densities. For the highest density, as the flow increases the ratio at which the water depth is influenced by 1 mm decreases, this is because a greater increase in downstream water level occurs as flow increases

(a)



(b)

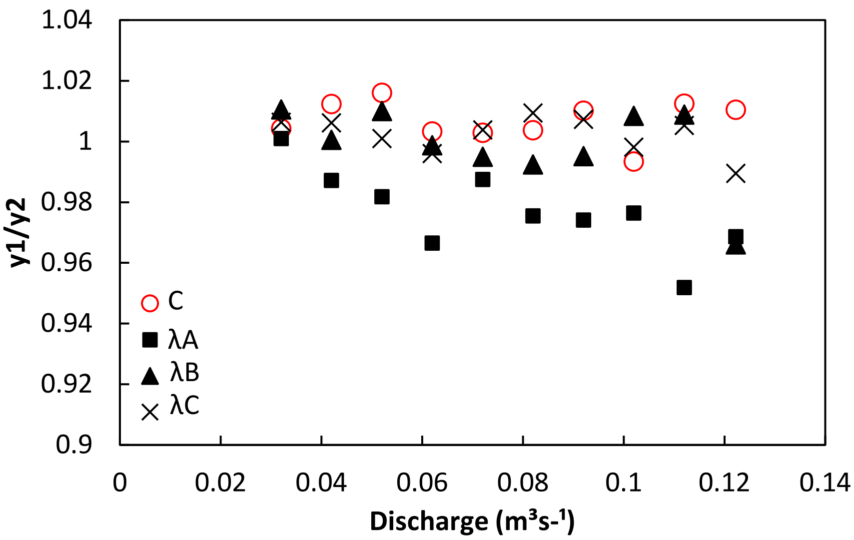


Figure A.4.11 Drowning ratio showing the effect of the different densities on modular limit.

A.4.4 Manning's n

Average velocities at the base of the weir downstream of the array were measured using an electromagnetic velocimeter and used to determine an approximate Manning's n for the densities tested during the gauging experiment.

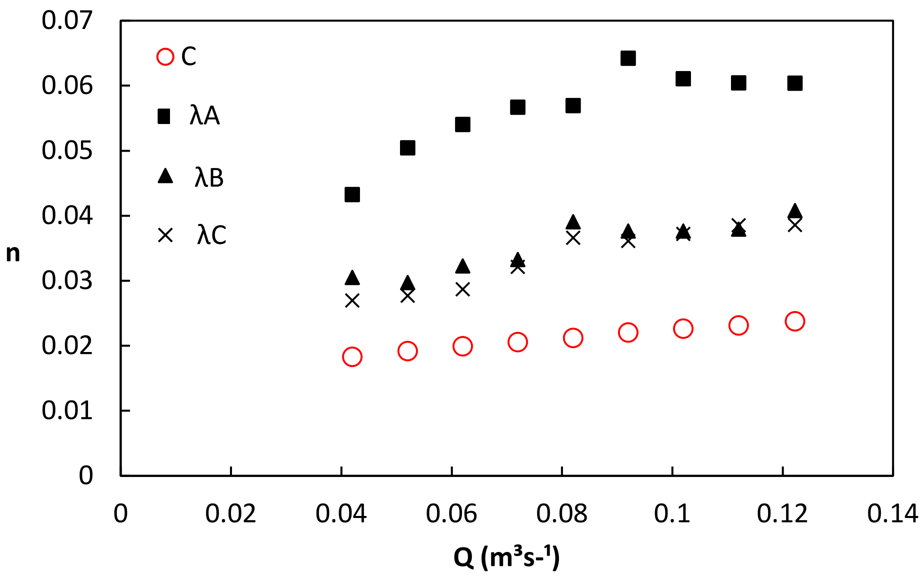


Figure A.4.10 Manning's coefficient for the densities tested during the gauging experiment.

Associated data:

Q	C	λA	λB	λC
0.042	0.018286	0.043232	0.030498	0.026938
0.052	0.019194	0.050428	0.029714	0.027678
0.062	0.019919	0.054029	0.03224	0.028666
0.072	0.020548	0.056689	0.033226	0.032109
0.082	0.021200	0.056907	0.039055	0.036602
0.092	0.022042	0.064204	0.037611	0.036104
0.102	0.022642	0.061043	0.03763	0.037167
0.112	0.023124	0.060438	0.03792	0.038511
0.122	0.023745	0.060385	0.040799	0.038564

A.5 Array Arrangements used during Experiments Documented in Chapter 6

All arrangements shown were trialled during hydraulic trials in Chapter 6. During fish passage trials in Chapter 6 the smaller spacings were excluded based on results from Chapters 4 and 5.

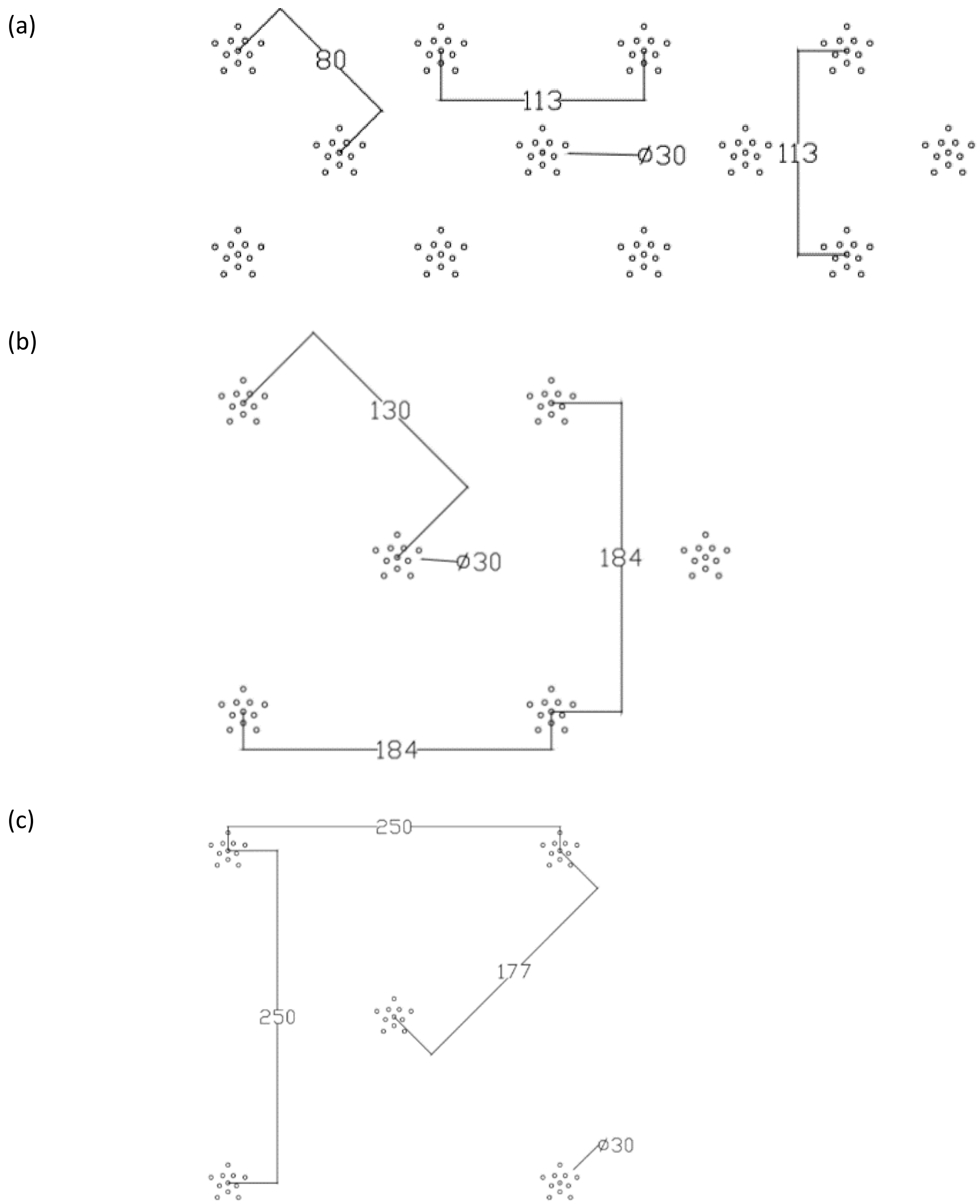


Figure A.5.1 Configurations were laser cut based on AutoCAD drawings produced where 0.03 m clusters were created with approximately 0.05, 0.1 and 0.15 m spacings ((a),(b) and (c) respectively).

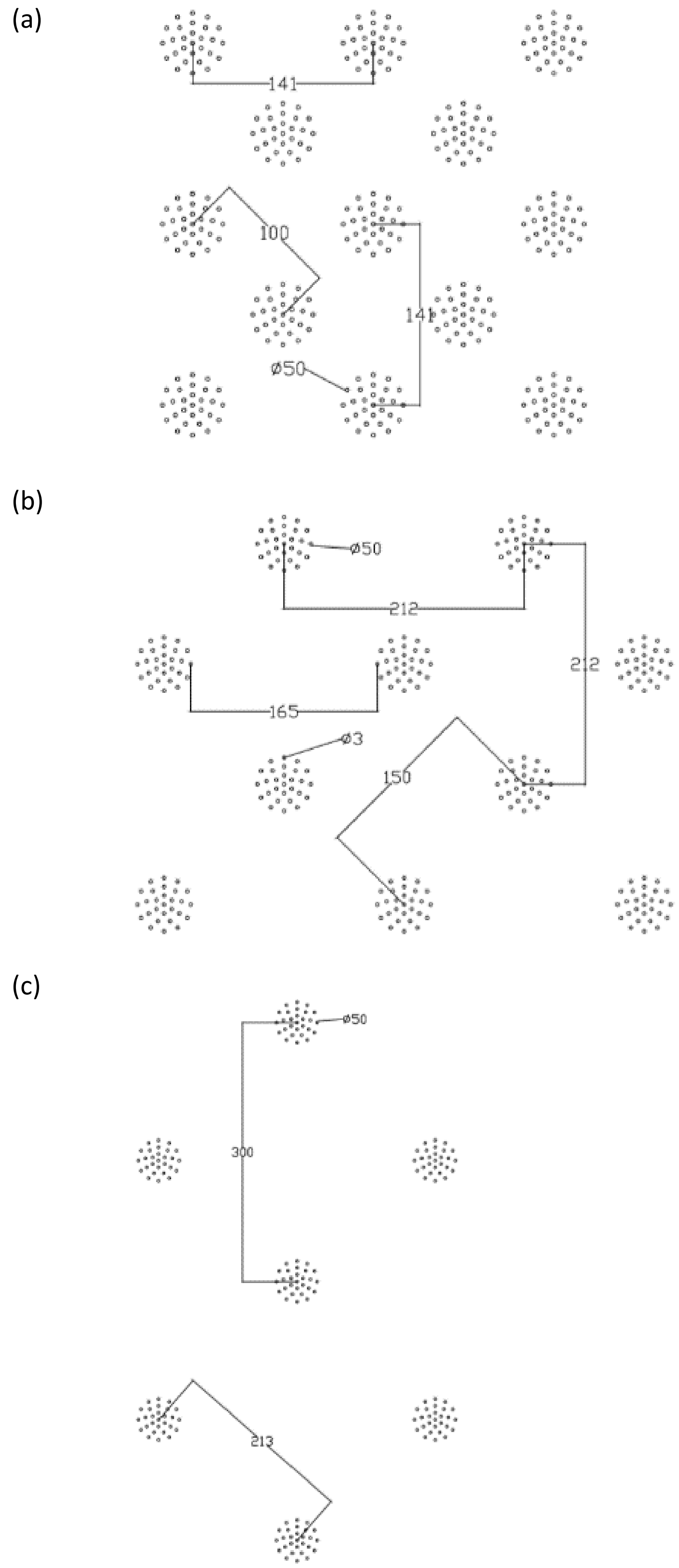


Figure A.5.2 Configurations were laser cut based on AutoCAD drawings produced where 0.05 m clusters were created with approximately 0.05, 0.1 and 0.15 m spacings ((a),(b) and (c) respectively).

(a)

(b)

(c)

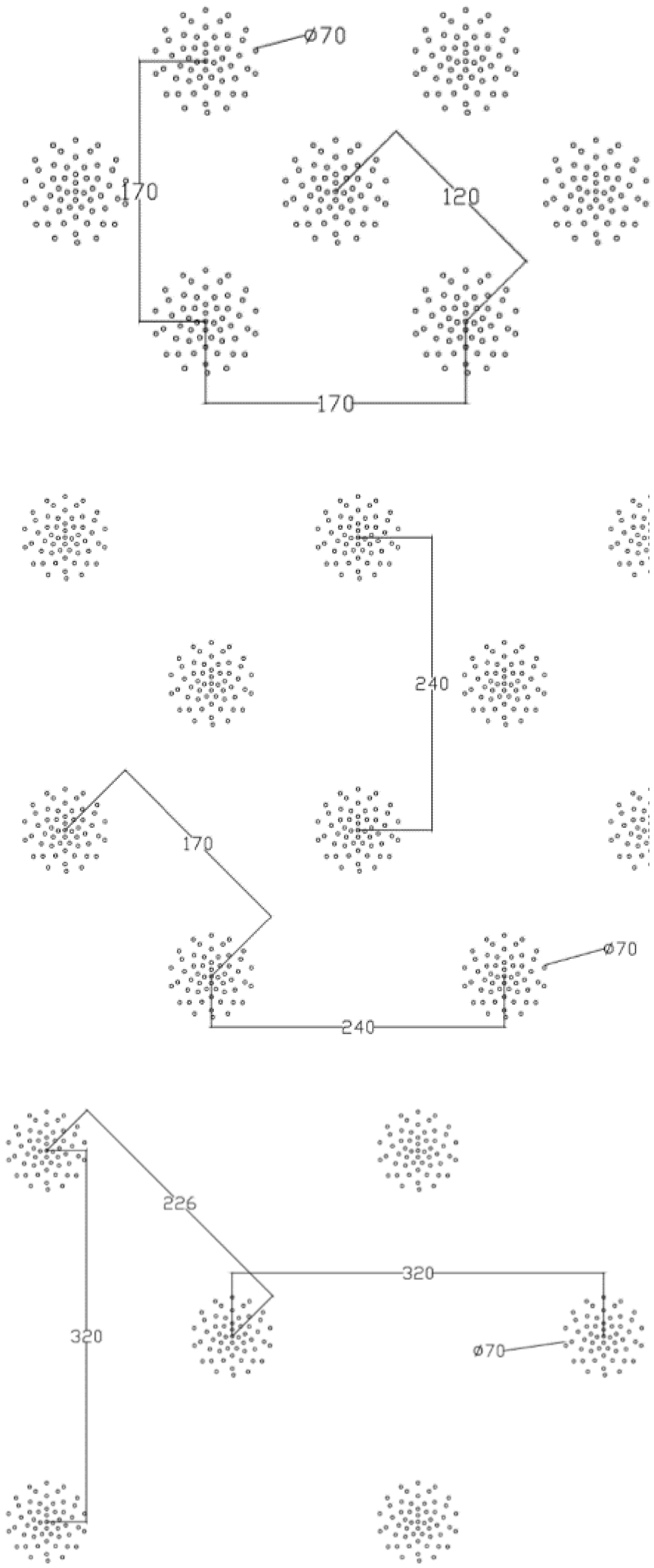


Figure A.5.3 Configurations were laser cut based on AutoCAD drawings produced where 0.07 m clusters were created with approximately 0.05, 0.1 and 0.15 m spacings ((a),(b) and (c) respectively).

A.6 Pictures of the Experimental Setup used during Fish Passage Trials Documented in Chapter 6

Below are a number of photographs taken of the experimental setup used to undertake fish passage experiments described in Chapter 5 of this thesis.

Figure A.6.1 Photograph from above with water running through a staggered array of clusters with 0.1 m diagonal spacing and 0.07 m diameter clusters.

Figure A.6.2 Photograph from above with water running through a staggered array of clusters with 0.15 m diagonal spacing and 0.07 m diameter clusters.

Figure A.6.3 Photograph from above with water running through a staggered array of clusters with 0.1 m diagonal spacing and 0.03 m diameter clusters.

Figure A.6.4 Photograph of some of the tanks used to home the fish during experiments.

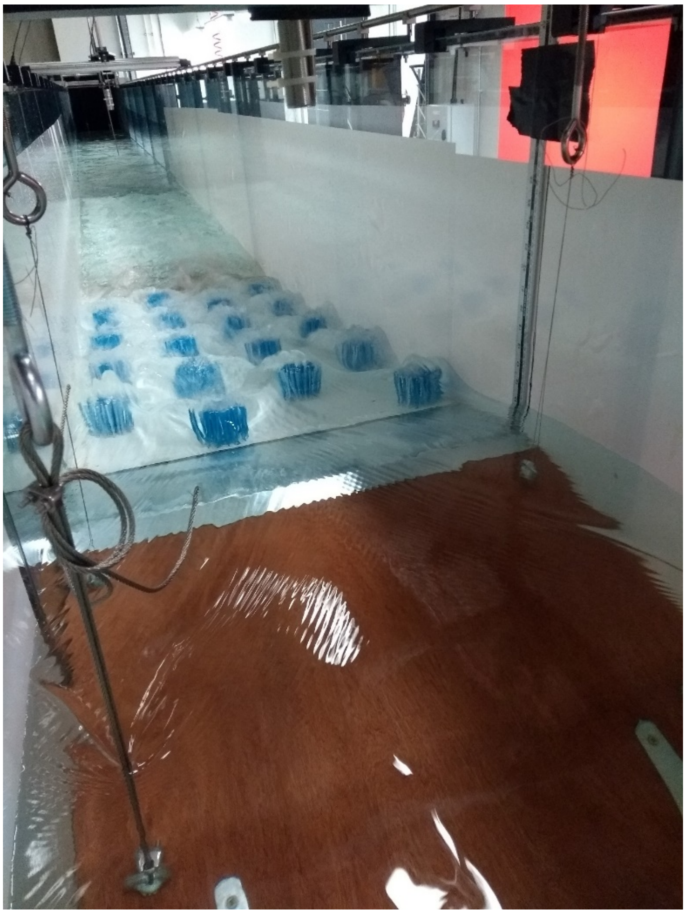


Figure A.6.5 Photograph of the CBCs on the weir face looking downstream. Cables shown were used to alter the weir slope between experiments to enable water velocities to be made comparable between different treatments of cluster density.

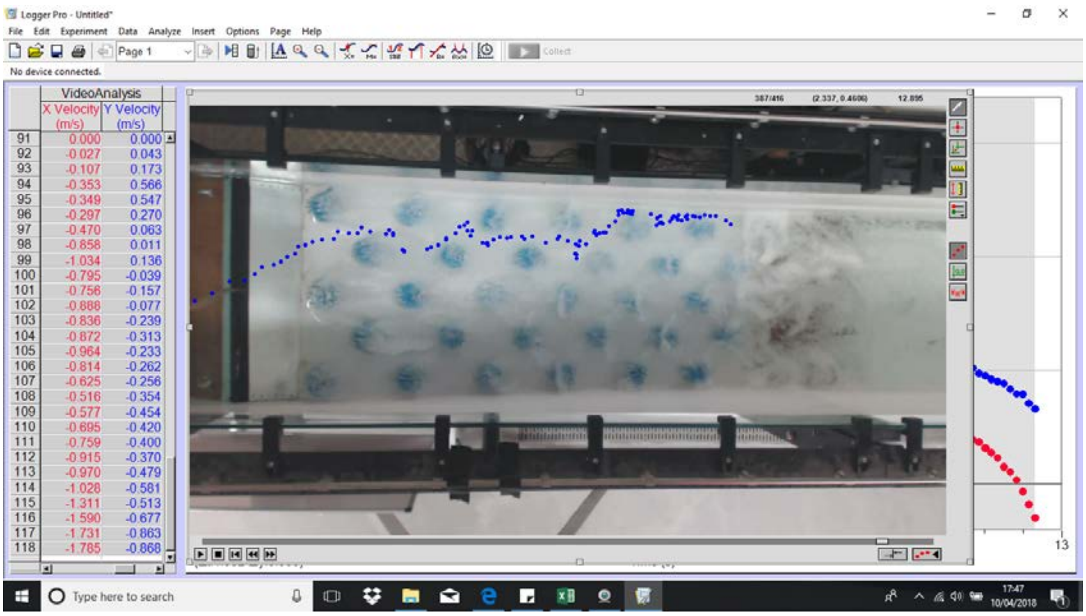


Figure A.6.6 Screenshot of a tracked fish pathway in Logger Pro using the videos collected during experimental trials and the corresponding x and y co-ordinates produced by the software.

A.7 Pictures of the Experimental Setup used during Hydraulic Experiments Documented in Chapter 6

Below are a number of photographs taken of the experimental setup used to undertake laboratory hydraulic experiments described in Chapter 6 of this thesis.

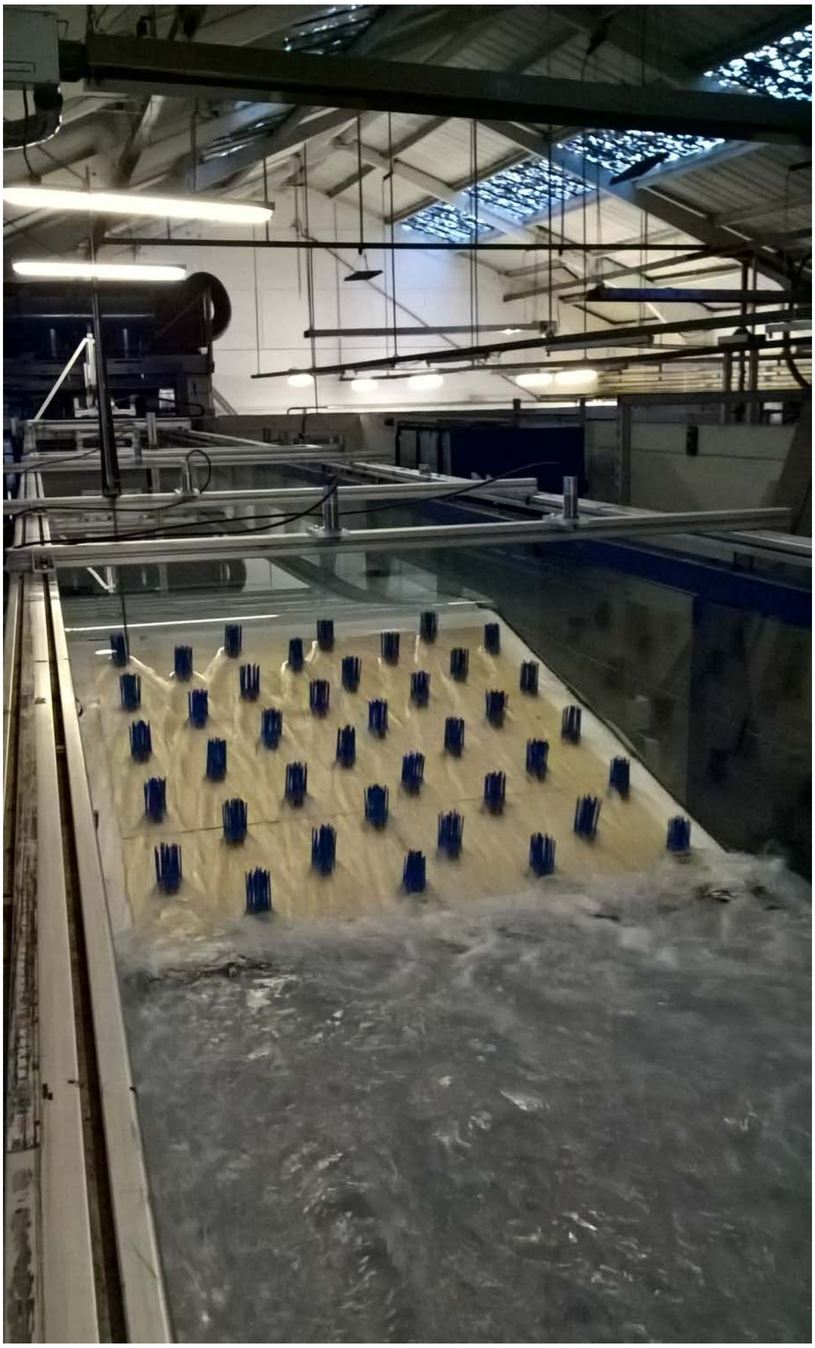


Figure A.7.1 An array configuration mounted onto a Crump weir installed in a recirculating hydraulic flume

Figure A.7.2 Undertaking point gauge measurements upstream of the CBC array.

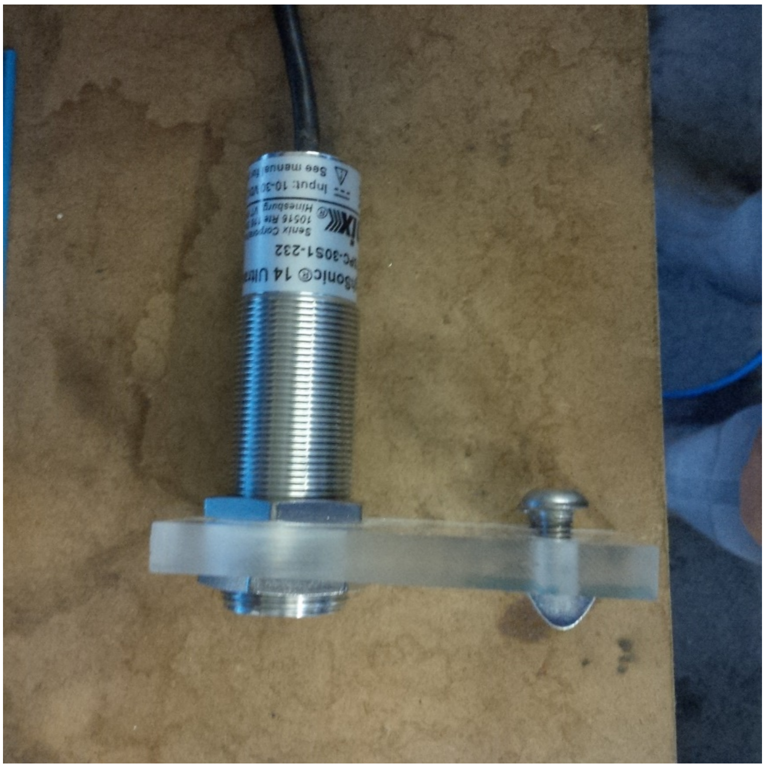
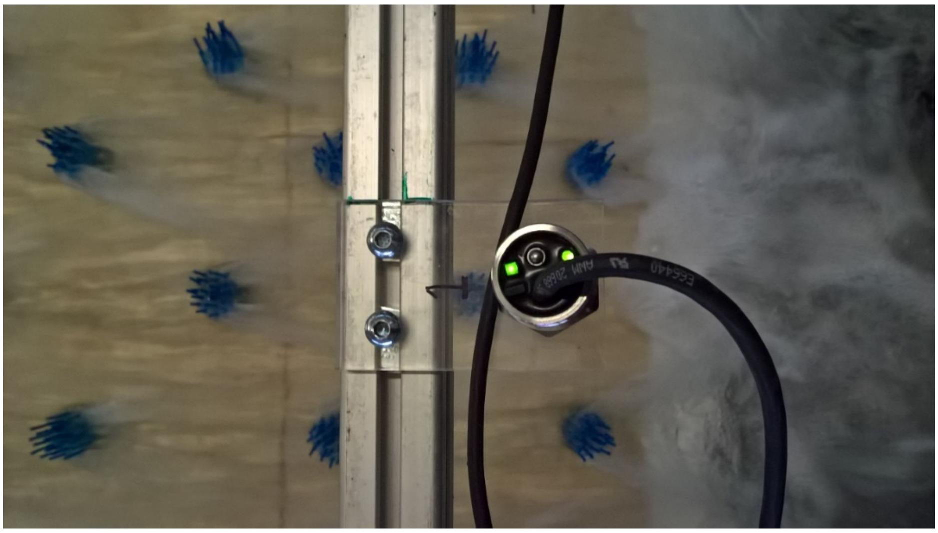


Figure A.7.3 The ultrasonic sensor used to measure water levels during hydraulic trials within the CBC array.

(a)

(b)



(c)

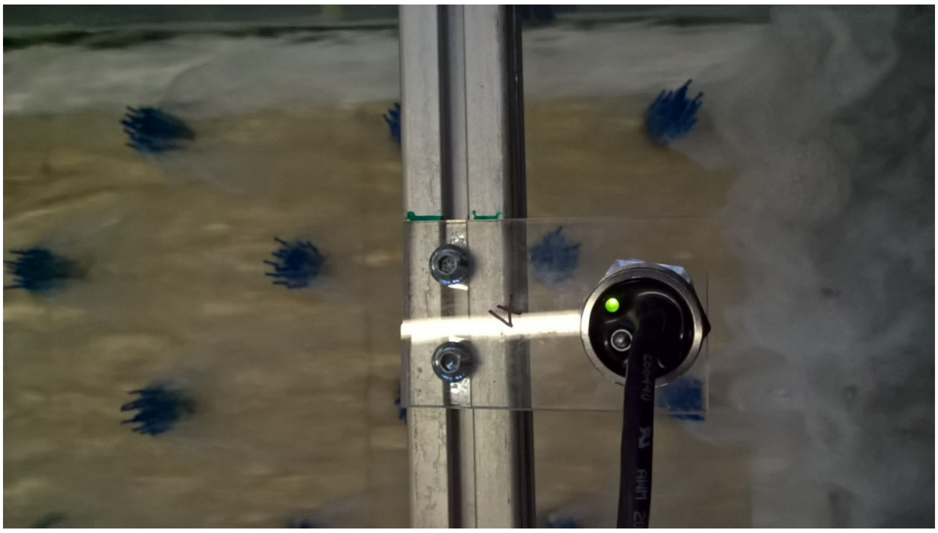


Figure A.7.4 Locations of the ultrasonic sensors above the CBC array showing (a) sensor inbetween the first set of clusters, (b) behind the cluster just upstream of the hydraulic jump and (c) inbetween the clusters just upstream of the hydraulic jump.

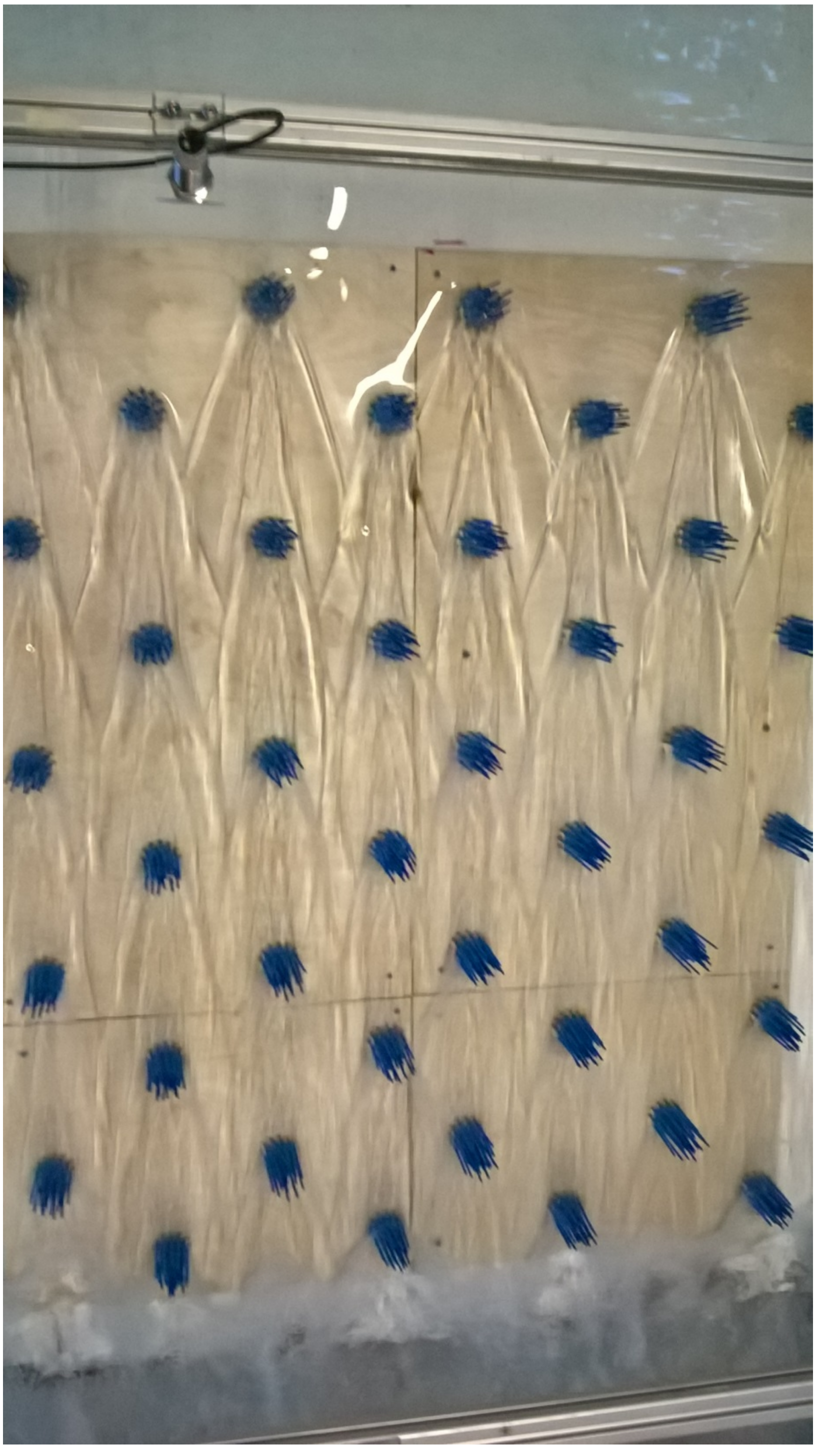


Figure A.7.5 Photograph of flow through a staggered array of cylindrical clusters

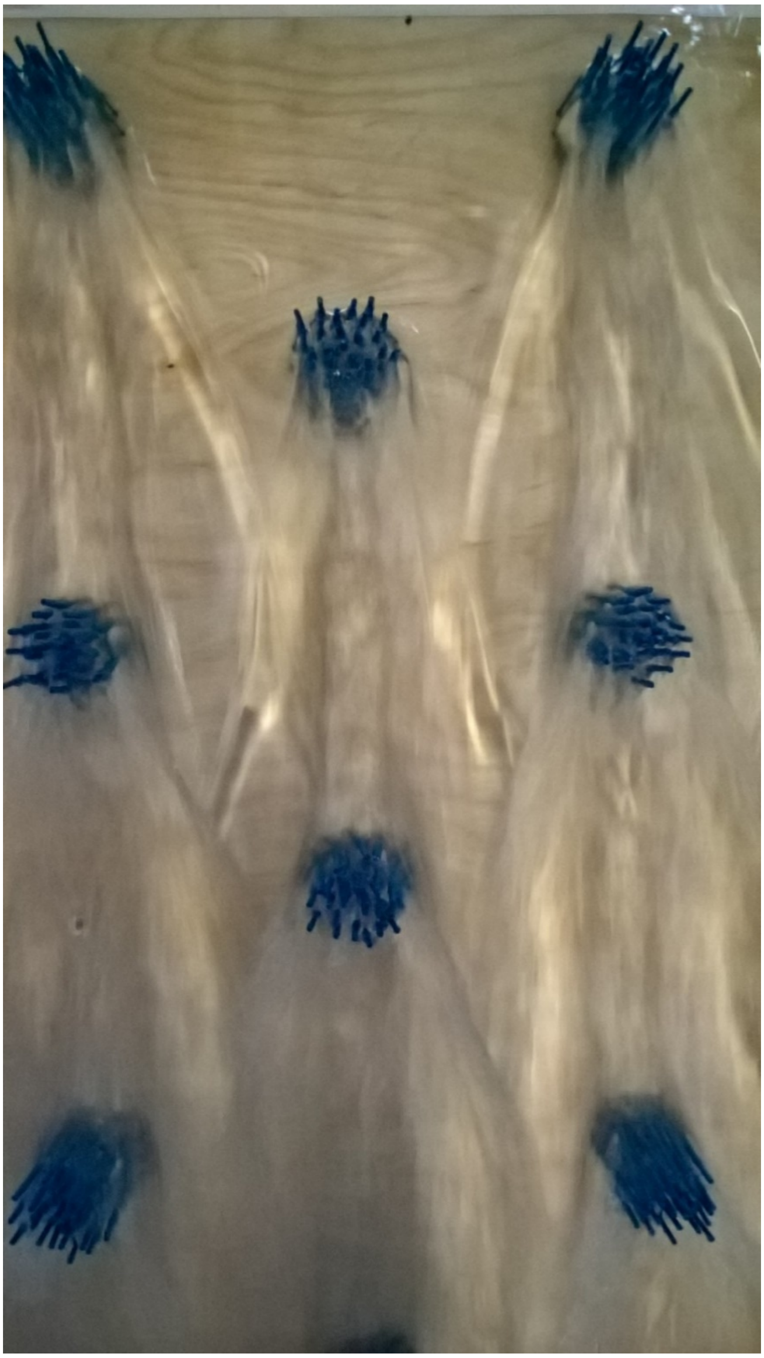


Figure A.7.6 A photograph of flow through unsubmerged staggered array of clusters.

Figure A.7.7 A photograph of flow through a staggered array of clusters with flow overtopping the clusters in places dependent on placement within the array.

Figure A.7.8 Water surface profile over the 0.07 m diaeter CBCs when submerged slightly showing an undulating water surface.

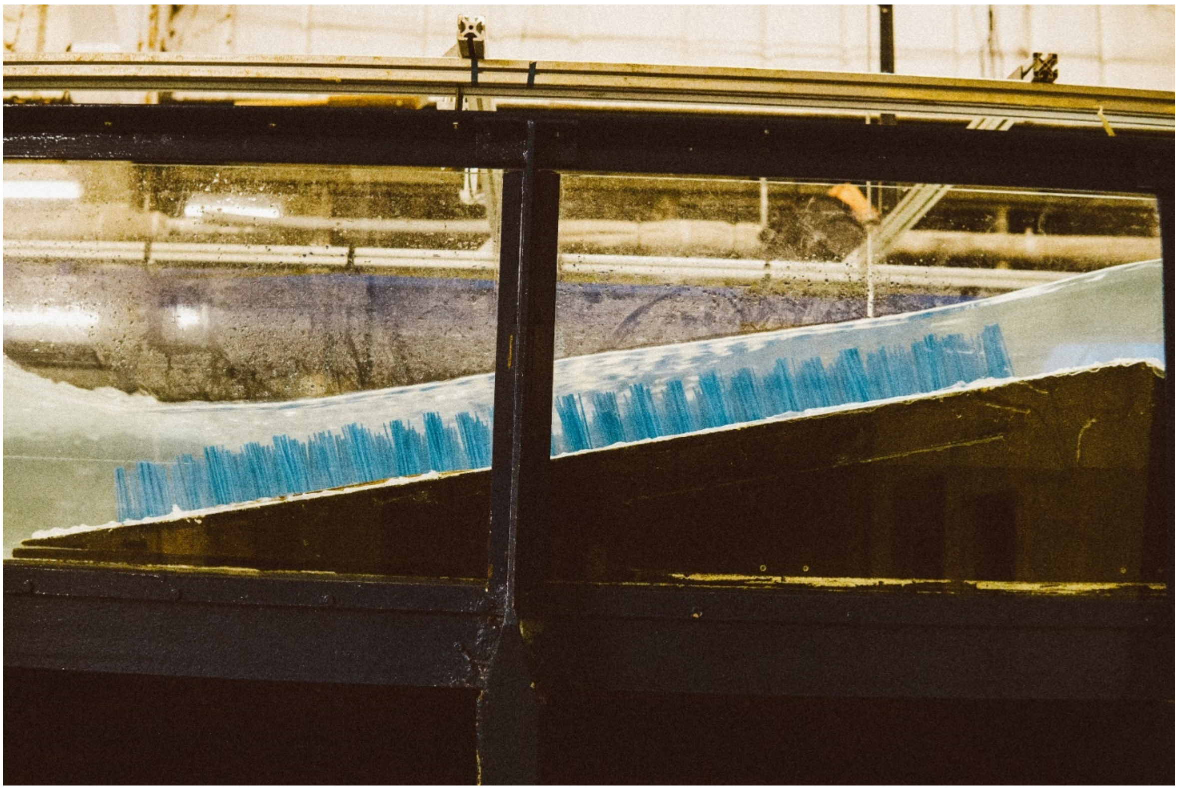


Figure A.7.9 Section view of the CBCs on the weir face showing the water surface profile under submerged conditions.

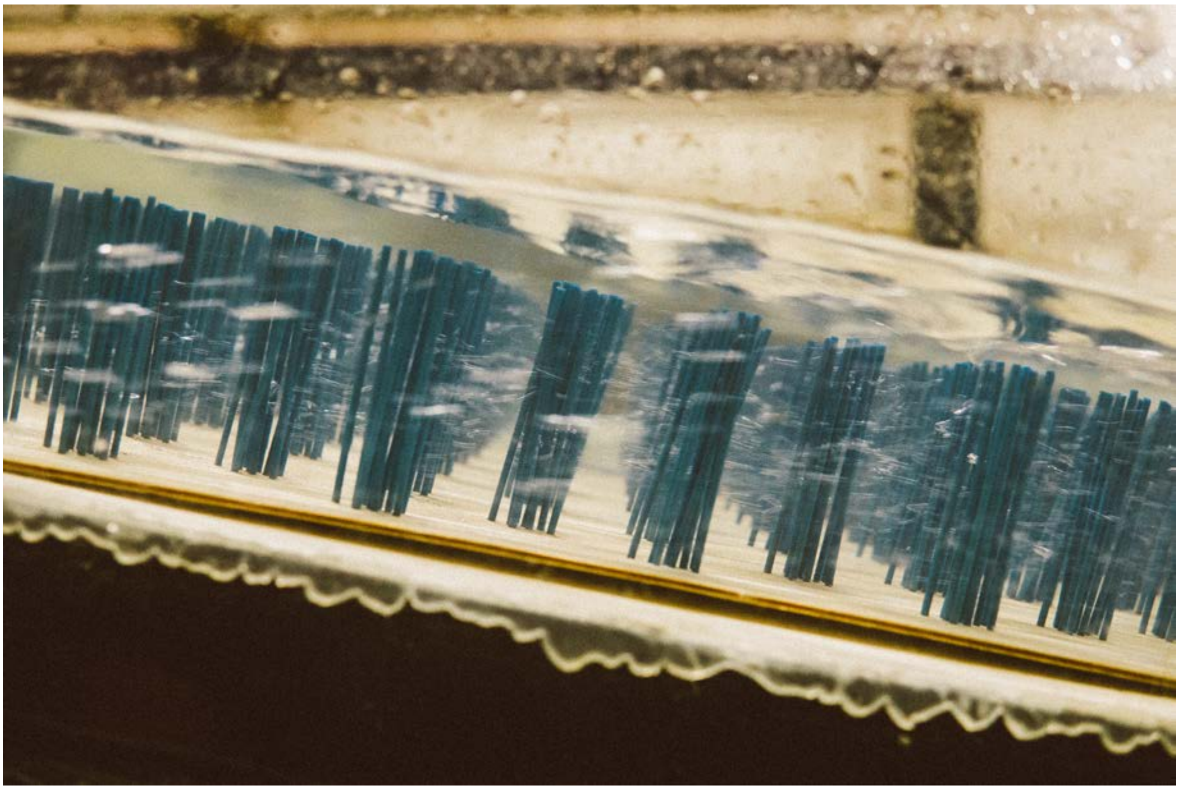


Figure A.7.10 Photograph of the aeration within the CBC array with 0.03 m diameter clusters when just submerged.

Figure A.7.11 Photograph of the water surface profile looking downstream with clusters only just submerged on the upstream end of the CBC array, progressively getting shallower.

Figure A.7.12 Plan view of a number of unsubmerged CBCs with water flowing from left to right showing the water diverging around the clusters and the wakes created.

Figure A.7.13 Plan view of a single CBC with water flowing from left to right.

(a)

(b)

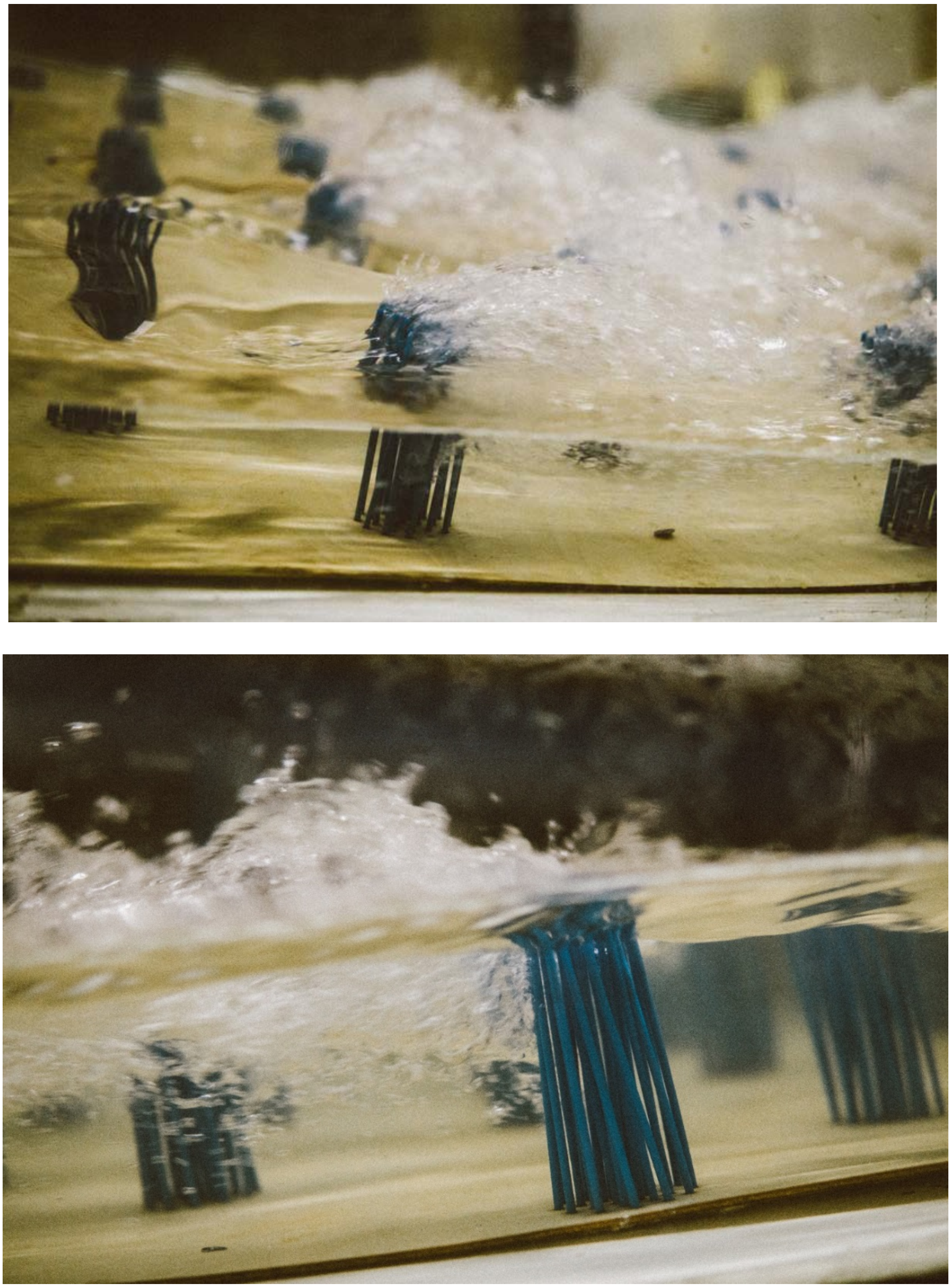


Figure A.7.14 Side view of the CBCs showing the free end effects created when water depth is equal to cluster height, hitting the tops of the bristles, creating aeration and energy loss with (a) water flowing from left to right and (b) water flowing from right to left.

References

Aberle, J. and Järvelä, J. (2013) Flow resistance of emergent rigid and flexible floodplain vegetation. Journal of Hydraulic Research, 51 (1), 33-45.

Amaral, S.D., Branco. P., Katopodis. C., Ferreira. M.T., Pinheiro. A.N. and Santos. J.M. (2019) Passage Performance of Potamodromous Cyprinids over an Experimental Low-Head Ramped Weir: The Effect of Ramp Length and Slope. *Sustainability*, *11*(5), 1456. https://doi.org/10.3390/su11051456.

Andre´n, H. (1994) Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. Oikos 71, 355–366.

Armstrong, G.S., Aprahamian, M.W., Fewings, A.G., Gough, P.J., Reader, N.A. and Varallo, P.V. (2010) Environment Agency Fish Pass Manual. Environment Agency.

Ashraf, I., Bradshaw, H., Ha, T-T., Halloy, J., Godoy-Diana, R. and Thiria, B. (2017) Phalanx pattern leads to energy saving in fish. Proceedings of the National Academy of Sciences, 114 (36) 9599-9604. doi: 10.1073/pnas.1706503114.

Auel, C., Albayrak, I. and Boes, R.M. (2014) Turbulence Characteristics in Supercritical Open Channel Flows: Effects of Froude Number and Aspect Ratio. Journal of Hydraulic Engineering, 140.

Bainbridge, R. (1957) The speed of swimming of fish as related to size and to the frequency and amplitude of the tail beat. The Zoological Laboratory, Cambridge, 109.

Baker, C. F. and Boubée, J. A. (2006) Upstream passage of inanga Galaxias maculatus and redfin bullies Gobiomorphus huttoni over artificial ramps. Journal of Fish Biology, 69: 668-681. doi:10.1111/j.1095-8649.2006.01138.x.

Baptist, M.J., Babovic, V., Rodríguez Uthurburu, J., Keijzer, M., Uittenbogaard, R.E., Mynett, A. and Verwey, A. (2007) On inducing equations for vegetation resistance. Journal of Hydraulic Research, 45 (4), 435-450.

Baras, E., Lambert, H., Philippart J.G. (1994) A comprehensive assessment of the failure of Barbus barbus spawning migrations through a fish pass in the canalized River Meuse (Belgium) Aquat. Living Resour, 7, pp. 181–189.

Beach, M.H. (1984) Fish pass design — criteria for the design and approval of fish passes and other structures to facilitate the passage of migratory fish in rivers. Fish. Res. Tech. Rep. No. 78. Ministry of Agriculture, Fisheries, and Food, Directorate of Fisheries Research, Lowestoft, UK.

Beal, D.N., Hover, F.S., Triantafyllou, M.S., Liao, J.C. and Lauder, G.V. (2006) Passive propulsion in vortex wakes. Journal of Fluid Mechanics, 549 (-1), 385.

Birkhofer, B., Meile, T., De Cesare, G., Jeelani, S.A.K. and Windhab, E. (2016) Use of gas bubbles for ultrasound Doppler flow velocity profile measurement. Flow Measurement and Instrumentation. 52. 10.1016/j.flowmeasinst.2016.10.015.

Blevins (1990) Flow Induced Vibration, 2nd Ed. Van Nostrand Reinhold.

British Standards Institution. (1986) BS3680 Measurement of liquid flow in open channels – Part 4: Weirs and flumes - Part 4B: Triangular Profile Weirs. London: BSI Standards Publication.

BS ISO 4377. (2012) Hydrometric determinations- flow measurement in open channels using structures - Flat-V weirs Switzerland: ISO.

Bunt, C.M., Castro-Santos, T. and Haro, A. (2012) Performance of Fish Passage Structures at Upstream Barriers to Migration. River Research and Applications, 28 (4), 457-478.

Burchsted, D., Daniels, M., Thorson,R. and Vokoun, J (2010) The River Discontinuum: Applying Beaver Modifications to Baseline Conditions for Restoration of Forested Headwaters BioScience, 60 (11):908. http://dx.doi.org/10.1525/bio.2010.60.11.7).

Castro-Santos, T. (2005) Optimal swim speeds for traversing velocity barriers: an analysis of volitional high-speed swimming behavior of migratory fishes. J Exp Biol, 208 (Pt 3), 421-432.

Castro-Santos, T., and B. H. Letcher. (2010). Modelling migratory energetics of Connecticut River American shad (Alosa sapidissima): implications for the conservation of an iteroparous anadromous fish. Canadian Journal of Fisheries and Aquatic Sciences 67:806-830.

Castro-Santos, T., Cotel, A. and Webb, P.W. (2009) Fishway evaluations for better bioengineering -- an integrative approach.

Chadwick, A., Morfett, J. and Brothwick, M. (2004) Hydraulics in Civil and Environmental Engineering, 4th ed. London: Spon Press.

Chanson, H. and Gonzalez, C.A. (2005) Physical Modelling and Scale Effects of Air-Water Flows on Stepped Spillways. Journal of Zhejiang University – Science A, 6(3), pp. 246-250.

References

Chen, Z., Ortiz, A., Zong, L. and Nepf, H. (2012) The wake structure behind a porous obstruction and its implications for deposition near a finite patch of emergent vegetation. Water Resources Research, 48 (9).

Cheng, N.-S. and Nguyen, H.T. (2011) Hydraulic Radius for Evaluating Resistance Induced by Simulated Emergent Vegetation in Open-Channel Flows. American Society of Civil Engineers, ASCE, 137, 995-1004.

Cheng, N.-S. (2015) Single-Layer Model for Average Flow Velocity with Submerged Rigid Cylinders. Journal of Hydraulic Engineering, 141 (10), 06015012.

Chow, V.T. (1959) Open-Channel Hydraulics. New York: McGraw Hill.

Clay, C.H. (1995) Design of Fishways and Other Fish Facilities. CRC Press, Inc.

Clemmens, A.J., Wahl, T.L., Bos, M.G. and Replogle, J.A. (2001) Water Measurement with Flumes and Weirs. International Institute for Land Reclamation and Improvement / ILRI P.O. BOX4 5, 6700 AA Wageningen, The Netherlands.

Clough, S.C. and Turnpenny, A.W.H. (2001) Swimming Speeds in Fish: Phase 1. Environment Agency.

Colavecchia, M., Katopodis, C., Goosney, R., Scruton D.A. and McKinley R.S. (1998) Measurements of burst swimming performance in wild Atlantic salmon (Salmo salar L.) using digital telemetry. Regulated Rivers: Research and Management 14: 41–51.

Cotel, A.J., Webb, P.W. and Tritico, H. (2006) Do Brown Trout Choose Locations with Reduced Turbulence? Transactions of the American Fisheries Society, 135 (3), 610-619.

Cotel, A.J. and Webb, P.W. (2015) Living in a Turbulent World - A New Conceptual Framework for the Interactions of Fish and Eddies, Integrative and Comparative Biology, Volume 55, Issue 4, 1, 662 – 672. https://doi.org/10.1093/icb/icv085.

Devenport, W. J. and Borgoltz, A. (2016) Flow past a circular cylinder http://www.dept.aoe.vt.edu/~aborgolt/aoe3054/manual/expt3/index.html.

Dibley, M., Child, S.I., R. and Wiggins, A. (2012) Fish and flow – Maintaining the balance between hydrometric uncertainty and aids to fish passage at flow gauging structures. 01-05.

Dixon, R., Montali-Ashworth, D., Potts, D. and Prince, J. (2014) Developing an environmentally friendly low cost flat-V gauging weir.

Don Catchment Rivers Trust. (2013) River Loxley: Fish Passage Scoping Study Options Report. Admiral House Rose Wharf 78 East Street Leeds LS9 8EE United Kingdom: Ltd, O.a.P.

Dodd, J.R., Cowx, I.G. and Bolland, J.D. (2018) Win, win, win: Low cost baffle fish pass provides improved passage efficiency, reduced passage time and broadened passage flows over a low-head weir. Ecological Engineering, 120, 68-75. https://doi.org/10.1016/j.ecoleng.2018.05.028.

Enders, E.C., Boisclair, D. and Roy, A.G. (2003) The effect of turbulence on the cost of swimming for juvenile Atlantic salmon (Salmo salar). Canadian Journal of Fisheries and Aquatic Sciences, 60 (9), 1149-1160.

Etminan, V., Lowe, R. J. and Ghisalberti, M. (2017) A new model for predicting the drag exerted by vegetation canopies, Water Resour. Res., 53, 3179–3196. doi:10.1002/2016WR020090.

European Commision, E. (2010) Water Framework Directive.

Fairfull, S. (2013) Fisheries NSW Policy and Guidelines for Fish Habitat Conservation and Management (2013 upate). Policy Number: TI-O-138. NSW Department of Primary Industries. ISBN 978 1 74256 283 4.

FAO. and DVWK. (2002) Fish passes – Design, dimensions and monitoring. Rome: FAO. 119pp.

Fathi-Maghadam, M. and Kouwen, N. (1997) Nonrigid, Nonsubmerged, Vegetative Roughness on Floodplains. Journal of Hydraulic Engineering, 123 (1), 51-57.

Fenzl, R. N. (1962). Hydraulic resistance of broad, shallow, vegetated channels, PhD thesis, Univ. of California, Berkeley, Calif.

Ferguson, J.W., Williams, J.G. and Meyer, E. (2002) Recommendations for Improving Fish Passage at the Stornorrfors Power Station on the Umealven, Umea, Sweden. U.S. Department of Commerce, National Marine Fisheries Service, Northwest Fisheries Science Center, Seattle, WA.

Fish, F.E. (2002) Balancing Requirements for Stability and Maneuverability in Cetaceans. Integrative and Comparative Biology, 42, 85- 93.

Folkard, A. (2005) Hydrodynamics of model Posidonia oceanica patches in shallow water, Limnol. Oceanogr., 50(5), 1592–1600. doi:10.4319/ lo.2005.50.5.1592.

Forty, M., Spees, J. and Lucas, M.C. (2015) Session E8: Not Just for Adults! Evaluating the Efficacy of Multiple Fish Passage Designs at Low-Head Barriers for the Upstream Movement of Juvenile and Adult Trout Salmo Trutta. International Conference on Engineering and Ecohydrology for Fish Passage. 24. https://scholarworks.umass.edu/fishpassage_conference/2015/June24/24

References

Forty, M., Spees, J. and Lucas, M.C. (2016) Not just for adults! Evaluating the performance of multiple fish passage designs at low-head barriers for the upstream movement of juvenile and adult trout Salmo trutta. Ecological Engineering, 94, 214-224.

Foulds, W.L. and Lucas, M.C. (2013) Extreme inefficiency of two conventional, technical fishways used by European river lamprey (Lampetra fluviatilis). Ecological Engineering 58: 423-433.

Franklin, P., Gee, E., Baker, C. and Bowie, S. (2018) New Zealand Fish Passage Guidelines for structures up to 4 metres. National Institute of Water & Atmospheric Research Ltd PO Box 11115 Hamilton 3251.

Freyhof, J. (2013) Salmo trutta. The IUCN Red List of Threatened Species 2013. Available from: http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T19861A9050312.en [Accessed 21/01/2019].

Froese, R. and Pauly, D. Editors. (2017) FishBase. World Wide Web electronic publication. www.fishbase.org, (10/2017).

Glebe, B. D. and Leggett, W. C. (1981) Temporal, intrapopulation differences in energy allocation and use by American shad (Alosa sapidissima) during the spawning migration. Canadian Journal of Fisheries and Aquatic Sciences 38: 795–805.

Gowans, A.R.D., Armstrong, J.D., Priede, I.G. and Mckelvey, S. (2003) Movements of Atlantic salmon migrating upstream through a fish pass complex in Scotland. Ecology of Freshwater Fish 12, 177-189.

Graf, W.H. and Yulistiyanto, B. (1998) Experiments on flow around a cylinder; the velocity and vorticity fields. Journal of Hydraulic Research, 36 (4), 637-654.

Grant, P.F. and Nickling, W.G. (1998) Direct Field Measurement of Wind Drag on Vegetation for Application to Windbreak Design and Modelling. Land Degradation and Development, 9, 57-66.

Gu, Z. (1996) On interference between two circular cylinders at supercritical Reynolds number. Journal of Wind Engineering and Industrial Aerodynamics, 62, 15.

Guardo, M. and Tomasello, R.S. (1995) Hydrodynamic Simulations of a Constructed Wetland in South Florida. Water Resources Bulletin American Water Resources Association, 31 (4).

Haro, A. & Kynard, B. (1997) Video evaluation of passage efficiency of American shad and sea lamprey in a modified ice harbor fishway. North American journal of fisheries management, 17, 981-987.

Haro, A. and Castro-Santos, T. (2012) Passage of American Shad: Paradigms and Realities. Marine and Coastal Fisheries, 4 (1), 252-261.

Henderson, F M (1966). Open channel flow. Macmillan.

Hintermann, M. and Hassinger, R. (2010) Bristled Fish Pass – the Au-Schönenberg Hydroelectric Dam Pilot project, fish migration assistance, hydropower, biological permeability. Water Policy Office Haus der Demokratie und Menschenrechte Greifswalder Str. 4, D - 10405 Berlin: GRUNE LIGA e.V.

Hockley, F.A., Wilson, C.A.M.E., Brew, A. and Cable, J. (2014) Fish responses to flow velocity and turbulence in relation to size, sex and parasite load. J. R. Soc. Interface, 11, 91.

Huai, W.-X., Chen, Z.-B., Han, J., Zhang, L.-X. and Zeng, Y.-H. (2009) Mathematical Model for The Flow with Submerged and Emerged Rigid Vegetation. Journal of Hydrodynamics, Ser. B, 21 (5), 722-729.

Huai, W.X., Zeng, Y.H., Xu, Z.G. and Yang, Z.H. (2009) Three-layer model for vertical velocity distribution in open channel flow with submerged rigid vegetation. Advances in Water Resources, 32 (4), 487-492.

Huthoff, F., Straatsma, M.W., Augustijn, D.C.M. and Hulscher, S.J.M.H. (2013) Evaluation of a Simple Hydraulic Resistance Model Using Flow Measurements Collected in Vegetated Waterways. Open Journal of Modern Hydrology, 03 (01), 28-37.

Ingram, A., Ibbotson, A. and Gallagher, M. (1999) The Ecology and Management of the European Grayling Thymallus thymallus (Linnaeus). Ecology, I.O.F.

Ishikawa, Y., Mizuhara, K. and Ashida, S. (2000) Effect of Density of Trees on Drag Exerted on Trees in River Channels. J. For. Res., 5, 271-279.

Jacobs Aquatic (2006) SWIMIT Version 3.3. Fawley, Southampton, Hampshire. Environment Agency.

Johnson, K., Wait, L.E., Monk, S.K., Rader, R., Hotchkiss, R. H. and Belk. M. C. (2019) Effects of Substrate on Movement Patterns and Behavior of Stream Fish through Culverts: An Experimental Approach. Sustainability, 11, 470.

Jones, J., Börger, L., Tummer, J., Jones, P., Lucas, M., Kerr, J., Kemp, P., Bizzi, S., Consuegra, S., Marcello, L., Vowles, A., Belletti, B., Verspoor, E., Van de Bund, W., Goughg, P. and de Leaniz, C.G.

References

(2019) A comprehensive assessment of stream fragmentation in Great Britain. Science of the Total Environment 673, 756–762, https://doi.org/10.1016/j.scitotenv.2019.04.125.

Kemp, P.S., Russon, I.J., Waterson, B., O'Hanley & J.R. and Pess, G.R. (2008) Recommendations for a "Coarse-Resolution Rapid-Assessment" methodology to assess barriers to fish migration and associated prioritization tools - Final report. Tech. rep., Scottish Environment Protection Agency, Stirling, UK.

Kerr, J.R., Karageorgopoulos, P. and Kemp, P.S. (2015) Efficacy of a side-mounted vertically oriented bristle pass for improving upstream passage of European eel (Anguilla anguilla) and river lamprey (Lampetra fluviatilis) at an experimental Crump weir. Ecological Engineering, 85, 121-131.

Kerr, J.R., Manes, C. and Kemp, P.S. (2016) Assessing hydrodynamic space use of brown trout, Salmo trutta, in a complex flow environment: a return to first principles. J Exp Biol, 219 (Pt 21), 3480-3491.

Knaepkens, G., Maerten, E. and Eens, M. (2007) Performance of a pool-and-weir fish pass for small bottom-dwelling freshwater fish species in a regulated lowland river. Animal Biology, 57 (4), 423-432.

Kothyari, U.C., Hayashi, K. and Hashimoto, H. (2009) Drag coefficient of unsubmerged rigid vegetation stems in open channel flows. Journal of Hydraulic Research, 47 (6), 691-699.

Kottelat, M. and Freyhof, J. (2007) Handbook of European freshwater fishes. Publications Kottelat, Cornol and Freyhof, Berlin. 646 pp.

Kouwen, N. and Unny, E.T. (1973) Flexible roughness in open channels. J. of Hydraulics Division, ASCE, Vol. 99(5), pp.713-729.

Lacey, R.W.J., Neary, V.S., Liao, J.C., Enders, E.C. and Tritico, H.M. (2012) The Ipos Framework: Linking Fish Swimming Performance in Altered Flows from Laboratory Experiments to Rivers. River Research and Applications, 28 (4), 429-443.

Larinier, M. (2002) Biological Factors to Be Taken into Account in the Design of Fishways, the Concept of Obstructions to Upstream Migration. Bulletin Français de la Pêche et de la Pisciculture, (364 supplément), 28-38.

Larinier, M. (2001) Dams, fish and fisheries Opportunities, challenges and conflict resolution. In: Marmulla, G. (ed.) Environmental Issues, Dams and Fish Migration.

Legault, A. (1992) Etude de quelques facteurs de sélectivité de passes à anguilles. Bulletin Français de la Pêche et de la Pisciculture, (325), 83-91.

Liao, J. C., Beal, D. N., Lauder, G. V. and Triantafyllou, M. S. (2003) The Kármán gait: novel body kinematics of rainbow trout swimming in a vortex street. J. Exp. Biol. 206, 1059-1073. doi:10.1242/jeb.00209Abstract/.

Liao, J.C. (2007) A review of fish swimming mechanics and behaviour in altered flows. Philos Trans R Soc Lond B Biol Sci, 362 (1487), 1973-1993.

Longo, S. (2006) The effects of air bubbles on ultrasound velocity measurements. Experiments in Fluids. 41. 593-602. 10.1007/s00348-006-0183-0.

Lothian, A.J., Gardner, C.J., Hull, T., Griffiths, D., Dickinson, E.R. and Lucas, M.C. (2019) Passage performance and behaviour of wild and stocked cyprinid fish at a sloping weir with a Low Cost Baffle fishway. Ecological Engineering, 130, 67 –79. https://doi.org/10.1016/j.ecoleng.2019.02.006.

Lucas, M. C., Thorn, T. J., Duncan, A., Slavik, O. (1998) Coarse Fish Migration Occurrence, Causes and Implications, Technical Report W 152., Environment Agency. Potter I. C. 1980.

Lucas, M.C. and Baras, E. (2001) Migration of Freshwater Fishes. Oxford: Blackwell Science.

Lucas, M.C. and Frear, P.A. (1997) Effects of a flow-gauging weir on the migratory behaviour of adult barbel, a riverine cyprinid. Journal of Fish Biology, 50, 14.

Lucas, M.C., and Bubb, D.H. (2005) Seasonal movements and the habitat use of grayling in the UK. Environment Agency Science Report SC030210/SR. Environment Agency, Bristol.

Lucas, M.C., Mercer, T., Peirson, G. and Frear, P. (2000) Seasonal movements of coarse fish in lowland rivers and their relevance to fisheries management. In Management and ecology of river fisheries (Cowx, I.G., ed.), pp87-100, Blackwell Science, Oxford.

Luhar, M. and Nepf, H.M. (2013) From the blade scale to the reach scale: A characterization of aquatic vegetative drag. Advances in Water Resources, 51, 305-316.

Lupandin, A.I. (2005) Effect of flow turbulence on swimming speed of fish. Biol. Bull. 32, 461–466 No. 5.

MacDonald, J.I. & Davies, P. E. (2007) Improving the upstream passage of two galaxiid fish species through a pipe culvert. Fisheries Management and Ecology, 14, 221–230.

References

Mallen-Cooper, M. and Brand, D.A. (2007) Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? Fisheries management and ecology, 14, 319-332.

Manes, C., Pokrajac, D. and McEwan, I. (2007) Double averaged open channel flows with small relative submergence. Journal of Hydraulic Engineering, 133 (8), 896-904. doi:10.1061/(ASCE)0733-9429(2007)133:8(896).

Marjoribanks, T.I., Hardy, R.J., Lane, S.N. and Parsons, D.R. (2014) High-resolution numerical modelling of flow—vegetation interactions. Journal of Hydraulic Research, 52 (6), 775-793.

McElroy, B., DeLonay, A. and Jacobson, R. B. (2012) Optimum swimming pathways of fish spawning migrations in rivers. Ecology 93:29–34.

Meire, D.W.S.A., Kondziolka, J.M. and Nepf, H.M. (2014) Interaction between neighboring vegetation patches: Impact on flow and deposition. Water Resources Research, 50 (5), 3809-3825.

Minto, C., Myers, R.A. and Blanchard, W. (2008) Survival variability and population density in fish populations. Nature, 452 (7185), 344-347.

Montali-Ashworth, D., Vowles, A.S., De Almeida, G. and Kemp, P. (2020). Use of Cylindrical Bristle Clusters as a novel multispecies fish pass to facilitate upstream movement at gauging weirs. Ecological Engineering. 143. 105634. 10.1016/j.ecoleng.2019.105634.

Montgomery, J.C., Mcdonald, F., Baker, C.F., Carton, A.G. and Ling, N. (2003) Sensory integration in the hydrodynamic world of rainbow trout. Proc Biol Sci, 270 Suppl 2, S195-197.

Mori, N., Suzuki, T. and Kakuno, S. (2007) Experimental study of air bubbles and turbulence characteristics in the surf zone, J. Geophys. Res., 112, C05014. doi:10.1029/2006JC003647.

Nepf, H.M. (1999) Drag, turbulence and diffusion in flow through emergent vegetation. Water Resources Research, 35 (2), 479-489.

Nepf, H.M. (2012) Hydrodynamics of vegetated channels. Journal of Hydraulic Research, 50 (3), 262-279.

Newbold, L.R., Karageorgopoulos, P. and Kemp, P.S. (2014) Corner and sloped culvert baffles improve the upstream passage of adult European eels (Anguilla anguilla) Ecological Engineering, 73, pp. 752-759. doi:10.1016/j.ecoleng.2014.09.076.

Nicolle, A. (2009) Flow Through and Around Groups of Bodies, Doctor of Philosophy, University College London.

Nicolle, A. and Eames, I. (2011) Numerical study of flow through and around a circular array of cylinders. Journal of Fluid Mechanics, 679, 1-31.

Nikora, V.I., Aberle, J., Biggs, B.J.F., Jowett, I.G. and Sykes, J.R.E. (2003) Effects of Fish Size, Time to Fatigue, and Turbulence on Swimming Performance: A Case Study of Galaxias maculatus. Journal of Fish Biology, 63, 17.

Noonan, M.J., Grant, J.W.A. and Jackson, C.D. (2012) A quantitative assessment of fish passage efficiency. Fish and Fisheries, 13 (4), 450-464.

Ojanguren, A. F. and Brana, F. (2003) Effects of size and morphology on swimming performance in juvenile brown trout (Salmo trutta L.). Ecology of freshwater fish, 12, 241-246.

Oldani, N. O., Baigún, C. R. M., Nestler, J. M. and Goodwin, R. A. (2007) Is fish passage technology saving fish resources in the lower La Plata River basin? Neotropical Ichthyology, 5: 89-102.

Ovidio, M., Parkinson, D., Sonny, D. and Philppart, J.-C. (2004) Spawning movements of European grayling Thymallus thymallus in the River Aisne (Belgium). Folia Zoologica, 53 (1), 87- 98.

Pavlov, D.S., Lupandin, A.I. and Skorobogatov, M.A. (2000) The effects of flow turbulence on the behavior and distribution of fish. J. Ichthyol. 40, S232-S261.

Pon, L.B., Hinch, S.G., Cooke, S.J., Patterson, D.A. and Farrell, A.P. (2009) Physiological, energetic and behavioural correlates of successful fishway passage of adult sockeye salmon Oncorhynchus nerka in the Seton River, British Columbia. J Fish Biol, 74 (6), 1323-1336.

Pringle, C.M. (2001) Hydrologic connectivity and the management of biological reserves: a global perspective. Ecological Applications 11: 981–998.

Przybilla, A., Kunze, S., Rudert, A., Bleckmann, H. and Brucker, C. (2010) Entraining in trout: a behavioural and hydrodynamic analysis. J Exp Biol, 213 (Pt 17), 2976-2986.

Resch, F.J. and Leutheusser, H.J., 1972. Le ressaut hydraulique: mesure de turbulence dans la re ´gion diphasique [The hydraulic jump: turbulence measurements in the two-phase flow region]. Journal La Houille Blanche, 4, 279 – 293, [in French].

Rickard, C., Day, R. and Purseglove, J. (2003) River Weirs – Good Practice Guide. Environment Agency.

Rooney, S.M., Wightman, G., Ó'Conchúir, R. and King, J.J. (2015) Behaviour of sea lamprey (Petromyzon marinus L.) at man-made obstacles during upriver spawning migration: use of telemetry to assess efficacy of weir modifications for improved passage. Biology and Environment: Proceedings of the Royal Irish Academy. Vol. 115B, No. 2, pp. 125-136.

Rosenberg, D. M., McCully, P., and Pringle, C. M. (2000) Global scale effects of hydrological alterations: Introduction. BioScience 50: 746– 751. https://doi.org/10.1641/0006-3568(2000)050[0746:GSEEOH]2.0.CO;2.

Roscoe, D.W. and Hinch, S.G. (2010) Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish and Fisheries, 11 (1), 12-33.

Russon, I.J., Kemp, P.S. and Lucas, M.C. (2011) Gauging weirs impede the upstream migration of adult river lamprey Lampetra fluviatilis. Fisheries Management and Ecology, 18 (3), 201-210.

Sagnes, P. and Statzner, B. (2009) Hydrodynamic abilities of riverine fish: a functional link between morphology and velocity use. Aquatic Living Resources, 22 (1), 79-91.

Servais, S.A. (2006) Physical modelling of low-cost modifications to the Crump weir in order to improve fish passage: Development of favourable swimming conditions and investigation of the hydrometric effect, Cranfield.

Sfakiotakis, M., Lane, D.M. and Davies, J.B.C. (1999) Review of Fish Swimming Modes for Aquatic Locomotion. IEEE Journal of Oceanic Engineering, 24 (2).

Silva, A.T., Katopodis, C., Santos, J.M., Ferreira, M.T. and Pinheiro, A.N. (2012) Cyprinid swimming behaviour in response to turbulent flow. Ecological Engineering, 44, 314-328.

Sonnenwald, F., Stovin, V. and Guymer, I. (2018) Estimating drag coefficient for arrays of rigid cylinders representing emergent vegetation, Journal of Hydraulic Research. doi: 10.1080/00221686.2018.1494050.

Sumer B. M. and Fredsoe J. (2006) Hydrodynamics around Cylindrical Structures, Advanced Series on Ocean Engineering, World Scientific, Singapore.

Supino, F. (2019) Pesci d'Acqua Dolce d'Italia. Milan, Italy: Ulrico Hoepli, Editore Libraio della Real Casa, 1916. Freshwater and Marine Image Bank. https://digitalcollections.lib.washington.edu/digital/collection/fishimages/id/35779/rec/1.

Szalay, M. (1967) Biology in the Engineering Practice, (in Hungarian). Budapest: Mûszaki Könyvkiadó.

Taddei, S., Manes, C. and Ganapathisubramani, B. (2016) Characterisation of drag and wake properties of canopy patches immersed in turbulent boundary layers. Journal of Fluid Mechanics, 798, 27-49.

Taddei, S. (2016) Turbulent flows interacting with groups of obstacles. University of Southampton, Faculty of Engineering and the Environment, Doctoral Thesis, 213pp.

Tinoco, R. O. and Cowen, E. A. (2013) The direct and indirect measurement of boundary stress and drag on individual and complex arrays of elements. Experiments in Fluids, 54(4), 1–16. doi: 10.1007/s00348-013-1509-3.

Tritico, H.M. and Cotel, A.J. (2010) The effects of turbulent eddies on the stability and critical swimming speed of creek chub (Semotilus atromaculatus). J Exp Biol, 213 (Pt 13), 2284-2293.

Tritton D.J. (2007) Physical Fluid Dynamics, Oxford University Press.

Tummers, J.S., Kerr, James, O'Brien, P., Kemp, Paul and Lucas, M.C. (2018) Enhancing the upstream passage of river lamprey at a microhydropower installation using horizontally-mounted studded tiles. Ecological Engineering, 125, 87-97. doi:10.1016/j.ecoleng.2018.10.015.

Turnpenny, A.W.H., Lawton, K. and Clough, S.C. (2002) Fish passage at flow gauging stations in England and Wales. Stage 1: Literature review and regional survey. Environment Agency R & D Technical Report W6-029/TR1.

Valeport Limited (1999) Model 801 Electromagnetic Flow Meter Operation Manual. Totnes, Devon, UK.

Vannote, R. R., Minshall, G. W., Cummins, K. W., Sedell, J. R. and Cushing, C. E. (1980) The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37: 130-137.

Videler, J. J. (1993) Fish Swimming. Fish and Fisheries Series 10, Chapman & Hall, London.

Vowles, A.S., Don, A.M., Karageorgopoulos, P., Worthington, T.A. and Kemp, P.S. (2015) Efficiency of a dual density studded fish pass designed to mitigate for impeded upstream passage of juvenile European eels (Anguilla anguilla) at a model Crump weir. Fisheries Management and Ecology, 22 (4), 307-316.

Vowles, A., Don, A. M., Karageorgopoulos, P., & Kemp, P. (2017). Passage of European eel and river lamprey at a model weir provisioned with studded tiles. Journal of Ecohydraulics, (2470-5357 (Print)), 1-11. doi: 10.1080/24705357.2017.1310001.

References

Walker, J.A. (2000) Does a Rigid Body Limit Manoeuvrability? The Journal of Experimental Biology, 203, 3391-3396.

Walters, G. (1996) Hydraulic model tests on the proposed fish pass structure for Hurn gauging weir Dorset. Environment Agency.

Wang, X.K., Gong, K., Liu, H., Zhang, J.-X. and Tan, S.K. (2013) Flow around four cylinders arranged in a square configuration. Journal of Fluids and Structures, 43, 21.

Ward, J. V. and Stanford, J. A. (1983) The serial discontinuity concept of lotic ecosystems. Fontaine, T. D. and Bartell, S. M. (Eds), Dynamics of Lotic Ecosystems. Ann Arbor Science, Ann Arbor. pp. 29-42.

Watz, J., Nilsson, P. A., Degerman, E., Tamario, C. and Calles, O. (2019) Climbing the ladder: an evaluation of three different anguillid eel climbing substrata and placement of upstream passage solutions at migration barriers. Anim Conserv. doi:10.1111/acv.12485.

Webb, P.W. (1975) Hydrodynamics and energetics of fish propulsion. Ottowa.

Webb, P.W. (1986) Effect of Body Form and Response Threshold on the Vulnerability of Four Species of Teleost Prey Attacked by Largemouth Bass (Micropterus salmoides). Canadian Journal of Fisheries and Aquatic Sciences, 43 (4), 763-771.

Webb, P.W. (1998) Entrainment by River Chub Noncomis Micropogon and Smallmouth Bass Micropterus Dolomieu on Cylinders Journal of Experimental Biology, 201, 9.

Welcomme, R.L. (1994) The status of large river habitats. In I.G.Cowx (ed.) Rehabilitation of Freshwater Fisheries. Oxford: Fishing News Books, Blackwell Scientific Publications, pp 11-20.

Wessels, P. and Rooseboom, A. (2009) Flow-gauging structures in South African rivers Part 1: An overview. Water SA. 35. 1-9. 10.4314/wsa.v35i1.76643.

White, W.R. and Hartley, W.G. (1966) Experiments to compare the passage of fish over two triangular profile Flat-Vee weirs. Report No. INT 67, Hydraulics Research Station, Wallingford, Berkshire, England, 48 pp.

White, W. R. Iredale, R. and Armstrong, G. (2006) Fishpasses at flow measurement structures Proceedings of the Institution of Civil Engineers - Water Management 159:3, 165-171.

White, W.R. and Woods-Ballard, B.A. (2003) The Investigation and Specification of Flow Measurement Structure Design Features that Aid the Migration of Fish without Significantly

Compromising Flow Measurement Accuracy, with the Potential to Influence the Production of Suitable British Standards. Environment Agency.

Wilkes, M. A., Maddock, I., Visser, F. & Acreman, M. C. (2013) Incorporating hydrodynamics into ecohydraulics: The role of turbulence in the swimming performance and habitat selection of stream-dwelling fish. In Ecohydraulics: an integrated approach (Maddock, I. M., Harby, A., Kemp, P. & Wood, P., eds.), pp. 9-30, John Wiley & Sons Ltd, Chichester.

Williams, J.G., Armstrong, G., Katopodis, C., Larinier, M. and Travade, F. (2012) Thinking Like a Fish: A Key Ingredient for Development of Effective Fish Passage Facilities at River Obstructions. River Research and Applications, 28 (4), 407-417.

Winter, H. V. and Van Densen, W. L. (2001) Assessing the opportunities for upstream migration of non-salmonid fishes in the weir-regulated River Vecht. Fisheries Management and Ecology, 8: 513-532. doi:10.1046/j.1365-2400.2001.00271.x.

Wu, F.-C., Shen, H.W. and Chou, Y.-J. (1999) Variation of roughness coefficients for unsubmerged and submerged vegetation. Journal of Hydraulic Engineering, 934-942.

Zdravkovich, M.M. (1987) The effects of interference between circular cylinders in cross flow. Journal of Fluids and Structures, 1 (1987), pp. 239-261

Zdravkovich, M.M. (1997) Flow Around Circular Cylinders. Fundamentals, vol. 1. Oxford University Press, 1997.

Zdravkovich, M.M. (2003) Flow around circular cylinders Vol 2: applications. Oxford University Press. Clarendon Street, Oxford, OX2 6DP.

Zong, L. and Nepf, H. (2012) Vortex development behind a finite porous obstruction in a channel. Journal of Fluid Mechanics, 691, 368-391.