This project was supported by the Centre for Global Eco-Innovation and is part financed by the European Regional Development Fund.

Centre for Global Eco-Innovation

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Assessing the Influence of Low Head Weirs and Low Head 'On Weir' Hydropower on the Phytobenthic Biofilm

This thesis is submitted to Lancaster University in partial fulfilment of the requirements for the degree of Doctor of Philosophy March 2017

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Declaration

I hereby declare that the information on which this research project is based has been collected by me personally, has not been plagiarised from any unacknowledged sources and has not been previously submitted for another higher degree.

Laura O'Keefe

March 2017

Preface

This project was funded by the European Regional Development Fund (ERDF) and industrial partner Green-Tide Turbines Ltd (GTT) as part of the Centre for Global Eco-Innovation (CGE). The main aim of CGE was to help North West based Small to Medium Enterprises (SMEs) collaborate with Universities to develop products and/or services for the global market place, which by virtue of use, would deliver positive environmental impacts. This would be achieved by providing the industrial partner with a Graduate Researcher who would carry out Research and Development (R&D) in the form of a PhD. As such the direction of research presented below was heavily influenced by the commercial aims of the industrial partner and readily changed as requested by GTT.

This particular project went through numerous transitions throughout the course of the PhD. Initially the industrial partner was focussing on developing hydro turbines for tidal stream farms and the original PhD aimed to assess tidal resource around the UK using oceanographic model simulations. Yet a year into the project the commercial aims of the industrial partner changed and GTT switched from developing turbines for tidal stream farms to turbines for small scale riverine hydro schemes; more specifically turbines that could be retrofitted to existing obsolete low head weir structures.

While tidal energy was associated with high upfront costs and was in the infancy stages of development low head hydro was considered a more economically viable option with lower costs and shorter feedback times. Moreover low head hydro had a vast history across the UK and there was significant potential for developing schemes at an existing 25,000 obsolete low head weirs across England and Wales. The industrial partner hence decided to develop and potentially deploy turbines in the riverine environment and increase revenue before branching out into the tidal energy market.

Going forward the industrial partner required help in understanding the market need for the new turbine and scheme design. As such I completed a market research report with the aim of assessing the viability of retrofitting GTT's turbine to low head weirs. This report was completed with the help of Inventya, a market research company and partner of CGE. Although this report identified a clear interest in low head hydro across the UK and a positive response towards GTT's turbine and scheme design this report also highlighted a number of barriers to low head hydro development.

One of the major barriers to development was the potential aquatic implications of low head hydro and the lack of knowledge and uncertainty surrounding this impact, which, together with the need to adhere to environmental legislation and important environmental targets was causing conflict between hydro developers and regulators. Despite the fact that many believed that low head hydro was "environmentally benign" there was a huge lack of evidence to support this claim and permitting decisions were based on expert opinion rather than observed evidence. Regulators were accused of erring on the side of caution and limiting the amount of electricity that a scheme could produce were environmental damage might not even occur. Yet regulators deemed this caution necessary and until more evidence could be gathered were concerned that existing schemes might already be altering the aquatic environment.

There was a keen interest from the regulators, hydro developers and GTT in particular to improve this situation. As such the focus of the PhD changed and aimed to investigate the aquatic implications of existing low head schemes in a bid to improve evidences bases and inform permitting decisions and future scheme designs. GTT wanted to utilise results from this study to inform the development process and aimed to produce a scheme that would have minimal environmental impact and in the long term hoped to be able achieve 'type approval' for installing their scheme at any weir in any UK river.

Throughout this project there was frequent dialogue between the industrial partner and myself. I was able to share knowledge with the industrial partner about the aquatic implications of existing low head schemes and how this related to important environmental targets. While this led to further adjustments in the commercial direction of GTT and even though GTT eventually decided to withdraw from developing a low head 'on weir' hydro schemes this decision was directly influenced by findings from this project.

By the end of this project GTT had designed an in stream hydro scheme with potential minimal impacts on the aquatic environment. The final scheme requires minimal civil engineering, does not utilise structures which impede river flow and does not divert flow away from the main river channel. The turbine does not need to be connected to the grid and could be used to provide energy and power to remote communities across the world in places like Nepal, Bangladesh and Kenya. The final design is currently going through testing in manmade and natural channels with aim of assessing power output and environmental impact.

Abstract

In recent years there has increased interest in low head ‘on weir’ hydro across the UK. This directly corresponds to carbon reduction targets, renewable energy targets and financial incentives directed at renewable energy generating schemes. Despite increased interests, current understandings of the aquatic implications of low head ‘on weir’ hydro are unclear and not one in field investigation has been carried out at an existing scheme. Yet with important environmental legislation preventing the deterioration of ecological river quality, mainly the Water Framework Directive (WFD), there is an urgent need to improve current understandings.

Fundamentally low head ‘on weir’ hydropower is a human activity that could potentially alter the aquatic environment, change natural biotic communities and cause failure to comply with WFD targets. On the other hand, as low head ‘on weir’ schemes are fitted on existing weirs which have already potentially altered the aquatic environment, there is the chance that adding a hydro scheme to a weir could in fact improve the aquatic environment and provide benefits for ecology whilst also providing meaningful amounts of electricity (EA, 2010).

The overarching aim of this project was to advance the understanding of how low head ‘on weir’ hydropower can influence physical and chemical habitat condition and the phytobenthic biofilm. In order to achieve the aim, this thesis also investigated how weirs themselves change physical and chemical riverine conditions and the phytobenthic biofilm. To investigate the influence of an existing low head weir on the phytobenthic biofilm comparisons were made between the tail riffle below an existing obsolete weir and riffles upstream and downstream of the weir over time. This design was also replicated for a low head ‘on weir’ hydro scheme. Large scale and small scale spatial surveys were also conducted to explore finer scale spatial patterns below the scheme.

There was evidence across this study to suggest that low head ‘on weir’ hydropower is having minimal effects of phytobenthic biomass and community composition. Moreover changes in biomass and community composition were more obvious over time than spatially across sampling locations. There was also evidence to suggest that low head ‘on weir’ hydro schemes can mask the effects of weirs by reducing the proportion of flow over the weir.

Acknowledgements

I would first like to thank the Centre for Global Eco-Innovation and Green-Tide Turbines Ltd who funded this project. Special thanks to Michael Evans, Dr Andy Pickard and Carolyn Hayes I will be forever grateful for this opportunity.

I would like to extend my thanks to my supervisor Dr Suzana Ilic. Thank you for encouraging me to attend conferences and thank for your guidance throughout this project. I could not have asked for a more approachable and supportive supervisor.

Special thanks to everyone that helped me in the field which includes Vassil, James, Gareth, Clayton, Meryn, Joe, Dan, Caitlin, my mum Hayley, dad Kevin and brother Michael. Thanks to Vassil who taught me how to use specialist kit and to James and my mum Hayley who helped collect data for 2 years without complaining.

Thank you to the volunteers at Stockport Hydro I am extremely grateful for your help. I am especially grateful to Mike Lees who would keep me updated on river levels and would grant me access to the site each week making sure I was safe. Thank you also to Phil Fern, for making my biological sampling signs and for providing me with photographs and logged information from the hydro scheme.

To my parents Hayley and Kevin I am so appreciative of the emotional and financial support. Thank you for always encouraging me to do my best and believing in me. To the rest of my family and friends who have put up with me through the highs and lows of this project, especially my grandparent (Bubs and Ginger) and my best friends (the Fabs). To my brother Michael thank you for your mathematical support and for listening to me talk things through. You will make an amazing teacher, good luck with your PGCE!

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Chapter 1: Introduction

1.1. Background and rationale

1.1.1. Low head 'on weir' hydropower

Presently the majority of the world's energy demands are satisfied by the burning fossil fuels; coal, oil and natural gas (Watkin et al., 2012). However over time it has been recognised that fossil fuel consumption is detrimental to the environment. The burning of fossil fuels emits millions of tonnes of Greenhouse Gases (GHG's) into the atmosphere per year which consequently contributes to global warming, climate change and ocean acidification (Gill, 2005; Blanchfield et al., 2008; Inger et al., 2009; Jacobson and Delucchi, 2011).

Subsequently there has been a drive to reduce fossil fuel consumption and to switch to cleaner ways of producing power. The UK government, in particular, in line with European (EU) targets have committed to reduce GHG emissions by up to 34% and to delivering 15% of its energy from clean renewable sources by 2020 (DECC, 2011). In a bid to increase renewable development, it has introduced financial incentives dedicated to renewable energy generating schemes. Financial incentives include grants, loans and the Feed-in Tariff (LGA, 2010).

The Feed- in Tariff has been the most influential incentive to date providing payments to developers of renewables for the amount of electricity sold to the national grid (Fraser et al., 2015; Mould et al., 2015a). The Environment Agency, regulators of hydropower in England, saw a significant increase in applications for hydropower permits following the introduction of the Feed-in Tariff in 2009; especially small scale hydro permits (Fraser et al., 2015). While there is no universal definition for small scale hydro, the UK government defines small scale hydro as a scheme that produces less than 5MW of electricity (GOV, 2013).

Though large scale hydro schemes naturally produce more power and would contribute more readily to renewable energy targets, there is limited availability across the UK for exploiting large scale hydro in a sustainable and environmentally acceptable way (GOV, 2013; Anderson et al., 2015a; Bilotta et al., 2016). On the other hand it is believed that there is scope to exploit the remaining small scale hydro potential in a less environmentally intrusive way (Robson et al., 2011; GOV, 2013, Anderson et al., 2015a).

Small scale hydropower can be split into a number of categories which includes in-stream, high head and low head schemes (Anderson et al., 2015a). Small scale, in-stream schemes simply use the power in the flow to turn the turbines to produce power but are in the infancy stages of development across the UK and are not explored any further in this thesis (Anderson et al., 2015a). Small scale, high head schemes are most common in high gradient rivers in Scotland and the North of England and utilise weirs to abstract flow for producing power. According to current trends in hydro applications, high head hydro schemes only accounted for 24% of the schemes permitted in England between 2009 and 2013 (Fraser at al., 2015). As such they are also excluded from this thesis but more information can be found in Robson et al., (2011).

Small scale, low head hydro has become particularly popular in England in recent years, with 85% of schemes permitted between 2009 and 2013 being classed as low head (Fraser et al., 2015). Small scale low head schemes are typically installed along low gradient lowland river reaches at existing obsolete low head weirs (Anderson et al., 2015a). Increased interest in low head hydro is, in part, down to an Environment Agency report which identified over 25,000 existing obsolete weirs across England and Wales suitable for low head hydro development (EA, 2010).

Many such weirs were originally used for producing power at freshwater mills before the industrial revolution. However with the introduction of fossil fuels, which could produce energy at a lower cost, many mills were deemed inefficient and uneconomic and as such the majority were left redundant. Yet most weir structures were not actively removed from British rivers (Aggidis et al., 2006) and with current calls for clean energy supplies there has been a drive to examine and exploit these opportunities wherever possible (Aggidis et al., 2006). The EA estimates that if all existing obsolete weirs were utilised low head hydropower could provide up to 1% of the UK 2020 energy demands (EA, 2010). While this appears to be a small proportion, it has been deemed a useful contribution to the future renewable energy mix (GOV, 2013). Current installed capacity for low head hydro, in England alone, is 8.07MW which is only 0.03% of the UK's current energy demands (EA, personal correspondence).

Low head hydro schemes can be separated into a further two categories which include low head 'mill leat' schemes and low head 'on weir' schemes. While both low head 'mill leat' and low head 'on weir' scheme utilise existing obsolete weirs and divert large volumes of water away from the main river channel there is a difference in layout. At low head 'mill leat' schemes water is diverted through an open channel/leat system at the intake and is returned back into the main river channel at the outlet. The turbines are located in a power house along the open channel/leat. The distance between the intake and outlet can cover many meters in length and as such creates a large area of depleted flow across the main river channel known as the depleted reach (EA, 2013; Anderson et al., 2015a). Figure 1.1 shows a schematic diagram of a low head 'mill leat' scheme and displays the intake, outlet and depleted reach. Low head 'mill leat' schemes are also often referred to as low head 'run of the river' schemes (Anderson et al., 2015a; Bilotta et al., 2016; Bilotta et al., 2017).

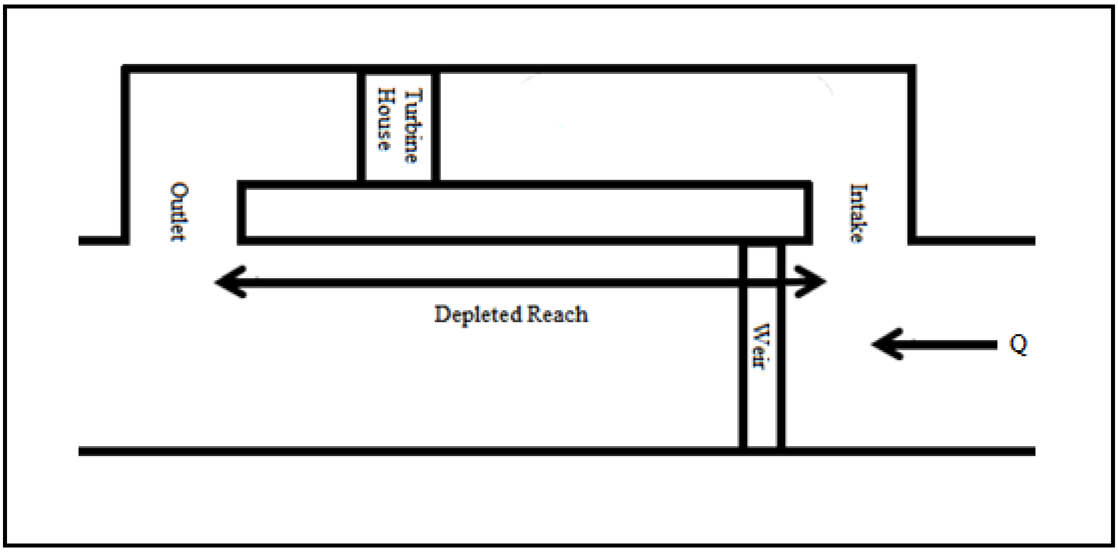

Figure 1.1: Schematic diagram of low head 'mill leat' scheme were flow is diverted through an open channel or mill leat (adapted from EA, 2016)

Low head 'on weir' schemes are typically fitted directly on top or directly adjacent to an existing low head weir in a turbine forebay (EA, 2016; Anderson et al., 2015a) and the majority in UK utilise Archimedes Screw turbines (Mould et al., 2015a). Flow is diverted to the turbines through the intake and the remaining flow is directed over the weir. Flow is returned to the main river channel at the outlet almost immediately below the weir. Figure 1.2 shows a schematic diagram of low head 'on weir' schemes utilising Archimedes Screw turbines and displays aerial images of schemes in the River Thames and the River Goyt. Even though large volumes of water are diverted to the turbines the distance between the intake and the outlet is so small that low head 'on weir' hydro schemes are considered to have a negligible depleted reach (EA, 2016).

According to recent hydropower permitting trends low head 'mill leat' schemes have not been as popular as low head 'on weir' schemes. Of the 150 new hydro schemes permitted in England between 2009 and 2013, 31% were classed as low head ‘mill leat’ schemes and 44% where classed as low head ‘on weir schemes (Fraser et al., 2015). Additionally while there are still plenty of opportunities for developing both low head ‘mill leat’ and low head ‘on weir’ schemes it seems likely that low head ‘on weir’ schemes will be more readily encouraged for development in future (personal correspondence with Environment Agency). This is likely down to the fact that they are perceived to have a lower environmental impact due to the absence of a depleted reach. As such low head ‘on weir’ schemes are the main focus of this study and ‘low head ‘mill leat’ schemes are not explored any further in this thesis. Further information on low head ‘mill leat’ schemes can be found in a review by Anderson et al., (2015a) and in results of an in-field investigation at a low head ‘mill leat’ scheme in Derbyshire, UK (Anderson et al., 2015b).

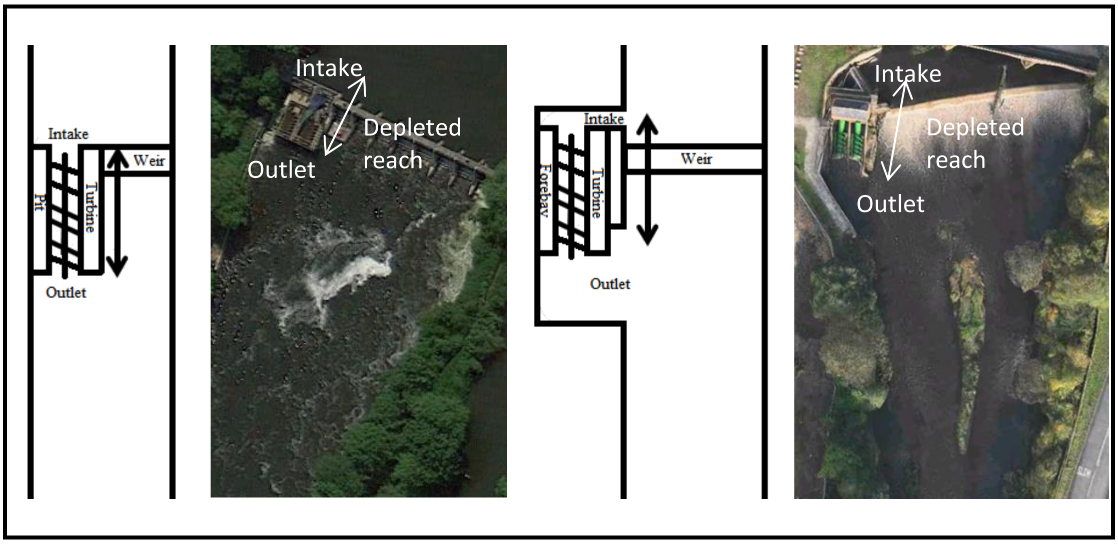

Figure 1.2: Schematic diagram of ‘on weir’ hydro schemes (adapted from EA, 2016) with areial images of an ‘on weir’ scheme in Windsor (SU9687277497) where the turbine is located ontop of Romney weir in the River Thames and Stockport (SJ9363489429) were the turbine is located adjacent to Ottersool Weir in the Rover Goyt (Google Earth, 2017a; Apple Maps, 2017a)

1.1.2. Potential aquatic implications

Despite carbon reduction and renewable energy targets and increased interests in developing low head ‘on weir’ hydro schemes many schemes often face barriers to development (Aggidis et al., 2006). While there is no single barrier to low head hydro development, developers often quote the improvised approaches to defining the aquatic implications of low head hydro as the most significant barrier (Aggidis et al., 2006). This improvised approach is down to a huge lack of evidence surrounding the impact of low head 'on weir' hydropower and often causes conflict between developers and regulators. As such there is interest from hydro developers and regulators alike to improve this situation.

Many academic studies claim that low head 'on weir' hydro is "environmentally benign" (Paish, 2002) displaying limited or negligible environmental impacts (Egre and Milewski, 2002; BHA, 2005; Kosnik, 2008). However there is very little empirical evidence available to support this assertion (Abbasi and Abbasi, 2011; Robson et al., 2011). To the best of my knowledge there is only one study that has investigated the aquatic implications of low head 'on weir' hydropower specifically (Mould et al., 2015a). Moreover results from this investigation are based on numerical modelling and conclusions surrounding the impacts of low head 'on weir' hydro on aquatic ecology is based on "expert opinion" and little in field data.

As a result of this lack of evidence, the regulators often struggle to judge permitting applications and developers often accuse the regulators of taking an overly cautionary approach. It feels like "unjustified burdens" are being placed on scheme development were significant environmental damage might not even occur (Bradley et al., 2013). On the other hand, the regulators fear that existing schemes might already be causing damage and deem this caution necessary until more evidence can be gathered. Especially in light of environmental legislation and environmental targets set by the Water Framework Directive (WFD) which the regulators are legally obliged to adhere to and which are directly quoted in the hydropower permitting guidelines. For example hydropower permitting guidelines state that a scheme will not be approved were it is deemed likely to interfere with WFD targets (EA, 2013).

WFD works to enhance water quality and prevent further deterioration of water bodies, aiming to return all water bodies back to as close to natural as possible with only slight deviations from natural quality (UKTAG, 2008). There is particular emphasis on biotic communities stating that biota must be consistent with only slight alterations from that expected in the absence of human activity (European Parliament and Council, 2000). The WFD refers to this as Good Ecological Status (GES) and the UK has a target to achieve GES across all water bodies by 2027 (Priestley, 2015). GES is based on four biotic communities including the phytobenthos, macrophytes, macro-invertebrates and fish and following a 'one out all out' approach changes in any one of these communities could cause failure to reach WFD targets.

Principally, low head 'on weir' hydropower is a human activity that could potentially alter the aquatic environment, change natural biotic communities and cause failure to comply with WFD targets. However, as low head 'on weir' schemes are fitted on existing weirs which might have already altered the aquatic environment, there is the chance that adding a hydro scheme to a weir could in fact improve the aquatic environment and provide benefits for ecology whilst also providing meaningful amounts of electricity (EA, 2010). On the other hand, adding a hydro scheme to a weir could cause negligible impacts and while the scheme might not improve the state of the environment it might not create any further issues for ecology. Although adding a hydro scheme to a weir will mean that the weir cannot be removed from the river during the lifetime of the scheme and essentially the riverine environment will not be returned back to a natural state. In the long term, whether the hydro scheme causes positive, negative or even negligible impacts regulators will need to find a balance between the need for renewable power and environmental protection.

Yet an understanding of this relies on an appreciation of the impacts of weirs alone and with a general lack of evidence surrounding this topic it is hard to know either way. While the physical and chemical impacts of weirs are thought to be understood, few empirical studies have assessed the ecological effects of weirs (Mbaka and Mwanki, 2015). Especially the ecological impacts associated with the area below the weir (Anderson et al., 2015a; Mkbaka and Mwaniki, 2015). Most knowledge about the ecological impacts of weirs is based on studies of large scale storage dams (Mkbaka and Mwaniki, 2015) and even though low head weirs are thought to reflect similar physical and chemical alterations to large scale dams, changes caused by a weir might not be biologically relevant, as the impacts will change with size and function of the structure (Poff and Hart, 2002).

In summary, understanding how adding an 'on weir' hydro scheme to a low head weir alters the aquatic communities offers a research topic which has been little addressed yet holds potentially large implications for low head hydro development, important environmental targets and renewable energy targets across the UK. Improving knowledge on the ecological impacts of 'on weir' hydropower could contribute significantly to knowledge, evidence bases and permitting decisions. With improved evidence bases regulators would no longer have to base permitting decisions on "expert opinion" but could base decisions on observed data and evidence. Moreover, given that the ecological impacts of weirs are uncertain and unclear it is crucial to study the effects of weirs on aquatic ecology in relation to this topic. This is particularly important if we wish to answer any subsequent questions as to whether the weir or scheme is driving change or in fact whether adding a hydro scheme to a weir is improving the aquatic environment and is in turn providing both benefits for ecology and meaningful amounts of renewable electricity or is in fact creating a problem for aquatic ecology where there are currently no issues. This thesis hence details an investigation into the aquatic implications of low head weirs and low head 'on weir' hydropower across the UK.

1.1.3. Study species

Given that low head weir and low head 'on weir' hydropower could alter a range of aquatic communities it was important to choose an appropriate community that would provide relatively speedy and extensive results for the purpose of this thesis. As such this thesis concentrated on the phytobenthic biofilm. The phytobenthic biofilm is often used as a biomonitoring tool to assess natural and human disturbance. The main reasons for this and the main reason why this community has been chosen for this study is because;

i) It is ubiquitous in the aquatic so can be monitored across a range of study sites
ii) It is essentially sessile so cannot migrate to avoid disturbance
iii) It has a short life cycles and is spatially compact
iv) It is easy to collect handle and store and can provide plentiful information a short space of time and space
v) Alterations in species composition and biomass can be used to predict effects on food web dynamics/ecosystem components
vi) It is monitored as part of the WFD so changes in this community could cause failure to comply with WFD targets (Law, 2011).

1.2. Aims and thesis structure

The overarching aim of this project is to advance the understanding of how low head 'on weir' hydropower can influence physical and chemical habitat condition and the phytobenthic biofilm. In order to achieve the aim, it will also investigate how weirs themselves change physical and chemical riverine conditions and the phytobenthic biofilm. It will also investigate whether low head 'on weir' hydro can improve the aquatic environment when it has been altered by low head weirs.

Chapter 2: provides a comprehensive literature review to summarise all applicable research regarding the phytobenthic biofilm, low head weirs and low head 'on weir' hydropower; identifies gaps in knowledge and develops specific objectives.

Chapter 3: provides descriptions of study sites and presents generic methods employed to address objectives identified in chapter two. More specific methods relating to precise hypotheses are described in chapters four, five and six.

Chapter 4: assesses the effect of an existing obsolete low head weir on the phytobenthic biofilm over the growing season.

C**hapter 5:** assesses the effect of an existing low head 'on weir' hydro scheme on the phytobenthic biofilm over the growing season

Chapter 6: explores the spatial distribution of physical and chemical habitat conditions and phytobenthic biomass and community structure in the area immediately below a low head 'on weir' hydro scheme.

Chapter 7: synthesises results of the research carried and presented in chapters four, five and six with the aim of providing further insights into the effects of small scale low head 'on weir' hydropower on the aquatic environment. It compares the influence of a low head weir to the influence of a low head 'on weir' hydro scheme over time, to help understand how adding a hydro scheme to a weir might improve the aquatic environment. It finishes by summarising key findings and their relevance for hydro scheme developers and regulators, discussing the limitations of this thesis and highlighting areas which require further investigation.

Chapter 2: Literature review and background

2.1. Overview

The chapter collates, reviews and summarises all applicable research surrounding the phytobenthic biofilm, low head weirs and low head 'on weir' hydropower. To begin this chapter gathers current knowledge surrounding the phytobenthic biofilm, how the biofilm responds to natural fluctuations in physical and chemical habitat conditions and how the phytobenthic biofilm has been known to alter in response to anthropogenic activity. Secondly this chapter collates current knowledge surrounding the physical and chemical implications of low head weirs and low head 'on weir' hydropower. This chapter ends by evaluating how the phytobenthic biofilm could potentially respond to changes in physical and chemical habitat conditions caused by low head weirs and low head 'on weir' hydropower, describes potential survey designs to detect the impact of low head 'on weir' hydropower and develops specific objectives that will be explored in subsequent chapters.

2.2. The phytobenthic biofilm

2.2.1. The role of the phytobenthic biofilm

The phytobenthic biofilm can grow and live on or in sediments, attached to cobbles on the river bed or on macrophytes. In this study, the focus is on communities attached to cobbles on the river bed namely epilithic biofilms (Round et al., 1990). The phytobenthic community consists of autotrophs (diatoms, green algae and cyanobacteria) and heterotrophs (bacteria, fungi and protists) in a polysaccharide matrix (Burns and Ryder, 2001). The autotrophic organisms often dominate primary production, are a persistent component of the biofilm (Geesey et al., 1978; Lock et al., 1984; Lamberti, 1996; Giller and Malqvist 1998; Hodoki, 2005; Brown et al., 2008) and are the main focus of this research.

The phytobenthic biofilm is essential for ecosystem functioning and in essence acts as the "grass" of the riverine environment (Biggs, 2000). The biofilm provides energy and habitat structure for higher trophic levels, is a major food resource for benthic invertebrates and acts as a chemical modulator removing contaminants and biodegradable material helping to purify river water (McIntire, 1973; Minshal, 1978; Boyle and Scott, 1984; Lock et al., 1984; Quinn and McFarlane, 1989; Lau and Liu, 1993; Chapman, 1995; Saravia et al., 1998; Biggs and Kilroy, 2000). As stated by Biggs (2000) if this community was removed rivers would be baron chutes of flow devoid of insects and fish.

2.2.2. Development: colonisation, growth, succession and autogenic sloughing

Naturally the phytobenthic biofilm develops over time and in space following two phases known as the accrual phase when the biofilm accumulates and biomass increases and the loss phase when cells detach and the biomass reduces (Figure 2.1). Initially propagules (seeds or spores which form new individuals) will colonise the substrate and grow exponentially accumulating biomass until the point of autogenic sloughing when biomass begins to reduce as a result of death (Figure 2.1). Peak biomass is essentially the highest biomass concentration before loss becomes more important than accrual (Biggs, 2000). Accrual is controlled by immigration, colonisation and growth (Biggs, 1996a). Autogenic sloughing is a self-generated process whereby the biofilm weakens, deteriorates and dies detaching from the substrate as a response to resource stress and disturbance (Peterson, 1996).

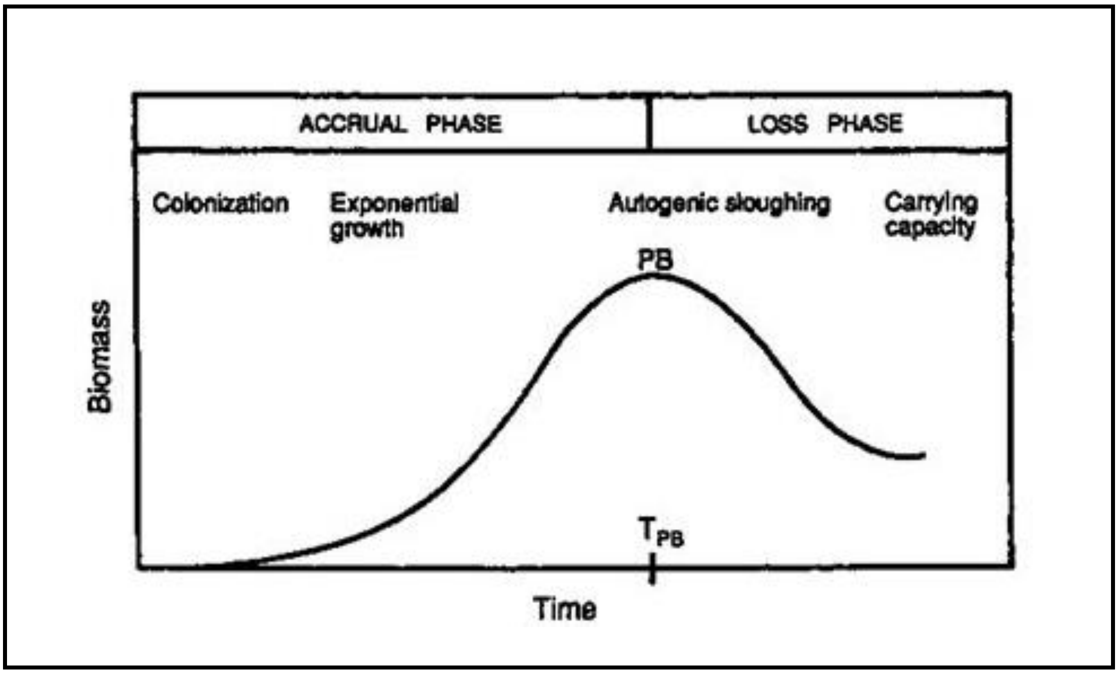

Figure 2.1: An idealised short-term accrual cycle were PB is peak biomass and were T_{PB} is the time to PB from commencement of colonisation (Biggs, 1996a)

If conditions allow, natural succession will take place through the growing phase. Communities will develop from a single layer of pioneer cells in low biomass to a mature three-dimensional climax community with upper and lower tiers also known as the overstory and understory (McCormick and Stevenson, 1991; Kelly et al., 2009b). Initial succession will begin with small adnate diatoms but over time apically and basally attached colonial diatoms will overgrow the adnate forms. Slow growing stalked and filamentous diatoms, green algae and cyanobacteria will eventually out-compete the adnate and apically attached species creating an upper canopy (Peterson and Grimm, 1992; Biggs, 1996a; Murdock et al., 2004).

In a mature three-dimensional community the lower tiers will consist of mucilaginous and gelatinous growth forms which attach to the rock in an adnate, crustose or prostrate position using mucilage pads lying parallel to the substrate. The upper tiers will consists of stalked and filamentous growth forms in an erect position lying perpendicular to the substrate. High numbers of motile species will exist unattached in the upper tiers entangled in the overstory (Law, 2011). Figure 2.2 is a schematic diagram of the individual different growth forms and Figure 2.3 is a schematic diagram of the different growth forms in a three-dimensional structure displaying upper and lower tiers in an extracellular matrix.

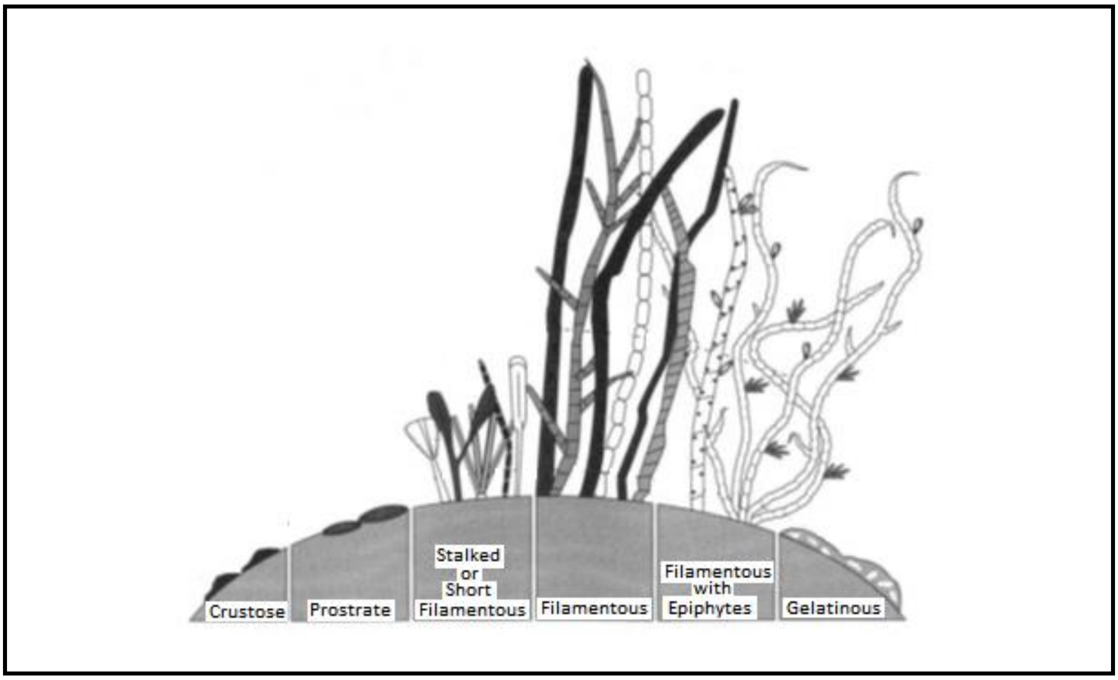

Figure 2.2: Schematic diagram of different growth which form the upper and lower tiers (adapted from Steinman, 1996)

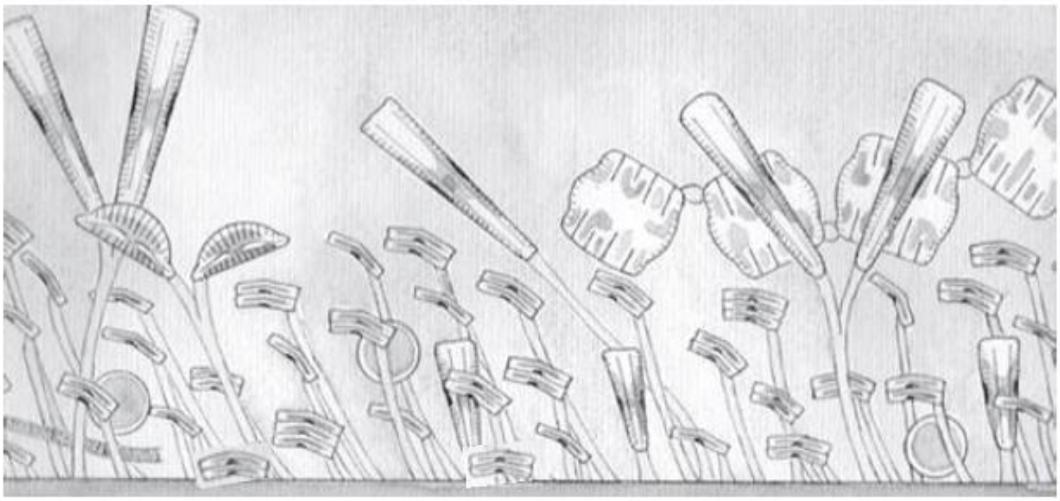

Figure 2.3: Three dimensional structural composition of the phytobenthic biofilm with an understory and overstory and motile species entangled in the extra cellular matrix (Snell, 2014, adapted from Kelly et al., 2009b)

Species are essentially arranged by morphological traits. Morphological traits have developed over time and are a reflection of adaptation to different environmental variables. Morphological traits are distinguished through specific modes of attachment and provide a way to explore the sensitivity of species to a range of environmental conditions. Morphological traits can be used explain how the biofilm succeeds in relation to specific environmental conditions and environment disturbance (Biggs et al., 1998a; Passy 2007a, b; Lange et al., 2011). Different communities can develop in response to a range of different environmental variables and specific species can dominate under certain conditions.

2.2.3. Factors affecting growth and community composition

A wide range of physical, chemical and biotic conditions can control growth and succession over time and in space (Law, 2011). Figure 2.4 displays the main physical, chemical and biotic conditions which influence the phytobenthic biofilm. Changes in any one of these variables can alter the phytobenthic biofilm by accelerating or decelerating growth or by altering or limiting the succession trajectory and introducing different species and communities (Poff, 1992; King et al., 2006). Yet it is often a combination of environmental variables that controls growth and community composition and as such it is often hard to distinguish which is the controlling factor (Law, 2011).

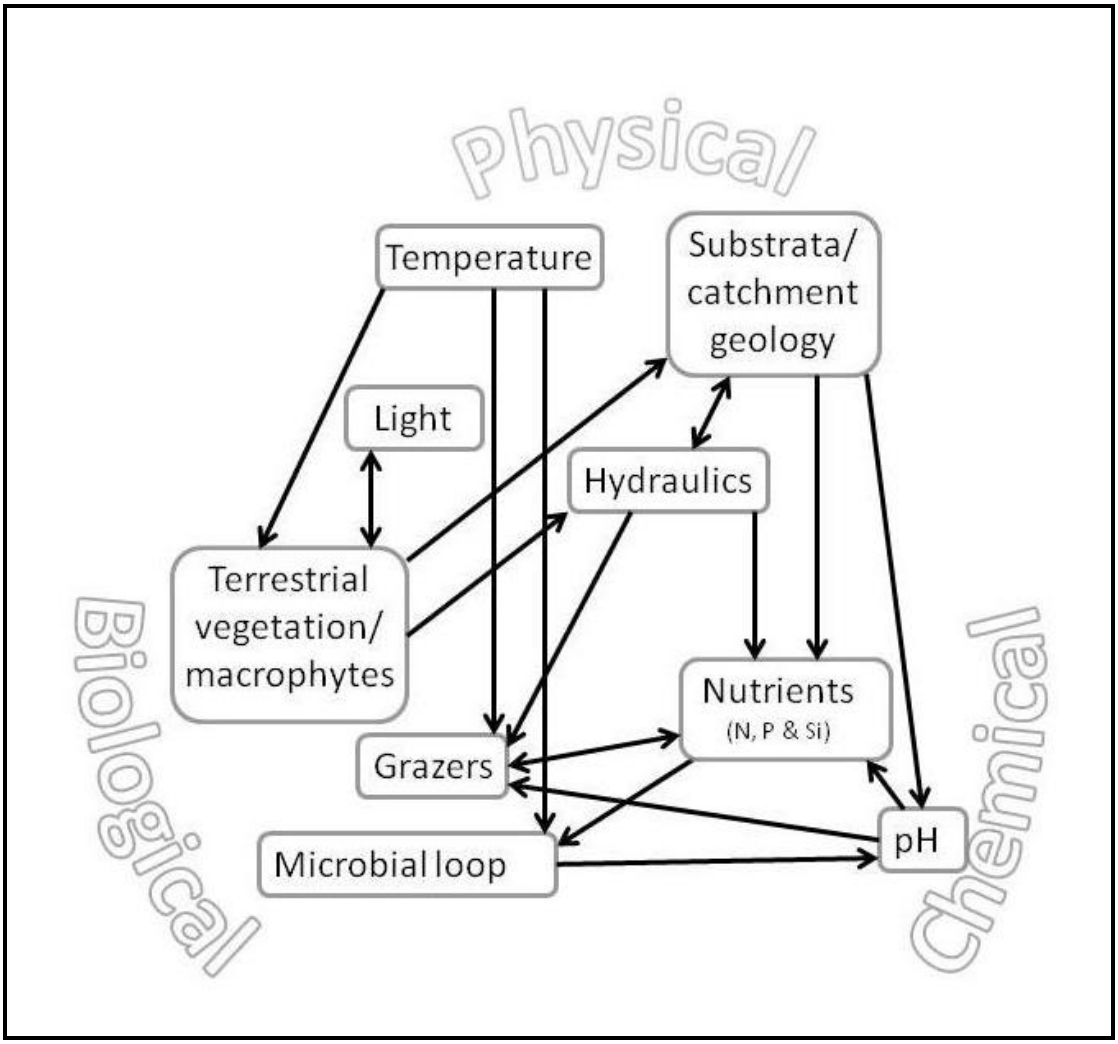

Figure 2.4: Major factors which affect phytobenthic growth in streams with arrows showing how dominant factors affect each other (Law, 2011)

Biggs (2000) describes these environmental variables as a hierarchy of environmental controllers. The hierarchy of environmental variables includes primary variables at the top and secondary/proximate variables at the bottom. The primary variables include catchment geology and climate variables such as precipitation and temperature which alongside anthropogenic activity can control landscape topography and vegetation. Landscape topography and vegetation can influence secondary or proximate variables which include the flow regime, water, quality and biotic communities. Secondary/proximate variables have a more direct and immediate effect on the biofilm (Biggs, 2000).

In general, patterns in growth (biomass accumulation) can be described by the secondary and proximate variables which include a number of resource and disturbance factors (Figure 2.5). Biomass accrual is controlled by the supply of resources including nutrients, light and temperature. All of which provide the energy that is required for photosynthesis and growth and shortages in any of these resources can limit the rate of growth and cell division (Biggs, 2000). Biomass loss is controlled by disturbance factors such as flow velocity, substrate instability and grazing. Patterns in succession and community composition can also reflect resource and disturbance factors (Werner and Kohler, 2005; King et al., 2006) with resources encouraging growth of erect, stalked and filamentous taxa and disturbance factors limiting succession and helping to maintain a community dominated by low growing tightly adhering taxa (Figure 2.5). Although in reality there are numerous factors which can affect growth and community compositions which are not directed included in Figure 2.5.

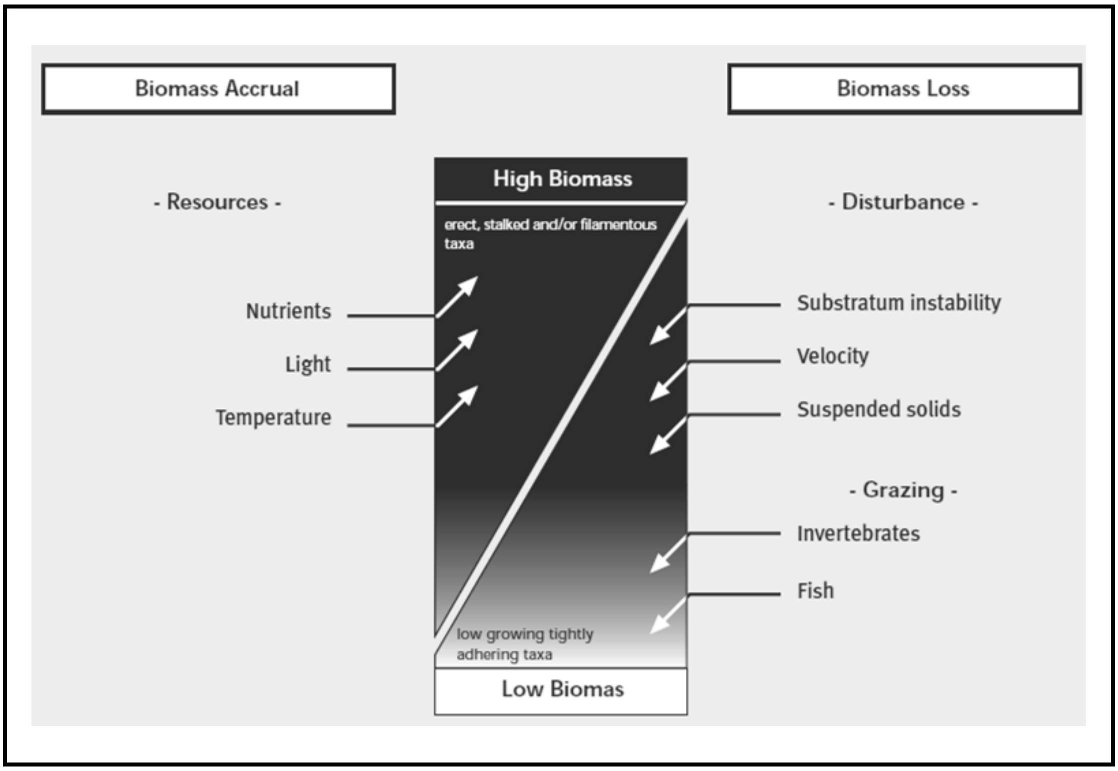

Figure 2.5: Summary of the resource and disturbance factors controlling growth and development of the phytobenthic biofilm (Biggs, 1996a)

The most significant factor controlling biomass, causing huge losses, is in fact extreme high flows and flood events (Law, 2011). High flood events greatly increase shear stress (Biggs and Close 1989; Biggs and Thomsen, 1995), increase levels of suspended sediment, increase abrasion (Tett et al. 1978; Francouer et al. 1998; Biggs et al. 1999) and can even cause increased bed-load movement (Biggs and Close 1989). All of which are disturbance factors and lead to losses in biomass as a result of scour (Biggs, 2000; Law, 2011).

However the amount of biomass loss can vary according to the intensity of the event and the resistance of the community which has been growing in the area prior to disturbance which in turn is controlled by a combination of the resource and loss factors as explained above (Biggs, 2000). For example low lying tightly adhering taxa have strong attachment capabilities and can withstand significantly high disturbance (Law, 2011). During small to medium sized floods low lying taxa, such as *Achnanthidium*, *Cymbella*, *Cocconeis* and *Synedra*, would be much less affected than tall growing taxa which have weaker attachment capabilities (Peterson, 1996).

This highlights how the effect of flood events can vary across streams. For example, phytobenthic communities growing in low nutrient concentrations are often dominated by low lying taxa adapt to low nutrient levels were as communities growing in nutrient rich streams are often dominated by filamentous communities adapt to high nutrient concentrations. As such the communities growing in the low nutrient stream would be much more resistant to floods than those growing in the high nutrient stream (Biggs and Thomsen, 1995). It would take a flood of much higher intensity to remove the biofilm and reduce biomass in the nutrient poor environment.

Nonetheless the most intense floods, which are those which occur over less than half the year, are often considered catastrophic and can remove all of the community regardless of the taxa present (Biggs, 2000). In these instances the whole community is removed and the succession trajectory is reset. In addition to this, intense flood events can also affect the time taken to reach peak biomass. Intense flood events can reduce the availability of propagules available to recolonise the substrate and as such can severely affect regeneration time (Biggs, 2000). Moreover this can be exacerbated in nutrient poor systems where, following an intense flood event, it can take up to 100 days to reach peak biomass (Biggs and Stokseth, 1996).

However there have been examples in the literature were biomass has accumulated rapidly and to high levels after a major flood event and this has been attributed to a “window of opportunity” after the flood event were invertebrate density is low (Scrimgeour and Winterbourn, 1989; Biggs and Stokseth, 1996). Invertebrates can take much longer to recolonise and reproduce in comparison to the phytobenthic biofilm following a flood event providing an opportunity for growth undisturbed by grazing.

2.2.5. Temporal patterns in growth and community composition

Taking into consideration the environmental variables discussed above Biggs (2000) has been able to identify long term patterns in growth and community composition. Patterns are most often related to the flow regime, nutrient and light regimes and in some instances patterns in grazer density (Biggs, 1996a; Young and Huryn, 1996; Biggs et al., 1998b; Biggs, 2000). According to Biggs (2000) long terms patterns in biomass either follow patterns of i) relatively constant low biomass ii) cycles of accrual and sloughing, or iii) seasonal cycles.

Constant low biomass is often found in streams which experience frequent disturbance from floods. When flood events are frequent enough and intense enough they can override the stimulatory effect of other variables such as nutrients, light and temperature and prevent the phytobenthic biofilm from succeeding into a highly diverse structure with high biomass (Biggs, 2000). Communities growing in such extreme environments are often dominated, most of the year, by disturbance resistant low profile pioneer diatoms such as *Achnanthidium*, *Cocconeis* and *Synedra* (Biggs, 2000).

Cycles of sloughing and accrual are often found in streams with moderate frequency or seasonal flood disturbance were extended periods of low flow (over 4-10 weeks) allows biomass to accumulate and slough naturally as a result of death. Over this prolonged period of low flow communities are able to succeed from a diatom dominated low lying community to communities dominated by large filamentous green algae and cyanobacteria growing in erect position with high biomass. Yet for this pattern to occur there needs to be at least moderate supplies nutrients and light (Biggs, 2000). Moreover in this situation, communities can be affected by only minor flood event as communities growing in erect position in high biomass only require small intensity flood events to reduce biomass (Biggs & Close, 1989).

Strong seasonal cycles in biomass and community composition can be mediated by the flood regime, grazer activity and light resources. When there are adequate nutrient regimes the flood regime can be seen to control seasonal patterns in both biomass and community composition. When floods are rare, seasonal patterns in grazer activity can control the phytobenthic biofilm over time. When neither the flood regime nor grazing is important patterns in phytobenthic biomass and community composition can reflect changes in light resources over time (Biggs, 1996a). Although in many cases patterns in biomass and community composition can be related to all three; flood regime, grazing and light intensity.

In many rivers high biomass can often be seen during the later stages of spring following the first period of low stable flow after the last late winter/early spring flood (Biggs, 2000). If this coincides with high light levels as result of low tree coverage and low invertebrate density as a result of cold water temperatures (Power, 1992) biomass can be particularly high. Green algae and cyanobacteria populations can increase during the summer as a result of low stable flow and while biomass levels can be high as a result of increased daylight, nutrient levels can be low, mixing can be limited and in some parts shading can be high as a result of tree cover which in turn could equally result in low biomass (Allan, 1995). Benthic autotroph biomass can increases again in autumn as a result of decreased shading but evidence to support this is scarce (Allan, 1995).

2.2.6. Spatial patterns in growth and community composition

While changes in environmental variables can be used to explain changes in phytobenthic biomass and community composition over time many studies have been able to establish spatial patterns in growth and community composition across regions, along river reaches, across sub reach hydraulic patches and even across individual substrate particles (Krejci and Lowe, 1986; Biggs and Hickney, 1994; Biggs and Stokseth, 1996). Yet spatial patterns in community composition and biomass are often best detected after prolonged periods of low flow (>6 weeks) when spatial variations in water velocity, nutrient concentrations, light intensity, temperature and grazer density become more important than discharge (Biggs, 2000; Mosisch et al., 2001; Jarvie et al., 2002; Battin et al., 2003a; Lange et al., 2011). Fundamentally spatial variations in biomass and community composition can be masked by high flow and flood events where biomass is reduced and the succession trajectory is reset regardless of position in the stream.

During stable low flows, patches of high biomass can be found on coarse substrata (Tett et al., 1978; Biggs and Shand, 1987) and patches of low biomass can be found on smaller substrata. Large substrates provide a larger surface area for growth and provide greater stability during floods which prevents scouring of the biofilm (Uehlinger, 1991). In addition differences in substrate size can cause differences in community composition. The smaller less stable substrate are often dominated by unicellular diatoms and the larger more stable substrate with filamentous green algae (Biggs and Shand, 1987).

Moreover patches can form as a result of light intensity. The River Continuum Concept (Vannote et al., 1980) proposes that biomass should increase with decreased shading and increased light intensity and that biomass should decrease as a result of increased water depths, higher turbidity and lower light intensity. Furthermore increases in nutrients along river reaches at specific points, attributed to intense land use and pollution, can also create patches of high growth and communities dominated by filamentous green algae (Biggs et al., 1998b).

Depth, flow velocity and shear stress can also drive spatial patterns in biomass and community composition; although responses can vary according to nutrient enrichment (Biggs, 2000). In streams with high nutrient concentrations, pools with higher water depths and lower flow velocities can support high biomass and communities dominated by filamentous green algae (Biggs, 2000). Yet riffles with lower depths, higher velocities and greater shear stress often experience reduced biomass and are comprised of communities dominated by low lying diatoms species such as *Cocconeis, Cymbella* and *Nitzchia* (Peterson and Stevenson, 1990; Poff and Ward, 1990). Conversely in streams with low nutrient concentrations the highest biomass is found in riffles and the lowest in pools (Scarsbrook and Townsend, 1993; Biggs and Hickey, 1994; Biggs and Stokseth 1996).

The way in which spatial variations in flow velocity create differences in biomass and community composition are often quite complex (Biggs et al., 1996b). Increased flow velocities can have stimulatory effects or loss effects depending on the availability of nutrients and species specific traits (Biggs et al., 1998a). Higher velocities can reduce the thickness of the diffusive boundary layer surrounding cells which in turn can enhances mass transfer of metabolites to and from the biofilm and increase metabolism and growth rates. On the other hand high flow velocities can increase friction and drag and can increase the rate of sloughing (Biggs, 1996b; Stevenson, 1996).

Specific communities can form patches as a result of different velocities. The outcome of spatial variation in flow velocity can depend on the growth form of the community and Biggs et al., (1998a) found three main responses across autotrophic communities. For example, communities consisting of filamentous communities in erect position will reduce in biomass with any increase in flow, communities dominated by stalked diatoms and short filamentous taxa will increase in biomass up until velocities of around 0.5m/s and then will start to decrease. Low lying mucilaginous mats will continue to increase within the typical velocity range for UK rivers which is up to 1.0m/s in most areas (Figure 2.6).

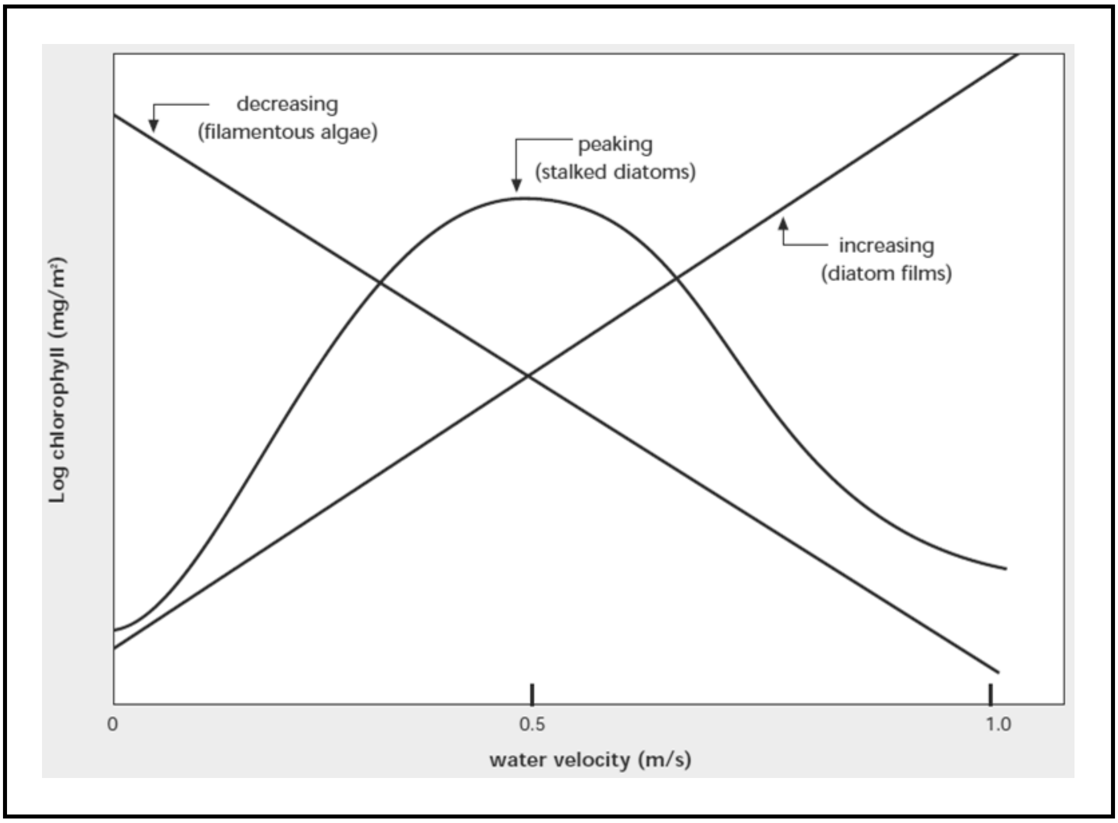

Figure 2.6: Three main community biomass responses to spatial variations in water velocity (Biggs, 2000)

2.2.7. The effect of human activity on growth and community composition

Anthropogenic activity can influence phytobenthic growth and community composition by changing important physical, chemical and biotic conditions. Yet the picture can be quite complex and often depends on pre-disturbed conditions and the natural community growing in the area pre-disturbance. The effects of anthropogenic activity can also change over time in line with natural flow, nutrient and light regimes as well as with changes in the density of grazers. Human activities which have been known to affect the phytobenthic biofilm and those that have been studied in great detail include dam installation and operation, farming practice/intensification of land use, sewage pollution and flow abstraction/diversion (Uehlinger et al., 2003; Growns and Growns, 2001; Dewson et al., 2007; Tang et al., 2013; Smolar-Zvanut and Mikos, 2014).

Dam installation, sewage discharge, abstraction/diversion and intensification of land use have all been known to cause severe increases in biomass and huge growths of nuisance filamentous green algae in line with reduced flow variability and reduced flow velocities, increased temperature and light intensity and increased nutrient concentration (Biggs et al., 1998b). Nuisance growths can have negative effects on water quality and ecosystem functioning and in the most extreme cases can lead to fish kills (McIntire, 1966; Fisher et al., 1982; Keithan and Lowe, 1985; Poff and Ward, 1990; Peterson and Stevenson, 1992; Dent and Grimm, 1999; Dewson et al., 2007; Tang et al., 2013; Smolar-Zvanut and Mikos, 2014). To be considered a "nuisance" growth the biomass concentration must be at or above 10µg/cm^2. The effect of pulsed flow releases from dam operation has been seen to have the opposite effect and reduce biomass/change community composition as a result of increased flow velocities (Flinders & Hart, 2009). Yet this has received far less attention across academic studies and the impacts of constant disturbance resulting from human activity such as low head weir installation and low head 'on weir' hydropower operation have not been studied

2.3 Low head weirs

The physical implications of weirs are thought to be relatively well understood and similar to the well documented impacts of large scale dams. Like large scale dams weirs have the potential to alter the natural riverine environment both above and below the structure. Figure 2.7 is a schematic diagram of the major physical alterations potentially caused by weirs. Shortly after construction the water level above the structure is likely to rise creating a weir pond which can extend for several kilometres upstream (Walters and Merritts, 2008). The area below the weir is a vast contrast to the weir pond and is unlikely to support features which are characteristic of a natural lowland river (Mould et al., 2015). The weir itself can act as a barrier to sediment, nutrients and particulate organic matter and can deprive the area below the weir of important sediment and nutrients (Skalak et al., 2009; Csiki and Rhoads, 2010; Stanley and Doyle, 2002). Although there are examples in the literature where low head dam structures have had no considerable effects on the geomorphology (Csiki and Rhoads, 2014).

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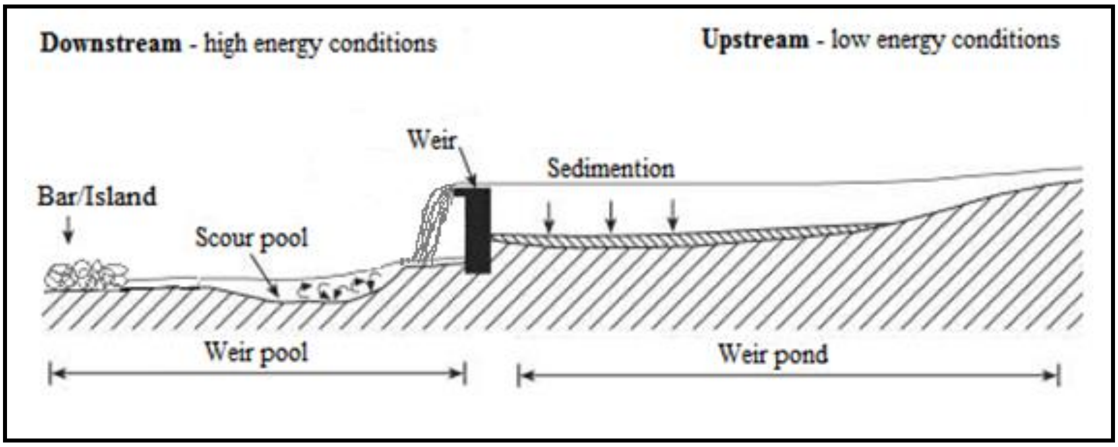

Figure 2.7: Typical physical habitat conditions above and below a weir (adapted from Downward and Skinner, 2005)

2.3.1 Physical and chemical alterations

2.3.1.1 The weir pond

The weir pond can eliminate the natural riffle/pool sequence and is typically associated with lower flow variability, higher water depths, slower flow velocity and fine sediment deposition (Csiki and Rhoads, 2010, Salant et al., 2012; Mueller et al., 2014; Anderson et al., 2015a). Yet very few studies have quantified the magnitude of impact and the degree to which flow is reduced is uncertain and is likely to vary with weir size and shape. The majority of low head weir studies have simply compared the area immediately above the weir to the area immediately below the weir (Mueller et al., 2011) or have coupled the effects of the weir with flow regulation and river diversion (Shiau and Wu, 2004) and are thus contributing to this lack of clarity.

Whilst studies surrounding weirs typically conclude that there is very little change in chemical river conditions as a result of weir installation (Miranda et al. 2005) sedimentation behind the weir could create turbid conditions in the weir pond (NSW, 2006) which in turn could affect light intensity. Furthermore, if the area behind the weir is not dredged sedimentation combined with increased evaporation in the summer months could reduce the depth of the river and increase the water temperature (NSW, 2006). However there is evidence in the literature were sediment transport has been observed over weirs, specifically in flumes, where flows overtopping the weir resulted in no accumulation of sediment upstream (Lauchlan, 2004).

2.3.1.2. The weir pool

The action of water dropping from the top of the weir to the area below the weir will create highly complex flow patterns, turbulent flow and high water velocities which are likely to be different to what would occur naturally (Fraser et al., 2015). In cases where sediment is trapped behind the weir, this cascading flow could cause clear water erosion downstream, which in turn could create a scour pool and in some cases bank undercutting (Downward and Skinner, 2005; NSW, 2006; Skalak et al., 2009; Csiki and Rhoads; 2010; Im et al., 2011, Mould et al., 2015). As a result of sediment deprivation and high flow velocities large bed rock could be exposed below the weir (Church, 1995). The high water velocities from weir discharge could help to maintain coarse large cobbles and boulders in the area below the weir (Bunt et al., 1998).

However the degree to which flow velocity increases is unclear as there is limited data on pre-disturbed conditions (Downward and Skinner, 2005). Moreover the degree of change is likely to differ according to weir shape and size and in response to different morphological features across river reaches. In instances were clear water erosion does occur the scoured material could be transported downstream and as the flow begins to reduce could be deposited forming a tail riffle or bar (Church, 1995; Mould et al., 2015). Figure 2.8 shows aerial images of bars which have formed below a series of weirs along the River Irwell and River Roch, UK. If a bar is formed constriction of flow between the bar and the river banks could cause further increases in flow velocity and bank undercutting.

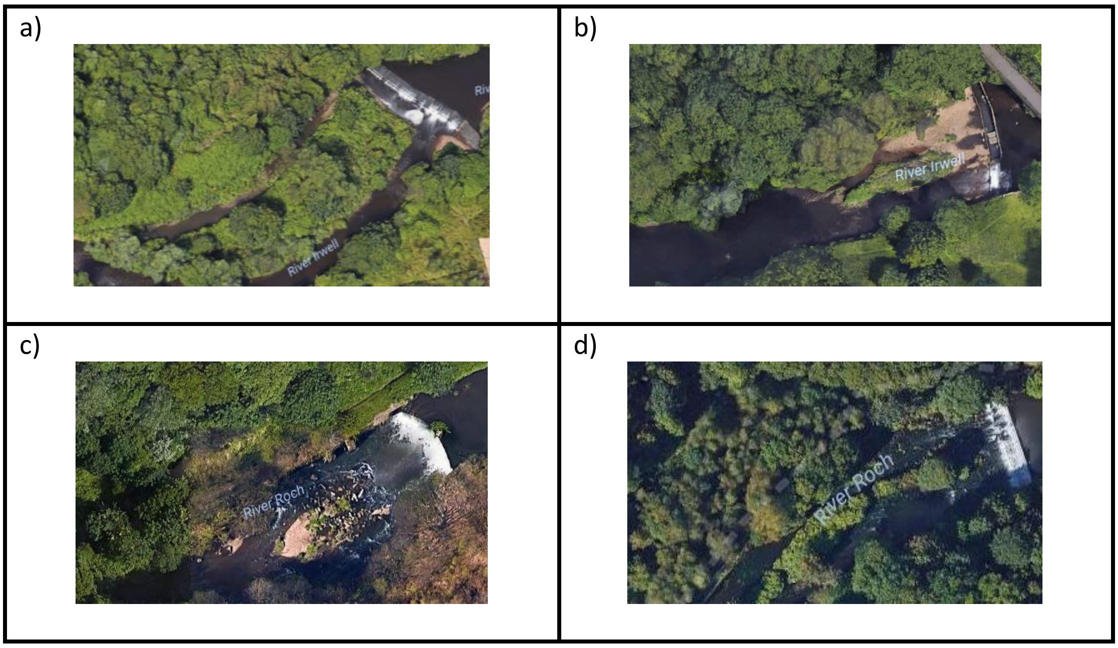

Figure 2.8: Aerial images of bars formed below weirs along the River Irwell, UK were a) is located (SD7941910003) (Google Earth, 2017b), b) is located (SD801181659) (Google Earth, 2017c), and River Roch, UK were c) is located (SD8330611263) (Google Earth, 2017d) and d) is located (SD8498211905) (Google Earth, 2017e)

The plunging jet of water which passes over a weir structure could create turbulent mixing and air entrainment which in turn could cause an increase in dissolved oxygen levels in the weir pool below the weir (Gulliver et al., 1988; Demars and Britton, 2011; Schilts, 2006). Figure 2.9 shows a schematic diagram and a photograph of turbulence and air entrainment below a weir. Whilst at high head river barriers this might cause supersaturation and is thus associated with adverse ecological effects (Brasher, 2003), there is no documented cases were aeration below weirs has caused supersaturation. Furthermore it is reported that shadows created by the weir could affect water temperature (Schilts, 2006; De Leaniz, 2008). Yet changes in chemical river conditions as a result of weir installation have been deemed minimal and too small to be biologically significant i.e. create noticeable or relevant changes in natural community composition and abundance or biomass and thus causing effects on general ecosystem functioning (Kelly et al., 2006).

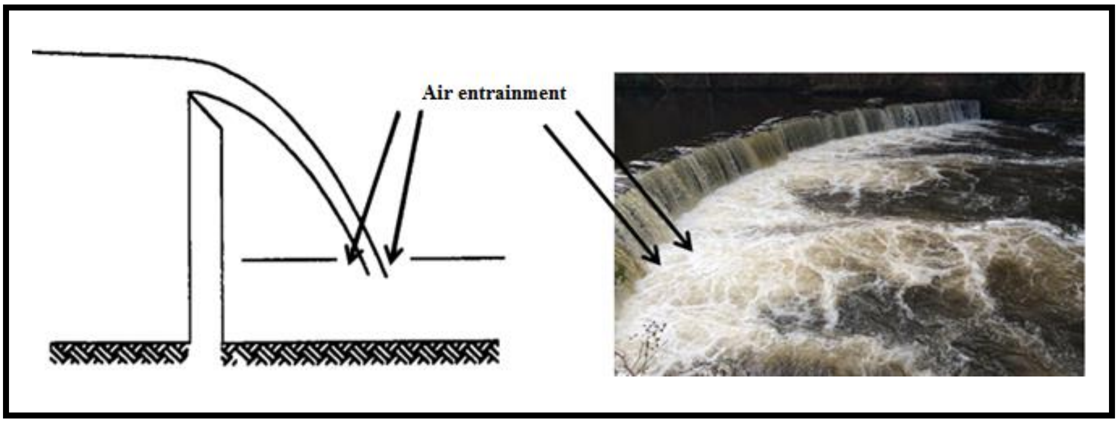

Figure 2.9: Schematic diagram of air entrainment below a weir and an 'in situ' example at Stringer's Weir (SJ9083790634) Stockport (adapted from Gulliver et al., 1988)

2.3.2 Implications for the phytobenthic biofilm

There are three possible biotic responses to low head weirs on the phytobenthic biofilm, which include no perceivable impact on community composition and biomass, a change in community structure and/or biomass or the introduction of species that did not previously occur in that location (Growns and Growns, 2001). In regards to the phytobenthic community specifically, only one study was found to have explored the impact of low head weirs on the phytobenthic biofilm (Mueller et al., 2011). So this section instead reviews how the community might respond by drawing information from studies across a variety of natural and human disturbances. Subsequent sections will focus on the weir including the area above the weir (the weir pond) and the area below the weir (the weir pool). As many obsolete weirs would have been part of the riverine environment for hundreds or even thousands of years (Downward and Skinner, 2005), the weir will be treated as a constant disturbance. Comparisons will be made in most parts between disturbed/regulated reaches to undisturbed areas and natural reaches.

2.3.2.1. The weir pond

One of the major alterations associated with the weir pond is reductions in flow velocity and flow variability. However the way in which the phytobenthic community will respond to reduced flow velocities will depend on previous flow conditions, the magnitude of change, and overlying natural physical and chemical and biotic habitat conditions which may vary seasonally and across river reaches. For example filamentous green algae or cyanobacterial growths can become dominant in streams with gravel substrates, low flow velocity and moderate to high resource supply between floods during summer months (Biggs 1990). Essentially with little disturbance, during the summer months a gradual succession occurs from diatoms to filamentous green algae or thick cyanobacterial mats with high biomass (Stevenson et al., 1996; Suren et al., 2003a; Suren and Riis, 2010). In one respect the reduced flow created by a weir, could lead to a reduction in biomass as a result of a reduction in the mass transfer/diffusion of nutrients at the boundary layer and decreased metabolic activity (Biggs, 2000). Moreover it could lead to a switch from a community dominated by filamentous green algae and cyanobacteria to a community dominated by more tolerant low lying diatom taxa. In extreme cases, where flow becomes stagnant, it could even lead to complete removal of the biofilm (Hondzo and Wang, 2002).

Yet if nutrients are plentiful, community structure might not alter as nutrient concentrations could be high enough to combat the effects of reduced flow (Biggs, 2000). But the reduced flow created by the weir could lead to an increase in biomass as a result of reduced scour and drag. This is similar to what has often been found in studies which investigate the effects of impoundments, abstraction and diversion (Biggs et al., 1996b; Biggs et al., 1998a). Across the literature, reduced flow velocity associated with human activity, in enriched systems, is often associated with high proliferations of filamentous green algal biomass. These proliferations are nearly always referred to as "nuisance" growths having negative effects on water quality and ecosystem functioning and in the most extreme cases leading to fish kills (McIntire, 1966; Fisher et al., 1982; Keithan and Lowe, 1985; Poff and Ward, 1990; Peterson and Stevenson, 1992; Dent and Grimm, 1999; Dewson et al., 2007; Tang et al., 2013; Smolar-Zvanut and Mikos, 2014). To be considered a "nuisance" growth the biomass concentration must be at or above 10µg/cm^2. Many of these studies also suggest that, as a result of this reduced flow, community diversity is greater and that succession rate is much more rapid (Lamb and Lowe, 1987).

Although Mueller et al., (2011), which is the only study that could be found to have investigated the impacts of low head weirs on the phytobenthic biofilm, found similar diversity figures in areas both above and below a number of weirs in rivers across Germany. Moreover this study also found that the area above the weir had lower species richness and a lower number of cells which contradicts the findings from impoundment, abstraction and diversion studies. Yet the study by Mueller et al., (2011) only compared the area above the weir to the area below the weir which are areas both altered by the weir structure and are therefore not representative of natural communities. The area below the weir is likely to have higher flow velocities and there are examples in the literature where communities growing in fast flowing environments have been seen to exceed those growing in slow flowing environments (Law, 2011). Highlighting how, when designing an investigation, careful consideration must be taken to sampling time and the comparisons that are made between different communities collected from different habitats. Biofilms growing in a slow flowing environment will go through the natural accrual and succession cycle and will eventually slough, die and recolonise. If an early colonising community in a slow flowing environment above a weir is compared to a mature community in fast flowing environment below a weir conclusion made about the different environments could be flawed.

To combat this issue many studies often compare communities from similar habitats (often riffles) in regulated river reaches with reduced flow to communities from unregulated reaches with more natural flow. These studies will collect samples on the same day and from the same river or a river with a similar discharge regime and will collect a wide range of physical, chemical and biotic data alongside samples of the phytobenthic community. As with the studies mentioned above these studies often find that regulated reaches with reduced flow and moderate to high nutrients are dominated by filamentous green algae with high biomass. In many instances the unregulated reaches with natural flow are dominated by low profile scour tolerant diatoms with low biomass and are completely different to communities found in the regulated reach with reduced flow (Tang et al., 2013). With reduced flow velocity in the regulated reach the community appears to be less constrained by flow shear stress, compositional shifts appear to occur and biomass seems to accumulate (Tang et al., 2013). This suggests that weir ponds in an enriched environment will be dominated by filamentous green algal species with high biomass and will differ in community composition and biomass to natural river/un-impacted sections in the same river.

However certain species have specific tolerance ranges and where a reduction in flow created by a weir is minimal there is the chance that the impacts will be negligible and that communities and/or biomass will not change. Yet this will depend on the community growing in the environment prior to weir installation and the overlying natural flow conditions. Disregarding other environmental variables communities growing in flows ranging from 0.05 to 0.3m/s are often dominated by growths of filamentous green algae. Communities growing in flows ranging from 0.3 to 0.7m/s are often dominated by growths of stalked or short filamentous diatoms and communities growing in flows ranging from 0.7-1.0m/s are dominated by thick mucilaginous diatoms (Biggs et al., 1998c). If the natural overlying conditions allow for a community to grow and succeed into a community dominated by stalked or short filamentous diatoms and the weir has not reduced flows below 0.3m/s the community could remain dominated by these species. While the relative contributions of mucilaginous growth forms, which lose their competitive advantage at reduced flows, could reduce and the relative contributions of filamentous greens which have a competitive advantage in reduced flows could increase, changes might not be great enough to have an effect on overall water quality and general ecosystem functioning.

There are also examples in the literature where grazer density, high discharge and low nutrient levels have been seen to mask the effect of reduced flow (Suren et al., 2003a; Suren et al., 2003b; Shiau and Wu, 2004; Townsend and Padovan, 2005; Tang et al., 2013) and thus there is the possibility that any reductions in flow created by a weir could lead to similar results. High discharge could increase velocities beyond critical thresholds regardless of the effect of the weir and areas above the weir and areas free from the influence of a weir could support similar communities (Tang et al., 2013). An example of this was seen in a regulated river reach in Hong Kong were during the dry season regulated reaches with reduced flow were dominated by stalked and mobile diatoms with high biomass but the unregulated reach was dominated by scouring-tolerant prostrate and adnate diatoms with low biomass (Tang et al., 2013). Yet in the wet season there was no difference between communities in each reach and this was attributed to the “background” discharge being relatively high (Tang et al., 2013). The high discharge led to an increase in flow velocities, in all locations, and the biofilm was scoured and the succession trajectory reset.

Suren et al., (2003b) attributed low biomass and diatom dominance during low flow to grazing pressure. Reduced flow velocity can increase invertebrate density which in turn can increase grazing pressure and reduce biofilm biomass (Steinman et al., 1987; Dudley and D’Antonia, 1991; Welch et al., 1992; Welch et al., 2000). In addition grazing pressure can help maintain a thin prostrate community dominated of diatoms (Law, 2011). If reductions in flow in the weir pond encourage high invertebrate density above the weir, it could cause a reduction in biomass and lead to a community dominated by low lying diatoms. As with high discharge described above grazers could mask the effects of decreased flow created by the weir. Yet in some situations, grazers are unable to alter phytobenthic succession as resources are already limiting. For example, in low light conditions filamentous forms would not persevere anyway, so the addition of grazers would have no effect in changing this succession (Steinman et al. 1989).

In other instances diatom dominated biofilms and low biomass in reduced flow have been attributed to nutrient depletion (Suren et al., 2003b). In an unenriched system even if reduced flow is conductive of a community dominated by filamentous green algae and high biomass, nutrient limitation can outweigh the benefits of reduced flow and can result in a community dominated by diatoms with low biomass (Suren et al., 2003b). Low profile diatom taxa are more tolerant to resource-limited environments (Passy, 2007b; Berthon et al., 2011) where a complex community cannot form due to low nutrient availability (Passy, 2007b; Passy and Larson, 2011). If a weir is installed in an unenriched system, the reduction in flow might not have any effect on the phytobenthic biofilm and its biomass and the community could be dominated by diatoms with low biomass regardless.

In addition to reduced flow the weir pond is often associated with sedimentation. While phytobenthic communities can develop on finer sediments such as sand and silt, the greater instability of these substrata can prevent development of thick and high biomass (Eriksson, 2001; Bastviken et al., 2003) and cause a reduction in suitable hard substrata for colonist (Biggs, 1995). Sedimentation can also smother the biofilm and cause a decrease in biomass. Orr et al., (2008) reported a 60% reduction in chlorophyll following sediment smothering and Matthaei et al., (2010) saw reduced algal biomass following flow reduction and increased sedimentation. Yet thick mats of the cyanobacteria *Phoridum* can occur over silts in low velocities (Biggs, 2000). Moreover whilst exploring the effect of sedimentation of the phytobenthic biofilm, Izagirre et al., (2009), saw an initial reduction in phytobenthic growth following sedimentation but signs of adaptation and increased photosynthetic efficiency just two weeks later. In situations where the weir has caused sedimentation to occur there could be differing results depending on the community present before weir installation and overlying physiochemical conditions. It is evident that the results of sedimentation vary and will be site specific.

Another alteration associated with the weir pond, is increased depth. As a result of high water depth, light intensity is often low. This is because the light cannot penetrate right through the water column to the bottom of the river bed (Stevenson, 1996). Assuming a high water depth, light intensity could be relatively low in the weir pond behind the weir. Moreover light intensity could also be reduced if the weir pond is turbid as a result of sedimentation. Light is a prerequisite for phototrophic existence and photosynthesis responds quantitatively to changes in light (Hill, 1996). Light can limit phytobenthic growth even when other resources such as nutrients are plentiful (Van Nieuwenhuyse and La Perriere, 1986; Davies-Colley et al., 1992; Greenwood and Rosemond 2005). If light intensity is low and photosynthesis is limited biomass levels in the weir pond could be low as a result.

Changes in light availability have also been known to affect community composition (NewCombe and MacDonald, 1991). Low light situations are often associated with diatom species (Hill, 1996). Some species such as *Achnanthes* and *Stigeoclonium* are even adapted to withstand multiple days (10 and 92 respectively) in the dark (Steinman et al. 1990; Tuchman et al. 2006). Lange et al. (2011) noticed that low-profile diatom species were prevalent at low light conditions whereas high-profile species dominated at higher light conditions. Whilst slow flow in the weir pond might support filamentous high profile algal species, the high water depths and potentially reduced light penetration might support low profile pioneer diatom species regardless of other physiochemical river conditions (Law, 2011).

In summary while a weir is likely to create a weir pond above the weir with high water depths, reduced flow velocity and increased sedimentation the way in which the phytobenthic biofilm will respond is uncertain and is likely to vary according to overlying river conditions. Studies at impoundments, abstractions and diversions with reduced flow often see communities dominated by nuisance growths of filamentous green algae. Yet this is often combined with high nutrient levels and low flow during summer months. Where nutrient levels are low, grazing pressure is high or when there has been a high flood event the effects of reduced flow could be masked and communities could be dominated by diatoms with low biomass regardless of the effect of the weir. Furthermore high water depths, sedimentation and low light intensity often result in low biomass and diatom dominance. Yet there are examples where cyanobacteria have grown with high biomass in areas of fine sediment deposition. This highlights how the impact of a low head weir is likely to be site specific and dependant on a number of interrelated variables. More investigations at low head weirs specifically across a range of environments would help to better understand the response and help to understand which river condition is driving change in community composition and biomass, if there is any change at all.

2.3.2.2. The weir pool

Studies at large scale dams often associate the area below dam/weir structures with nuisance growths of filamentous green algae. This is often attributed to reduced flows and a stable flow regime as a result of flow storage (Arscott et al., 2007; Chester and Norris, 2006). In contrast to large scale dams low head weirs are routinely overtopped with flow and the area below the weir is associated with complex flow patterns, turbulent flow and high flow velocities which are likely to differ from natural conditions (Mould et al., 2015a). Little can be gained from contrasting the area below a dam to the area below a low head weir and very few studies have explored the effect of consistent high flow on the phytobenthic biofilm.

Understanding that the phytobenthic biofilm reflects a balance between flow induced accrual and loss processes (Biggs, 1996a) can assist in interpreting the way in which the community might respond to changes in flow caused by a low head weir (Hart et al., 2013). While increases in flow velocity can reduce the thickness of the diffusive boundary layer at the biofilm surface and enhance mass transfer of dissolved nutrients and increase metabolic processes and in turn increase biomass (McIntire, 1966; Horner et al., 1990; Jørgensen and Des Marais, 1990; Ku¨hl et al., 1996). High flow velocities above critical thresholds can create drag forces, which in turn can cause sloughing and a reduction in biofilm biomass and a switch to more tolerant low lying diatom species (Keithan and Lowe, 1985; Bergey et al., 1995; Biggs et al., 1998a; Hondzo and Wang, 2002; Battin et al., 2003). Physical shear stress imposed by increased current strength can strongly influence the abundance of different growth forms (Stevenson, 1996; Hart and Finelli, 1999). With increased flow velocity, community development can be constrained and compositional shifts can be limited. High flow velocities below the weir could keep the community in an early succession state and prevent the community from developing to a three-dimensional structure with high biomass.

Yet critical velocities vary according to growth form and as such the effects of increased flow created by a weir could vary according to specific species growing in the area prior to weir installation and the magnitude of change induced by the weir. If flow velocity is increased below the weir but is still within the tolerance range of the community already growing in that area then the community might not change. For example flows ranging from 0.05 to 0.3m/s are suitable for growths of filamentous green algae, flows ranging from 0.3 to 0.7m/s are more suited for growths of stalked or short filamentous diatoms and flows ranging from 0.7-1.0m/s are more suited for thick mucilaginous diatoms or cyanobacteria (Biggs et al., 1998c) which can even increase in biomass in flow velocities up to 1.5m/s (Biggs and Hickney, 1994). If the community is dominated by stalked or short filamentous diatoms and the weir does not increase flows beyond 0.5m/s the community could remain similar.

Increased flows, in general, are however often associated with a reduction in biomass and a switch from a community dominated by filamentous green algae to a community dominated by low profile diatoms (Horner et al., 1990; Ghosh and Gaur, 1998). This is especially true at exceptionally high flows between 0.76 and 1.78 m/s (Antoine and Benson-Evans, 1982). The mucilage content of these low lying taxa aid attachment and counteracts drag from the current (Hoagland et al. 1993; Biggs and Hickey 1994; Peterson et al., 1994) and is a reason why diatoms might dominate communities below weirs. Mueller et al., (2011) identified high cell numbers of diatom species such as *Navicula* and *Gomphonema* below weirs in German rivers and as such supports this assertion. Yet Bunt et al., (1998) found large mats of filamentous green algae immediately downstream of a weir. While Mould et al., (2015a) related this to the high flow velocity from the flow overtopping the weir, the large mats could be a result of the combined effect of the high flow velocity, plentiful nutrients/light, low grazer density, high substrate complexity (Stevenson, 1996) and/or the preceding discharge regime.

The actual response of the community is likely to be a result of the combined effect of a wide range of interrelated variables. Biggs and Hickey, (1994) report how the composition of communities can be a reflection of both flow velocities and nutrients. Small prostrate species such as *Cocconeis* can be found in fast flowing water with low nutrients and large stalked species such as *Gomphonema* being found in fast flowing water with high nutrients. The effect of flow velocity and nutrients can be considered as a subsidy stress response. Higher original nutrient concentrations reduce the delivery benefit associated with high flow velocity but in higher nutrient concentrations thicker mats may develop and will need high flow velocities to deliver nutrients to the base (Horner et al., 1990; Humphrey and Stevenson, 1993). In a nutrient poor river, high velocities can inhibit phytobenthic growth because nutrients will be rinsed out of the mat and will not be replenished. Composition and biomass can also be a reflection of both flow velocities and grazer density. High flow velocities can wash away grazers and in turn increase biomass levels as a result. High flows have been known to prevent snail grazing, as motile organisms move much slower in increased flow (Hart and Finelli, 1999). This highlights how the effect of a low head weir will be site specific and will vary across different aquatic environments with differing overlying environmental variables.

Moreover when overall discharge is high and a river is in flood, the effect of a weir could be masked. Changes caused by a weir might not be sufficient enough to cause a response. In other words high discharge can increase flow velocities beyond critical thresholds in both areas below a weir and areas uninfluenced by a weir and can result in similar community composition and biomass concentrations across a whole river reach despite the presence of a weir (Tang et al., 2013). Yet communities growing in high current velocities are more resistant and resilient when floods do occur (Peterson and Stevenson, 1992; Biggs and Thomsen, 1995) and as such the mere presence of a weir and the consistent high flow velocities under which the community has grown, could result in a more resistant community and as such higher biomass concentrations below a weir when compared to areas free from a weir after a flood event.

In addition to increased flow velocities a weir structure can also create and maintain habitats with coarse, stable substrate free of silt. All of which have been known to be beneficial to benthic organisms including the phytobenthic biofilm (Bunt et al., 1998; Ligon et al., 1995). The reduced fine sediment below the weir could reduce abrasion and as a result, even during the highest flows, could maintain relatively high biomass. Moreover high biomass accumulation has often been observed on larger stones, cobbles, and gravel as opposed to sand and clay. Large cobbles can provide a stable platform for growth (Law, 2011) and a larger surface area to shelter from the main current (Biggs, 2000; Ahn et al., 2013). Biggs et al., (1999) state that sites with coarse, stable bed sediments, have a mean monthly biomass 2 to 10 times higher than sites with unstable bed sediments. This highlights the possibility that the area below the weir could support biofilms with high biomass if other conditions allow. However when larger cobbles and boulders are moved during the most intense flood events, they can cause a larger effect on the biofilm than the smaller cobbles and pebbles (Peterson, 1996). The exact shear stress required for this type of movement does however depend on the size of bed-load particles (Biggs and Close, 1989) and will only occur at flow magnitudes much greater than that required to suspend sediments or shear biofilms.

To summarise, it is apparent that given the amount of interrelated environmental variables which affect the phytobenthic biofilm, there is no clear cut answer as to how a weir pool will impact community composition and biomass. Little is known about the degree to which the weir will alter the environment below the weir and how this will vary seasonally with overlying environmental variables including nutrients/light levels, the discharge regime and grazer density. While the majority of studies associate high flow velocities with diatom dominated communities in low biomass, a weir could increase biomass and encourage succession as a result of reduced grazer density. Moreover it could increase biomass by providing a stable platform for growth on coarse stable substrate. Yet the effect of the weir could be masked by flood events and low nutrient levels. More investigations need to be carried at weir structures to see how the phytobenthic community responds to the creation of a weir pool below a weir.

2.4 Low head 'on weir' hydropower

2.4.1 Physical and chemical alterations

Adding a low head 'on weir' hydro scheme to a weir could affect the area above and area below the weir but with changes in the area below the weir being more prevalent. Without a hydro scheme all flow would be directed over the weir but with the addition of a hydro scheme the flow will be split between the weir and turbine, with the turbine utilising as much flow as possible in line with regulatory conditions and turbine capacity. As the intake for the hydro scheme is situated on or directly alongside the weir itself, this re-distribution of flow will only cover the weir and the area below the weir.

As a result of this re-distribution of flow, large volumes of water could be concentrated towards one side of the channel (the hydro side). This in turn could change flow pattern, energy dissipation and morphology (Robson et al., 2011) and could alter mesoscale spatial variations in flow velocity. Essentially this could cause an increase in flow velocity towards the hydro side of the channel and a decrease in flow velocity towards the non-hydro side of the channel; in the most extreme cases causing the hydro side of the weir to dry out (Mould et al., 2015).

The hydro scheme could also provide a pathway for sediment and hence improve sediment movement downstream (Anderson et al., 2015a). This could also lead an increase in depth behind the weir as any sediment that might have built up behind the weir over time will now be able to pass downstream. Figure 2.10 is a photograph of a weir in the River Irwell, UK where the non-hydro side of the weir appears to have less flow than the hydro side. Yet empirical evidence to prove this is scarce and more research needs to be conducted to verify this assertion.

Figure 2.10: Photograph of a low head ‘on weir’ hydro scheme in the River Irwell, UK were the non-hydro side of the weir appears to be covered in less flow than the hydro side

Although large volumes of water are returned back into the main river channel almost immediately below the weir, potential problems might arise as a result of this re-distribution of flow. High velocities could extend from outlet and create increased turbulence and scour which in turn could result in erosion of the river bed and banks (Demars and Britton, 2011). Figure 2.11 is a photograph which was taken below Whalley Hydro, a low head ‘on weir’ hydropower scheme in the River Calder, UK. This photograph shows evidence of turbulence below the turbine. It seems likely that this increased flow velocity and turbulence will be controlled by the amount of flow diverted through the hydro scheme. Much of this is, however, based on anecdotal evidence rather than empirical evidence and hence more data needs to be collected to define the scale of impact.

Figure 2.11: Photograph of turbulence below the turbine at a low head ‘on weir’ scheme in the River Calder, UK

The most significant impacts may occur where water from the hydropower scheme meets the flow from the weir below the scheme, forming a confluence (Anderson et al., 2015b). Changes in flow pattern, velocity and morphology could potentially echo distinct hydrological and morphological features, typically associated with the interface of flows at river confluences. While the mechanisms of flow patterns and bed morphology below the outlet of an ‘on weir’ hydro scheme have not been extensively researched the body of research at confluences is extensive and as such river confluence studies could be used to facilitate the development of a conceptual model of outlet confluence dynamics and provide context for future field research.

Figure 2.12 is a schematic diagram adapted from river confluence studies showing the potential hydraulic alteration which could be caused by a low head ‘on weir’ scheme where the turbine is directly adjacent to the weir. The diagram is split into hydraulic zones of impact which could have markedly different hydraulic conditions. A stagnation zone of reduced flow velocities at the upstream junction corner and separation zone of reduced flow velocities at the downstream junction corner could develop. Shear layers could form in the downstream direction from the point of stagnation and along the separation zone. The mixing and shear layers could create a boundary and the merging flows passing through this narrowed constricted cross-section could increase in velocity and form a section of high flow velocity or acceleration zone up until the point of flow recovery where the mixing and shear layers expand and dissipate laterally. High velocities could cause the river bed to erode, creating a scour hole and as the velocity decreases and recovers the eroded material could be deposited and a downstream bar could be formed. In turn bar formation could cause constriction of flow and further increases in velocity (Mosley, 1976; Ashmore and Parker, 1983; Best and Reid, 1984; Best, 1988; Best and Roy, 1991; Biron et al., 1996a, b; McLelland et al., 1996; Rhoads, 1996; DeSerres et al., 1999; Rhoads and Sukhodolov, 2001).

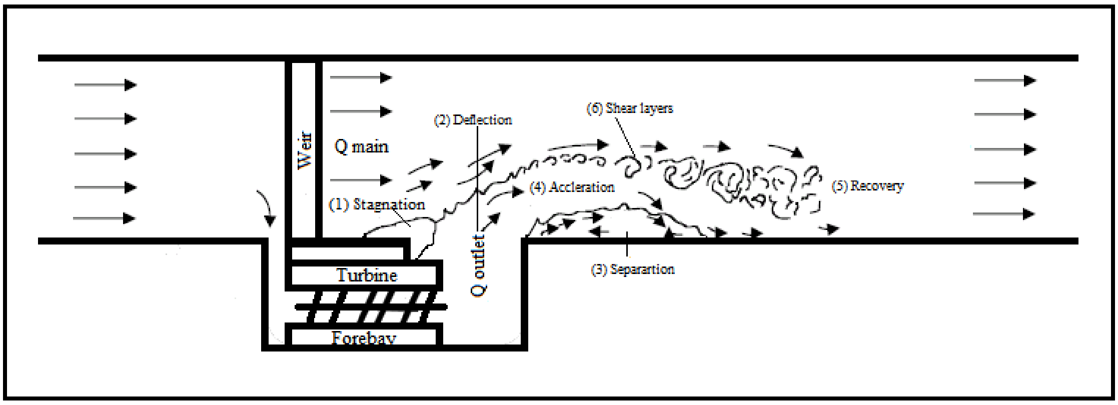

Figure 2.12: Potential hydrological features associated with the interface of two flows below the outlet of a low head 'on weir' hydro scheme (adapted from Best, 1987)

Figure 2.13 is a photograph of the area below the outlet of a low head 'on weir' scheme in the River Goyt, UK. One can clearly distinguish an area of separation, at the downstream junction corner and a constricted cross section, defined by boundary layers extending from the outlet. While this is circumstantial observed evidence, investigations could be carried out at existing schemes to draw more solid conclusions. Hence an investigation into whether the same processes are evident as at river confluence needs to be conducted.

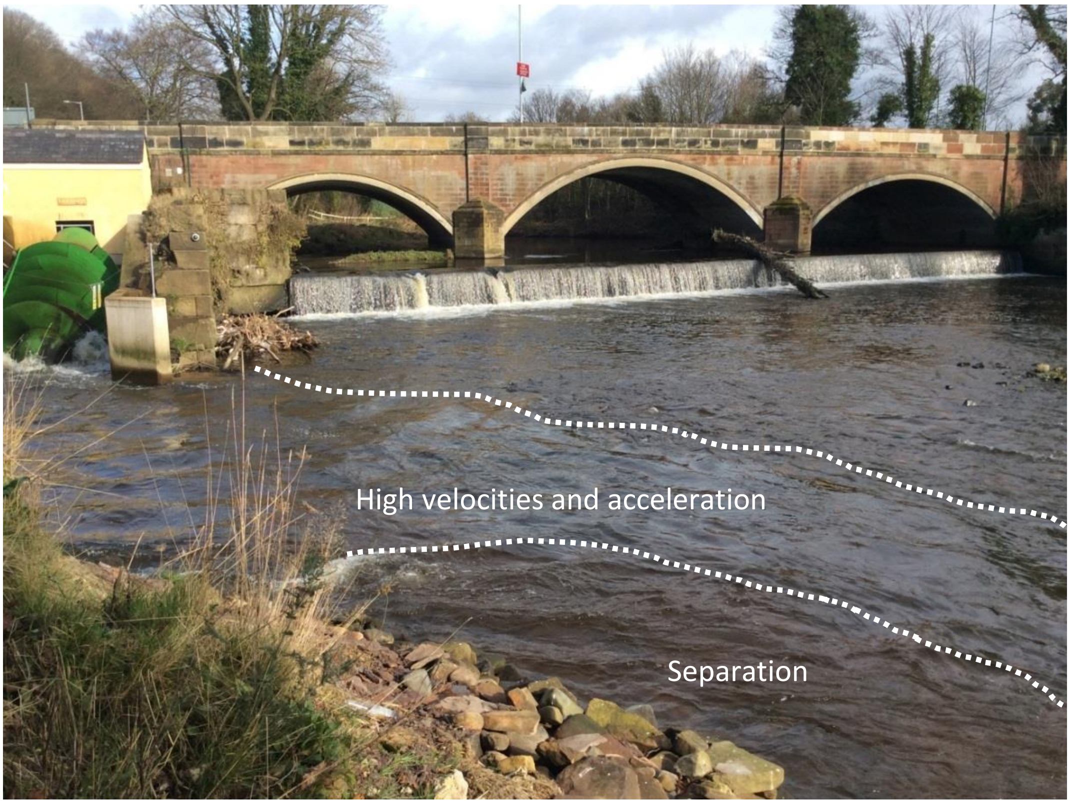

Figure 2.13: Photograph of the confluence below a low head 'on weir' hydro scheme in the River Goyt, UK showing evidence of an area of separation and acceleration.

Following analogy or river confluence studies the position of each hydraulic zone of impact is likely to depend on the momentum ratio (M_r) between the two channels, the angle between the two channels (junction angle) and the degree of bed concordance between the channel beds. The momentum ratio is defined as:

$$M_r = \rho Q U_{outlet} / \rho Q U_{main}$$

where p is the water density, Q is the discharge and U is the mean velocity. As the momentum of the outlet channel becomes more dominant and/or the inflow angle increases, the contracted cross section of high flow velocity is likely to extend further towards the opposing river side (non-hydro side), unless the river is separated by a mid-channel island and in this case the hydraulic zones of impact will be confined to the hydro side of the river. As the angle between the two channels decreases and/or the outlet channel momentum becomes less dominant, the section of high velocity is likely to taper towards the river bank closest to the outlet (Mosley, 1976; Best and Reid, 1984; Best, 1987; Best and Roy, 1991; Biron et al., 1993a, b; Rhoads and Kenworthy, 1995; Biron et al., 1996a, b; DeSerres et al., 1999; Boyer et al., 2006). When the scheme is situated directly on top of the weir and the outlet is not angled the contracted high velocity cross section will simply extend from the bottom of the turbine.

While field studies at low head 'on weir' schemes are limited, a modelling study by Mould et al., (2015a) at Romney weir on the River Thames saw increases in velocities towards the hydro side of the channel and subsequent decreases in velocities on the non-hydro side of the channel during the operation of low head 'on weir' scheme situated directly on top of the weir during moderate and high flows. Furthermore when the position of the scheme was changed i.e. the scheme was moved from one bank to the other the same pattern was observed with an increase in velocities along the hydro side bank and a decrease in velocities on along the non-hydro side bank (Figure 2.14). Changes in velocities were limited to within 20 meters of the weir beyond which there was minimal change in velocity patterns (Mould et al., 2015a). The distance of 20 meters could cover the pool and the riffle below the weir.

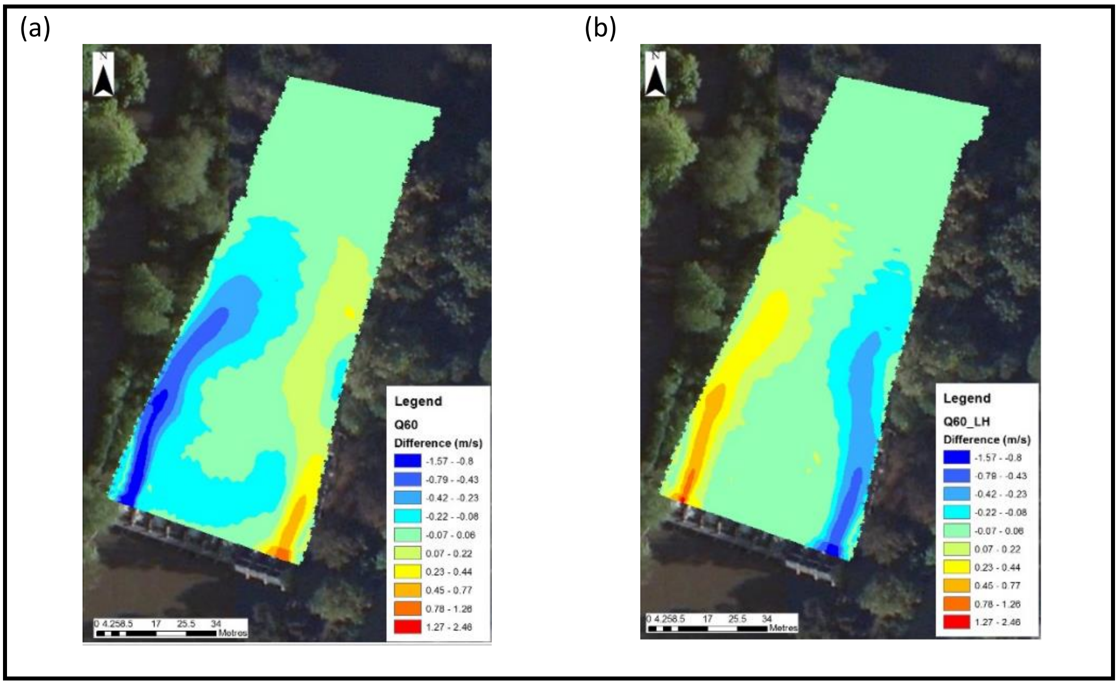

Figure 2.14: Changes in velocities associated with the operation of a low head 'on weir' hydro scheme in the River Thames, UK with the hydro scheme installed on the right bank (a) and hydro scheme installed on the left back (b) (Mould et al., 2015b)

Changes in velocities were also evident at an in situ investigation below the outlet of a low head hydro scheme in the River Lathkill, Derbyshire (Anderson et al., 2015b). Higher velocities were recorded below the outlet on the hydro side of the river when compared to the opposing side. Essentially below the outlet there were notable increases in velocities on the hydro side and decreases in velocities on the non-hydro side. Anderson et al., (2015b) explains how the extent of this pattern depended on the degree of abstraction and how during high abstraction when large volumes of water were directed toward the turbine, the higher velocities extended further towards the opposing river bank.

2.4.2 Implications for the phytobenthic biofilm

One of the major alterations associated with low head 'on weir' hydropower is a change in flow pattern in the area below the weir. With a re-distribution of flow there could be a change in flow velocities and an increase in velocities towards the hydro side of the channel and a decrease in velocities towards the non-hydro side of the channel. This change in velocity could cause shifts in communities and changes in biomass. Although Mould et al., (2015a) concludes that changes in flow are unlikely to be biologically relevant this is based on expert opinion and does not consider the phytobenthic biofilm which is sensitive to changes in flow velocity.

As a result of differences in flow velocities between the hydro and non-hydro side of the channel potentially different communities could develop either side of the river. Spatially the phytobenthic biofilm often forms highly patchy distributions as a result of spatial variations in flow velocity (Biggs et al., 1998a; Hart et al., 2013). The importance of 'mesoscale' or 'habitat-scale' (Harper and Everard, 1998) hydraulic 'patches' (Newson et al., 1998) and microscale flow hydrodynamics for understanding the pattern in diatom diversity has long been recognised (Crowder and Diplas, 2000).

Whilst increased flow on the hydro side could increase shear stress and ultimately prevent the community from succeeding into a diverse community and hence could be dominated by low lying diatoms in low biomass. Stalked and filamentous species in high biomass could dominate on the non-hydro side of the channel as a result of reduced drag and scour. However, the increased flow on the hydro side could equally increase biomass by enhancing the mass transfer of nutrients and increasing metabolic processes (McIntire, 1966; Horner et al., 1990; Stevenson, 1996; Biggs et al., 1998a; Hart and Finelli, 1999) and decreased flow on the non-hydro side could reduce biomass by decreasing this process. Ultimately the hydro and non-hydro side of the channel could differ in terms of community composition and biomass but the way in which the community will be affected will depend in overlying natural physiochemical river conditions, the discharge regime and the amount of flow diverted through the turbines (i.e. the magnitude of change).

For example in an unenriched system the communities could be the same on either side of the channel regardless of the hydro scheme. Whilst the reduced flow on the non-hydro side of the channel would usually encourage stalked or filamentous communities to develop the benefits of reduced flow could be overshadowed by the lack of nutrients in the system. Low profile diatom taxa which are more tolerant to resource-limited environments (Passy, 2007b; Berthon et al., 2011) would likely thrive on either side of the channel. Anderson et al., (2015b) saw no differences in invertebrates between sampling locations at the outlet confluence zone and perhaps this will also be the case for the phytobenthic biofilm.

Further alterations in biofilm biomass and community structure could occur as a result of the formation of hydraulic zones of impact with differing hydraulic characteristics below the outlet on the hydro side of the channel. The area of stagnation at the upstream junction corner could cause a reduction in biomass or complete removal. Even though reduced flows often support filamentous green algal communities with high biomass Hondzo and Wang (2002) noticed that filamentous green algal growth was minimal in stagnant water, emphasising the mixing and delivery function provided by current to ensure a net influx of nutrients to the biofilm.

The acceleration area extending from the outlet, characterised by high flow and shear stress, is more likely to support a community dominated by scour tolerant low profile diatoms with low biomass. High flow and shear stress can cause increased drag on the biofilm and reduce growth (McIntire, 1966; Horner et al., 1990; Stevenson, 1996; Biggs et al., 1998c; Hart and Finelli, 1999). Although it is evident that less mobile large bed substrate, increased temperatures and higher nutrients in the tail waters of large hydro schemes has led to the proliferation of filamentous green algae (Blinn et al. 1998; Munn and Brusven 2004; Chester and Norris 2006).

The area of separation which sits directly adjacent to the acceleration zone will have lower flow velocity than the acceleration zone but higher than the stagnation zone. Without knowing the exact degree to which the flow is altered it is hard to determine how the biofilm will respond. Yet the lower velocity could essentially encourage the community to succeed from a diatom dominated scour tolerant community to a three-dimensional structure with stalked or filamentous forms and high biomass. Even though the two zones sit directly adjacent to each other the spatial variation in flow could mean that the communities differ (Biggs et al., 1998a; Hart et al., 2013).

However as with the above the extent to which the communities and biomass will differ will come down to the amount of flow diverted through the turbine (i.e. the magnitude of change) and it will also rely on the angle of the outlet. The angle of the outlet and amount of flow diverted will determine the position of the zones and in turn the spatial distributions of community and biomass. In a bid to improve knowledge on how low head 'on weir' hydro influences the phytobenthic biofilm specific surveys need to be designed in a way which will detect this impact.

2.5. Potential survey designs to detect impact

There are many ways in which the ecological impacts of low head weirs and low head on weir hydropower can be explored and evidence improved. Whilst monitoring impacted rivers both before and after installation in control and impacted river sections (BACI surveys) would provide the most robust results this design can be time consuming and can take several years to complete (Demars and Britton, 2011). Furthermore many weirs were installed hundreds and even thousands of years ago and as such pre-disturbed conditions and information on pre-disturbed ecological communities are unclear (Downward and Skinner, 2008). Furthermore the majority of existing hydro schemes were granted permits and installed without any substantial pre-or post- installation monitoring (Robson et al., 2011).

On the other hand were pre-installed data does not exist comparing reference sites uninfluenced by an installation to impacted sections along the same river reach could provide rapid results (Demars and Britton, 2011). This design could be echoed across numerous rivers with differing conditions to broaden results (Demars and Britton, 2011). However one of the main problems with this approach is the lack of pristine conditions. There are very few pristine reference conditions across rivers in the UK as anthropogenic activity has been common for decades. As such it could be hard to determine if observed changes are a result of the installation in question or another anthropogenic activity.

Yet visually assessing the reach for other forms of anthropogenic activity, obtaining data on discharges, abstractions and water quality from the Environment Agency and collecting a wide variety of environmental variables alongside species using detailed spatial surveys could help to improve this issue. As such this study often uses a comparative approach comparing sites uninfluenced by installations to impacted sites influenced by an installation and collects a wide variety of environmental variables and data from the Environment Agency and often conducts detailed spatial surveys to assess how low head weirs and low head 'on weir' hydropower influence biotic communities.

2.6. Conclusions and future research needs

This review has highlighted a lack of studies and peer reviewed publications on the physical and ecological impacts of low head weirs and low head 'on weir' hydropower and has attempted to evaluate potential implications from other riverine infrastructure and personal observations. It is apparent that low head weirs have the potential to alter the physical and chemical habitat conditions and the phytobenthic biofilm both above and below the weir. However the magnitude of change and extent to which the biofilm will respond is uncertain. The majority of weirs have been part of our riverine environment for hundreds and even thousands of years and little is known about pre-disturbed conditions or how the area above and below the weir compare to natural undisturbed reference or control reaches. The area above the weir is likely to consist of higher water depths, reduced flow velocity and flow variability and high levels of sedimentation. The area below the weir is likely to consist of highly complex flow patterns, turbulent flow, higher flow velocities and a bed of coarse large cobbles and boulders. Yet effects on the phytobenthic biofilm are likely to differ between rivers according to a combination of environmental variables and will be seasonally driven by preceding discharge, grazing density, light regimes and nutrient concentrations.

Only one study could be identified that had evaluated the impact of low head 'on weir' hydropower on the aquatic environment and many hydro schemes have been installed with little pre- and post-installation monitoring (Mould et al., 2015a). It is hence unclear as to how adding a hydro scheme to a weir will further impact the riverine environment. The study by Mould et al., (2015) concludes that low head 'on weir' hydro is unlikely to affect biotic communities but conclusions are based on "expert opinion" rather than empirical evidence and are not validated using in field evidence. A low head 'on weir' hydro scheme could cause changes in the area above and below the weir but changes in the area below the weir are likely to be more prevalent. The intake which is situated directly on top or directly alongside the weir will cause a re-distribution of flow. Instead of the majority of flow being distributed over a single long weir crest, it will be split between the weir and a turbine channel. This channel will create a pathway for sediment movement which might increase water depths above the weir but in many respects could have a greater impact on the area below the weir by decreasing sediment deprivation. The area below the weir will experience a complete re-distribution of flow, changes in spatial flow patterns and flow velocities and could experience hydraulic and morphological zones of impact, similar to that at river confluences. As such this study concentrates on the area below the weir from here in.

As with low head weirs, the effects of adding a scheme to a weir, on the phytobenthic biofilm, are likely to differ between rivers according to a combination of environmental variables and will be seasonally driven by preceding discharge, grazing density, light regimes and nutrient concentrations (Tett et al., 1978; Biggs and Price, 1987; Suren et al., 2003b; Berthon et al., 2011; Tang et al., 2013). Moreover changes created by a hydro scheme are likely to alter in accordance with the amount of flow diverted through the turbines (i.e. the magnitude of change). It is hence important to consider a range of inter-related environmental variables, preceding flow conditions and the magnitude of change when evaluating how the phytobenthic community might respond to the weir and hydro scheme. The hydro scheme could cause changes in biomass and shifts in community structure as a result of changes in the spatial distribution of flow velocities creating a difference between communities on the hydro and non- hydro side of the channel and between hydraulic zones of impact. While extreme changes can be detrimental for the whole community, small changes might not be biologically relevant i.e. will not be great enough to effect water quality or general ecosystem functioning.

Based on issues described above this PhD will concentrate on advancing understandings of the influence of existing low head weirs on the aquatic environment by using temporal and spatial surveys; in the most part using a comparative approach. As pre-disturbed conditions are often unknown comparing reference sites uninfluenced by an installation to impacted sections along the same river reach is the best option (Demars and Britton, 2011). This design could be echoed across numerous rivers with differing conditions to broaden results (Demars and Britton, 2011). Furthermore collecting a wide variety of environmental variables alongside species and using detailed spatial surveys could also help to improve understandings.

Based on the review presented above and gaps identified, the objectives of this PhD are following:

1. Assess the influence of an existing obsolete low head weir on longitudinal changes in phytobenthic biomass and community structure in the weir pool below the weir through the growing season.

2. Assess the influence of an existing low head 'on weir' hydro scheme on longitudinal changes in phytobenthic biomass and community structure in the weir pool below the weir through the growing season.
3. Compare the influence of an existing obsolete low head weir to the influence of an 'on weir' hydro scheme on longitudinal changes in phytobenthic biomass and community structure through the growing season.
4. Assess the influence of an 'on weir' hydro scheme on the spatial distribution of physical and chemical habitat conditions and the phytobenthic biofilm below the weir.

These objectives will be achieved through a series of hypotheses presented in each chapter.

Chapter 3: Methods

This chapter introduces the sites investigated in this thesis, the method used to assess the influence of the hydro scheme and weir, field measurements and other generic methods used. The three results chapters that follow contain details of experimental design specific to those parts of the thesis.

3.1. Study sites and site characteristics

3.1.1. Site location: The River Goyt (Etherow to Tame)

A list with low head 'on-weir' schemes was obtained from the Environment Agency. A number of schemes were selected in the North West for closer inspection. Stockport Hydro scheme which is located on Otterspool weir along the river Goyt, on the reach between the confluence with the river Etherow and river Tame, was chosen for detailed field investigation. Mainly because it is a low head 'on-weir' scheme which is easily accessible but also because there are several other weirs along the same reach, of which Stringer's weir, which is currently redundant, is under consideration for a new hydro scheme. Thus making it an ideal location to investigate the aquatic implications of both low head weirs and low head 'on weir' hydropower. Not only as individual anthropogenic entities but also as combined man-made structures as per research objectives (see section 2.6).

The River Goyt is located in the Upper Mersey catchment in the North West of England, UK. The total catchment area is 365 km^2. The river drains from Wheston Ridge (520m AOD), near Buxton, flows through Errwood and Fernilee reservoirs (NRA, 1996) and forms the River Mersey in Stockport were the River Goyt and River Tame meet. The entire catchment is on strata of Carboniferous age with alternating sequences of shales, mudstone, siltstones and sandstones. Whilst the upper reaches of the Goyt consist of fast flowing boulder/cobble substrate with riffle/pool sequences, the more low lying land between the confluence with the River Etherow and River Tame, which is the main focus of this study, are more noticeably influenced by man (NRA, 1996). This reach not only has a number of redundant weirs and a hydro scheme along its length but also and a number of storm sewage overflow pipes and industrial discharge points. Figure 3.1 shows the reach between the confluence with the River Etherow and the confluence with the River Tame and displays the locations of Otterspool weir, Stringer's weir and a number of redundant weirs.

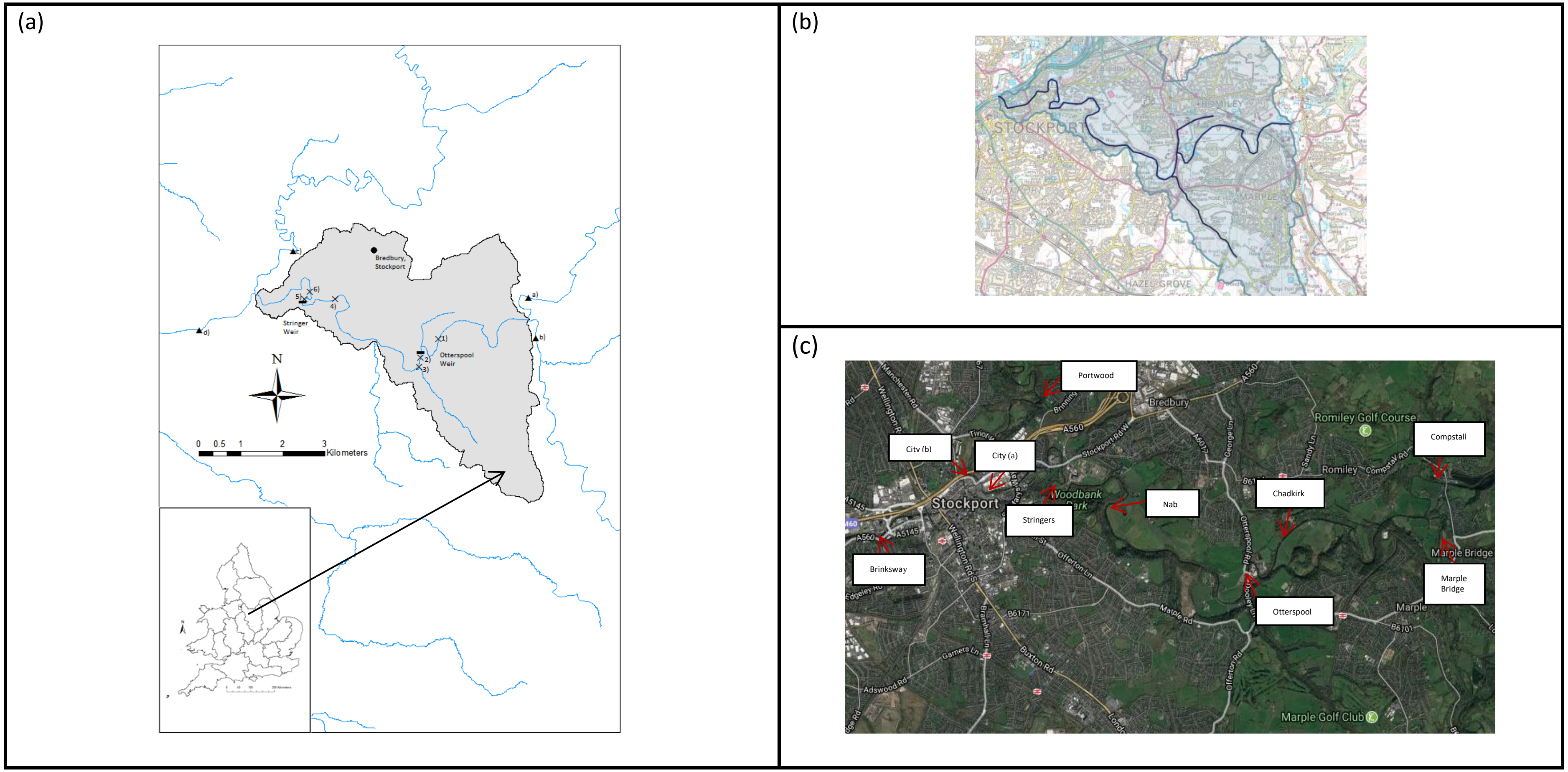

Figure 3.1: River Goyt, Etherow to Tame sub-catchment showing positions of the ‘on weir’ hydro scheme at Otterspool weir with sampling locations 1) upstream, 2) below scheme, 3) downstream, the redundant weir (Stringer’s weir) with sampling locations 4) upstream, 5) below weir, 6) downstream where (a) is a map of the sub-catchment with gauging stations a) Compstall, river Etherow, b) Marple Bridge, river Goyt, c) Portwood, river Tame and d) Brinksway, river Mersey © Crown copyright and database rights 2017 Ordnance Survey (Digimap License) (b) is the location of the sub-catchment (EA, 2017) and (c) is an aerial image of the sub-catchment with locations of all weirs along the reach (Google Earth, 2017f)

Otterspool weir was constructed in the 19th century and is approximately 40 meters long and 1.4 meters in height (Taylor, 2010a). The 'on weir' hydro scheme was constructed directly adjacent to Otterspool weir (SJ936789441) in 2011. The scheme consists of twin Archimedes Screw Turbines and a fish pass with a combined capacity of 100KW (Figure 3.2). At the hydro scheme a proportion of overall discharge is diverted to the turbines and fish pass and the remaining flow is directed over the weir. The scheme has a "Hands off Level" (HOF) of 6cm meaning that a minimum of 6cm's must remain on the weir crest at all times during hydro operation. As long as 6cm's remains on the weir crest the rest of the flow can be utilised and diverted to the turbines and fish pass.

Figure 3.2: Photograph of the twin Archimedes Screw Turbines at Otterspool weir

Stringer's weir is approximately 5km's downstream from Otterspool weir and the 'on weir' hydro scheme (Figure 3.3). Stringer's weir was originally constructed for the abstraction of water for power and although it serves no current purpose it has received recent interest from hydro developers. The weir itself is approximately 36 meters long and 1.8 meters in height and at present all flow is directed over the weir (Taylor, 2010b).

Figure 3.3: Photograph of Stringer's weir along the river Goyt

3.2. Field procedure

Measurements across this study were taken in riffles upstream, below and downstream of the hydro scheme on Otterspool weir, and upstream, below and downstream of Stringer's weir, monthly throughout April – September 2014 and April – September 2015, identified by numbers 1 to 6 in Figure 3.1 and referred to as temporal comparative surveys (chapter 4 and 5). In each of these locations 6-20 samples of various parameters were taken (see section 3.2.1. and section 3.2.2.2). Sampling was increased from 6 samples in 2014 to 20 samples in 2015 for better statistical accuracy and was achievable as the rate at which measurements could be collected in one day increased due to improved site and equipment familiarity.

Riffles were chosen based on accessibility and were the first most accessible riffles upstream, below and downstream of both Otterspool and Stringer's weir. They were characterised by shallow disturbed water surfaces and unconsolidated cobble substrate beds. Each riffle was located at the foot of a glide and a range of water quality parameters were measured on each sampling occasion to ensure that riffles were similar and typical for the reach. Flow velocities where considered the controlling parameter and the parameter most likely to be altered by the weir and hydro scheme. Each riffle had similar water quality conditions throughout sampling. Water velocities differed between some riffles and were therefore considered in further analysis. Species samples were also collected on numerous occasions across the temporal comparative surveys during both 2014 and 2015 (see section 3.2.2.3).

In addition spatial surveys were conducted in July and September 2014 and August 2015 (chapter 6). During each of the spatial surveys a large number of physical, chemical and biotic parameters were measured below Otterspool weir and the hydro scheme in as many points as possible (see section 3.2.1 and section 3.2.2 below).

3.2.1. Physiochemical sampling

Flow velocities were measured using a Valeport Electromagnetic Flow (EMF) meter, model 801. The EMF flow meter has a sampling range between -5m/s and 5m/s with a measurement accuracy ±0.5% of the reading plus 5mm/s. The sensing volume is a cylinder of approximately 20mm ø x 10mm high and the instrument needs a minimum depth of 5cm for measuring purposes. Data is updated to the control display unit at 1 Hz and can be averaged over any number of seconds from 1 to 600 seconds. The small sampling volume makes it very suitable for shallow flows and using an averaging period of 30 seconds or above reduces the noise associated with turbulence. The instrument can operate in temperatures between -5˚C and 40˚C and is calibrated by the manufacturer up to 1m/s (Valeport, 2016). The measurements were taken as close as possible to the bed (5cm from bed). Short 30s measurements were taken and averaged over all sampling locations. This instrument was used for all monthly velocity measurements in 2014 and 2015 over temporal surveys and for spatial surveys in July and September 2014 and August 2015.

Topography was measured with an RTK-GPS during a spatial field survey in August 2015 (chapter 6). Other physical and chemical parameters such as nitrates, dissolved oxygen, turbidity, conductivity, temperature and pH were measured using the Aqua Read AP 2000 multi-parameter probe across both temporal comparative surveys (chapter 4 and 5) and spatial surveys (chapter 6). Rapid calibration was performed prior to each field measurements using just one calibration solution. The so called RapidCal calibrates conductivity @ 2570 µS/cm, the pH7.00 point and the optional Optical Electrode Zero point simultaneously (AquaRead, 2014). A full calibration, which is recommended to be taken once per week, was performed regularly.

3.2.2. Biotic sampling

3.2.2.1. Justification for using phytobenthic biomass and community composition to detect changes created by weir and hydro scheme

Phytobenthic diatom communities are widely used as indicators for the assessment of environmental conditions and have become part of common practice in the assessment of the ecological state of rivers (Kelly et al., 2009a; Blanco et al., 2012). They dominate riverine biofilms, especially in spring and can sustain through a range of environmental conditions (Moore, 1977; Taylor et al., 2007; Feio et al., 2009). They have developed different life forms, for example motile, colonial, pioneer or tube-dwelling (Rimet and Bouchez, 2011), in response to environmental pressures such as grazing, flow and nutrients. Their abundance and composition reflect riverine conditions across a range of resource and disturbance factors including light, nutrients, temperature, flow etc. These are the main reasons as to why they have been used widely to assess water quality and detect anthropogenic activity (King et al., 2006).

The phytobenthic community makes an excellent study species for this study, enabling fine scale spatial analysis and reach scale spatial analysis of the impacts of low head weirs and low head 'on weir' hydropower over time. As such community composition and biomass were explored using a wide variety of biomonitoring techniques across temporal comparative surveys (chapter 4 and 5) and spatial surveys (chapter 6) (see section 3.2.2.2, section 3.2.2.3 and section 3.2.2.4).

3.2.2.2 The BenthoTorch

Phytobenthic biomass and assemblage composition were measured on cobbles using the bbe moldeanke BenthoTorch an in-situ fluorometry device during both temporal comparative surveys (chapter 4 and 5) and spatial surveys (chapter 6). The BenthoTorch measures the photoautotrophic components of the biofilm (diatoms, green algae, cyanobacteria) and determines the relative densities of each component as a measure of chlorophyll-a ($\mu g/cm^2$). The relative densities of each component can be summed together to derive total chlorophyll-a concentration which is often used as a measure of live biomass. As such the BenthoTorch allows for a direct comparison of community structure and biomass in the field (Snell, 2014). The torch was used in both the temporal comparative surveys (chapters 4 and 5) and the spatial surveys (chapter 6).

To take measurements, the 'torch' is placed on the cobble surface. It is based on the principle that fluorescence is primarily emitted by the chlorophyll-a of the photosystem II antenna system, which contains evolutionally conserved chlorophyll-a core antenna and species dependant peripheral antennae (Aberle et al., 2006). The technical principles and development as well as how to use the BenthoTorch in the field is given by (Snell, 2014). The pulses of excitation light from LEDs at wavelengths of 470 nm, 525 nm and 610 nm are emitted to the benthic biofilm. The resulting fluorescence response from the phytobenthos is recorded at 690 nm, with an optical filter preventing excitation light from reaching the detector and causing an offset. Additional excitation light at 700 nm is used to correct for fluorescence due to reflection of light from the substratum. This enables to record chlorophyll-a concentration in $\mu g/cm^2$ and individual 'spectral signature groups' of green algae (which contain chlorophyll a/b), cyanobacteria (containing phycobilisomes rich in phycocyanin) and diatoms (containing chlorophyll a/c and green light absorbing xanthophylls) facilitates determination of their respective densities. The probe requires calibration.

3.2.2.3 Species sampling

The field sampling of species comprised of a selection of cobbles, of which the upper surface areas were scraped using a toothbrush (Kelly et al., 1998). The samples were then carefully placed in bottles and taken to the laboratory for further processing adhering to the following procedure. The samples were homogenised first by shaking the sample bottle, then transferred to a 200 ml beaker. Next 50 ml of 30% (100 volume) hydrogen peroxide (H_2O_2) solution was added to the beaker and heated on a hotplate at 80 °C (± 10 °C) until all organic material had been oxidized (minimum of 120 minutes). Samples were then removed and beakers topped-up with distilled water. Following settling, for a minimum of 24 hours, the supernatant was decanted. The beaker containing the diatom suspension was then re-filled with distilled water. This settling period was repeated three times, with a minimum of 24 hours between each settling period (CEN, 2003). Permanent slides were prepared by allowing a drop (approximately 100 µl) of diatom suspension to dry onto a clean coverslip at room temperature and fixed using Naphrax, a diatom mountant with a refractive index of 1.73. Three hundred diatom valves were identified according to recommendations in Kelly et al., (1998) for routine analysis and counted along transects at 1000x magnification, under oil immersion, with a Zeiss Axioskop microscope (CEN, 2004). Valves were identified using standard floras (primarily Krammer and Lange-Bertalot, 1986, 1988, 1991).

3.2.2.4. Metrics used to describe community composition

A range of objective measures/indices were used to describe community composition.

3.2.2.5. Trait based analysis: Ecological guilds

Diatoms have been grouped into ecological guilds, which are group of taxa adapted to living the same environment. Species across guilds have similar traits which make them suited for the environment in which they thrive (Passy, 2007b). The guilds of high profile, low profile and motile have been used by Lange et al., (2011) and Rimet and Bouchez (2011) to explain differences in resource levels and pesticide contamination in stream mesocosms. Ecological guilds are used equally to examine other disturbance factors including flow. In terms of flow high profile species are adapted to low flow conditions, low profile species are adapted to high flow conditions and motile species are extremely sensitive to high flow conditions. Ecological guilds were used in this in this study alongside chlorophyll-a concentration and community composition to assess different physical and chemical conditions around the weir and low head 'on weir' hydro scheme studied. Species from samples collected during the temporal comparative surveys (chapter 4 and 5) were separated into guilds based on assemblage composition following Rimet and Bouchez (2012). .

3.2.2.6. Species richness: Margalef richness index

Species richness index is simply a count of the number of different species in a given sample. An estimate of species richness was calculated for samples collected from the temporal comparative surveys (chapter 4 and 5) using the Margalef richness index (d; Margalef, 1958) given by the following equation:

$$d = (s - 1)/\ln(n) \qquad (3.1)$$

where *S* is the number of taxa (species recorded), and *n* is the number of individuals in the sample. Margalef richness index was calculated in Primer v 6 (Clarke and Gorley, 2006).

3.2.2.7. Species evenness: Pielou's evenness index

Species evenness is used to estimate how evenly the individual species in a community are distributed. The Pielou's evenness index (J'; Pielou, 1969; Pielou, 1975), which estimates how close in numbers each species in a community are, was used in this study across samples from the temporal comparative surveys (chapter 4 and 5). J' can take a value between 0 and 1. The lower the variation in individuals among species the higher J’ is (Magurran, 2004). J’ was calculated using Primer v6 (Clarke and Gorley, 2006) and is represented by

$$J = H'/H'_{max}{}' \tag{3.2}$$

where H’ is the number derived from Shannon-Wiener diversity index and H'_{max} is the maximum value of H’ equal to:

$$H'_{max} = -\sum_{i=1}^{S} \frac{1}{S} \ln \frac{1}{S} = \ln S \tag{3.3}$$

3.2.2.8. Assemblage diversity: Shannon-Wiener diversity

Assemblage diversity was estimated using the Shannon-Wiener diversity index (H’) (Shannon and Weaver, 1949) using samples from the temporal comparative surveys (chapter 4 and 5). It is based on assumptions that individual species are randomly sampled; from an infinitely large community; and that all species are presented in the community. H’ is based on species number and the distribution of individuals between species. When all species are equally common, the index has the largest values (5). A value of 0 represents a community with only one species. Typical values are between 1.5 and 3.5; rarely exceeding 4 (Magurran, 2004). H’ was calculated as Shannon-Wiener index (H´) (log base = *e*)) in Primer v 6 (Clarke and Gorley, 2006) and is represented by the following formula:

$$H' = -\sum p_i \ln p_i \tag{3.4}$$

where p_i is the proportion of individuals found in the i*th* species.

3.3. Secondary data

3.3.1. Discharge estimates

As the biofilm is more likely to represent previous flow conditions (Law, 2011) and can take up to 4 weeks to develop and mature (Biggs and Kilroy, 2000) total discharge for both Otterspool weir and Stringer’s weir were calculated leading up to each sampling occasions across both the temporal comparative surveys (chapter 4 and 5) and spatial surveys (chapter 6). Yet given that both Otterspool and Stringer’s weir are ungauged it was necessary to estimate discharge at each structure using the nearest flow gauging stations in the catchment. Figure 3.1 shows the positions of the flow gauging stations which were closest to each weir. The nearest flow gauging stations to Otterspool weir and the 'on weir' hydro scheme were Compstall on the river Etherow and Marple Bridge on the river Goyt which are both upstream of Otterspool weir (Figure 3.1). Discharge from Compstall was added to discharge at Marple Bridge to gain an estimate of discharge at Otterspool weir and the hydro scheme. Given that there were no tributaries, river confluences or abstraction points along the river Goyt from Marple Bridge and Otterspool weir, apart from the confluence with the river Etherow which is accounted for in this calculation; it was assumed that this was a good estimate of discharge at this weir.

The two nearest flow gauging stations to Stringer's weir were Portwood on the river Tame and Brinksway on the river Mersey which are both downstream of Stringer's weir (Figure 3.1). Discharge from Portwood was subtracted from discharge at Brinksway to estimate flow at Stringer's weir. Given that there were no major tributaries, river confluences or abstraction points along the reach between Stringer's weir and Brinksway, apart from the confluence with the river Tame which is accounted for in the calculation; it was assumed that this was a good estimate of discharge at this weir.

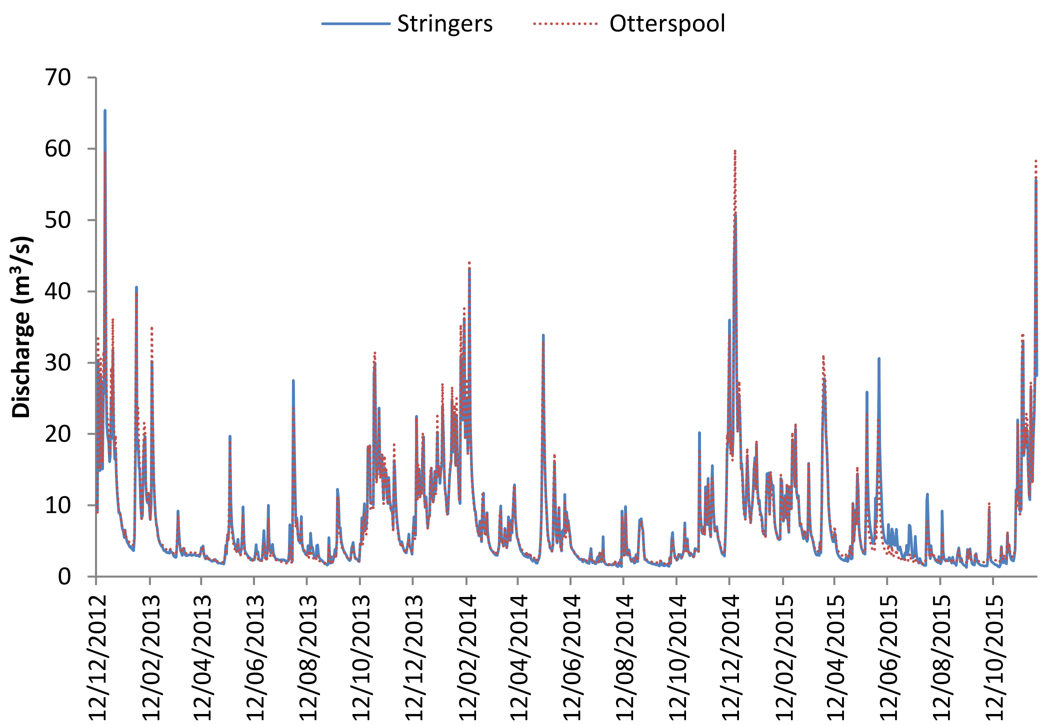

Figure 3.2: Estimated discharge between December 2012 to December 2015 at both Otterspool Weir and Stringer's Weir

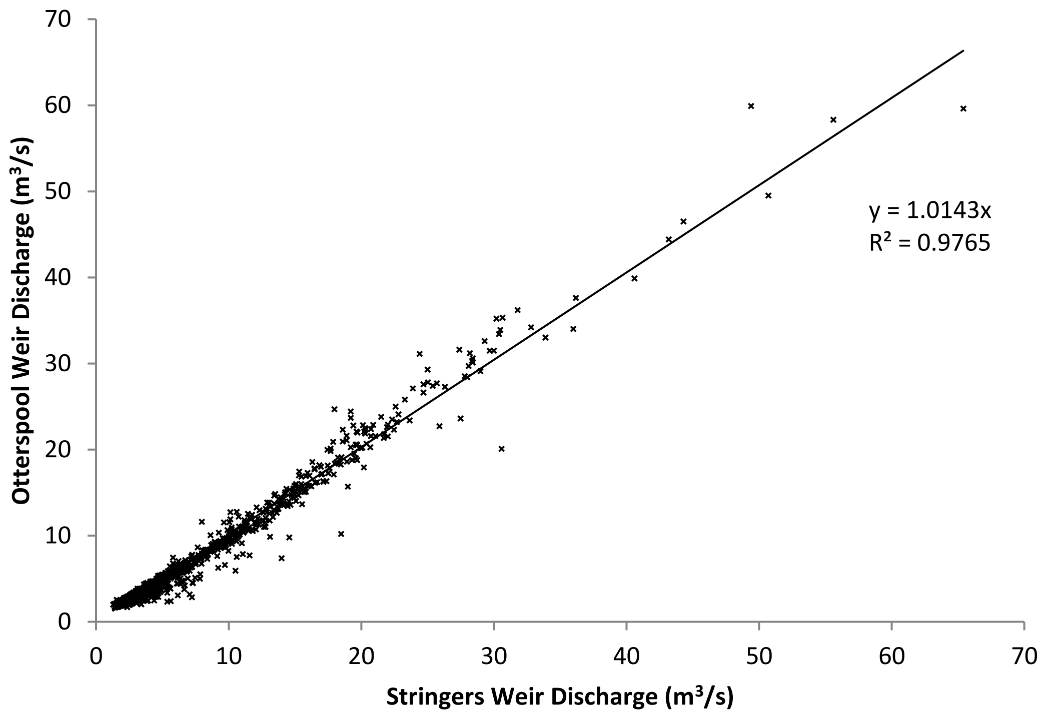

Figure 3.3: Relationship between Otterspool Weir and Stringer's Weir estimated discharge data from December 2012 to December 2015

The estimated discharge was similar at Otterspool weir and Stringer's weir, which was expected given that there is only 5km between them and no major confluences, abstractions or discharges between them (Figure 3.2, Figure 3.3). The discharge was slightly higher at Stringer's weir but the calculations were considered a good estimate and a good representation of the discharge at each weir and were used as a relative measure for comparative reasons and not an absolute figure.

3.3.2. Preceding discharge calculations

In a bid to help evaluate and describe discharge leading up to each sampling occasion for both Otterspool weir and Stringer's weir for both the temporal comparative surveys (chapter 4 and 5) and the spatial surveys (chapter 6), total discharge was calculated over a 28 day period leading up to each sampling occasion. The 28 day period was referred to as the preceding period. For each day over the preceding period flow was also separated into flow condition categories in accordance with the Flow Duration Curves (FDC) for both Otterspool and Stringer's weir; taken from Stockport Hydro Feasibility Study (Water Power Enterprises, 2008). Table 3.1 shows the categories used to describe flow conditions for Otterspool weir and the hydro scheme and Table 3.2 shows the categories used to describe the flow conditions for Stringer's weir. The high flow category represented flow events which have a probability of happening between 1-10% of the year, moderate between 11-40% of the year and low between 41-100% of the year (Table 3.1 and 3.2).

Table 3.2: Overall discharge separated into flow condition categories using the Flow Duration curve for Otterspool weir taken from Water Power Enterprises (2008)

Flow Probability	Discharge (m^3/s)	Flow Condition
10% - 1%	14.829-32.320	High flow
40% - 11%	5.476-14.828	Moderate flow
100% - 41%	1.287-5.475	Low flow

Table 3.2: Overall discharge separated into flow condition categories in accordance with the Flow Duration Curve from Stringer's weir taken from Water Power Enterprises (2008)

Flow Probability	**Discharge (m^3/s)**	**Flow Condition**
10%-1%	15.867 to 34.582	High flow
40%-11%	5.859 to 15.866	Moderate flow
100%-41%	1.377 to 5.858	Low flow

For the temporal comparative surveys (chapter 4 and 5) the number of days with high flow, medium flow and low flow as well as total low flow, total medium flow and total high flow were calculated individually over each of the preceding periods leading up to each sampling occasion for each weir. This was used to assess the frequency and intensity of the flood regime. The number of days with low flow prior to each measurement was also calculated. The maximum flow over each of the preceding periods was also identified.

3.3.3. Abstraction data and the flow split

As overall discharge is split between the weir and hydro turbines, fish pass and other parts of the scheme at Otterspool weir it was necessary to gain estimates of this split across both the temporal comparative surveys (chapter 5) and the spatial surveys (chapter 6). As such abstraction discharge data from Stockport Hydro was utilised. Abstraction discharge calculated by and provided by Stockport Hydro, which includes the flow through the turbines, fish pass and other parts of the scheme, was subtracted from overall discharge at Otterspool weir (as calculated and estimated using the methodology described in section 3.3.1). This gave an estimate of discharge over the weir during hydro operation. This was used throughout this study. The percentage of flow diverted through the scheme and directed over the weir was used to describe the split.

3.4. Data Analysis

A mean and standard deviation of all measured physiochemical habitat conditions and total chlorophyll-a concentration from each sampling occasion in each sampling location was calculated to see how measured river conditions differed between locations across temporal comparative surveys (chapter 4 and 5). Statistical difference, in longitudinal change in flow velocity and total chlorophyll-a concentration, between the riffle below the weir and riffles upstream and downstream of the weir where tested using a one-way ANOVA with post-hoc Tukey tests (chapter 4). Statistical differences, in longitudinal change in flow velocity and chlorophyll-a between the riffle below the hydro scheme and the riffles upstream and downstream of the hydro scheme where also tested using a one-way ANOVA with post-hoc Tukey tests (chapter 5).

An ANOVA is used to test differences between two or more means assuming that: i) data is normally distributed, there is homogeneity in variance and observations are obtained independently and randomly. Post-hoc Tukey tests are used to find the means that are significantly different from each other. All data was tested for normality using the Shapiro-Wilk test of normality and similarity of variance using the Levene's test. Differences at $p<0.05$ were accepted as significant. All statistical tests were conducted in IBM SPSS Statistics 22.

To explore spatial patterns in measured river conditions spatial survey data including near bed flow velocities, bed elevation, depth, water quality parameters and phytobenthic biomass was interpolated using kriging methods in Surfer Software (chapter 6). Kriging was chosen after comparing the Root Mean Square Error (RMSE) of different mapping/interpolation techniques (Kriging, IDW, nearest neighbour). Kriging was the most accurate at predicting actual data. Kriging methods are often good with irregularly spaced points like the data measured in this study (Fortin and Dale, 2005). Kriging estimates spatial autocorrelation and fits a Variogram model to the data. Kriging then uses this model to interpolate and predict missing sample points. Interpolated maps where annotated to display distinct hydrological and morphological features.

To see if there was a difference in measured river conditions between the hydro and non-hydro side of the river survey data was split into hydro and non-hydro side and a mean and standard error of all measured river conditions was calculated for each side (chapter 6). Data was tested for normality and equal variance. Independent 2 sample t-tests were performed in SPSS V.7 to see if there was a significant difference between the hydro and non-hydro side river conditions. Where there was unequal variance between samples the Welch test was conducted. Where data was not normally distributed and there was unequal variance between samples a Mann-Whitney U-test was performed.

To compare the difference in longitudinal change in flow velocity and chlorophyll-a between the upstream hydro riffle and riffle below the hydro scheme with longitudinal change in flow velocity and chlorophyll-a between the upstream weir riffle and riffle below the weir a mean and standard deviation of flow velocity and chlorophyll-a concentration from each sampling location on each sampling occasion was calculated (chapter 7). Statistical differences in longitudinal change between the upstream hydro riffle and the riffle below the hydro scheme and between the upstream weir riffle and riffle below the weir were tested using a two-sample t-test. All data was tested for normality using the Shapiro-Wilk test and similarity of variance using the Levene's test. Differences at $p<0.05$ were accepted as significant. All statistical tests were conducted in IBM SPSS Statistics 22.

Chapter 4: Assessing the influence of low head weirs on the phytobenthic biofilm in the tail riffle below the weir

4.1. Overview

This chapter investigates the influence of an existing low head weir on the phytobenthic biofilm by comparing phytobenthic biomass and community structure between the tail riffle below an existing obsolete weir and riffles upstream and downstream of the weir to advance understandings of the ecological impacts of weirs on downstream ecology which at present is uncertain and unclear. To begin, this chapter provides a brief introduction to the physical and chemical implications of low head weirs and how the phytobenthic biofilm could respond to changes in physical and chemical habitat conditions created by the weir; with particular emphasis on flow velocity and the tail riffle environment. The introduction ends by explaining the main aim of this chapter and provides specific hypotheses that will be tested throughout the investigation. This chapter then goes on to describe the methods used to assess the influence of the weir on the phytobenthic biofilm. Subsequent sections present the results of the investigation. The final section provides a discussion of the results in relation to previous studies involving phytobenthic biofilm and a summary of the main findings.

4.2. Introduction

As identified in chapter 2 the area below a weir is likely to consist of a scour pool and tail riffle and/or bar characteristic of complex flow patterns, turbulent flow, high flow velocities, large coarse substrate, low levels of fine sediment and high dissolved oxygen concentrations (Downward and Skinner, 2005; NSW, 2006; Skalak et al., 2009; Csiki and Rhoads; 2010; Im et al., 2011; Mould et al., 2015a).Yet there is little evidence on how potential changes created by the weir might influence biotic communities, especially the phytobenthic biofilm. The complex flow patterns and high flow velocities, if different to pre-disturbed conditions or natural undisturbed reaches, could support distinctly different phytobenthic communities and create differences in biomass. However not one study could be identified that had compared the phytobenthic biofilm in the tail riffle below the weir to the phytobenthic biofilm in natural undisturbed riffle habitats.

From previous studies on how the phytobenthic biofilm alters and responds to natural and anthropogenic induced habitat conditions, parallels were drawn on how the phytobenthic biofilm might respond to the physical and chemical conditions created by weirs (Chapter 2). In general, it was identified, that increased flow velocity could either accelerate or decelerate growth resulting in changes in biomass or could alter the succession trajectory by halting the natural pathway and/or encouraging growth of species which would not occur naturally (Poff and Ward, 1990). Principally, the increased flow could prevent the community from developing into a three-dimensional community by increasing drag and scouring the biofilm selecting communities adapted to high flow velocity and being of low biomass such as low lying/low profile pioneer diatoms (Biggs, 2000; Passy, 2007b). Alternatively the increased flow could reduce the boundary layer and improve nutrient mixing and metabolic uptake encouraging growth and increasing biomass accumulation (Horner et al., 1990; McIntire, 1966).

However it became apparent that increased flow below the weir could cause a variety of effects depending on the point along the growing season in which the change is induced and on the community already growing in that area before the change is provoked. Moreover it was fairly transparent that each of these factors depended on patterns in other important environmental variables including the seasonality of flow regimes, nutrient concentrations, grazer density and light intensity (Biggs, 2000). It was also deduced that, in some instances, these environmental variables could have greater effects on the biofilm and could mask the effect of the weir. Of these variables, flow regime was deemed the most important factor and it was assumed that different aspects of the flow regime could cause varying results.

For example high intensity flood events could scour the biofilm and reset the succession trajectory regardless of the effect of the weir. In this instance communities across the whole reach could be dominated by low profile diatoms in low biomass and as such there would be no difference in community composition and/or biomass between the tail riffle below the weir and undisturbed riffles. Yet following periods of low stable (steady) flow, communities growing in the tail riffle below the weir could be distinctly different to communities growing in undisturbed riffles. Communities growing in undisturbed riffles could succeed into three dimensional structures in high biomass and communities growing in the riffle below the weir could remain in an early colonisation state in low biomass.

The main aim of this chapter is to evaluate the impacts of a low weir on downstream ecology over the growing season. This will be met by comparing phytobenthic communities in the tail riffle below the weir to phytobenthic communities in riffles upstream and downstream of the weir over the growing season. This chapter aims to address the following two hypotheses;

i) There will be differences in phytobenthic community structure and biomass between the riffle below the weir and riffles upstream and downstream of the weir as a result of increased velocities below the weir i.e. low lying diatoms with low biomass below the weir and higher biomass in areas upstream and downstream of the weir.

ii) That difference in community composition and biomass between riffles will be more pronounced following periods of stable low flow and will be less pronounced following periods of high and frequent flood events when the effect of the weir is masked by the flow regime.

4.3. Methods

4.3.1. Study site

The field campaign was conducted in the North West of England in the River Goyt. Sampling locations where situated along the reach between the confluence with the river Etherow and the confluence with the river Tame. The weir analysed in this chapter is called Stringer's weir and is described in more detail in chapter 3 (section 3.1.1). To assess the impact of Stringer's weir comparisons were made between the area below the weir and areas upstream and downstream of the weir (upstream, weir, downstream). All sampling locations were shallow edge riffle habitats; important for the productivity. The same habitats were also chosen to help eliminate potential differences caused by habitat itself and to ensure that data could be collected all year round.

The upstream riffle was approximately 1km away from the weir and the downstream riffle was approximately 0.5km's away from the weir. The riffle below the weir was situated along the right hand river bank below the outlet of a proposed hydro scheme. Figure 4.1 shows an aerial image of the area below Stringer's weir and displays the proposed location of the hydro scheme and shallow edge riffle habitat were measurements were collected. By collecting measurements in the area below the proposed outlet this investigation was also able to provide a baseline for any future studies that might be conducted below the scheme once it has been installed.

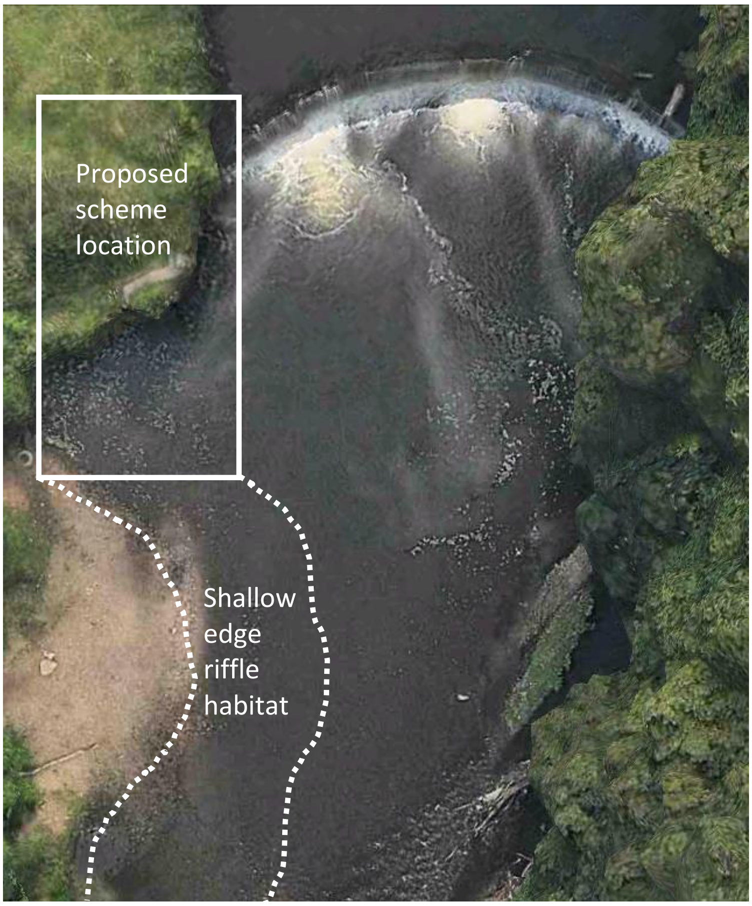

Figure 4.1: Aerial image of the area below Stringer's weir (Apple maps, 2017b) with location of the proposed scheme and the shallow riffle edge habitat were measurements were collected

Figure 4.2 shows a map of the sub-catchment showing the sampling locations in relation to features along the reach. Figure 4.3 shows a schematic of the survey design. Riffles upstream and downstream of the weir were chosen based on accessibility and were considered far enough away from the weir to be free from its influence.

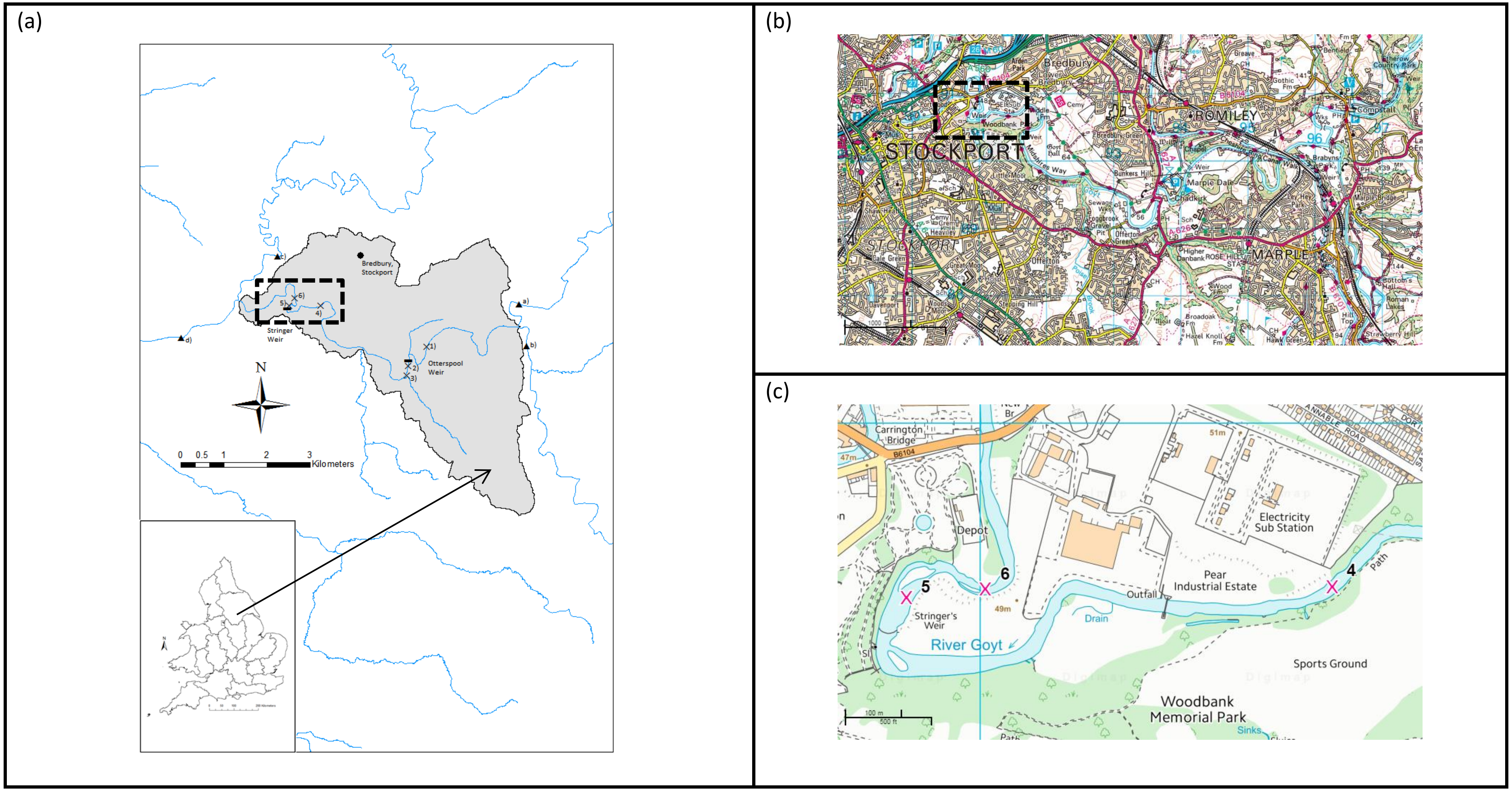

Figure 4.2: River Goyt, Etherow to Tame sub-catchment showing positions of the redundant weir, Stringer's weir and sampling locations 1) upstream, 2) below weir, 3) downstream where (a) is a map of the sub-catchment (b) is the location of sub-catchment and (c) is the reach section © Crown copyright and database rights 2017 Ordnance Survey (Digimap License)

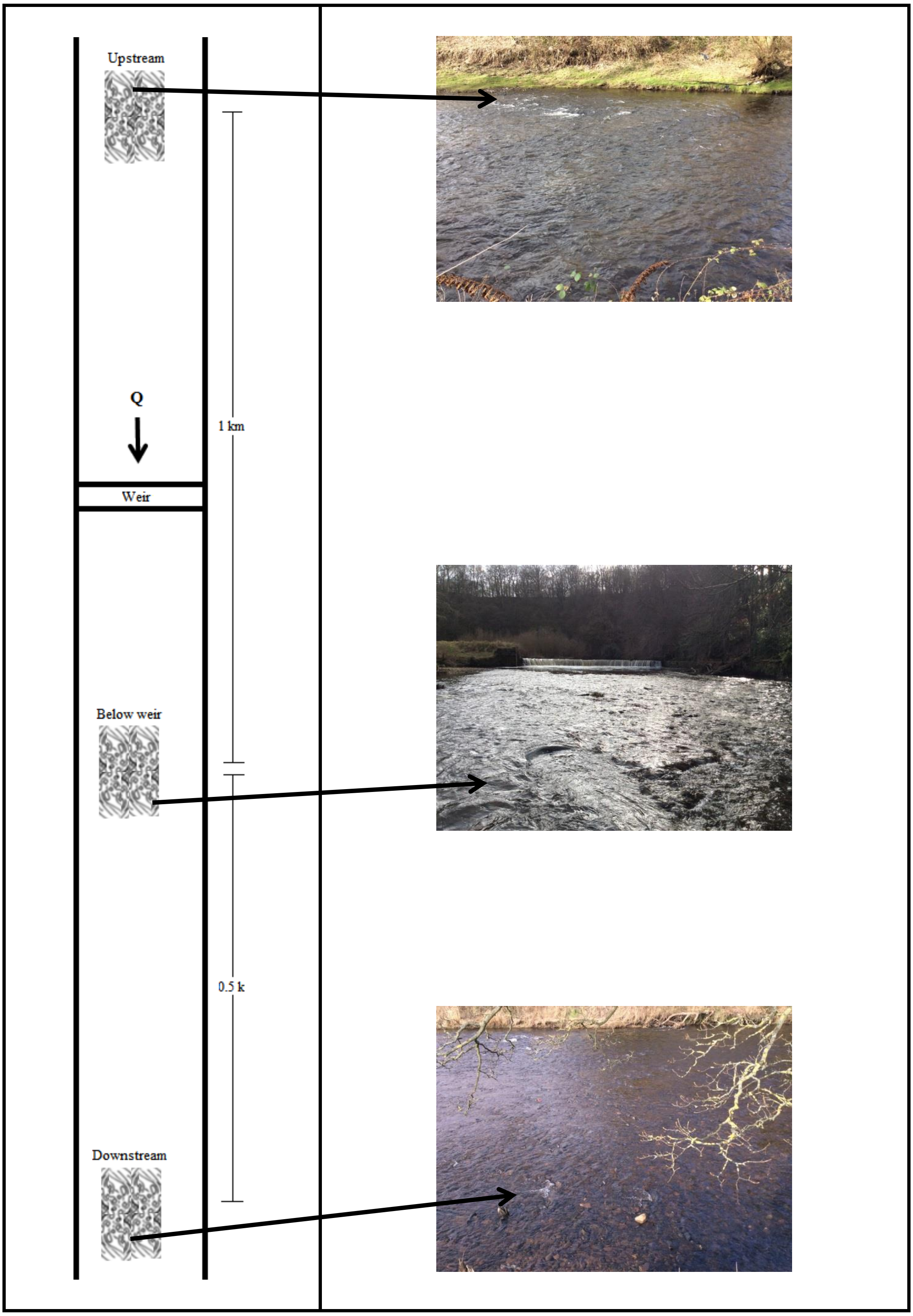

Figure 4.3: Schematic diagram of the sampling design with photographs of the upstream and downstream riffles and the riffle below the weir

4.3.2. Field procedure

To investigate a range of flow conditions and to explore annual variation, two long term field campaigns were conducted. The first field campaign was conducted in 2014 and data was collected on six sampling occasions (29/04/2014, 21/05/2014, 17/06/2014, 29/07/2014, 26/08/2014 and 30/09/2014). The second field campaign was conducted in 2015 and data was collected during a further six sampling occasions (29/04/2015, 26/05/2015, 24/06/2015, 27/07/2015, 04/08/2015 and 28/09/2015). The discharge for Stringer's weir was estimated as described in chapter 3 (section 3.3.1) using the two nearest flow gauging stations. Discharged was calculated for a 28 day preceding period leading up to each sampling occasion (see section 3.3.2).

A range of physiochemical and biotic habitat conditions were measured on each sampling occasion in each riffle during each sampling campaign as described in chapter 3 (see section 3.2.1 and section 3.2.2). Measurements of flow velocity are missing from the April 2014 and May 2014 sampling occasions and measurements of turbidity and nitrate concentration are missing from the April 2014, May 2014 and June 2014 sampling occasions due to equipment failures. Species samples were collected on three occasions during 2014 campaign (17/06/2014, 26/08/2014 and 30/09/2014) and on one occasion during 2015 (28/09/2015) as described in chapter 3 (see section 3.2.2.3). Figure 4.4 shows biotic samples being collected. Species were separated into morphological guilds based on resilience to disturbance (see section 3.2.2.4.1). Species richness, evenness and diversity were calculated using the Margalef richness index, Pielou's evenness index and the Shannon-Weiner diversity index in Primer software version 7 (see chapter 3).

A mean and standard deviation of all measured physiochemical habitat conditions and total chlorophyll-a concentration from each sampling occasion and in each sampling location was calculated to see how measured river conditions differed between locations. Statistical differences, in flow velocity and total chlorophyll-a concentration, between the riffle below the weir and riffles upstream and downstream of the weir were tested using a one-way ANOVA with post-hoc Tukey tests (section 3.4).

Figure 4.4: Photographs of the BenthoTorch and the species samples sampling procedure respectively

4.4 Results

4.4.1 Physiochemical habitat conditions

Flow velocity was significantly higher in the riffle below the weir when compared to riffles upstream and downstream of the weir during all sampling occasions across the 2014 (Figure 4.5, Table 4.2) and 2015 sampling campaigns (Figure 4.6, Table 4.2). Mean velocities were typically higher in the riffle below the weir during the 2015 campaign in comparison to the 2014 campaign (Figure 4.5 and Figure 4.6). Mean velocities were consistently above 0.70m/s in the riffle below the weir and even reached 0.90m/s during the July 2015 sampling occasion (Figure 4.6). In contrast, mean flow velocity did not surpass 0.70m/s across the 2014 sampling campaign (Figure 4.5).

There was no significant difference in flow velocity between the upstream and downstream riffles alike during all 2014 (Figure 4.5, Table 4.2) and 2015 sampling occasions (Figure 4.6, Table 4.2). Mean velocities were between 0.30m/s and 0.60m/s in the upstream and downstream riffles across both the 2014 and 2015 sampling campaigns (Figure 4.5 and Figure 4.6).

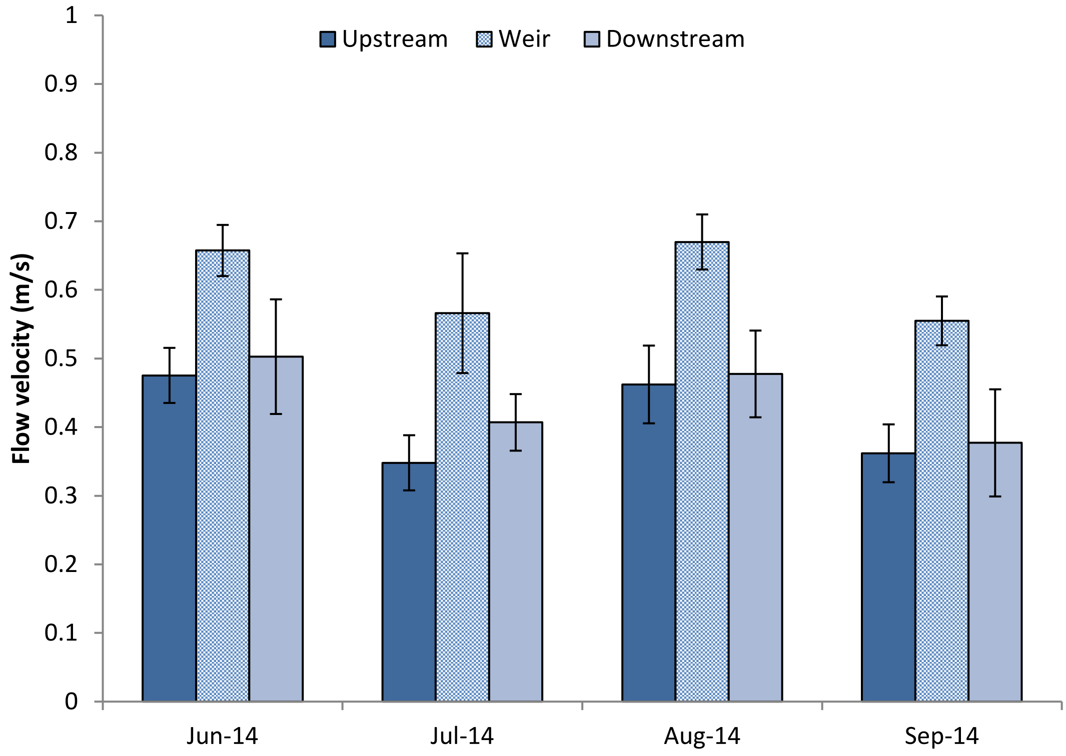

Figure 4.5: Flow velocity, averaged over sampling locations in the riffle below the weir and the riffles both upstream and downstream of the weir during each of the 2014 sampling occasions

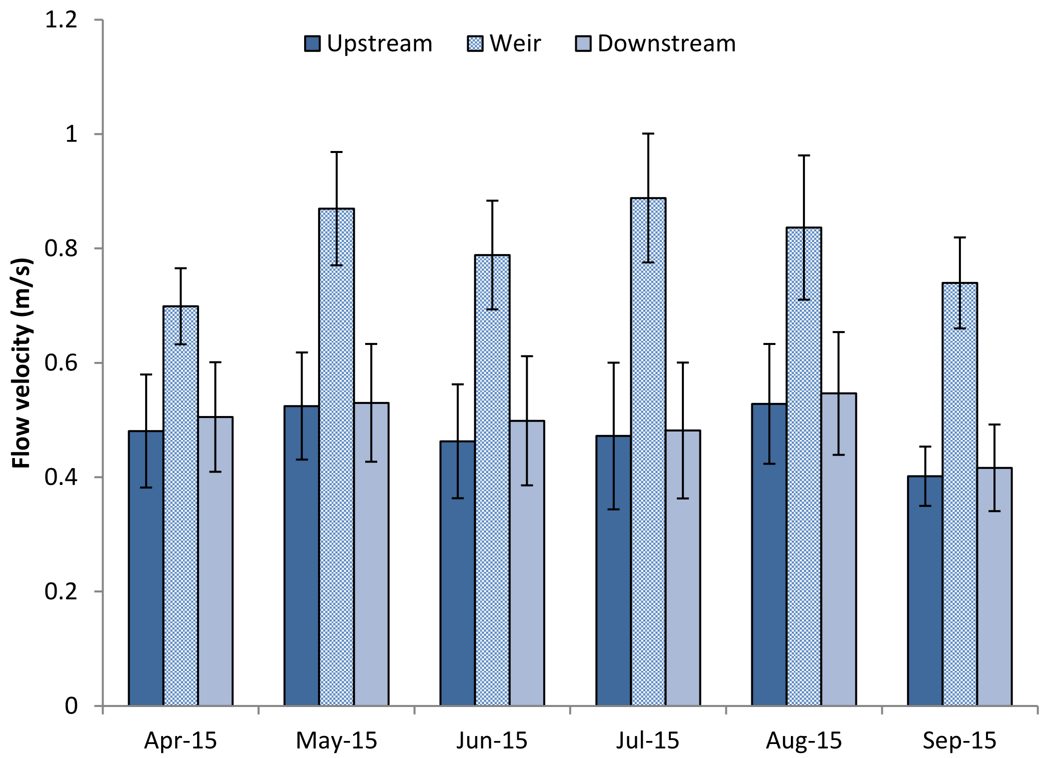

Figure 4.6: Flow velocity, averaged over sampling locations in the riffle below the weir and the riffles both upstream and downstream of the weir during each of the 2015 sampling occasions

Table 4.2: One-way ANOVA and post-hoc Tukey test results comparing flow velocity between the riffle below the weir to the upstream and downstream across the 2014 and 2015 sampling campaigns were *p<0.05* was considered significant and highlighted in bold

Campaign	**Sampling date**	**Comparison**	***df***	***F-value***	***P-value***
2014	Jun-14	Upstream*Weir	2	17.375	**0.000**
		Downstream*Weir			**0.000**
		Upstream*Downstream			0.696
	Jul-14	Upstream*Weir	2	20.348	**0.000**
		Downstream*Weir			**0.001**
		Upstream*Downstream			0.250
	Aug-14	Upstream*Weir	2	27.357	**0.000**
		Downstream*Weir			**0.000**
		Upstream*Downstream			0.877
	Sept-14	Upstream*Weir	2	22.689	**0.000**
		Downstream*Weir			**0.000**
		Upstream*Downstream			0.884
2015	Apr-15	Upstream*Weir	2	36.637	**0.000**
		Downstream*Weir			**0.000**
		Upstream*Downstream			0.656
	May-15	Upstream*Weir	2	80.303	**0.000**
		Downstream*Weir			**0.000**
		Upstream*Downstream			0.983
	Jun-15	Upstream*Weir	2	60.375	**0.000**
		Downstream*Weir			**0.000**
		Upstream*Downstream			0.516
	Jul-15	Upstream*Weir	2	78.294	**0.000**
		Downstream*Weir			**0.000**
		Upstream*Downstream			0.965
	Aug-15	Upstream*Weir	2	46.751	**0.000**
		Downstream*Weir			**0.000**
		Upstream*Downstream			0.867
	Sept-15	Upstream*Weir	2	49.801	**0.000**
		Downstream*Weir			**0.000**
		Upstream*Downstream			0.784

During the 2014 and 2015 sampling campaigns measured water quality parameters differed more over time (across sampling occasions) than spatially (across sampling locations) (Table 4.3 and Table 4.4). There were only small differences in measured water quality parameters across all sampling locations over both years. On a few occasions across the 2014 sampling campaign water temperature differed spatially across sampling locations. This was more of a reflection of the order in which the sites were visited with an increase from the upstream riffle to the riffle below the weir and the downstream riffle. This pattern was most apparent during the April 2014 sampling occasion (Table 4.2). The lowest water temperatures were recorded during the April 2015 sampling occasion and the highest water temperatures were recorded during the July 2015 sampling occasion (Table 4.7). Mean water temperature was much higher during the April 2014 sampling occasion in comparison to the April 2015.

The lowest nitrate concentrations were recorded during the August 2015 sampling occasion (Table 4.7). Mean pH across most of the sampling occasion was very close to a pH level of 7 (Table 4.7). Mean pH was slightly elevated during the July 2015 sampling occasion and was higher than 7. Mean TDS was also highest during the July 2015 sampling (Table 4.7). Overall there is no clear spatial or temporal trend detected in all of these parameters.

Table 4.3: Mean water quality measurements taken from the riffle below the weir and the riffles both upstream and downstream of the weir during the 2014 sampling occasions

		Upstream		Weir		Downstream	
Date	Measured Variable	Mean	Std dev	Mean	Std dev	Mean	Std dev
Apr-14	Temperature (°c)	13.9	0.1	14.2	0.1	14.5	0.1
	pH	8.70	0.06	8.72	0.00	8.80	0.01
	Dissolved Oxygen (mg/l)	12.65	0.18	11.88	0.02	11.69	0.03
	Conductivity	255	1	260	2	258	2
	TDS (mg/l)	166	1	168	1	167	2
	Turbidity (NTU)	-	-	-	-	-	-
	Nitrate (mg/l)	-	-	-	-	-	-
May-14	Temperature (°c)	15.5	0.1	15.9	0.1	16.1	0.1
	pH	7.59	0.03	7.69	0.01	7.70	0.01
	Dissolved Oxygen (mg/l)	9.96	0.03	10.16	0.02	10.14	0.06
	Conductivity	211	2	215	1	213	1
	TDS (mg/l)	136	1	139	1	138	1
	Turbidity (NTU)	-	-	-	-	-	-
	Nitrate (mg/l)						
Jun-14	Temperature (°c)	14.5	0.1	14.6	0.1	14.8	0.1
	pH	7.61	0.04	7.66	0.01	7.60	0.05
	Dissolved Oxygen (mg/l)	10.56	0.09	10.83	0.02	10.71	0.03
	Conductivity	228	1	232	0	235	1
	TDS (mg/l)	148	1	150	0	153	1
	Turbidity (NTU)	-	-	-	-	-	-
	Nitrate (mg/l)	-	-	-	-	-	-
Jul-14	Temperature (°c)	17.7	0.1	17.8	0.1	17.8	0.0
	pH	7.42	0.04	7.47	0.05	7.49	0.03
	Dissolved Oxygen (mg/l)	9.77	0.02	10.05	0.08	10.07	0.01
	Conductivity	279	1	281	1	279	1
	TDS (mg/l)	181	1	182	0	181	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	6.81	0.10	7.12	0.26	7.65	0.80
Aug-14	Temperature (°c)	13.8	0.0	13.9	0.0	13.9	0.0
	pH	7.01	0.06	7.33	0.21	7.37	0.05
	Dissolved Oxygen (mg/l)	10.51	0.01	10.91	0.01	10.90	0.03
	Conductivity	267	1	266	0	265	1
	TDS (mg/l)	174	1	173	1	171	2
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	7.44	0.34	7.50	0.31	7.61	0.17
Sep-14	Temperature (°c)	13.9	0.0	14.1	0.2	14.0	0.0
	pH	6.96	0.16	7.22	0.11	7.47	0.08
	Dissolved Oxygen (mg/l)	10.79	0.04	11.21	0.09	11.18	0.02
	Conductivity	243	1	247	1	246	0
	TDS (mg/l)	157	1	160	1	159	0
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	7.60	0.56	8.16	0.85	8.33	0.17

Table 4.4**:** Mean water quality measurements taken from the riffle below the weir and the riffles both upstream and downstream of the weir during the 2015 sampling occasions

		Upstream		Weir		Downstream	
Date	Measured Variable	Mean	Std dev	Mean	Std dev	Mean	Std dev
Apr-15	Temperature (°c)	9.3	0.0	9.4	0.1	9.5	0.1
	pH	6.99	0.00	6.99	0.00	6.99	0.01
	Dissolved Oxygen (mg/l)	12.97	0.04	13.37	0.06	13.13	0.03
	Conductivity	247	1	249	1	248	1
	TDS (mg/l)	160	1	161	1	161	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	6.9	1.5	7.6	1.3	7.2	1.3
May-15	Temperature (°c)	11.5	0.1	11.5	0.0	11.6	0.0
	pH	6.96	0.01	6.97	0.00	6.98	0.00
	Dissolved Oxygen (mg/l)	11.12	0.13	11.37	0.02	11.33	0.01
	Conductivity	243	1	241	0	241	1
	TDS (mg/l)	157	1	156	0	156	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	8.65	0.57	9.18	0.82	8.90	0.64
Jun-15	Temperature (°c)	14.2	0.0	14.2	0.0	14.3	0.1
	pH	7.08	0.01	7.07	0.01	7.08	0.01
	Dissolved Oxygen (mg/l)	10.82	0.04	11.05	0.05	10.97	0.05
	Conductivity	269	1	272	2	269	1
	TDS (mg/l)	173	2	175	3	174	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	8.84	0.64	9.03	0.26	8.69	0.72
Jul-15	Temperature (°c)	17.6	0.1	17.7	0.1	17.8	0.1
	pH	7.43	0.05	7.47	0.05	7.48	0.03
	Dissolved Oxygen (mg/l)	9.85	0.14	10.03	0.12	9.92	0.60
	Conductivity	279	1	281	2	279	2
	TDS (mg/l)	181	1	183	2	181	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	6.84	0.13	7.07	0.26	7.23	0.53
Aug-15	Temperature (°c)	15.3	0.0	15.5	0.1	15.5	0.0
	pH	6.81	0.03	6.85	0.03	6.81	0.04
	Dissolved Oxygen (mg/l)	10.03	0.02	10.38	0.03	10.34	0.01
	Conductivity	215	1	215	1	215	1
	TDS (mg/l)	140	1	139	1	139	0
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	3.36	0.31	3.93	0.46	3.51	0.20
Sep-15	Temperature (°c)	14.8	0.2	15.1	0.1	15.2	0.1
	pH	7.10	0.01	7.12	0.01	7.12	0.00
	Dissolved Oxygen (mg/l)	9.92	0.06	10.35	0.04	10.36	0.06
	Conductivity	247	2	248	1	248	1
	TDS (mg/l)	160	1	160	1	160	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	7.39	0.69	7.80	0.69	7.48	0.41

4.4.2. Preceding discharge

Figures 4.5 and 4.6 display the mean daily discharges derived for Stringer's weir for the duration of 2014 and 2015 field campaigns respectively. In both years, there is a distinctive seasonal difference in flow between April-June and July-September periods. During the period leading up to April 2014 sampling occasion, there were a few peaks in flow fluctuating between moderate and low flow categories (Figure 4.5). The largest peak occurred 20 days before sampling reaching a maximum of 12.89m^3/s and from this point on flow reduced and was in the low flow category for 17 days leading up to the sampling occasion (Figure 4.5). Leading up to the May 2014 sampling period, overall discharge was low and stable until a high flood event occurred just 8 days before sampling, reaching a maximum of 33.90m^3/s (Figure 4.5). Leading up to the June 2014 sampling occasion overall flow was flashy and regularly fluctuated between low and moderate flow categories with one peak reaching the high flow category 23 days before sampling at 15.96m^3/s (Figure 4.5).

Similar pattern of high flows in April, May and June is repeated in 2015 (Figure 4.6). Overall discharge started in the high flow category but reduced steadily throughout the period leading up to the April 2015 sampling occasion. The highest discharge was recorded 29 days before sampling at 24.70m^3/s. Overall discharge was in the low flow category for 13 days leading up to the sampling occasion (Figure 4.6). Leading up to the May 2015 sampling occasion, there was great variation in flow. Just 6 days before sampling discharge peaked and was in the high flow category at 25.90m^3/s (Figure 4.10). This was lower than the high peak recorded in May 2014. Leading up to the June 2015 sampling occasion flow fluctuated between the low, moderate and high flow categories. The highest peak was recorded 22 days before sampling and was in the high flow category at 30.59m^3/s. There were three moderate peaks in flow closer to the sampling occasion at 7.31m^3/s 12 days before sampling, 6.69m^3/s 8 days before sampling and 6.66m^3/s 5 days before sampling.

Low flows were recorded during both summers. Leading up to the July 2014 sampling occasion, there were a few peaks in flow yet all peaks were still in the low flow category. The largest peak occurred just 9 days before sampling reaching a maximum of just 5.61m^3/s (Figure 4.5). Leading up to the August 2014 sampling occasion, there was some fluctuation in flow. Two peaks reached the moderate flow category at 9.19m^3/s 15 days before sampling and 9.81m^3/s 11 days before sampling. Leading up to the September 2014 sampling occasion overall discharge was mainly low and stable. There was a 25 day stable low flow period leading up to the September 2014 sampling occasion (Figure 4.5).

Leading up to the July 2015 sampling occasion there was some variation in flow, yet only one peak reached the moderate flow category at 7.24m^3/s 20 days before sampling (Figure 4.6). There was a 12 day stable low flow period leading up to the sampling occasion (Figure 4.6). The August 2015 sampling occasion was just 9 days after the July 2015 sampling occasion (Figure 4.10). There was a moderate peak the day after the July 2015 sampling occasion, 8 days before the August 2015 sampling occasion at 11.58m^3/s (Figure 4.10). Leading up to the September 2015 sampling occasion there was some variation in flow (Figure 4.6). But while there were a few small peaks in flow there were no peaks which exceeded the low flow category (Figure 4.6).

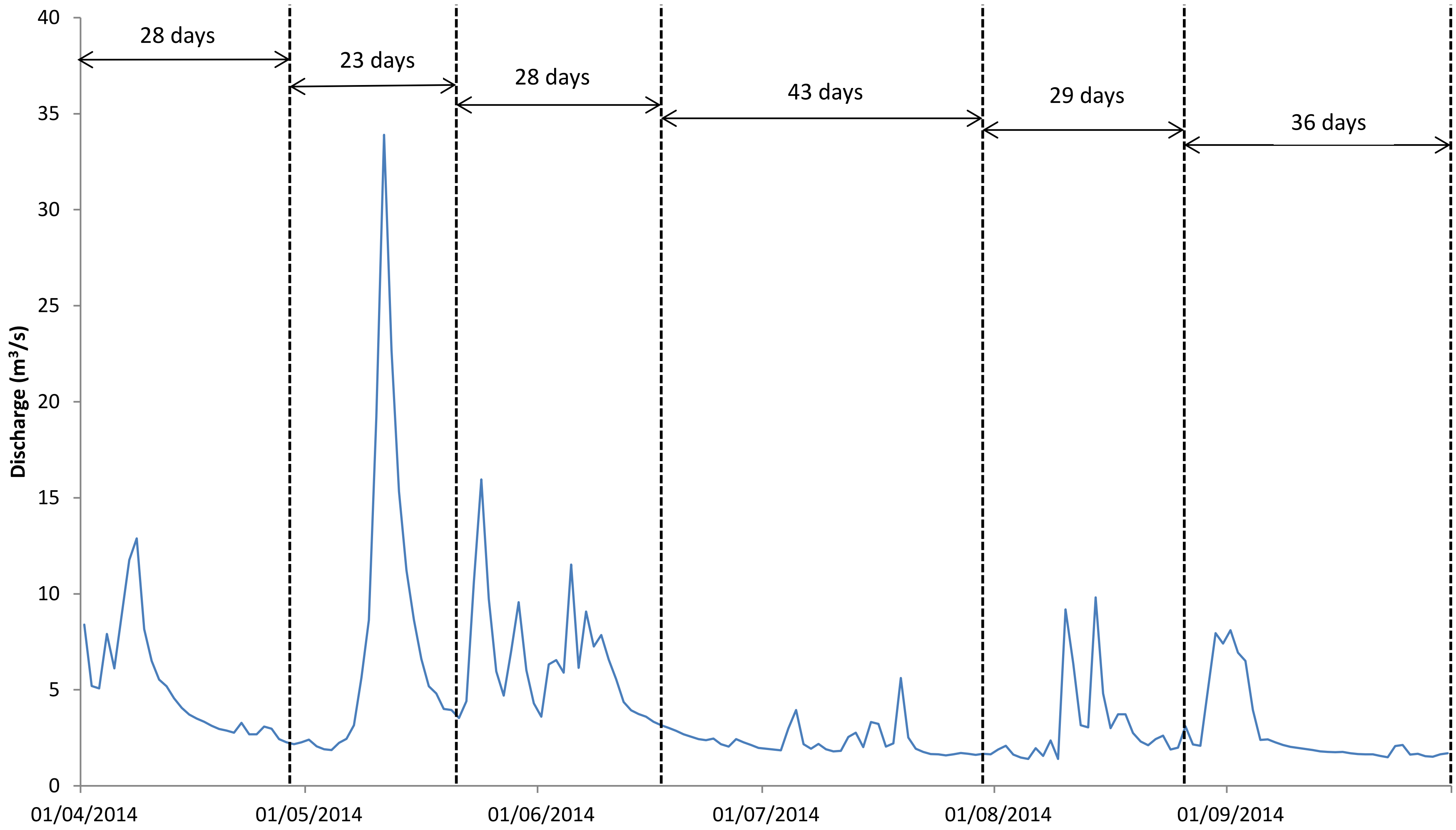

Figure 4.5: Discharge over the 2014 sampling campaign and number of days between sampling occasions represented by dashed lines and arrows

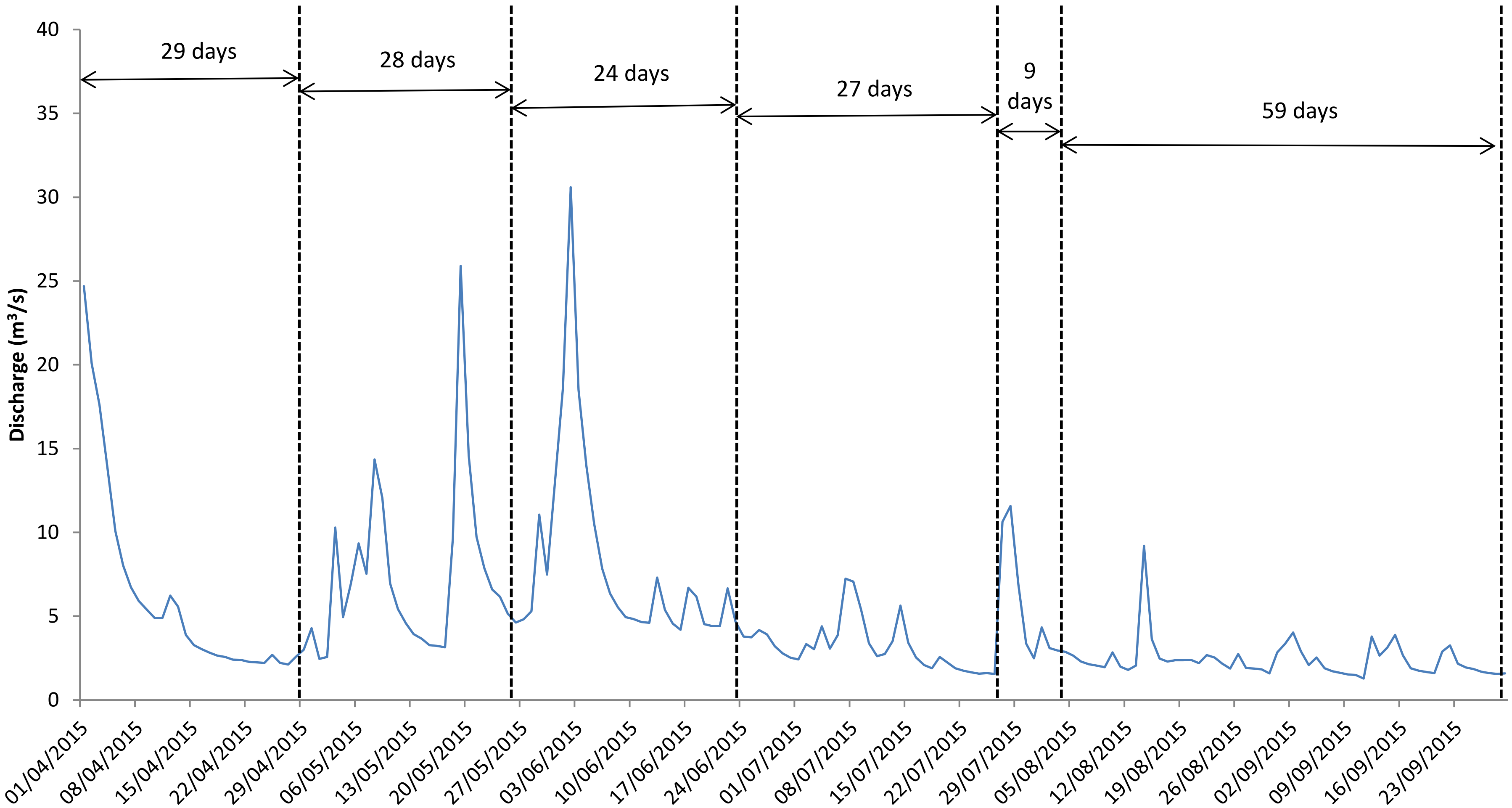

Figure 4.6: Discharge over the 2015 sampling campaign and number of days between sampling occasions represented by dashed lines and arrows

Table 4.5: A summary of total flow during preceding periods before surveys took place and other parameters derived.

	Max Flow m^3/s	Total Flow m^3/s	No. of days with Low Flow	No. of days with Medium Flow	No. of days with High Flow	No. of days of Low Flow prior to measurements	Total Low Flow m^3/s	Total Medium Flow m^3/s	Total High Flow m^3/s
29/04/2014	12.89	141.97	20.00	8.00	0.00	18.00	71.30	70.67	0.00
21/05/2014	33.90	186.43	20.00	5.00	3.00	4.00	60.22	50.43	75.78
17/06/2014	15.96	181.08	12.00	15.00	1.00	6.00	49.01	116.11	15.96
29/07/2014	5.61	64.30	28.00	0.00	0.00	28.00	64.30	0.00	0.00
26/08/2014	9.81	83.61	25.00	3.00	0.00	11.00	58.24	25.37	0.00
30/09/2014	6.93	63.35	26.00	2.00	0.00	26.00	49.92	13.43	0.00
29/04/2015	24.70	173.31	19.00	6.00	3.00	16.00	60.13	50.77	62.41
26/05/2015	25.90	200.18	14.00	13.00	1.00	1.00	52.24	122.04	25.90
24/06/2015	30.59	231.69	14.00	11.00	3.00	1.00	66.83	97.18	67.68
27/07/2015	7.24	87.77	26.00	2.00	0.00	18.00	73.46	14.31	0.00
04/08/2015	11.58	107.71	23.00	5.00	0.00	5.00	64.28	43.43	0.00
28/09/2015	4.03	65.73	28.00	0.00	0.00	28.00	65.73	0.00	0.00

Table 4.5 gives a summary of the total flow calculated over the preceding periods leading up to each sampling occasion, as well as total number of days in each flow category. It also gives total flow in each of the flow categories. While there is not much variation in low flow between the same months of different years, there is a greater difference in total medium and high flow. The overall highest flow was measured in the preceding period leading up to the May 2014 survey. The highest moderate flow was measured in the preceding period leading up to the May 2015 sampling occasion.

4.4.3. The phytobenthic biofilm biomass concentration (chlorophyll-a)

Figures 4.7 and 4.8 show mean total chlorophyll-a concentration for each sampling location across the 2014 and 2015 field campaigns respectively. The results of the ANOVA and post-hoc Tukey analysis are given in tables 4.5 and 4.6. The figures clearly show that there are differences in the total chlorophyll-a concentration across all locations; upstream, below the weir and downstream riffle. These are more pronounced and significantly different between the riffle below the weir and those upstream and downstream of the weir riffles across the July 2014, August 2014, September 2014, April 2015, May 2015 and September 2015 sampling occasions.

There was one occasion when chlorophyll-a concentration was significantly different between the upstream riffle and the riffle below the weir but not between the riffle downstream of the weir and the riffle below the weir and this was during the April 2014 sampling occasion. In all of these occasions except the May 2015 sampling occasion, the concentration below the weir was higher than that in the riffles upstream and downstream of the weir. There were no significant differences between sampling locations upstream and downstream of the weir across all sampling occasions. The lowest concentration across all sampling locations was recorded during the May 2014 sampling occasion, which was after the highest flow peak recorded across the whole campaign. This peak occurred just 8 days before sampling took place. Lower concentrations with no significant difference between locations were also recorded in the period between June and August 2015. All of these indicate that there is some influence from the weir on the chlorophyll-a concentration.

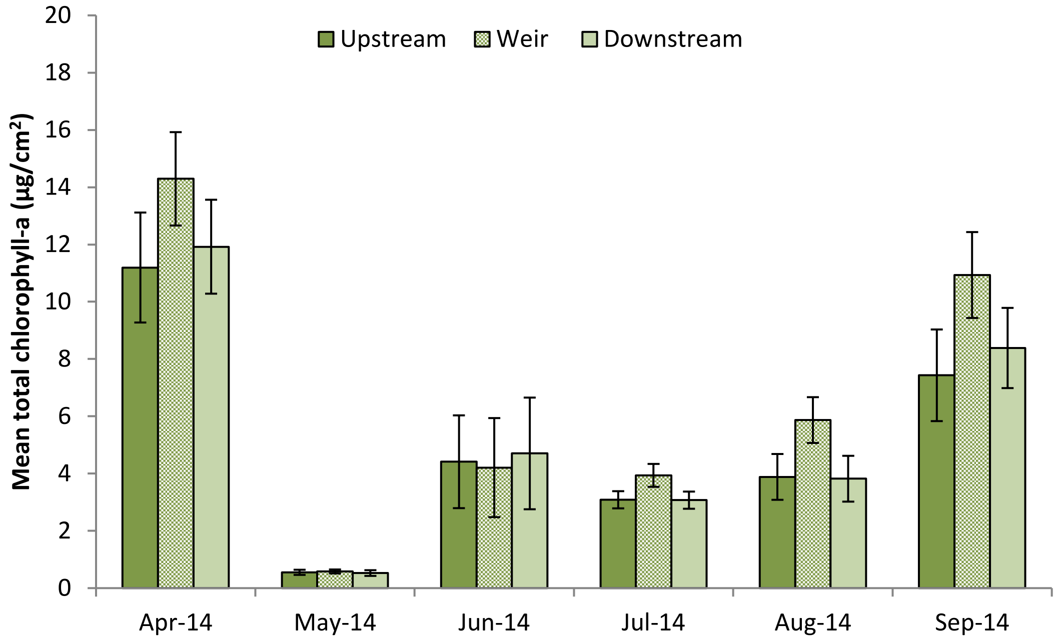

Figure 4.7: Mean total chlorophyll-a concentration calculated from the sum of the photoautotrophic components of the biofilm in the riffle upstream of the weir, riffle below the weir and riffle downstream of the weir across the 2014 sampling occasions were error bars represent standard deviation

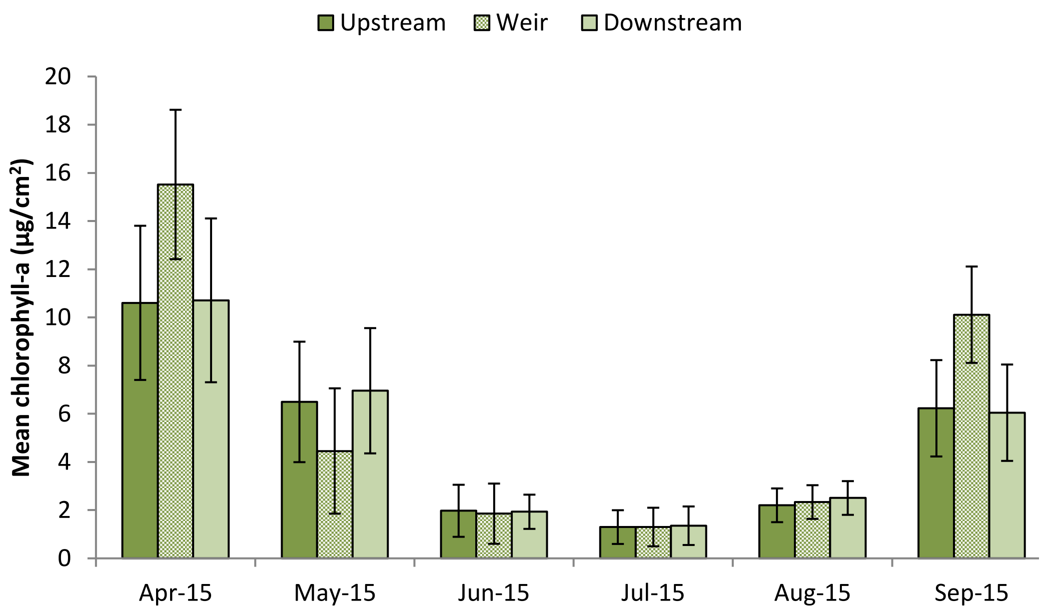

Figure 4.8: Mean total chlorophyll-a concentration calculated from the sum of the photoautotrophic components of the biofilm in the riffle upstream of the weir, riffle below the weir and riffle downstream of the weir across the 2015 sampling occasions were error bars represent standard deviation

Table 4.5: One-way ANOVA and post-hoc Tukey test results comparing total chlorophyll-a concentration between the riffle below the weir to the upstream and downstream riffles and between the upstream and downstream riffles were $p<0.05$ was considered significant and is highlighted in bold

Sampling date	**Comparison**	***df***	***F-value***	***P-value***
Apr-14	Upstream*Weir	2	5.241	**0.019**
	Downstream*Weir			0.076
	Upstream*Downstream			0.752
May-14	Upstream*Weir	2	0.077	0.975
	Downstream*Weir			0.919
	Upstream*Downstream			0.983
Jun-14	Upstream*Weir	2	0.118	0.978
	Downstream*Weir			0.880
	Upstream*Downstream			0.957
Jul-14	Upstream*Weir	2	9.185	**0.006**
	Downstream*Weir			**0.005**
	Upstream*Downstream			0.997
Aug-14	Upstream*Weir	2	13.588	**0.001**
	Downstream*Weir			**0.001**
	Upstream*Downstream			0.989
Sept-14	Upstream*Weir	2	8.516	**0.003**
	Downstream*Weir			**0.028**
	Upstream*Downstream			0.536

Table 4.6: One-way ANOVA and post-hoc Tukey test results comparing total chlorophyll-a concentration between the riffle below the weir to the upstream and downstream riffles and between the upstream and downstream riffles were $p<0.05$ was considered significant and is highlighted in bold

Sampling date	**Comparison**	***df***	***F-value***	***P-value***
Apr-15	Upstream*Weir	2	15.07	**0.000**
	Downstream*Weir			**0.000**
	Upstream*Downstream			0.994
May-15	Upstream*Weir	2	5.374	**0.039**
	Downstream*Weir			**0.009**
	Upstream*Downstream			0.836
Jun-15	Upstream*Weir	2	0.081	0.917
	Downstream*Weir			0.963
	Upstream*Downstream			0.980
Jul-15	Upstream*Weir	2	0.033	1.000
	Downstream*Weir			0.975
	Upstream*Downstream			0.972
Aug-15	Upstream*Weir	2	0.967	0.813
	Downstream*Weir			0.721
	Upstream*Downstream			0.354
Sept-15	Upstream*Weir	2	26.820	**0.000**
	Downstream*Weir			**0.000**
	Upstream*Downstream			0.951

4.4.4. The phytobenthic biofilm community structure

Relative contributions of the photoautotrophic components of the biofilm were derived from the BenthoTorch readings. Figures 4.9 and 4.10 show the relative contributions of concentrations of diatoms, cyanobacteria and green algae to the mean total concentration of the chlorophyll-a. This is also summarised in Table 4.7. The contribution of diatoms dominated across all sampling locations and all surveys (more than 55%). The contribution of cyanobacteria was the second largest and its contribution mainly increased as contribution of diatoms decreased and vice versa. Green algae were found only on several occasions.

Generally the largest diatom concentration was measured below the weir, except on three occasions (May 2014 and 2015 and July 2015) when concentration measured below the weir was smaller than that upstream and downstream of the weir. However, the differences between locations were overall quite small. Yet the contribution of diatoms varied in time. Lowest contribution was measured in May and September 2015 (around 50%), while the largest contribution was measured in May 2014 (94%) followed by July 2015. It is interesting to see that both the smallest and largest contributions were measured in May. The total flow in May 2015 was larger than that in May 2014, but the largest proportion of flow was categorised as high flow in May 2014. These high flow conditions could be potentially more favourable for diatoms than other species. Equally, there could be a higher nutrient supply from run-off.

Contribution of cyanobacteria was the second largest and was generally lower in the riffle below the weir than upstream and downstream of the weir. There were only two occasions (May 2014 and 2015), when their contribution was higher in the riffle below the weir. The spatial contribution pattern mimicked very much the contribution of diatoms, though in the opposite way. It is worthwhile to stress that spatial differences are not large and probably not biologically relevant i.e. not great enough to have an effect on general ecosystem functioning. As in the case of diatoms, temporal changes are more pronounced. The lowest contributions were recorded in July 2015 and May 2014, while the largest contributions were recorded in May 2015, July 2014 and September 2015. Relative contributions of cyanobacteria decreased in all sampling locations during the April 2014, September 2014 and July 2015 sampling occasion.

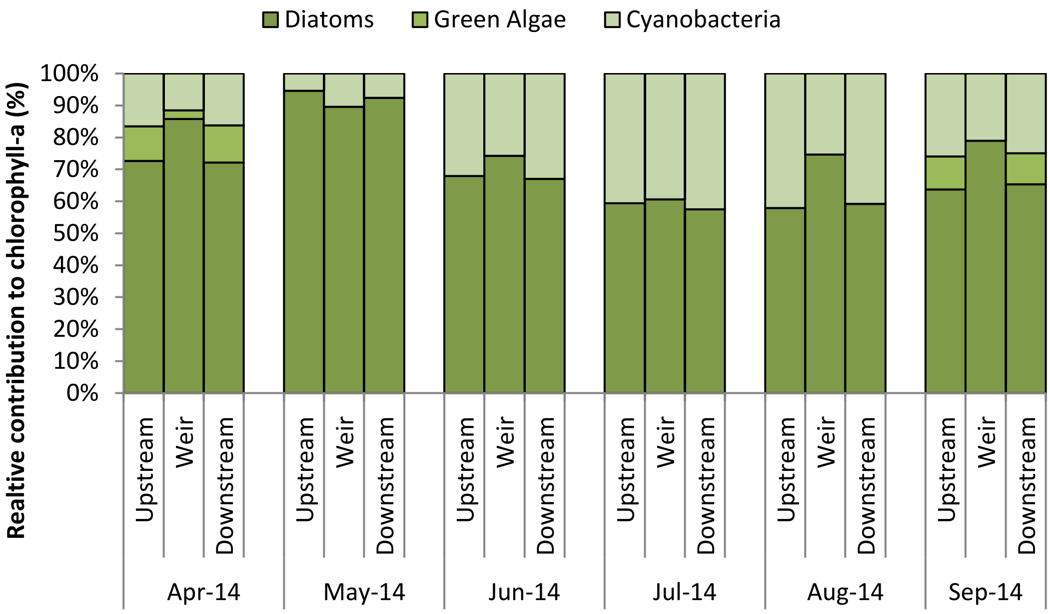

Figure 4.9: Relative contributions of the concentration of photoautotrophic components of the biofilm (diatoms, cyanobacteria and green algae) in relation to mean total chlorophyll-*a* concentration for the upstream riffle, riffle below the weir and downstream riffle during the 2014 sampling occasions

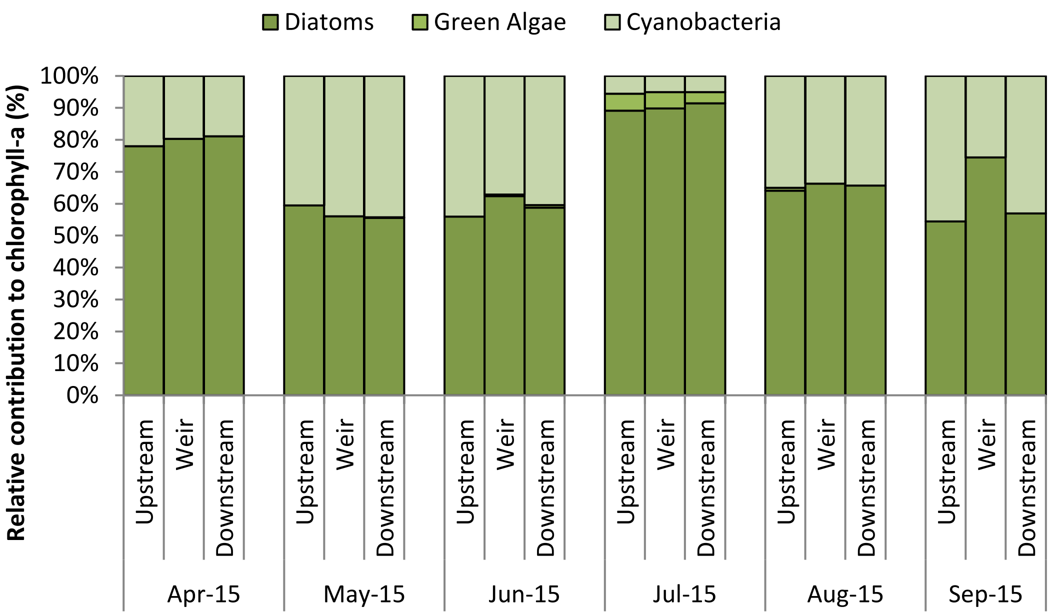

Figure 4.10: Relative contributions of the concentration of photoautotrophic components of the biofilm (diatoms, cyanobacteria and green algae) in relation to mean total chlorophyll-*a* concentration for the upstream riffle, riffle below the weir and downstream riffle during the 2015 sampling occasions

Table 4.7 Relative contributions of the concentration of photoautotrophic components of the biofilm (diatoms, cyanobacteria and green algae) in relation to mean total chlorophyll-*a* concentration for the upstream riffle (Up), riffle below the weir (Weir) and downstream (Down) riffle in all sampling occasions

	Diatoms			**Cyanobacteria**			**Green Algae**		
	Up	Weir	Down	Up	Weir	Down	Up	Weir	Down
29/04/2014	73%	86%	72%	17%	11%	16%	10%	3%	12%
21/05/2014	94%	89%	92%	6%	11%	8%	0%	0%	0%
17/06/2014	68%	74%	67%	32%	26%	33%	0%	0%	0%
29/07/2014	59%	61%	57%	41%	40%	43%	0%	0%	0%
26/08/2014	58%	75%	60%	42%	25%	40%	0%	0%	0%
30/09/2014	64%	79%	65%	26%	21%	25%	10%	0%	10%
29/04/2015	78%	80%	81%	22%	20%	19%	0%	0%	0%
26/05/2015	60%	56%	56%	40%	44%	44%	0%	0%	0%
24/06/2015	56%	62%	59%	44%	37%	40%	0%	1%	1%
27/07/2015	89%	90%	91%	5%	5%	4%	6%	5%	5%
04/08/2015	64%	66%	66%	35%	34%	34%	1%	0%	0%
28/09/2015	54%	75%	57%	46%	25%	43%	0%	0%	0%

In addition to BenthoTorch readings, species samples were collected during the June, August and September 2014 and September 2015 sampling occasions. Identified species were separated into ecological guilds. Assemblages differed between all sampling occasions but were relatively similar between sampling locations (Figure 4.11). Species richness, evenness and diversity were similar between sampling locations (Table 4.8). During the June 2014 sampling occasion low profile species dominated all sampling locations (Figure 4.11). Low profile species made up 57% of the upstream riffle assemblage, 61% of the assemblage in the riffle below the weir and 59% of the assemblage in the riffle downstream (Figure 4.11). Motile species made up 24% of the upstream riffle, 20% of the riffle below the weir and 22% of the downstream riffle (Figure 4.11). High profile species made up 18% of the upstream riffle, 18% of the riffle below the weir and 19% of the downstream riffle (Figure 4.11). *Cocconeis placentula*, a low profile species was the most dominant species in all sampling locations making up 40% of the upstream riffle assemblage, 33% of the assemblage in the riffle below the weir and 46% of the downstream riffle assemblage.

During the August 2014 sampling occasion species were considerably evenly spread between high profile, low profile and motile species in all locations (Figure 4.8). The most dominant species in the upstream riffle were *Navicula lanceolata* a motile species which contributed to 31% of the assemblage, in the riffle below the weir *Cocconeis plancentula* which made up 20% of the assemblage and in the downstream riffle were *Navicula lanceolata* which made up 30% of the assemblage. During the September 2014 sampling occasion high profile and motile species contributed most to assemblages in all sampling locations. Motile species contributed to 44% of the assemblage in the upstream riffle, 43% of the riffle below the weir and 47% of the assemblage in the downstream riffle. High profile species contributed to 43% of the assemblage in the upstream riffle, 43% of the riffle below the weir and 42% of the assemblage in the downstream riffle. Low profile species contributed to 12% of the assemblage in the upstream riffle, 14% of the riffle below the weir and 11% of the assemblage in the downstream riffle (Figure 4.8). The most dominant species in all riffles was *Navicula lanceolata* a motile species which made up 33% of the assemblage in the upstream riffle, 28% of the assemblage below the weir and 36% of the assemblage in the downstream riffle.

High profile and motile species contributed most to the assemblages in all sampling locations in samples taken during the September 2015 sampling occasion. High profile species made up 41% of the upstream riffle, 49% of the downstream riffle and 46% of the downstream riffle (Figure 4.11). Motile species made up 48% of the upstream riffle, 41% of the riffle below the weir and 47% of the downstream riffle (Figure 4.11). Low profile species contributed to 11% of the assemblage in the upstream riffle, 10% in assemblage in the impacted riffle below the weir without hydropower and 7% of the assemblage in the downstream riffle (Figure 4.13). There were also minimal differences in the most dominant species across sampling locations. The most abundant species in all riffles was *Navicula lanceolata* a motile species which made up 36% of the assemblage in the upstream riffle, 33% of the assemblage in the riffle below the weir and 36% of the assemblage in the downstream riffle.

Functional measures, described above, relate to how certain species have adapted to specific environmental conditions i.e. low profile species have adapted certain morphological traits enabling them to thrive in high flow conditions and high profile species have adapted different morphological traits enabling them to thrive in low flow conditions. Functional measures can be used to understand habitat conditions. High presence of low profile species in an assemblage could indicate that the assemblage has been taken from a high flowing environment. Taxonomic measures including species evenness, richness and diversity, though less descriptive in terms of species specific traits, are often used as indicators of general ecosystem health. All taxonomic measures relate to the variety of species in an assemblage. The higher the variety, the higher the biodiversity and the healthier the system is often believed to be. Both functional and taxonomic measures can be used to detect the impact of anthropogenic activity but a significant difference, in each of these measures between sampling locations is needed for the impact to be explored further. Diversity values are measured between 0 and 5 and typical values are between 1.5 and 3.5; rarely exceed 4. Values above and below typical values could indicate some a biologically relevant difference. Similar to the functional measures described above species richness evenness, and diversity were similar across all sampling locations (Table 4.9). Diversity values where in the typical range for UK rivers across all sampling locations across all sampling occasions.

Table 4.8: Species richness, evenness and diversity across sampling locations during the June, August and September sampling occasions

		Sampling location		
Date	**Index**	**Upstream**	**Weir**	**Downstream**
Jun-14	Richness	2.8	3.1	3.0
	Evenness	0.7	0.7	0.7
	Diversity	3.3	3.9	3.8
Aug-14	Richness	3.2	3.6	3.3
	Evenness	0.7	0.8	0.7
	Diversity	3.2	3.9	3.7
Sep-14	Richness	3.1	3.2	3.0
	Evenness	0.7	0.8	0.7
	Diversity	3.3	3.0	3.3
Sept-15	Richness	3.1	3.2	3.0
	Evenness	0.7	0.7	0.7
	Diversity	3.7	3.5	3.5

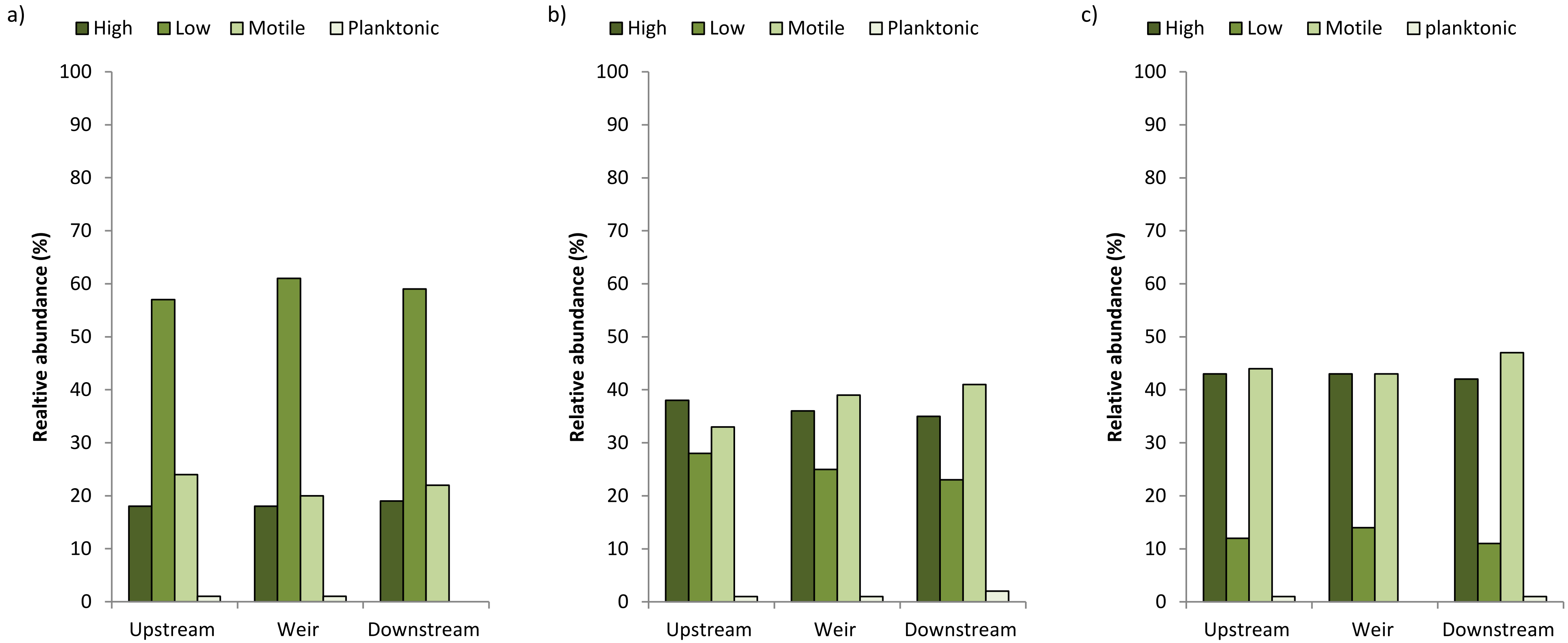

Figure 4.11: Relative abundance of species in each ecological guild in the assemblages collected from the riffle upstream of the weir, the riffle below the weir and the riffle downstream of the weir during the a) June 2014, b) August 2014 and c) September 2014 sampling occasion.

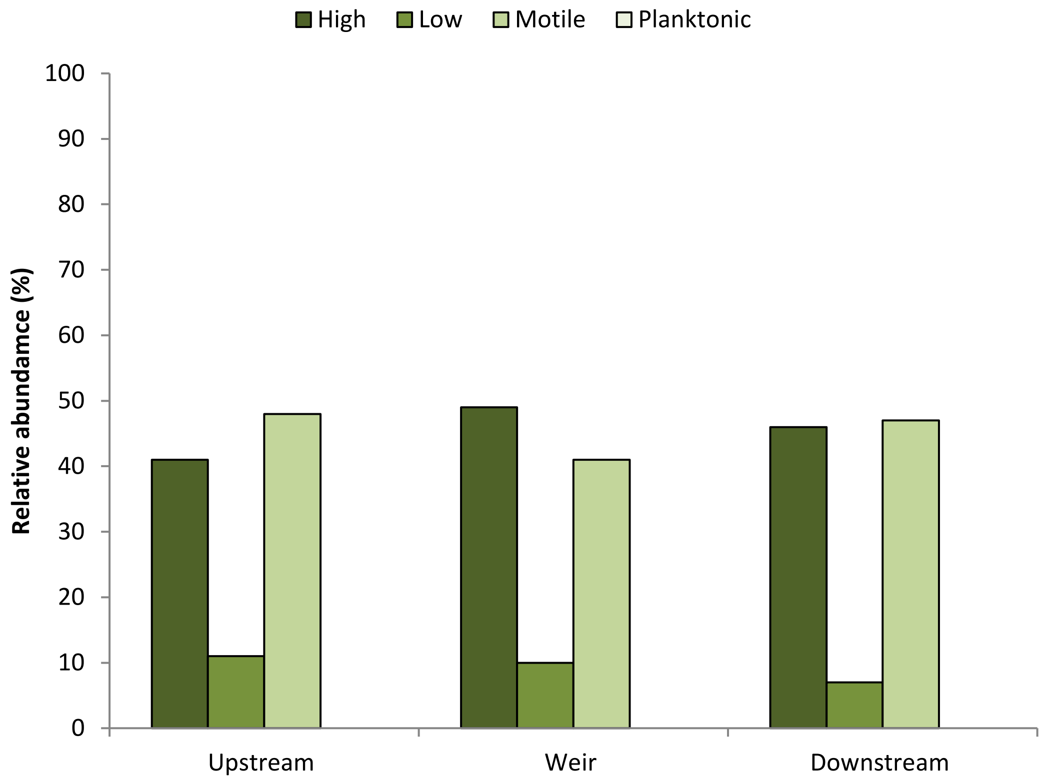

Figure 4.12 : Relative abundance of species in each ecological guild in the assemblages collected from the riffle upstream of the weir, the riffle below the weir and the riffle downstream of the weir during September 2015 sampling occasion

4.5. Discussion

4.5.1. Spatial patterns in growth and community composition

The hypotheses put forward prior to this study have been found only partially valid. It was hypothesised that there would be a difference in biomass between the riffle below the weir and riffles upstream and downstream of the weir. There were many occasions across this investigation where chlorophyll-a concentration differed spatially between sampling locations (April 2014, July 2014, August 2014, September 2014, April 2015, May 2015 and September 2015). The riffle below the weir had significantly higher chlorophyll-a concentration than both the upstream and downstream riffles on all listed occasions except the May 2015 sampling occasion when chlorophyll-a concentration was significantly lower below the weir (Figure 4.7 and Figure 4.8). There were also some occasion across this investigation where there was no significant difference in chlorophyll-a across any of the sampling locations (May 2014, June 2014, June 2015, July 2015 and August 2015). Moreover in cases when there were differences in biomass across sampling locations, statistical significance was not always considered biologically relevant or important (ESFA, 2011). On most occasions differences were small and were unlikely to have any adverse effects on ecosystem functioning and general ecosystem health. The difference in chlorophyll-a concentration was far greater temporally across sampling occasions i.e. from one month to the next in comparison to the difference in chlorophyll-a concentration spatially across sampling locations i.e. from one riffle to another.

It was also hypothesised that there would be differences in community compositions between different riffle sites. Overall, community composition was similar across all sampling locations over both sampling campaigns (Figure 4.10, Figure 4.10, Figure 4.11 and Figure 4.12). This suggests that some other environmental factors might be having greater influence on the community composition, rather than the weir itself. Although this could also be related to the fact that communities can tolerate a range of environmental conditions before they alter. For example stalked and short filamentous diatoms can dominate in moderate flow velocities between 0.3-0.7m/s were as mucilaginous diatoms can dominate at high velocities above 0.7m/s (Biggs et al., 1998c).

While differences in chlorophyll-a concentration could be attributed to a number of environmental variables (Biggs, 2000) there is evidence in this investigation which suggests that observed differences in chlorophyll-a concentration could be related to differences in flow velocity. Flow velocities were significantly higher below the weir when compared to both the upstream and downstream riffles across both the 2014 and 2015 sampling campaigns (Figure 4.5 and Figure 4.6). At the same time, there were minimal differences in the majority of other physical and chemical parameters across sampling locations over all sampling occasions. There is evidence across the literature which suggests that increased flow velocity can have positive effects on phytobenthic biomass accrual by reducing the thickness of the diffusive boundary layer and enhancing the mass transfer of dissolved nutrients, stimulating metabolic processes such as nutrient uptake, photosynthesis, respiration and reproduction and increasing biomass as a result (Poff and Ward, 1990; Stevenson, 1990; Horner et al., 1990; McIntire, 1966; Arnon et al., 2007). It is hence possible that during the occasions when there was significantly higher chlorophyll-a concentration below the weir that that the higher flow velocities were having a stimulatory effect on the biofilm and increasing biomass. However, in order to assess the validity of these relationships, further permanent flow velocity measurements is required.

The second hypothesis was that difference in community composition and biomass between sampling locations would be more pronounced following periods of stable low flow and less pronounced following periods of high and frequent flood events when the effect of the weir is masked by the flow regime. While this pattern was not always detected there were some patterns in biomass and community composition temporally and spatially which could be related to flow regime. The measurements of chlorophyll-a concentration taken in May 2014 and 2015, after periods of high total flow illustrate importance of flow intensity. In 2014, the concentrations were very low across all the sampling sites. Yet concentrations were higher in May 2015 and were significantly lower in the riffle below the weir in comparison to the upstream and downstream riffles.

While increases in flow can increase biomass as a result of increased nutrient mixing (McIntire, 1966; Horner et al., 1990) there comes a point when velocities become critical and loss becomes more important than accrual (Dodds and Biggs, 2002). In some instances flow velocities can scour the biofilm and reduce biomass as a result of increased drag and shear stress. In May 2015, there had been a high flow event just six days before sampling which reached 25.90m3/s. On this occasion the increased flow could have reached critical velocities strong enough to scour the biofilm below the weir and across all other locations. It is also reasonable to assume that communities, across all sampling locations, were in the early accrual stages of development as the sampling took place just six days after the flood and the biofilm can take up to 4 weeks to grow to peak biomass. High flood events can significantly increase disturbance factors, reduce biomass and reset accrual (Biggs, 2000; Law, 2011). Moreover during the accrual phase communities growing in faster currents can grow more slowly than those growing in slower currents (Law, 2011). Assuming that flow velocity was consistently higher below the weir in comparison to riffles upstream and downstream of the weir it is possible that the increased flow was slowing the development and causing reduced biomass below the weir as a result of slowing the growth.

On the other hand during the May 2014 sampling occasion, chlorophyll-a concentrations were considerably lower across all sampling locations and were the lowest recorded across the whole sampling campaign. Even though there had been eight days after the flood event for the biofilm to grow, which is 2 days more than that in the preceding period leading up to the May 2015 sampling occasion, chlorophyll-a concentration had remained low across all sampling locations. However the flood event leading up to the May 2014 sampling occasion was the highest recorded across the whole campaign reaching a maximum of 33.90m^3/s at the upper boundary of high flows. Only the most extreme flood events can completely remove the biofilm from the substrate (Grimm & Fisher, 1989; Biggs and Thomsen, 1995) and reduce the availability of propagules available to recolonise the substrate and as such can significantly slow regeneration times (Biggs, 2000). It seems plausible that in this instance the high flow event was strong enough to completely remove the biofilm and reduce the number of propagules across all sampling locations masking the effect of the weir and reducing regeneration times across all sites. This in turn suggests that at this site, only flood events at or above 33.90m^3/s can mask the effect of the weir.

Looking at diatom species samples and how species were distributed across ecological guilds there appeared to be a pattern in relation to discharge over time. This is unsurprising considering the flow regime has often been quoted as the most significant factor controlling growth and succession (Biggs, 1996b, Biggs, 2000; Law, 2011). However this pattern was more related to the species samples than the BenthoTorch readings. Following a period of frequent high flows in June 2014 low profile diatoms dominated community composition. Low profile diatoms are most adapted to live in high flow conditions (Passy, 2007a) and this hence explains their dominance. Leading up to the August 2014, September 2014 and September 2015 sampling occasions discharge was in the low flow category for the majority of the preceding period and in August 2014, September 2014 and September 2015 there was a dominance of high and motile species which are better adapted to low flow conditions (Passy, 2007a). Furthermore both the September 2015 and 2014 sampling occasions showed a significant reduction in the presence of low profile diatoms. This in turn shows that it can take a long period of time for changes in species to register the changes in flow i.e. species do not change as quickly as flow changes.

Possible reasons for not detecting clearer relationships between phytobenthic biofilm and flow spatially between sampling locations can be found in the fact that while increased flow velocity can create differences in biomass spatially, the picture can be quite complicated as a whole. A range of other important environmental variables and environmental regimes can mask the effects of increased flow velocities if they are more important for growth (Biggs, 2000). Flow, nutrient and light regimes as well as grazing activity can all have significant effects on growth (Biggs, 1996a).

During the summer months, in particular the July 2015 and August 2015 sampling occasions, it is possible that increased tree coverage across all locations had reduced light penetration and masked the effect of the weir. Light is an essential resource for photosynthesis and growth

(Biggs, 2000) and when light is limited it can also limit growth. For example Hill and Fanta (2008) showed that light alone explained 67% of the variation in phytobenthic biomass. Moreover during the June 2014 and June 2015 sampling occasions there appeared to be a higher number of invertebrates across sites (observed evidence). This was also evident during the June 2015 sampling occasion. During both the June 2014 and June 2015 sampling occasions increased invertebrates in all sampling locations could have masked the effect of the weir. Biggs (2000) states how when floods are infrequent, patterns in grazer activity can control the phytobenthic biofilm. Hence there is a scope for further studies measuring a number of parameters simultaneously.

4.6. Summary

It is apparent from this investigation that low head weirs can alter the phytobenthic biofilm in the tail riffle below the weir with increased flow velocity potentially driving differences in biomass. It was found that flow velocity is significantly higher below the weir studied although this could be site and time specific. Changes caused by the weir have limited impacts on community structure but when other variables are not limiting growth (flood, light, nutrients) the increased flow velocity below the weir during the inter-flood periods can have a stimulatory effect on the biofilm and increase biomass below the weir. The effect of the weir is masked when overall discharge is high or when light is limiting due to tree coverage. There is evidence to suggest that only flood events at or above 33.90m^3/s were great enough to mask the effect of the weir at this study site. Temporal rather than spatial changes in riffles below the weir and upstream and downstream of the weir are more pronounced. This leads to a conclusion that changes are driven mostly by total flow and intensity of flow in periods preceding measurements. Changes in community composition and biomass were not more pronounced following periods of low flow. Other factors such as decreased light intensity and increased grazing activity could have also been masking the effect of the weir although this needs to be explored further.

Chapter 5: Assessing the influence of a low head 'on weir' hydro scheme on the phytobenthic biofilm in the weir pool below the weir

5.1. Overview

This chapter investigates the influence of an existing low head 'on weir' hydro scheme on the phytobenthic biofilm by comparing phytobenthic biomass and community structure between the tail riffle below the scheme and riffles upstream and downstream of the scheme to advance understandings of the ecological impacts of low head 'on weir' hydro which at present is uncertain and unclear. To begin, this chapter provides a brief introduction to the potential physical implications of low head 'on weir' hydro and how the phytobenthic biofilm could respond to changes in physical and chemical habitat conditions created by the scheme; with particular emphasis on flow velocity and the tail riffle environment. The introduction also describes potential differences in physical and chemical habitat conditions below a weir with a hydro scheme. The introduction ends by explaining the main aim of this chapter and provides specific hypotheses that will be tested throughout the investigation. This chapter then goes on to describe the methods used to detect impact. Subsequent sections present the results of the investigation. The final section provides a discussion of the results in relation to previous studies on phytobenthic communities and a summary of the main findings.

5.2. Introduction

As identified in chapter 2, low head 'on weir' hydro has the potential to increase flow velocity below the outlet of the scheme. While low head weirs have the potential to increase flow velocity below the weir, the increased flow velocity below the outlet is likely to surpass velocities created by the weir. Whilst at low head weirs flow is distributed across a long weir crest, at an 'on weir' hydro schemes large volumes of water are constricted through a turbine forebay and released back into the main river channel at the outlet below the scheme. As identified in chapter 2 it seems likely that high velocities will extend from the outlet and that the area below the outlet will consist of high flow velocities and turbulent flow as a result of constriction. Given that the scheme is likely to be consistently operating and that the majority of schemes can utilise large volumes of water daily with the only stipulation being that flow over the weir must be kept at a minimum level, which is indicative of low flow conditions, the increased flow below the outlet is likely to be a constant disturbance. It will also increase with the proportion of flow diverted through the turbines.

The highly complex flow patterns and high flow velocities, if different to pre-disturbed conditions or natural undisturbed reaches, could support distinctly different phytobenthic communities and create differences in biomass. The increased flow could accelerate or decelerate the succession trajectory and cause increases or decreases in biomass or could change the succession trajectory completely by halting or encouraging growth of species which would not occur naturally (Poff and Ward, 1990). The increased flow could prevent the community from developing into a three dimensional community by increasing drag and scouring the biofilm and selecting communities adapted to high flow velocity in low biomass. Alternatively, it could reduce the boundary layer and improve nutrient mixing and metabolic uptake encouraging a switch from low profile diatom dominated communities in low biomass to a mature community with a three-dimensional structure and a mix of low profile and high profile species in high biomass (Biggs, 2000).

Yet the effect of the scheme on species is likely to depend on previous flow conditions and preceding physical and chemical variables which vary seasonally and across rivers. Where other important environmental conditions are having a greater effect on the biofilm than the increased flow the effect of the scheme could be masked. For example, the effects of increased flow below the outlet could be masked by high flood events. A high flood event could scour the biofilm and reset the succession trajectory regardless of the effect of the scheme. In this instance the community across the whole reach could be dominated by low profile diatoms in low biomass. On the other hand following periods of low stable flow the community below the scheme could be distinctly different to natural undisturbed conditions with areas free from the influence of the scheme dominated by high profile, filamentous green algal and cyanobacterial species in high biomass and the area below the scheme dominated by low profile pioneer diatom communities in low biomass.

Changes in phytobenthic community composition and biomass would also depend on the magnitude of change caused by the scheme. If the magnitude of change is still within the tolerance range of specific communities and is not beyond critical thresholds, the increased flow could cause only slight changes in the relative contribution of species within the community. The community growing in the area below the scheme could still follow the same successional trajectory and have similar biomass levels. For example filamentous green algal species dominate in flows between 0.05 and 0.3m/s (Suren et al., 2003b). If flow is increased but is still within this range the community could still be dominated by filamentous green algal species. Yet biomass could be lower or higher below the scheme depending on whether the magnitude of change and increased flow is high enough and reaches critical velocities high enough to scour the biofilm and reduce biomass or increase nutrient uptake and increase biomass as a result of increased metabolic processes (Poff and Ward, 1990).

The main aim of this chapter is to advance the understanding of the influence of low head 'on weir' hydropower on the phytobenthic biofilm in the tail riffle below the scheme and aims to test the hypotheses that;

i) there will be differences in phytobenthic community structure and biomass between the riffle below the outlet of the hydro scheme and riffles upstream and downstream of the scheme uninfluenced by the scheme
ii) differences in community structure and biomass between riffles will be more pronounced following periods of high abstraction and low weir discharge
iii) differences in community structure and biomass between riffles will be more pronounced following periods of stable low flow and will be less pronounced following periods of high flashy flow when the effect of the scheme is masked by high background discharge

5.3. Methods

5.3.1. Study site

The field campaign was conducted in the North West of England in the River Goyt. Sampling locations were situated along the reach between the confluence with the river Etherow and the river Tame. Along this stretch is Otterspool weir and the 'on weir' hydro scheme, namely Stockport Hydro, which is the main focus of this chapter. More details on Otterspool weir and the hydro scheme can be found in chapter 3 (section 3.1.1). To assess the impact of the hydro scheme comparisons were made between the area below the scheme and areas upstream and downstream of the scheme. All sampling locations were shallow edge riffle habitats, which are important for river productivity. The sites were chosen in such a way that potential differences caused by habitat are minimised and to ensure that data could be collected all year round.

The upstream riffle was approximately 1km away from the weir and hydro scheme and the downstream riffle was approximately 0.5 km from the weir and hydro scheme. Figure 5.1 shows the position of each sampling location and Figure 5.2 shows the survey design. Riffles upstream and downstream of the scheme were chosen based on accessibility and were considered far enough away from the weir to be free from its influence.

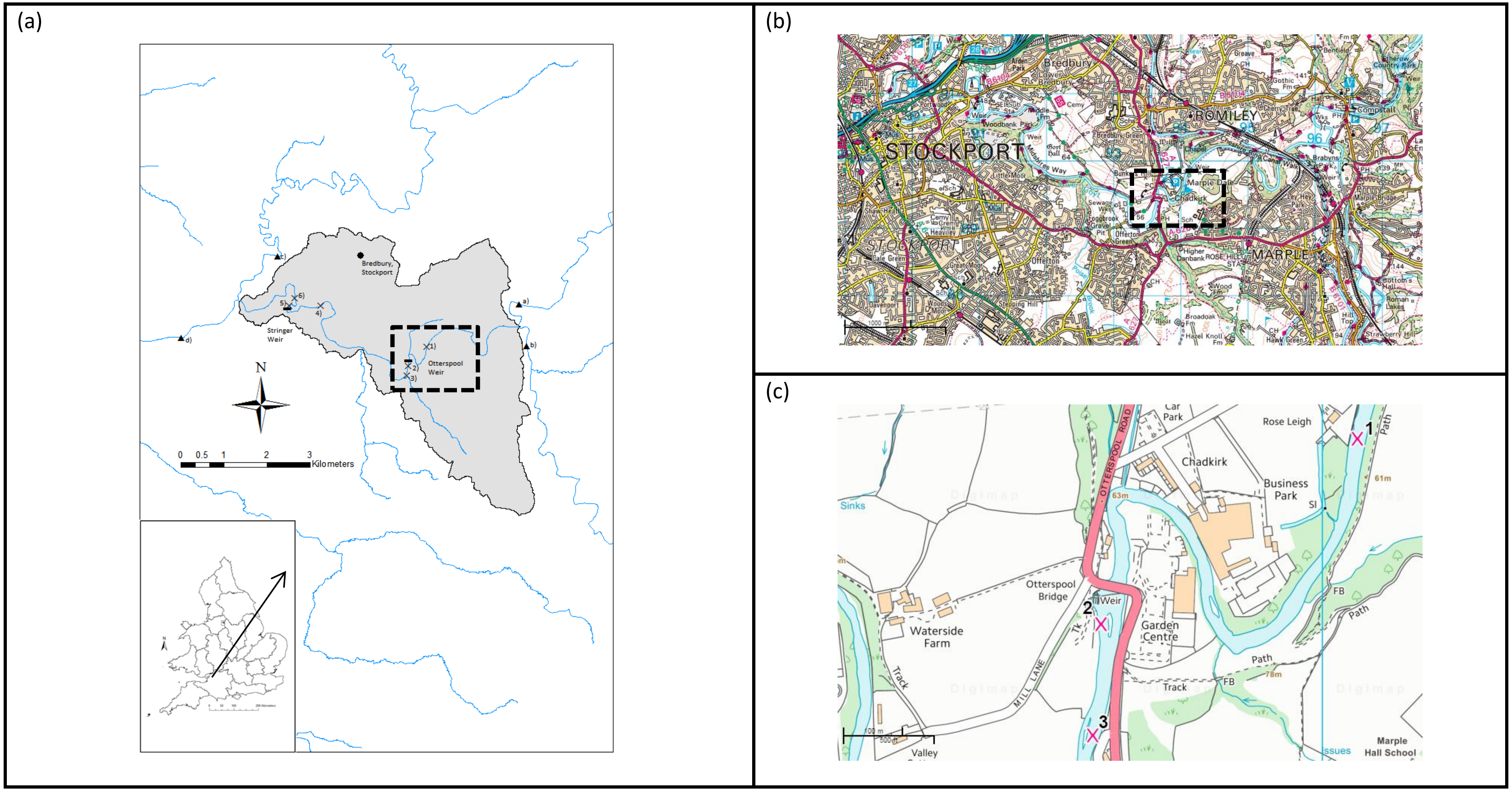

Figure 5.1: River Goyt, Etherow to Tame sub-catchment showing positions of the 'on weir' hydro scheme at Otterspool weir and sampling locations 1) upstream, 2) below scheme, 3) downstream where (a) is a map of the sub-catchment (b) is the location of sub-catchment and (c) is the reach section © Crown copyright and database rights 2017 Ordnance Survey (Digimap License)

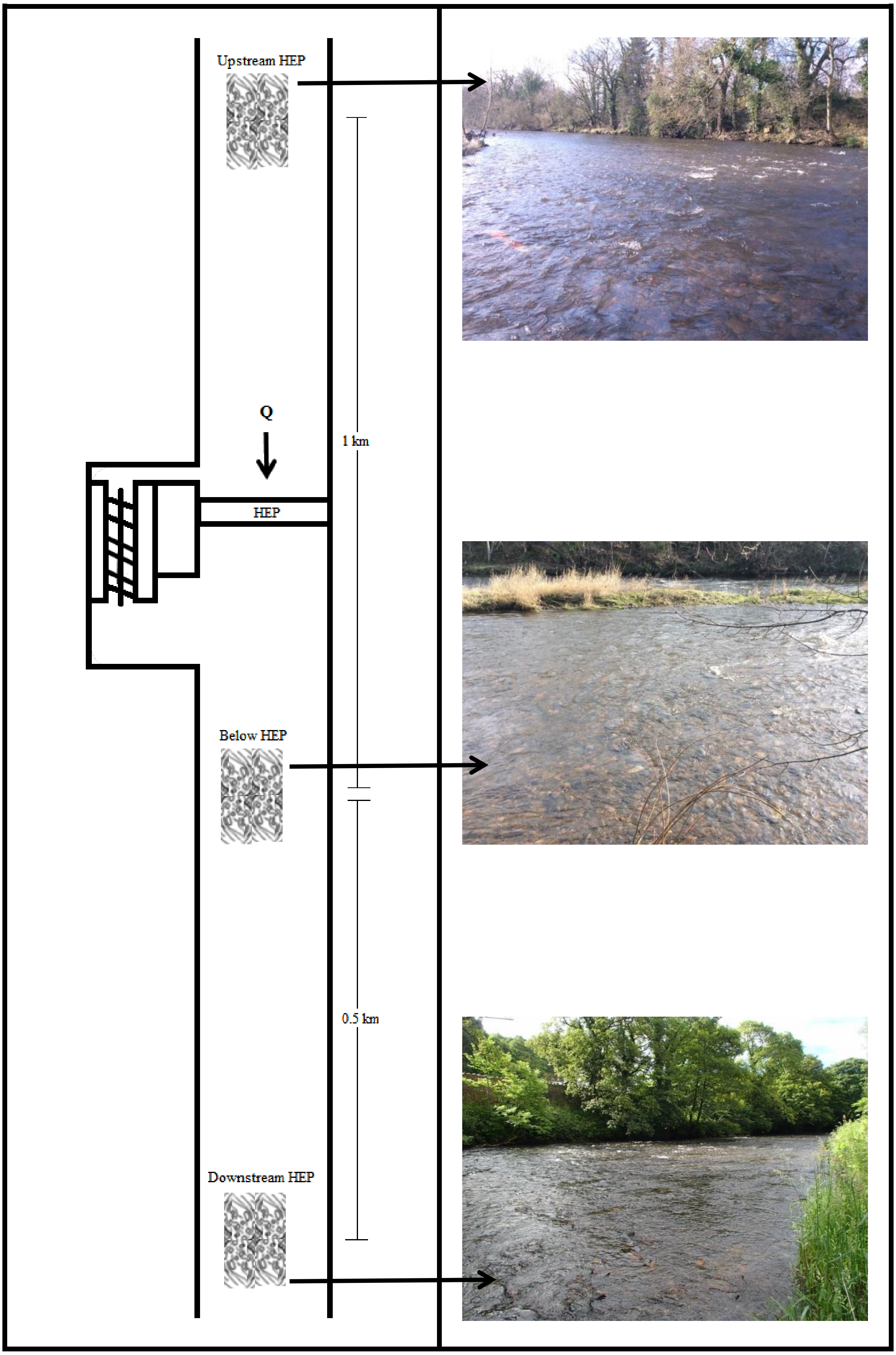

Figure 5.2: Schematic diagram of the sampling design with photographs of the upstream and downstream riffles and the riffle below the 'on weir' hydro scheme

5.3.2. Field procedure

To replicate the experiment under potentially contrasting flow conditions and to explore annual variation two field campaigns were conducted; the first field campaign took place in 2014 and the second campaign in 2015. In 2014, six sampling occasions were selected (29/04/2014, 21/05/2014, 17/06/2014, 29/07/2014, 26/08/2014 and 30/09/2014). In 2015, a further six sampling occasions where selected (29/04/2015, 26/05/2015, 24/06/2015, 27/07/2015, 04/08/2015 and 28/09/2015). It must be noted that, at the hydro scheme, both turbines were operational during the 2014 sampling but only one turbine was operational during the 2015 sampling campaign due to technical issues. The discharge at Otterspool weir was estimated as described in chapter 3 (section 3.3.1) using the two nearest flow gauging stations. Discharge was calculated for a 28 day preceding period leading up to each sampling occasion (see section 3.3.2). The flow split between the weir and hydro scheme was calculated using abstraction discharge data from Stockport Hydro (see section 3.3.3).

A range of physiochemical and biotic habitat conditions were measured on each sampling occasion in each riffle during each sampling campaign as described in chapter 3 (see section 3.2.1 and section 3.2.2). Measurements of flow velocity are missing from the April 2014 and May 2014 sampling occasions and measurements of turbidity and nitrate concentration are missing from the April 2014, May 2014 and June 2014 sampling occasions due to equipment failures. Species samples were collected on three occasions during 2014 campaign (17/06/2014, 26/08/2014 and 30/09/2014) and on one occasion during 2015 (28/09/2015) as described in chapter 3 (see section 3.2.2.3). Species were separated into morphological guilds based on resilience to disturbance (see section 3.2.2.4.1). Species richness, evenness and diversity were calculated using the Margalef richness index, Pielou's evenness index and the Shannon-Weiner diversity index in Primer software version 7 (see chapter 3).

A mean and standard deviation of all measured physiochemical habitat conditions and total chlorophyll-a concentration from each sampling occasion and in each sampling location was calculated to see how measured river conditions differed between locations. Statistical differences, in flow velocity and total chlorophyll-a concentration, between the riffle below the scheme and riffles upstream and downstream of the scheme were tested using a one-way ANOVA with post-hoc Tukey tests (section 3.4).

5.4. Results

5.4.1. Physiochemical habitat conditions

The mean daily discharge was in the low flow category during all sampling occasions. There were only two occasions when weir flow dominated which were during the July 2014 and July 2015 sampling occasions. During the July 2014 sampling occasion 63% of overall discharge was directed over the weir (Table 5.1), while 65% of the total discharge passed over the weir in July 2015 (Table 5.2).

Table 5.1: Discharge estimates at Otterspool Weir were the daily mean discharge and category is used to describe discharge before the flow was split between the weir and the turbine and were turbine flow is the amount of flow diverted through the turbines and weir flow is the amount of flow directed over the weir during each sampling occasion across the 2014 sampling campaign

		Overall Discharge		Turbine Flow		Weir Flow	
Year	Date	(m^3/s)	Category	(m^3/s)	(%)	(m3/s)	(%)
2014	29/04/2014	2.594	Low	1.524	59	1.070	41
	21/05/2014	3.665	Low	2.229	62	1.376	38
	17/06/2014	3.251	Low	1.743	54	1.508	46
	29/07/2014	1.740	Low	0.652	37	1.088	63
	26/08/2014	3.071	Low	1.717	56	1.354	44
	30/09/2014	1.988	Low	1.089	55	0.899	45

Table 5.2: Discharge estimates at Otterspool Weir were the daily mean discharge and category is used to describe discharge before the flow was split between the weir and the turbine and were turbine flow is the amount of flow diverted through the turbines and weir flow is the amount of flow directed over the weir during each sampling occasion across the 2015 sampling campaign

		Overall Discharge		Turbine Flow		Weir Flow	
Year	Date	(m^3/s)	Category	(m^3/s)	(%)	(m3/s)	(%)
2015	28/04/2015	2.988	Low	1.744	58	1.244	42
	26/05/2015	3.682	Low	1.827	50	1.855	50
	24/06/2015	2.705	Low	1.615	60	1.090	40
	26/07/2015	2.576	Low	0.907	35	1.669	65
	04/08/2015	3.068	Low	1.778	58	1.290	42
	28/08/2015	2.047	Low	0.967	47	1.080	53

There was no significant difference in flow velocity between all sampling locations across all sampling occasions during the 2014 and 2015 sampling campaigns (Figure 5.3, Figure 5.4). This was also confirmed with statistical analysis in Tables 5.3 and 5.4. While there was no significant difference in flow velocity across sampling occasions flow velocity was higher in the riffle below the hydro scheme than in riffles upstream and downstream of the scheme during the July 2014 and July 2015 sampling occasions (Figure 5.3 and Figure 5.4). This coincides with the sampling occasions when weir flow dominated at 63% and 65% respectively (Table 5.3 and 5.4). Flow velocities ranged between 0.3m/s and 0.6m/s in all locations in both field campaigns. According to Law (2011), this is the typical velocity range experienced in riffle habitats. Overall more variation in flow velocities was observed in 2015.

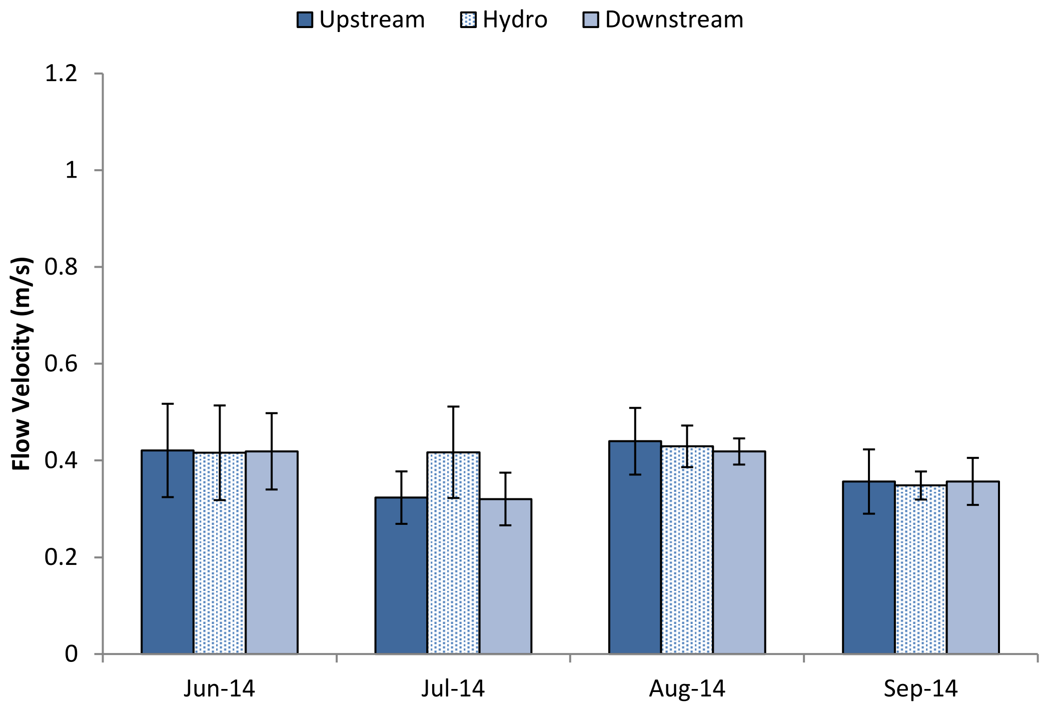

Figure 5.3: Flow velocity at a point in time measured in the riffle below the hydro scheme and the riffles both upstream and downstream of the scheme during each of the 2014 sampling occasions

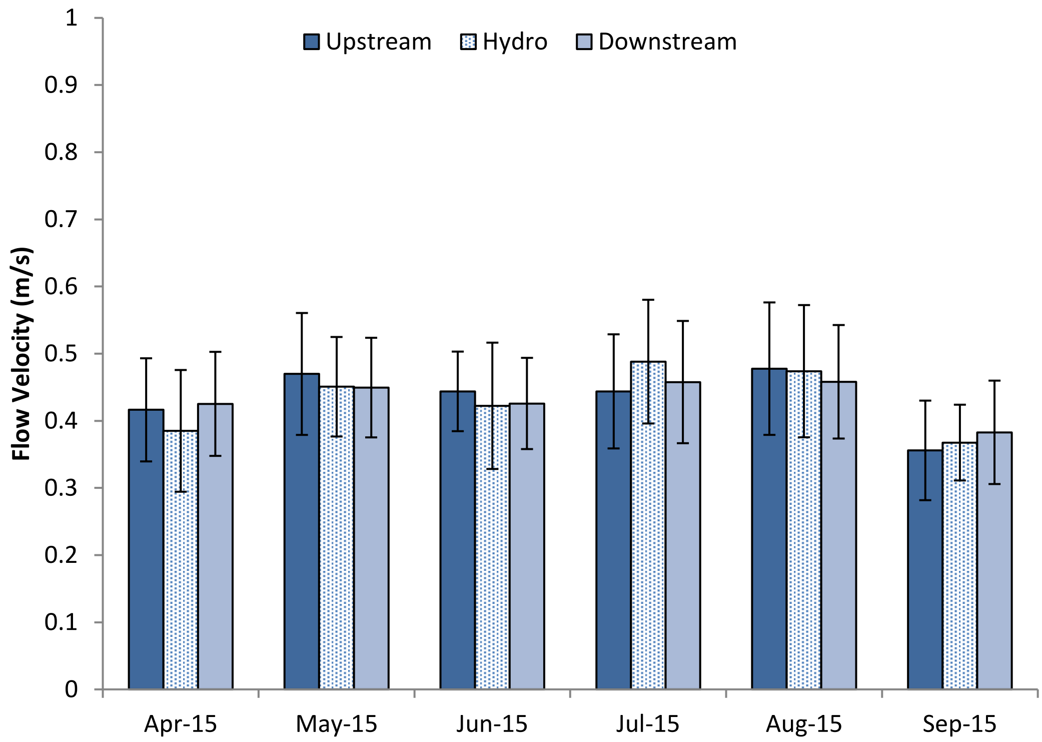

Figure 5.4: Flow velocity at a point in time measured in the riffle below the hydro scheme and the riffles both upstream and downstream of the scheme during each of the 2015 sampling occasions

Table 5.3: One-way ANOVA and post-hoc Tukey test results comparing flow velocity between the riffle below the hydro scheme to the upstream and downstream riffles and between the upstream and downstream riffles were *p<0.05* was considered significant and highlighted in bold

Sampling date	Comparison	*df*	*F-value*	*P-value*
Jun-14	Upstream*Hydro	2	0.004	0.995
	Downstream*Hydro			0.998
	Upstream*Downstream			0.999
Jul-14	Upstream*Hydro	2	3.660	0.086
	Downstream*Hydro			0.075
	Upstream*Downstream			0.997
Aug-14	Upstream*Hydro	2	0.275	0.928
	Downstream*Hydro			0.926
	Upstream*Downstream			0.743
Sept-14	Upstream*Hydro	2	0.055	0.958
	Downstream*Hydro			0.954
	Upstream*Downstream			1.000

Table 5.4: One-way ANOVA and post-hoc Tukey test results comparing flow velocity between the riffle below the hydro scheme to the upstream and downstream riffles and between the upstream and downstream riffles were *p<0.05* was considered significant and highlighted in bold

Sampling date	Comparison	*df*	*F-value*	*P-value*
Apr-15	Upstream*Hydro	2	1.330	0.453
	Downstream*Hydro			0.275
	Upstream*Downstream			0.937
May-15	Upstream*Hydro	2	0.404	0.733
	Downstream*Hydro			0.999
	Upstream*Downstream			0.703
Jun-15	Upstream*Hydro	2	0.035	0.962
	Downstream*Hydro			0.988
	Upstream*Downstream			0.992
Jul-15	Upstream*Hydro	2	1.264	0.274
	Downstream*Hydro			0.537
	Upstream*Downstream			0.878
Aug-15	Upstream*Hydro	2	0.243	0.991
	Downstream*Hydro			0.856
	Upstream*Downstream			0.789
Sep-15	Upstream*Hydro	2	0.748	0.858
	Downstream*Hydro			0.770
	Upstream*Downstream			0.447

There were minimal differences in measured water quality parameters across sampling locations and water quality parameters differed more across time than spatially (Tables 5.5 and 5.6). During the April 2014 sampling occasion, pH, conductivity and TDS were slightly higher below the hydro scheme when compared to riffles upstream and downstream of the scheme (Table 5.5). There were also small differences in water temperature across sampling locations during the April 2014 sampling occasion but patterns in water temperature matched the order in which the sampling locations were visited with an increase in temperature from the upstream riffle to the riffle below the hydro scheme and the downstream riffle (Table 5.5).

During the May 2014 and August 2014, when conductivity was slightly higher in the upstream riffle in comparison to the riffle below the weir and the downstream riffle TDS was also higher (Table 5.5). The June 2014 and July 2014 had the lowest variation in water quality parameter across sampling locations with minimal differences in measured conditions across all sites (Table 5.5). The highest water temperatures were recorded during the July 2014 sampling occasion and the highest conductivity was recorded during the August 2014 sampling occasion (Table 5.5). Across all sampling locations during all sampling occasions turbidity was zero (Table 5.5). From personal observation when water depths were low enough cobbles and boulders in the river bed were visual from the surface of the water.

There were minimal differences in other measured parameters across sampling locations and water quality parameters differed more across time than spatially. There is not much difference in values of parameters measured at different locations. As in 2014, they vary more in time than spatially. Overall the values measured in 2015 are comparable with those measured in 2014 (Table 5.6).

Table 5.5: Mean water quality measurements taken from the riffle below the hydro scheme and riffles both upstream and downstream of the hydro scheme during the 2014 sampling occasions

		Upstream		Hydro		Downstream	
Date	Measured Variable	Mean	Std dev	Mean	Std dev	Mean	Std dev
Apr-14	Temperature (°C)	12.4	0.0	12.9	0.1	13.6	0.2
	pH	7.88	0.02	8.58	0.00	8.80	0.04
	Dissolved Oxygen (mg/l)	10.89	0.04	12.34	0.03	12.97	0.10
	Conductivity	226	0	228	1	220	1
	TDS (mg/l)	146	0	148	0	143	1
	Turbidity (NTU)	-	-	-	-	-	-
	Nitrate (mg/l)	-	-	-	-	-	-
May-14	Temperature (°C)	15.2	0.0	15.1	0.0	15.2	0.0
	pH	7.53	0.01	7.67	0.03	7.66	0.00
	Dissolved Oxygen (mg/l)	9.15	1.03	9.11	1.34	9.49	0.78
	Conductivity	213	2	198	1	203	2
	TDS (mg/l)	138	1	128	1	132	1
	Turbidity (NTU)	-	-	-	-	-	-
	Nitrate (mg/l)	-	-	-	-	-	-
Jun-14	Temperature (°C)	13.8	0.0	14.4	0.2	14.1	0.2
	pH	7.61	0.03	7.85	0.02	7.67	0.02
	Dissolved Oxygen (mg/l)	10.50	0.04	10.67	0.03	10.53	0.07
	Conductivity	212	1	212	1	213	2
	TDS (mg/l)	137	0	137	0	138	1
	Turbidity (NTU)	-	-	-	-	-	-
	Nitrate (mg/l)	-	-	-	-	-	-
Jul-14	Temperature (°C)	17.4	0.1	17.5	0.1	17.4	0.1
	pH	7.53	0.11	7.51	0.10	7.34	0.05
	Dissolved Oxygen (mg/l)	9.75	0.06	9.92	0.18	9.76	0.07
	Conductivity	259	1	255	1	258	2
	TDS (mg/l)	168	1	165	1	167	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	6.59	0.65	6.69	0.61	5.94	0.19
Aug -14	Temperature (°C)	13.8	0.0	13.8	0.0	13.8	0.0
	pH	7.21	0.06	7.22	0.08	7.17	0.13
	Dissolved Oxygen (mg/l)	10.47	0.01	10.48	0.06	10.39	0.05
	Conductivity	267	1	261	2	259	1
	TDS (mg/l)	173	1	169	1	169	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	6.65	0.55	7.26	0.12	7.07	0.21
Sep-14	Temperature (°C)	13.9	0.1	13.9	0.0	13.9	0.1
	pH	7.07	0.20	7.08	0.01	6.96	0.21
	Dissolved Oxygen (mg/l)	10.66	0.05	10.68	0.08	10.57	0.07
	Conductivity	243	1	243	1	239	1
	TDS (mg/l)	158	1	157	1	155	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	7.69	0.68	7.36	0.05	7.31	0.61

Table 5.6: Mean water quality measurements taken from the riffle below the hydro scheme and riffles upstream and downstream of the hydropower scheme during the 2015 sampling occasions

		Upstream		Hydro		Downstream	
Date	Measured Variable	Mean	Std dev	Mean	Std dev	Mean	Std dev
Apr-15	Temperature (°C)	9.1	0.0	9.0	0.1	8.9	0.0
	pH	7.00	0.01	7.01	0.01	7.02	0.01
	Dissolved Oxygen (mg/l)	13.74	0.05	13.51	0.05	13.44	0.06
	Conductivity	218	1	219	1	224	2
	TDS (mg/l)	141	1	142	1	144	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	8.42	1.61	7.38	1.37	8.43	1.58
May-15	Temperature (°C)	11.3	0.1	11.2	0.1	11.1	0.0
	pH	7.00	0.00	7.00	0.00	6.99	0.01
	Dissolved Oxygen (mg/l)	11.22	0.01	11.07	0.02	11.04	0.04
	Conductivity	228	1	232	1	232	1
	TDS (mg/l)	148	1	150	0	143	2
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	8.75	0.31	8.01	0.95	8.10	1.95
Jun-15	Temperature (°C)	13.8	0.1	13.9	0.1	14.0	0.0
	pH	7.10	0.03	7.08	0.01	7.09	0.01
	Dissolved Oxygen (mg/l)	10.79	0.06	10.85	0.05	10.97	0.02
	Conductivity	257	1	256	1	255	0
	TDS (mg/l)	167	1	166	1	165	0
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	8.01	1.45	8.49	1.35	8.22	1.34
Jul-15	Temperature (°C)	17.3	0.2	17.5	0.1	17.4	0.1
	pH	7.50	0.10	7.47	0.13	7.39	0.10
	Dissolved Oxygen (mg/l)	9.76	0.06	9.87	0.18	9.81	0.13
	Conductivity	258	2	257	2	257	2
	TDS (mg/l)	168	1	166	2	167	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	6.92	0.86	6.67	0.73	6.17	0.49
Aug-15	Temperature (°C)	15.2	0.0	15.3	0.1	15.3	0.0
	pH	6.77	0.02	6.75	0.03	6.77	0.09
	Dissolved Oxygen (mg/l)	10.15	0.01	9.91	0.14	9.78	0.03
	Conductivity	206	1	205	2	202	1
	TDS (mg/l)	133	1	132	1	131	0
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	2.19	0.50	2.06	0.57	2.44	0.52
Sept-15	Temperature (°C)	14.3	0.1	14.5	0.1	14.6	0.1
	pH	6.98	0.05	6.95	0.01	6.96	0.01
	Dissolved Oxygen (mg/l)	10.75	0.11	11.11	0.09	11.25	0.10
	Conductivity	239	2	241	1	241	1
	TDS (mg/l)	155	1	156	1	156	1
	Turbidity (NTU)	0	0	0	0	0	0
	Nitrate (mg/l)	7.36	0.48	7.46	0.49	7.29	0.45

5.4.2. Preceding discharge and the phytobenthic biofilm

Figures 5.5 and 5.6 display measured mean daily discharge, abstracted daily flow and the residual flow (flow over the weir) during period of field surveys in 2014 and 2015. Table 5.7 gives a summary of the total discharge in periods of 28 days prior to field surveys. During the period leading up to April 2014 sampling occasion, there were a few peaks in flow fluctuating between moderate and low flow categories. The largest peaks occurred 21 and 20 days before sampling reaching 12.41m^3/s and 12.74m^3/s. From this point on flow reduced and was in the low flow category for 17 days leading up to the sampling occasion. Turbine flow dominated for the majority of the flow period leading up to the April 2014 sampling occasion (Figure 5.5) except during the moderate peaks 21 and 20 days before sampling when weir flow dominated. This is likely because flow was so high that the turbines had reached their capacity. Leading up to the May 2014 sampling occasion, the total discharge was low and stable and was split considerably evenly between the weir and turbine until a high flood event occurred just 8 days before sampling reaching a maximum of 33.00m^3/s (Figure 5.5). During the high flow event, weir flow dominated but as overall discharge reduced turbine flow dominated.

Leading up to the June 2014 sampling occasion overall flow was flashy and regularly fluctuated between low and moderate flow categories with one peak reaching the high flow category 23 days before sampling (max 17.28m^3/s). When the total discharge was in the upper half of the moderate flow category and the high flow category then, the weir flow dominated). When overall flow was in the high flow category, 23 days before sampling, weir flow dominated at 76%. When overall flow was in the lower half of the moderate flow category, turbine flow dominated. During the week leading up to the sampling occasion overall discharge was in the upper range of the low flow category and turbine flow dominated.

Leading up to the July 2014 sampling occasion there were a few peaks in flow yet all peaks were still in the low flow category. The largest peak occurred just 9 days before sampling reaching a maximum of just 3.83m^3/s. Discharge was split considerably evenly between the weir and the turbine throughout the preceding period leading up to the July 2014 sampling occasion. Leading up to the August 2014 sampling occasion there was some fluctuation in flow. Two peaks reached the moderate flow category at 8.36m^3/s 15 days before sampling and 8.92m^3/s 11 days before sampling. While flow was in the low flow category for the majority of the sampling occasion flow was not stable (Figure 5.6). Apart from the two moderate flow peaks flow was considerably evenly distributed between the weir and turbine. During the two peaks in the flow, weir flow dominated. Leading up to the September 2014 sampling occasion overall discharge was mainly low and stable and flow was split considerably evenly between the weir and the turbine throughout the preceding period leading up to the September 2014 sampling occasion.

It must be noted that there was only one turbine operational during the 2015 sampling campaign and as such turbine flow was lower in 2015 than in 2014. Leading up to the April 2015 sampling occasion, the total discharge started in the high flow category but reduced steadily throughout the flow period. The highest discharge was recorded 29 days before sampling at 27.6m^3/s. Overall discharge was in the low flow category for 13 days leading up to the sampling occasion (Figure 5.6). Weir discharge dominated for the majority of the preceding period with only 5 days towards the end of the flow period being dominated by turbine flow. Leading up to the May 2015 sampling occasion, there was great variation in flow. Just 6 days before sampling, the discharge peaked and was in the high flow category at 22.70m^3/s (Table 5.7). Like the flow period leading up to the April 2014 sampling occasion the majority of flow was directed over the weir throughout the flow period.

Leading up to the June 2015 sampling occasion, flow fluctuated between the low, moderate and high flow categories (Figure 5.6). The highest peak was recorded 22 days before sampling and was in the high flow category at 22.30m^3/s (Table 5.7). There were three more peaks in flow closer to the sampling occasion at 4.49m^3/s 12 days before sampling, 4.21m^3/s 8 days before sampling and 3.77m^3/s 5 days before sampling (Figure 5.6). Yet each of the peaks closer to the sampling occasion where in the low flow category. Weir flow dominated across the preceding period. Leading up to the July 2015 sampling occasion, there was some variation in flow yet flow was in the low flow category throughout the flow period (Figure 5.11). Flow was considerably evenly split between the weir and turbine throughout the preceding period (Figure 5.11).

The August 2015 sampling occasion was just 9 days after the July 2015 sampling occasion (Figure 5.11). There was a moderate peak the day after the July 2015 sampling occasion, 8 days before the August 2015 sampling occasion at 7.70m^3/s (Figure 5.6). While weir flow dominated during the peaks turbine flow dominated throughout the rest if the preceding period (Figure 5.11). There was a long period between the August and September 2015 sampling occasions with 59 days between sampling. Leading up to the September 2015 sampling occasion there was some variation in flow (Figure 5.6). There was a moderate peak in flow on 14/08/2015 reaching 6.25m^3/s but this occurred 46 days before sampling. From this point forward discharge was low and while there were a few small peaks in flow there were not peaks which exceeded the low flow category (Figure 5.6). As such overall discharge was considerably evenly split between the weir and the turbine throughout the preceding period (Figure 5.6).

Overall, the total discharges were higher in periods preceding April, May and June surveys than those in July and August across both years. The largest total flows in high flow categories were measured in periods preceding May 2014 and April 2015. Abstracted flow varied between 29.53 m^3/s (prior to July 2014) and 87.48 m^3/s (prior to June 2014). However the percentage of abstracted flow varied between 28% when only one turbine operated in April 2014 and 55% in September 2014. It appears that higher abstraction rates were achieved during periods of moderate flow dominance.

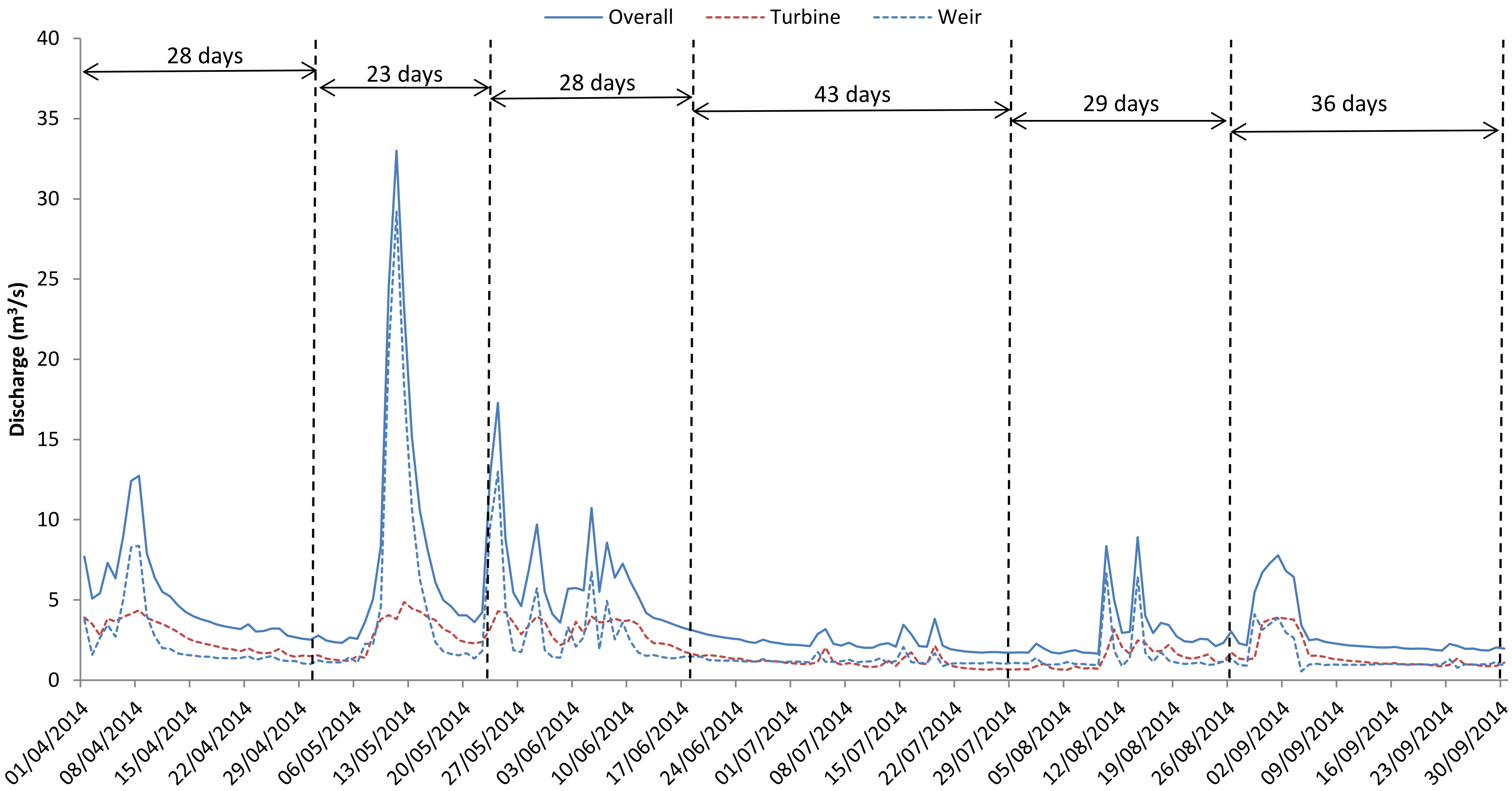

Figure 5.5: Discharge over the 2014 sampling campaign showing overall discharge before the flow split, discharge through the turbine and discharge over the weir after the flow split and number of days between sampling occasions represented by dashed lines and arrows

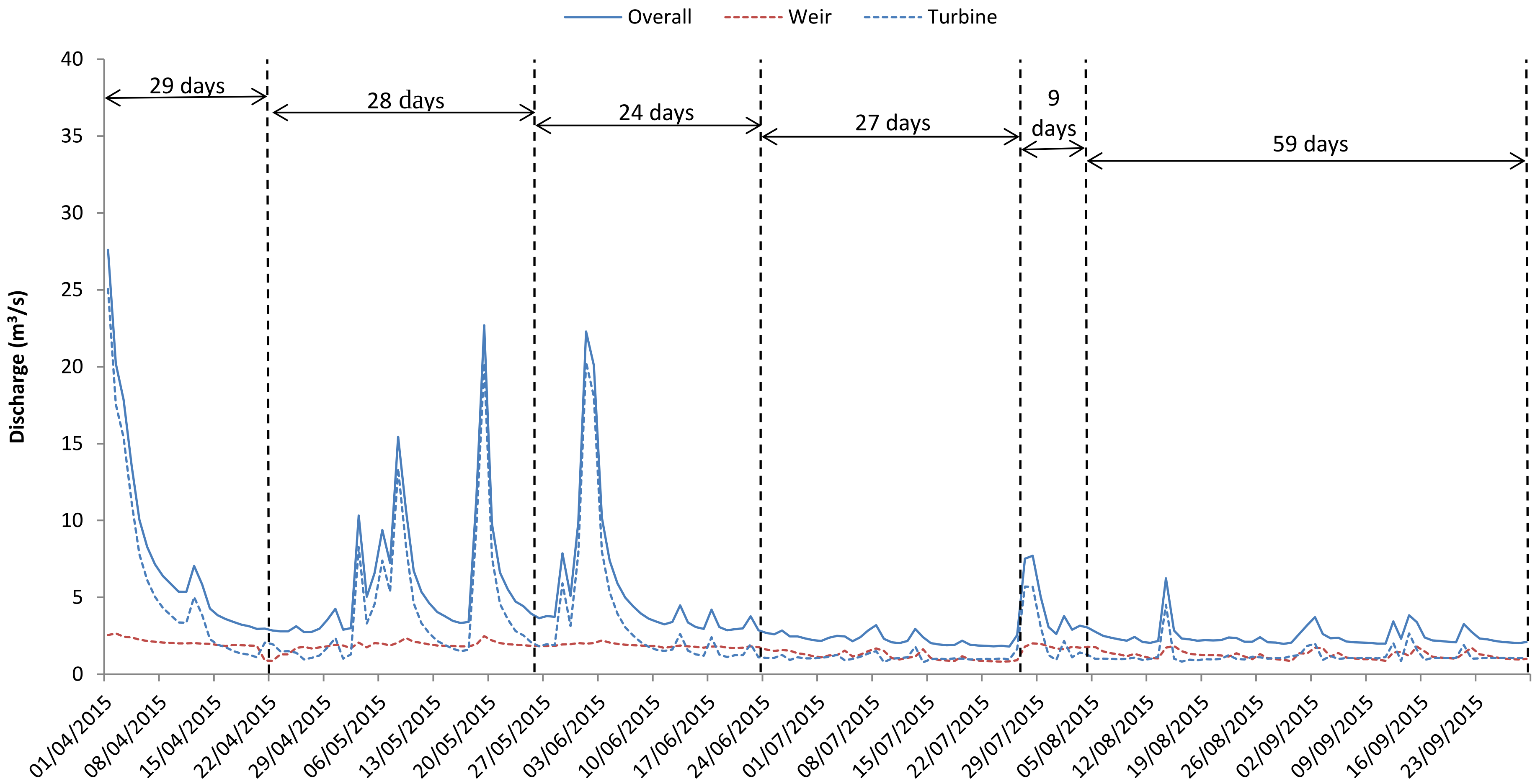

Figure 5.6: Discharge over the 2015 sampling campaign showing overall discharge before the flow split, discharge through the turbine and discharge over the weir after the flow split and number of days between sampling occasions represented by dashed lines and arrows

Table 5.7: Summary of flow conditions preceding field surveys in 2014 and 2015

	Max Flow m³/s	Total Flow m³/s	Total Abstracted Flow m³/s	Percentage %	No. of days with Low Flow	No. of days with Moderate Flow	No. of days with High Flow	No. of days of Low Flow prior to measurements	Total Low Flow m³/s	Total Medium Flow m³/s	Total High Flow m³/s
29/04/2014	12.74	146.16	77.04	531	20.00	8.00	0.00	18.00	76.32	69.84	0.00
21/05/2014	33.00	193.57	69.45	36	20.00	5.00	3.00	4.00	64.63	48.30	80.64
17/06/2014	17.28	176.32	87.48	50	18.00	9.00	1.00	6.00	81.72	77.32	17.28
29/07/2014	3.83	62.88	29.53	47	28.00	0.00	0.00	28.00	62.88	0.00	0.00
26/08/2014	8.92	80.88	37.95	47	26.00	2.00	0.00	11.00	63.60	17.28	0.00
30/09/2014	6.80	68.95	37.98	55	26.00	2.00	0.00	26.00	55.72	13.23	0.00
29/04/2015	27.60	187.97	53.22	28	17.00	8.00	3.00	15.00	58.10	64.21	65.66
26/05/2015	22.70	185.36	54.70	30	17.00	10.00	1.00	4.00	68.30	94.36	22.70
24/06/2015	22.30	159.84	52.29	33	21.00	5.00	2.00	18.00	76.24	41.21	42.39
27/07/2015	3.19	62.17	31.61	51	28.00	0.00	0.00	28.00	62.17	0.00	0.00
04/08/2015	7.70	79.33	36.03	45	26.00	2.00	0.00	6.00	64.11	15.21	0.00
28/09/2015	3.83	69.98	34.95	50	28.00	0.00	0.00	28.00	69.98	0.00	0.00

Chlorophyll-a concentration differed between sampling occasions but there was no significant difference in chlorophyll-a concentration across sampling locations during all sampling occasions (Figures 5.7 and 5.8, Tables 5.8 and 5.9). The highest chlorophyll-a concentrations were recorded during the April 2014 sampling occasion but chlorophyll-a reduced between the April 2014 and May 2014 sampling occasion. The May 2014 sampling occasion had the lowest recorded chlorophyll-a concentration, measured across both years (Figure 5.7). The lowest chlorophyll-a concentration coincided with the largest flow event during the 2014 sampling campaign which occurred just 8 days before sampling. Chlorophyll-a concentration increased between the May 2014 and June 2014 sampling occasions but decreased between the June2014 and July 2014 sampling occasions (Figure 5.7). Chlorophyll-a concentration increased again between the July 2014 and August 2014 sampling occasion and the August 2014 and September 2014 sampling occasions but did not reach levels recorded during the April 2014 sampling occasion (Figure 5.7).

There was no statistically significant difference in chlorophyll-a concentration between all sampling locations and the sampling occasions in 2015, except the May 2015 sampling occasion (Figure 5.8, Table 5.9). During the May 2015 sampling occasion chlorophyll-a concentration were significantly lower below the scheme when compared to riffles upstream and downstream of the scheme (Figure 5.8, Table 5.9). Although chlorophyll-a concentration appeared higher below the scheme when compared to the riffles upstream and downstream of the scheme during September 2015 this relationship was not significant (Table 5.9). Chlorophyll-a concentration was highest during the April 2015 sampling campaign and lowest during the July 2015 sampling campaign (Figure 5.8). Yet chlorophyll-a concentration appeared to be relatively similar between the June 2015, July 2015 and August 2015 sampling occasions (Figure 5.8). Chlorophyll-a concentration increased between the August 2015 and September 2015 sampling occasion but did not reach the levels reached during the April 2015 sampling occasion (Figure 5.8).

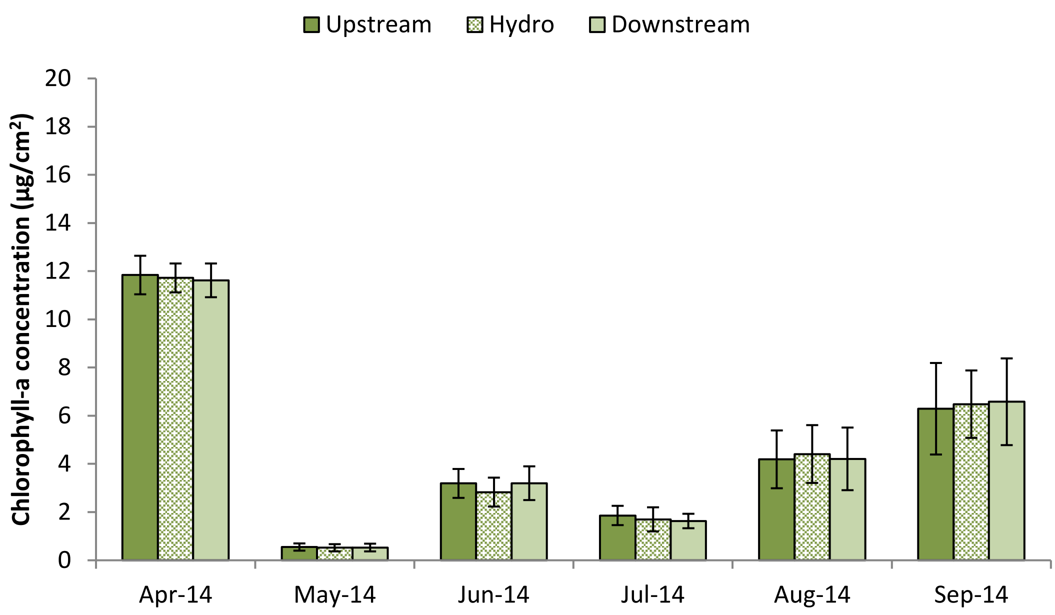

Figure 5.7: Mean total chlorophyll-a concentration calculated from the sum of the photoautotrophic components of the biofilm in the riffle upstream of the hydro scheme, riffle below the scheme and riffle downstream of the scheme across the 2014 sampling occasions were error bars represent standard deviation

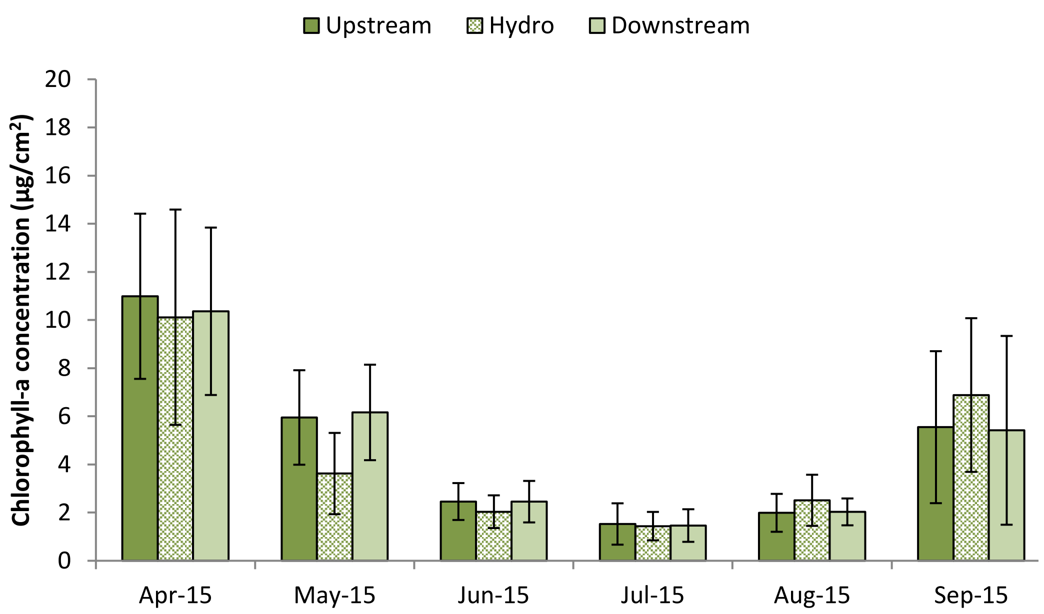

Figure 5.8: Mean total chlorophyll-a concentration calculated from the sum of the photoautotrophic components of the biofilm in the riffle upstream of the hydro scheme, riffle below the scheme and riffle downstream of the scheme across the 2015 sampling occasions were error bars represent standard deviation

Table 5.8: One-way ANOVA and post-hoc Tukey test results comparing total chlorophyll-a concentration between the riffle below the hydro scheme to the upstream and downstream riffles and between the upstream and downstream riffles were *p<0.05* was considered significant and is highlighted in bold

Sampling date	Comparison	*Df*	*F-value*	*P-value*
Apr-14	Upstream*Hydro	2	0.139	0.955
	Downstream*Hydro			0.970
	Upstream*Downstream			0.860
May-14	Upstream*Hydro	2	0.055	0.943
	Downstream*Hydro			0.993
	Upstream*Downstream			0.976
Jun-14	Upstream*Hydro	2	0.458	0.699
	Downstream*Hydro			0.685
	Upstream*Downstream			1.000
Jul-14	Upstream*Hydro	2	0.450	0.798
	Downstream*Hydro			0.958
	Upstream*Downstream			0.633
Aug-14	Upstream*Hydro	2	0.061	0.948
	Downstream*Hydro			0.954
	Upstream*Downstream			1.000
Sept-14	Upstream*Hydro	2	0.044	0.981
	Downstream*Hydro			0.994
	Upstream*Downstream			0.953

Table 5.9: One-way ANOVA and post-hoc Tukey test results comparing total chlorophyll-a concentration between the riffle below the hydro scheme to the upstream and downstream riffles and between the upstream and downstream riffles were $p<0.05$ was considered significant and is highlighted in bold

Sampling date	Comparison	*df*	*F-value*	*P-value*
Apr-15	Upstream*Hydro	2	0.121	0.876
	Downstream*Hydro			0.964
	Upstream*Downstream			0.972
May-15	Upstream*Hydro	2	11.209	**0.001**
	Downstream*Hydro			**0.000**
	Upstream*Downstream			0.934
Jun-15	Upstream*Hydro	2	1.962	0.204
	Downstream*Hydro			0.212
	Upstream*Downstream			1.000
Jul-15	Upstream*Hydro	2	0.081	0.920
	Downstream*Hydro			0.994
	Upstream*Downstream			0.957
Aug-15	Upstream*Hydro	2	2.438	0.126
	Downstream*Hydro			0.168
	Upstream*Downstream			0.988
Sept-15	Upstream*Hydro	2	1.112	0.443
	Downstream*Hydro			0.375
	Upstream*Downstream			0.992

From the BenthoTorch readings, the concentration of the photoautotrophic components was derived. Their relative contributions in relation to the mean total chlorophyll-a concentration are shown in Figures 5.9 and 5.10. The summary is also given in Table 5.10. There was minimal variation in community structure between sampling locations while there are some variations between surveys, particularly in 2015. Diatom concentrations were the dominant component of total chlorophyll-a concentration (above 57%) across all sampling locations and all surveys in 2014. Diatom contribution reached 80% of the mean chlorophyll-a concentration in the upstream riffle in April 2014. Only slightly smaller percentages (77% and 76%) were measured in the riffle below the weir and the downstream riffle (Figure 5.9). Their dominance reduced slightly through May 2014, June 2014 and July 2014 (down to 57%) and increased again in August 2014 and September 2014 (up to 65%).

Diatoms dominated total chlorophyll-a concentration in all locations during the April 2015 sampling occasion yet the relative contributions of diatoms were slightly lower below the scheme (Figure 5.10). Diatoms contributed to 80% of total chlorophyll-a concentration in the upstream riffle, 64% in the riffle below the weir and 83% in the downstream riffle. A similar pattern was again observed in May 2015, though the percentage of contribution was lower (52% to 66%). The contribution reduced significantly in June 2015 (down to 42%) then increased rapidly in July 2015 (up to 95%) and then decreased again in September 2015 (down to 35%). It is still not clear, whether this might be an artefact of the BenthoTorch. In September 2015, the contribution increased again to similar levels (higher 50%) than September 2014.

Cyanobacteria were the second most abundant component. As the diatom contributions reduced or increased so its contribution increased or reduced (see Table 5.10). There is no difference in contributions across the sampling locations except in April 2015 and May 2015 when the largest contributions were found below the hydro scheme (36% and 48%). Sudden increase and decrease of their contribution were recorded in June 2015, July 2015 and August 2015. Contribution of green algae was very small (1-3%) or none. They were identified in the downstream riffle in May 2014 and below the hydro scheme in June 2015and August 2015.

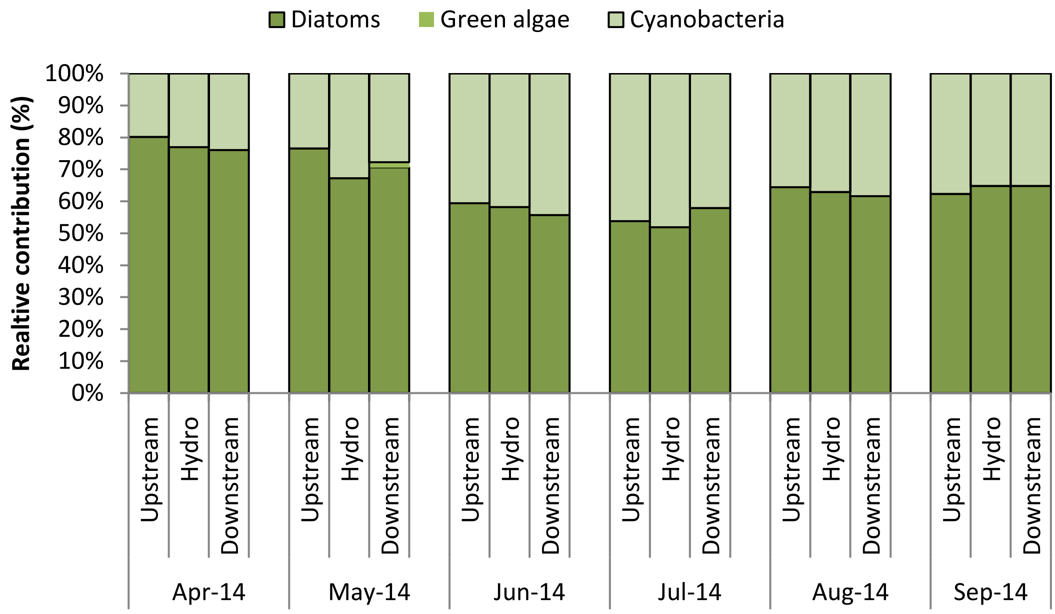

Figure 5.9: Relative contributions of the photoautotrophic components of the biofilm (diatoms, cyanobacteria and green algae) concentration in relation to mean total chlorophyll-*a* concentration for the upstream riffle, riffle below the hydro scheme and downstream riffle during the 2014 sampling occasions

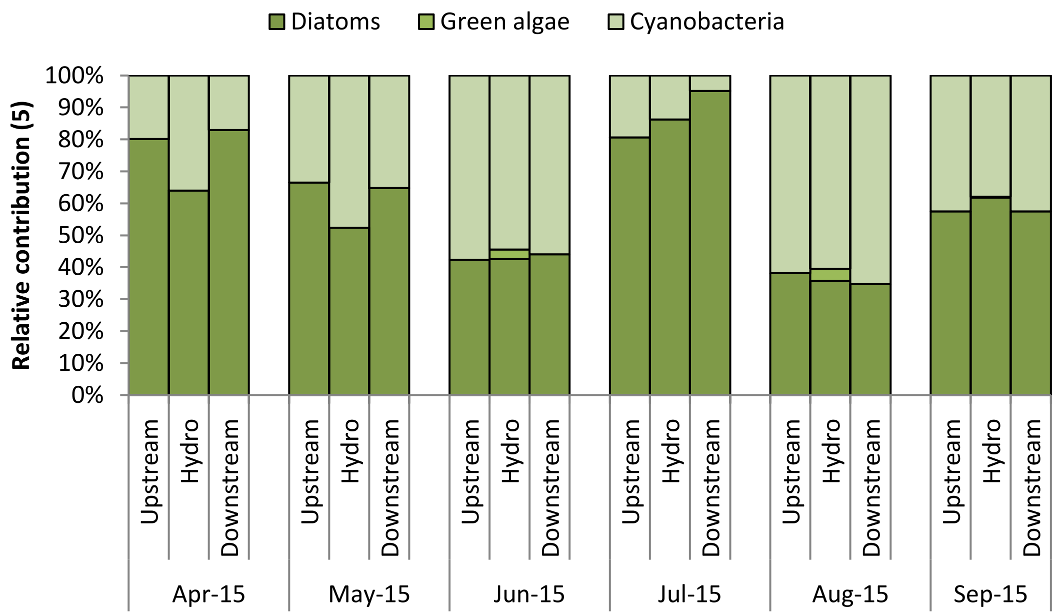

Figure 5.10: Relative contributions of the photoautotrophic components of the biofilm (diatoms, cyanobacteria and green algae) concentration in relation to mean total chlorophyll-*a* concentration for the upstream riffle, riffle below the scheme and downstream riffle during the 2015 sampling occasions

Table 5.10: Relative contributions of the photoautotrophic components of the biofilm (diatoms, cyanobacteria and green algae) concentration in relation to mean total chlorophyll-a concentration for the upstream riffle, riffle below the scheme and downstream riffle during the 2014 and 2015 sampling occasions

	Diatoms			**Cyanobacteria**			**Green Algae**		
	Up	Weir	Down	Up	Weir	Down	Up	Weir	Down
29/04/2014	80%	77%	76%	20%	23%	24%	0%	0%	0%
21/05/2014	77%	67%	71%	23%	33%	28%	0%	0%	1%
17/06/2014	59%	58%	56%	41%	42%	44%	0%	0%	0%
29/07/2014	59%	60%	57%	41%	40%	43%	0%	0%	0%
26/08/2014	64%	63%	61%	36%	37%	39%	0%	0%	0%
30/09/2014	62%	65%	65%	38%	35%	35%	0%	0%	0%
29/04/2015	80%	64%	83%	20%	36%	17%	0%	0%	0%
26/05/2015	66%	52%	64%	34%	48%	36%	0%	0%	0%
24/06/2015	42%	43%	44%	58%	54%	56%	0%	3%	0%
27/07/2015	81%	86%	95%	19%	14%	5%	0%	0%	0%
04/08/2015	38%	36%	35%	62%	61%	65%	0%	3%	0%
28/09/2015	57%	62%	57%	43%	38%	43%	0%	0%	0%

Species sample were collected during the June 2014, August 2014, September 2014 and September 2015 sampling occasion and identified species were separated into ecological guilds. Assemblages differed between all sampling occasions but were relatively similar between sampling locations (Figure 5.10). Species richness, evenness and diversity (Table 5.11) were also similar across sampling locations and sampling occasions.

Functional measures, relate to how certain species have adapted to specific environmental conditions i.e. low profile species have adapted certain morphological traits enabling them to thrive in high flow conditions and high profile species have adapted different morphological traits enabling them to thrive in low flow conditions. Functional measures can be used to understand habitat conditions. High presence of low profile species in an assemblage could indicate that the assemblage has been taken from a high flowing environment. Taxonomic measures including species evenness, richness and diversity, though less descriptive in terms of species specific traits, are often used as indicators of general ecosystem health. All taxonomic measures relate to the variety of species in an assemblage. The higher the variety, the higher the biodiversity and the healthier the system is believed to be. Both functional and taxonomic measures can be used to detect the impact of anthropogenic activity but a significant difference, in each of these measures between sampling locations is needed for the impact to be considered further. Diversity values are measured between 0 and 5 and typical values are between 1.5 and 3.5; rarely exceed 4. Values above and below typical values could indicate some form of anthropogenic impact. Diversity values where in the typical range for UK rivers across all sampling locations.

During the June 2014 sampling occasion there was a high percentage of low profile species in all sampling locations (Figure 5.11). *Cocconeis placentula*, a low profile pioneer species, dominated all sampling locations making up 52% of the assemblage in the riffle below the scheme, 45% in the upstream riffle and 47% in the downstream riffle. Species were considerably evenly distributed amongst high profile, low profile and motile species in all sampling locations during the August 2014 sampling occasion (Figure 5.11). The dominant species in the upstream and downstream riffles were *Cocconeis plancentula* a low profile pioneer species which made up 24% of the assemblage in the upstream riffle and 26% in the downstream riffle, *Navicula lanceolata* a motile species which made up 15% of the assemblage in the upstream riffle and 16% in the downstream riffle and *Diatoma vulgare* a high profile species which made up 15% of the assemblage in the upstream riffle and 6% in the downstream riffle. The dominant species in the riffle below the hydro scheme were N*avicula lanceolata* at 29%, *Cocconeis placentula* at 14% and *Rhoicosphenia abbreviata* a low profile species at 14% of the assemblage.

High profile and motile species dominated in all sampling locations during the September 2014 sampling occasion (Figure 5.11). The most dominant species in the riffle upstream of the hydro scheme were *Navicula lanceolata* which made up 33% of the assemblage, *Diatoma vulgare* which made up 19% of the assemblage and *Gomphonema minutum,* which made up 11% of the assemblage. The most dominant species in the riffle downstream of scheme were *Navicula lanceolate* which made up 35% of the assemblage, *Diatoma vulgare* which made up 16% of the assemblage and *Gomphonema minutum* which made up 19% of the assemblage. The most dominant species in the riffle below the hydro scheme were *Navicula lanceolata* which made up 35% of the assemblage, *Diatoma vulgare* which made up 20% of the assemblage and *Gomphonema minutum* which made up 13% of the assemblage.

During the September 2015 sampling occasion high profile and motile species dominated all sampling locations. The most dominant species in the upstream riffle were *Navicula lanceolata* a motile species which made up 29% of the assemblage, *Diatoma vulgare* a high profile species which made up 23% of the assemblage and *Melosira varians* a high profile species which made up 12% of the assemblage. The most dominant species in the riffle below the hydro scheme were *Navicula lanceolata* which made up 34% of the assemblage, *Diatoma vulgare* a high profile species which made up 22% of the assemblage and *Melosira varians*, which made up 9% of the assemblage. The most dominant species in the downstream riffle were *Navicula lanceolata,* which made up 30% of the assemblage, *Diatoma vulgare,* which made up 28% of the assemblage and *Diatoma milforme* a high profile species, which made up 42% of the assemblage.

Table 5.11: Richness, Evenness and Diversity Indices

		Sampling location		
Date	Index	Upstream	Hydro	Downstream
Jun-14	Richness	2.7	2.7	2.6
	Evenness	0.6	0.6	0.6
	Diversity	3.2	3.5	3.0
Aug-14	Richness	3.3	3.2	3.2
	Evenness	0.8	0.7	0.7
	Diversity	3.3	3.5	3.7
Sep-14	Richness	3.0	2.8	2.9
	Evenness	0.7	0.7	0.7
	Diversity	3.0	2.5	2.6
Sep-15	Richness	3.1	3.0	3.1
	Evenness	0.7	0.7	0.7
	Diversity	3.7	3.7	3.5

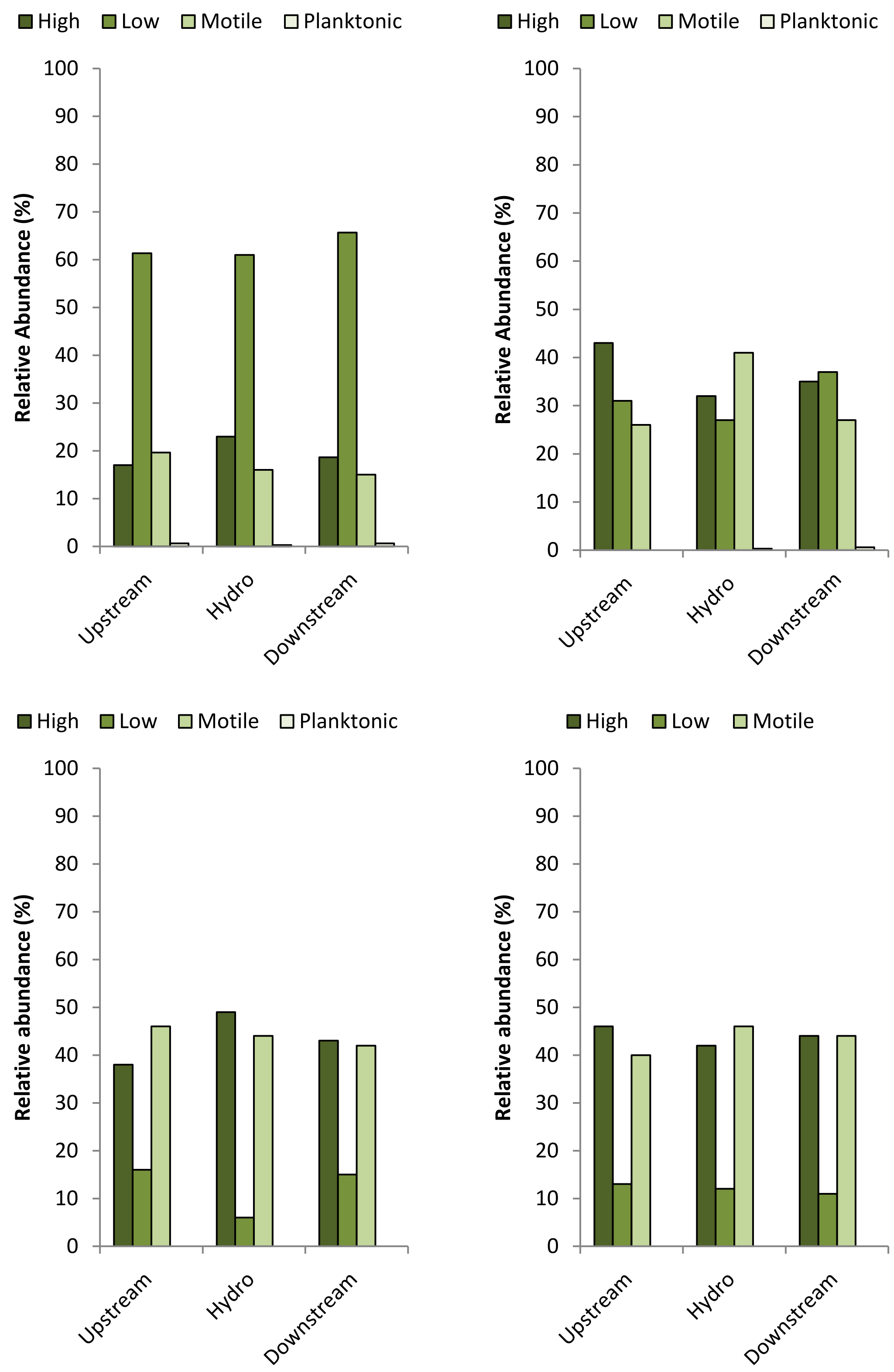

Figure 5.11: Relative abundance of species in each ecological guild in the assemblages collected from the riffle upstream of the hydro scheme, the riffle below the scheme and the riffle downstream of the scheme during the a) June 2014, b) August 2014 and c) September 2014 sampling occasion d) September 2015 .

5.4. Discussion

Results from this investigation did not agree with the proposed hypothesis that flow velocity and the phytobenthic community composition and biomass would differ across sampling locations. There was no significant difference in flow velocity and chlorophyll-a concentration between all sampling locations across the majority of sampling occasions except the May 2015 sampling occasion when chlorophyll-a concentration was significantly lower below the scheme. There were some differences in community composition, derived from the BenthoTorch readings, across sampling locations in April 2015 and May 2015 but there were very little differences in community composition according to species samples. During the April 2015 and May 2015 sampling occasions there were higher proportions of cyanobacteria below the scheme when compared to upstream and downstream riffles but diatoms dominated in all locations and contributed most to total chlorophyll-a concentration in the riffle below the scheme and riffles upstream and downstream of the scheme.

During the June 2015 and August 2015 there was evidence of green algae below the scheme but green algal contribution was minimal and apart from this community composition was similar across all sampling locations. There was minimal difference in diatom species derived from field samples across sampling locations, except in August 2014 when slightly higher abundance of motile species was found below the hydro scheme in comparison with those found upstream and downstream of the scheme. The metrics deployed to describe community composition (richness, evenness, diversity and ecological guilds) shows no difference between community compositions at different locations.

While it was hypothesised that community composition and biomass would differ below the scheme when compared to riffles upstream and downstream of the scheme as a result of increased velocities there was no difference in flow velocity across any of the sampling occasions. Moreover it was hypothesised that with a greater proportion of flow diverted to the scheme there would be a greater increase in velocity in the riffle below the scheme. Even on occasions when turbine flow dominated at 62% during the May 2014 sampling occasion and 60% during the June 2015 sampling occasion flow velocity was similar between all sampling locations. However, these were occasions when the discharge was typically low and perhaps different results would be obtained during periods of moderate and high flow.

Given that measurements were collected in the shallow riffle edge habitat it could be possible that the high velocity below the outlet did not extend towards the bank were measurements were collected. As discussed in chapter 2 the outlet confluence zone below the scheme is likely to consist of a number of hydraulic zones of impact which will differ in hydraulic character. From personal observation and photographic evidence (Figure 5.12) it was apparent that the shallow riffle edge habitat where measurements were collected were not within the acceleration zone but downstream of it. As such future investigations should focus on spatially mapping the area below the scheme to gain better understanding of the positions and effects of the hydraulic zones of impact and how these might alter spatial distributions of the phytobenthic biofilm below the scheme.

Figure 5.12: Photograph of the confluence below the hydro showing evidence of an area of separation towards the bank

In concurrence with velocities, it was expected that differences in community structure and biomass between riffles would be more pronounced following a period of high abstraction and low weir discharge. In contrary, the abstraction rate was low and flow over the weir was in high/moderate flow regime on two occasions when the difference in chlorophyll-a concentration has been registered (April 2015 and May 2015). In particular during the May 2015 sampling occasion, chlorophyll-a concentration was significantly lower below the scheme when compared to both the upstream and downstream riffles. There was a high flow event just six days before the sampling occasion and given that high flow/flood events are believed to have the strongest effect on biofilm growth scouring the biofilm as a result of increased drag and abrasion and reducing biomass as a result (Law, 2011) it would be expected that biomass would be reduced in all sampling locations. Possible explanation for the observed differences is that dominant flow over the weir and flow through the turbines have a joint effect just below the turbine, introducing higher drag and shear-stress during these high flow events.

It is possible that, in this instance, the high flow velocity and acceleration zone from the scheme tapered towards the shallow riffle habitat and increased velocities beyond natural background discharge and caused greater increase in flow velocity than natural levels and greater drag and scour on the biofilm resulting in lower biomass. From confluence studies it is apparent that the position of the acceleration zone and high velocity zone can change according to a number of variables and conditions with one being the flow velocity in confluence channel. On the other hand one turbine was operational during the May 2015 sampling occasion and this was the turbine closest to the right hand river bank. As such large volumes of flow were diverted through a narrower channel and the increases in flow might have been greater and closer to the bank as a result.

A high flow event 8 days before the May 2014 sampling occasion reduced the chlorophyll-a concentration significantly and there was no difference in chlorophyll-a concentration between any of the sampling locations. In this instance background flow could have been high enough to scour the biofilm in all sampling locations. It was the highest flow event recorded during the whole sampling campaign reaching a maximum of $33.00m^3/s$ and the lowest chlorophyll-a concentration recorded across all sampling locations, in fact nearly all biomass was removed. This is in agreement with the hypothesis that difference in community structure will be less pronounced following periods of high flashy flow when the effect of the scheme is masked by high background discharge. From observations above, there is an indication that there are threshold flows below or above, which there will be no differences in conditions upstream, below and downstream of the scheme.

Also while there were minimal differences in measured physical and chemical river conditions across sampling locations this study cannot eliminate the influence of other environmental variables, such as light intensity, phosphate concentration and grazer density, on biofilm growth. While sampling locations were in close proximity and efforts were made to choose the most comparable sites free from the influence of any other human activity, tree coverage could have varied across sites. As a result of increased tree coverage light intensity could have been reduced below the scheme causing a decrease in biomass. Hill and Fanta, 2008 showed that light alone explained 67 % of the variation in phytobenthic biomass. Furthermore, while nitrate concentration was measured across sampling locations there are examples in the literature were phosphate concentration has altered biofilm growth (Law, 2011). Conductivity, which is often used as a measure of enrichment, did not vary across sampling locations during all sampling occasions. However if this was the case one would expect differences in biomass over more than one sampling occasion.

In addition there were changes in biomass and community composition temporally across sampling occasions. High chlorophyll-a concentration was recorded during the April 2014 and April 2015 sampling occasions which is consistent with the literature. During the spring when light levels are high and shading by tree coverage low, discharge is variable but not destructive and invertebrate grazing is low, biomass is often high (Allan, 1995). Lower chlorophyll-a concentration during the summer months (June, July and August) is also consistent with the literature. While stable low flow during the summer months can encourage growth and succession from a singled layered community to three-dimensional structure, reduced flow velocity can have a negative impact on the biofilm by decreasing nutrient mixing and decreasing biomass as a result. It is hence recommended that further studies taking into account a combination of factors simultaneously should be conducted in the future.

5.5. Conclusions

This chapter highlights the effects of an 'on weir' hydro scheme on flow velocity and the phytobenthic biofilm. Generally no difference in velocities, chlorophyll-a concentration, photoautotrophic components and diatom species was detected between riffles below the scheme and riffles upstream and downstream of the scheme over the two field campaigns in 2014 and 2015. In contrast to hypotheses, it was found that during low abstraction rates during high flow conditions, there is the likelihood that there will be a difference in chlorophyll-a concentration and species composition between different sites. It was also observed that high flow rate will mask the effect of the scheme as expected. This chapter also highlights the need for continuous monitoring over time as opposed to spot sampling and the need to carry out measurements across the field.

Chapter 6: Assessing spatial patterns in flow velocity, phytobenthic biomass and community structure about the outlet of the low head 'on weir' hydro scheme

6.1. Overview

This chapter investigates the influence of a low head 'on weir' hydro scheme on spatial patterns in phytobenthic community structure and biomass in the area below the scheme in a bid to advance understandings of the ecological impacts of low head 'on weir' hydro which at present is uncertain and unclear. A large scale spatial survey was conducted to compare how flow velocity and phytobenthic biomass and community structure differ between the hydro side and non-hydro side of the channel and to see how the hydro scheme influences fine scale patterns in flow velocity and phytobenthic biomass below the weir. To begin this chapter provides a brief introduction to the potential physical implications of low head 'on weir' hydro and how the phytobenthic biofilm could respond to changes in physical habitat conditions created by the scheme; with particular emphasis on flow velocity. The introduction ends by explaining the main aim of this chapter and provides specific hypotheses that will be tested throughout the investigation. This chapter then goes on to describe the methods used to detect impact. Subsequent sections present the results of the investigation. The final section provides a discussion of the results in relation to studies on the phytobenthic biofilm and a summary of the main findings.

6.2. Introduction

By adding a low head 'on weir' hydro scheme to a weir and diverting large volumes of water through the scheme, a low head 'on weir' scheme could cause changes in flow pattern and morphology in the area below the weir. At a low head 'on weir' scheme flow is directed through a turbine forebay and then back into the main river channel at the outlet. Instead of large volumes of water being directed over the large weir crest, large volumes of water are directed through a narrow turbine forebay. While the remaining flow is directed over the weir, the scheme has essentially caused a re-distribution of flow. As identified in chapter two this re-distribution of flow could cause increases in velocity toward the hydro side of the channel and subsequent decreases in velocities on the non-hydro side of the channel.

The large volumes of flow which are constricted through the narrow turbine forebay will naturally increase in velocity and while this flow will be returned back into the main river channel at the outlet this could create an area with highly complex flow patterns, high flow velocities and turbulence below the outlet. As the water from the turbine forebay re-enters the main river channel it could take some time for the flow from the turbine and flow from the main river channel to merge and combine. Shear layers could from in the downstream direction extending from the outlet. The shear layers could create a boundary and constricted cross section and an acceleration zone with high flow velocities on the hydro side of the channel. Alternatively with lower amounts of flow being directed over the weir and across the long weir crest there could be a subsequent decrease in velocities towards the non-hydro side of the channel. Essentially by redistributing flow the scheme could create two distinctly different hydraulic habitats directly adjacent to one another (Mould et al., 2015a).

In response to the potential changes created by the scheme there could be changes in phytobenthic community composition and biomass. As a result of differences in flow velocities between the hydro and non-hydro side of the channel different communities could develop either side of the river. Spatially the phytobenthic biofilm often forms highly patchy distributions as a result of spatial variations in flow velocity (Biggs et al., 1998a; Hart et al., 2013). Whilst increased flow on the hydro side could increase shear stress and could prevent the community from succeeding into a diverse community (McIntire, 1966; Horner et al., 1990; Stevenson, 1996; Biggs et al., 1998a; Hart and Finelli, 1999) decreased flow on the non-hydro side could accelerate succession and support diverse communities with upper and lower tiers in high biomass.

Moreover whilst high velocities could extend from the outlet and create an acceleration zone in the main channel a number of distinct hydrological and morphological features could also form in the downstream direction. These hydraulic features could be similar to those associated with the interface of flows at river confluences. For the purpose of this chapter they have been termed hydraulic zones of impact. A stagnation zone of reduced flow velocities could develop at the upstream junction corner as well as a separation zone of reduced flow velocities at the downstream junction corner where characteristically the flow detaches from the bank and creates a horizontal vortex (Wuppukondor and Chandra, 2017). As discussed above shear layers could form and extend from the outlet along the separation zone. The shear layers could create a boundary and the high flow velocities which extend from the outlet could form an acceleration zone. While the acceleration zone may take some time to dissipate and expand it will reach a point where the shear layers expand and dissipate laterally and flow velocities decrease (Best, 1988; Best and Roy, 1991; Biron et al., 1996a, b; McLelland et al., 1996; Rhoads, 1996; Rhoads and Sukhodolov, 2001). As such while velocities will be high below the outlet velocities should decrease with distance from the outlet.

Considering the hydraulic zones of impact there could be further alterations in phytobenthic biofilm biomass and community structure. Even though the hydraulic zones of impact sit directly adjacent to each other, spatial variation in flow could create differences in biomass and community structure (Biggs et al., 1998a; Hart et al., 2013). Yet the extent to which the communities and biomass will differ will come down to the amount of flow diverted through the turbines, which in turn might change the size and positions of the hydraulic zones of impact. Moreover other inter-related variables such as nutrients, light and grazers, which will vary across streams naturally, could also have an effect on the extent to which the communities are altered.

Moreover in some instances, these environmental variables could have greater effects on the biofilm and could mask the effect of the scheme. Of these variables, flow regime is often the most important factor and different aspects of the flow regime could cause varying results. For example high intensity flood events could scour the biofilm and reset the succession trajectory regardless of the effect of the scheme. In this instance communities across the whole reach could be dominated by low profile diatoms in low biomass and as such there would be no difference in community composition and/or biomass between the hydro and non-hydro side of the channel and hydraulic zones of impact. Yet following periods of low stable (steady) flow spatial variations in flow velocity become more important (Biggs, 2000; Mosisch et al., 2001; Jarvie et al., 2002; Battin et al., 2003; Lange et al., 2011) and distinctly different communities and differing levels of biomass could form on either side of the channel and across hydraulic zones of impact.

The main aim of this chapter is to expand the understanding of the influence of the 'on weir' hydropower on localised flow velocity, phytobenthic biofilm biomass and phytobenthic community structure in the area below the scheme and will test the hypotheses that;

(i) There will be differences in flow velocity, phytobenthic biofilm biomass and community composition between the hydro and non-hydro side of channel with the hydro side having higher flow velocity, lower biomass and low profile communities adapt to high flow
(ii) The collision of flows from the outlet and weir will cause the formation of hydrological zones of impact and morphological features similar to those at river

confluences including zones of stagnation, deflection, acceleration, separation, scour and deposition

(iii) Phytobenthic biofilm biomass and community composition will differ between hydrological zones of impact and natural physical biotopes.

6.3. Methodology

6.3.1. Study site

The field campaign was conducted in the River Goyt, UK, below Otterspool weir and Stockport Hydro in the reach between the confluence with the River Etherow and River Tame (Figure 6.1). Specific details relating to the river reach and Otterspool weir are described in more detail in chapter 3 (section 3.1.1). The site below the weir has a well-defined island in the middle of the river covered in vegetation and a number of permeable concrete structures on the non-hydro side river bank. The permeable concrete structures were not installed as part of the scheme. The island was a feature in the river before the scheme was installed and is only covered by flow during high flows approximately 3-4 times a year in a normal winter period (observations from volunteers at Stockport Hydro). During data collection the island extended from the middle of the river in line with the outlet and separated the river into a hydro and non-hydro side (Figure 6.1). Island and bar formation is often a direct impact of weir installation and could be a common feature below low head schemes (Csiki and Rhoads, 2010). Deposits and islands have the potential to intensify the influence of the outlet by blocking the water from the outlet extending towards the non-hydro side river bank causing further constriction and further acceleration in flow.

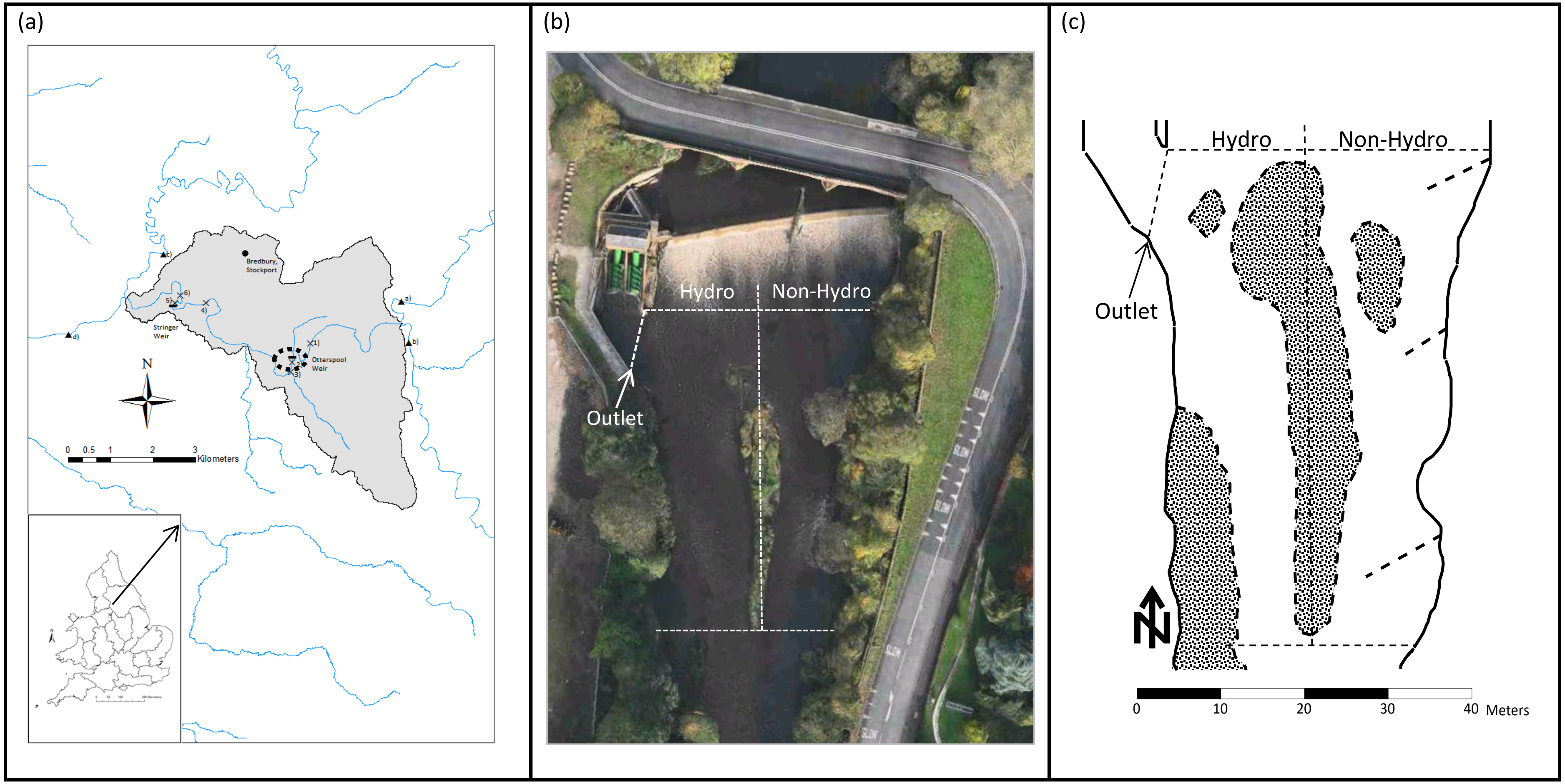

Figure 6.1: Images of the sampling location were (a) is a map of the River Goyt from Etherow to Tame with the sampling location Otterspool weir circled, (b) is an aerial image of the sampling location with the hydro and non-hydro side of the river and the position of the outlet clearly defined (Apple Maps, 2017a) and (c) is map of the sampling location produced in Surfer Software with the hydro and non-hydro side of the river and the position of the outlet clearly defined

6.3.2. Spatial surveys

Large scale spatial surveys were conducted on 22nd July 2014, 14th September 2014 and on the 24th August 2015. It must be noted that both turbines were operational during the 2014 surveys but only one turbine was operational during the 2015 survey. The operational turbine was the turbine closest to the hydro side bank directly adjacent to the fish pass. During each sampling occasion a number of river conditions were measured wherever conditions permitted; deep areas and areas surrounding concrete structures were often difficult to measure meaning that some areas were not sampled. A description of how each river condition was measured can be found in chapter 3 (section 3.2.1 and section 3.2.2). Figures 6.2a, 6.2b and 6.2c show the points were measurements were recorded.

The discharge at Otterspool weir was estimated as described in chapter 3 (section 3.3.1) using the two nearest flow gauging stations. Discharge was calculated for a 28 day preceding period leading up to each sampling occasion (see section 3.3.2). The flow split between the weir and hydro scheme was calculated using abstraction discharge data from Stockport Hydro (see section 3.3.3). Additional measurements were collected during the August 2015 sampling occasion taking forward lessons learned from the original surveys during July and September 2014. Elevation was measured using an RTK GPS and water depth was measured using a simple rigid meter ruler. Using River Habitat Survey (RHS) descriptors (Raven et al., 1998) and river confluence descriptors (Best, 1988) habitats were also sketched onto aerial images of the site.

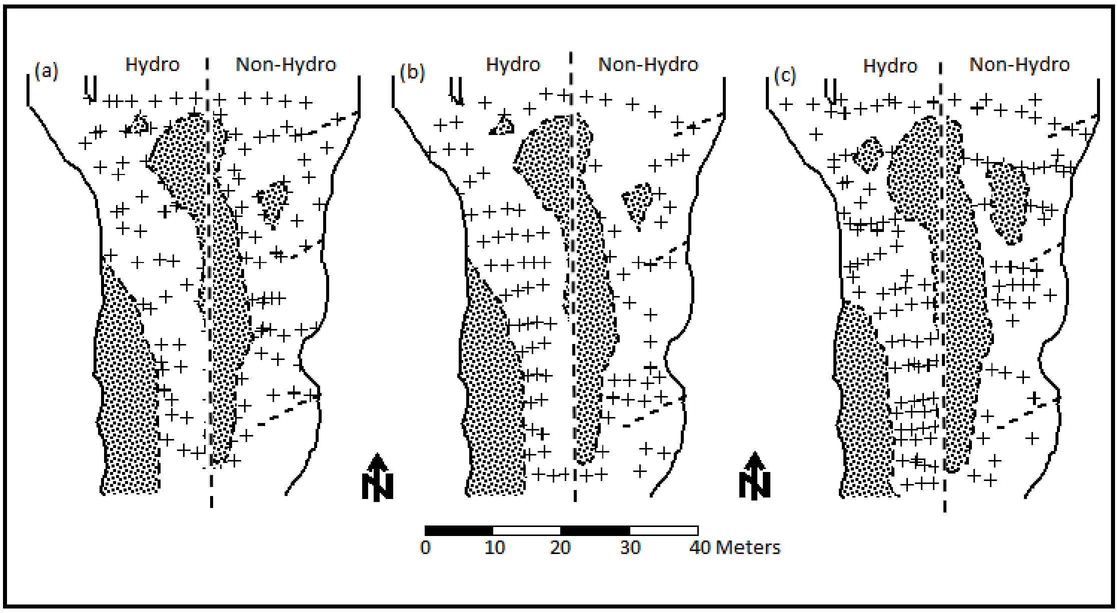

Figure 6.2: Spatial survey points from the large scale surveys where crosses represent sampling points and dashed lines on the non-hydro side river bank represent permeable concrete structures for (a) Survey 1 - 22nd July 2014 (n= 75), (b) Survey 2- 14th September 2014 (n= 108) and (c) Survey 3 - 24th August 2015 (n= 130)

All measured river conditions were separated into hydro and non-hydro side to explore the hypothesis that the hydro and non-hydro side of the channel would differ in terms of flow velocity and phytobenthic biofilm biomass and community structure. For each river condition a mean and standard deviation was calculated. To test the difference in flow velocity and chlorophyll-a concentration between the hydro and non-hydro side of the channel a one-way ANOVA was conducted using robust tests of equality of means, namely the Welch Tests. While an attempt was made to collect an equal number of samples deep areas and areas surrounding concrete structures were hard to sample. As such there was unequal variance and unequal sample sizes across the hydro and non-hydro side of the channel. While traditionally a one-way ANOVA does not perform well with unequal variance and sample sizes Tomarken and Serlin (1986) highlights how the Welch test can be reliable in these circumstances.

To see how flow velocity and chlorophyll-a concentration varied in space, survey data from each sampling occasion was interpolated using kriging methods in Surfer Software and displayed as spatial maps. Elevation data from the August 2015 survey was also interpolated using kriging methods in surfer software to illustrate bed topography and water depths across the area below the scheme. Linear regression was used explore the relationship between flow velocity and chlorophyll-a concentration across all sampling occasions. Linear regression was conducted in IBM SPSS V7 and at *p values* <0.05 it was accepted that the overall regression model significantly predicted the outcome and there was a significant relationship between the parameters tested and chlorophyll-a concentration i.e. that flow velocity could be used to predict chlorophyll-a concentration. Habitat sketches were also transferred to a map of the local area below the scheme in Surfer Software to see how habitats varied spatially.

6.3. Results

For the 4 week period leading up to the July 2014 sampling occasion discharge was in the low flow category (Figure 6.4). Although there were a few small peaks in flow overall discharge did not surpass 3.83m^3/s (Figure 6.4). During this period overall flow was relatively evenly split between the weir and the turbine (Figure 6.4). For the majority of the 4 week period leading up to the September 2014 sampling occasion overall discharge was in the low flow category (Figure 6.4). There were a few peaks in flow over a 6 day period which reached the moderate flow category. Yet moderate flow subsided leaving a 12 day low flow period leading up to the sampling occasion (Figure 6.4). The largest peak occurred 14 days before sampling reaching 7.79m^3/s. Like the flow period leading up to the July 2014 sampling occasion flow was relatively evenly split between the weir and the turbine (Figure 6.4). Over the period leading up to the August 2015 sampling occasion there were two moderate peaks 28 and 27 days before sampling at 7.51m^3/s and 7.77m^3/s respectively (Figure 6.4). During each peak weir flow dominated and utilised 76% and 74% of overall flow (Figure 6.4). Another moderate peak occurred 10 days before sampling reaching 6.25m^3/s. On this occasion weir flow dominated and utilised 72% of overall flow. For the remaining days flow was low and split considerably evenly between the weir and the turbine (Figure 6.4). There was only one turbine operation during the 2015 sampling occasion meaning that the scheme could not utilise as much flow as the 2014 sampling occasions.

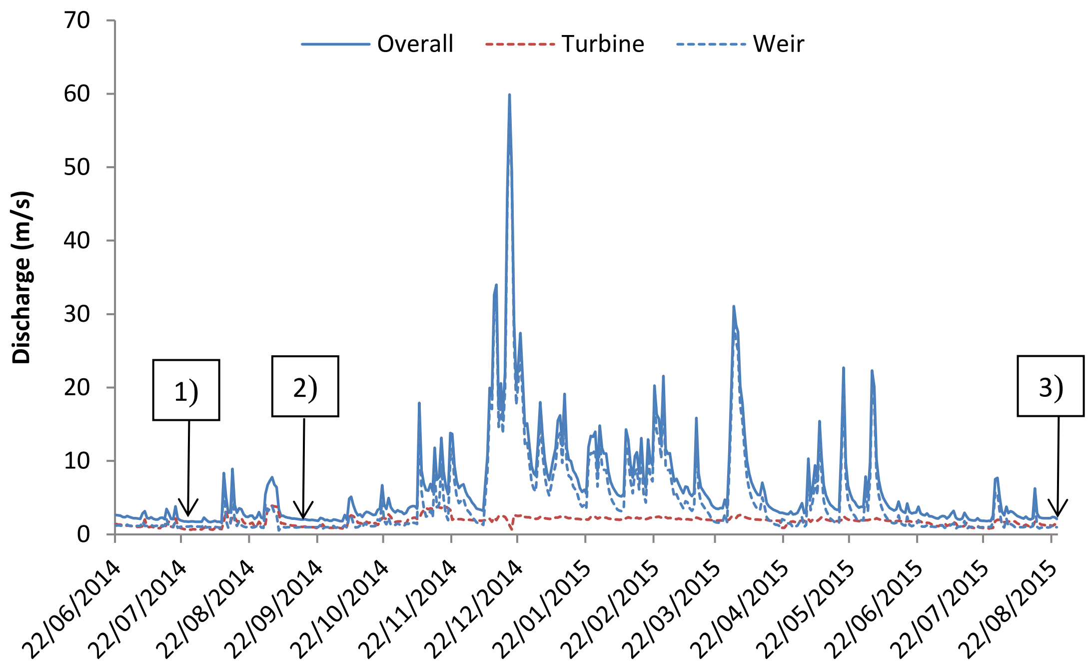

Figure 6.4: Discharge leading up to each sampling occasion were 1) is the July 2014 sampling occasion, 2) is the September 2014 sampling occasion and 3) is the August 2015 sampling occasion showing overall discharge before the flow split, discharge through the turbine and over the weir after the split

There was little variation in overall discharge and turbine flow across all sampling occasions. The level on the weir remained at 6cm's across all sampling occasion and weir discharge remained at 1.00m3/s across all sampling occasions. Overall discharge was in the low flow category during all sampling occasions (Table 6.1). Overall discharge was highest during the August 2015 sampling occasion when turbine flow dominated utilising 53% of overall flow. Discharge was lowest during the July 2014 sampling occasion yet weir flow dominated utilising 55% of overall discharge (Table 6.1). During the September 2014 sampling occasion flow was split exactly evenly between the weir and the turbine (Table 6.1).

Table 6.1: Discharge estimates with standard deviation at Otterspool Weir were overall discharge and category is used to describe discharge before the flow was split between the weir and the turbine and were turbine flow is the amount of flow diverted through the turbines and weir flow is the amount of flow directed over the weir during each sampling occasion calculated from 15 minute interval data

		Overall Discharge		Turbine Flow		Weir Flow	
Year	Date	(m^3/s)	Category	(m^3/s)	(%)	(m3/s)	(%)
2014	22/07/14	1.80 ± 0.04	Low	0.80 ± 0.04	45	1.00	55
	14/09/14	2.00 ± 0.03	Low	1.00 ± 0.03	50	1.00	50
2015	24/08/14	2.11 ± 0.02	Low	1.11 ± 0.02	53	1.00	47

Flow velocity was consistently higher on the hydro side of the channel when compared to the non-hydro side of the channel (Figure 6.5) during the July 2014 survey (ANOVA df-1, f-4.599, p-0.035), the September 2014 (ANOVA df-1, f-11.942, p-0.001) and August 2015 sampling occasion (ANOVA df-1, f-8.593, p-0.03). The difference in flow velocity between the hydro and non-hydro side of the channel was relatively similar across sampling occasions which is likely down to the fact that there were minimal differences in discharge flow split between the weir and the turbines (Table 6.1). There were only small differences in all other measured river conditions between the hydro and non-hydro side across all sampling locations (Table 6.2). Turbidity was zero across both sides of the channel over all sampling occasions.

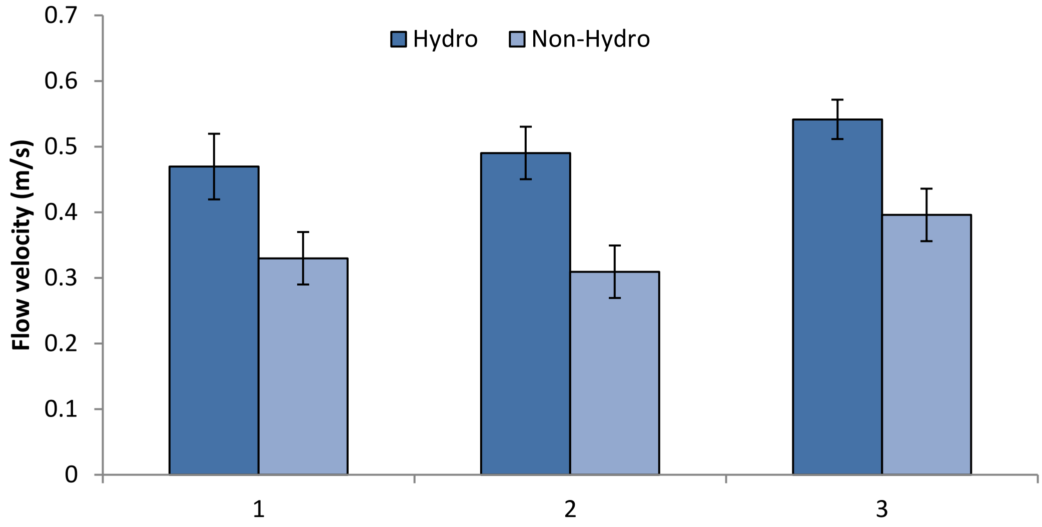

Figure 6.5: Mean flow velocity on the hydro and non-hydro side of the river taken from the large scale surveys where error bars represent standard error for (a) Survey 1 - July 2014 (hydro side n= 31 and non-hydro side n=44), (b) Survey 2 - September 2014 (hydro side n=62 and non-hydro side n=46) and (c) Survey 3 - August 2015 (hydro side n=75 and non-hydro side n=55)

Table 6.2: Mean and standard deviations of measured water quality variables across the hydro and non-hydro side of the channel during large scale spatial surveys

		Hydro		Non-Hydro	
Survey	**Variable**	**Mean**	**Std dev**	**Mean**	**Std dev**
Jul-14	Temperature (°c)	18.0	0.2	18.3	0.4
	pH	7.78	0.06	7.87	0.06
	Dissolved Oxygen (mg/l)	10.01	0.11	10.04	0.10
	Conductivity	243	7	245	3
	TDS (mg/l)	157	4	158	2
	Turbidity (NTU)	0	0	0	0
	Nitrate (mg/l)	7.52	1.81	7.24	0.50
Sep-14	Temperature (°c)	14.6	0.3	15.1	0.2
	pH	7.77	0.31	8.11	0.18
	Dissolved Oxygen (mg/l)	11.15	0.44	11.33	0.41
	Conductivity	249	11	250	7
	TDS (mg/l)	161	7	162	4
	Turbidity (NTU)	0	0	0	0
	Nitrate (mg/l)	8.18	0.38	8.48	0.96
Aug-15	Temperature (°c)	16.3	0.3	16.0	0.2
	pH	7.02	0.02	6.99	0.01
	Dissolved Oxygen (mg/l)	10.85	0.13	10.83	0.08
	Conductivity	231	17	234	9
	TDS (mg/l)	150	11	152	6
	Turbidity (NTU)	0	0	0	0
	Nitrate (mg/l)	5.90	1.81	5.06	2.66

Mean chlorophyll-a concentration (Figure 6.7) and community composition (Figure 6.8) was relatively similar between the hydro and non-hydro side of the channel across all spatial surveys. There was no significant difference in chlorophyll-a concentration across the July 2014 (ANOVA df-1, f-2.477, p-0.107) and September 2014 (ANOVA df-1, f-0.180, p-0.681) but chlorophyll-a concentration was significantly higher on the non-hydro side when compared to the hydro side during the August 2015 (ANOVA df-1, f-11.486, p-0.001) sampling occasions. Overall chlorophyll-a concentration was highest during the September 2014 sampling occasion on both the hydro and non-hydro side of the channel (Figure 6.7). Overall chlorophyll-a concentration was similar during the July 2014 and August 2015 sampling occasions (Figure 6.7).

Diatoms dominated on both the hydro and non-hydro side during the July 2014 sampling occasion contributing to 54% of total chlorophyll-a concentration on the hydro side and 57% on the non-hydro side (Figure 6.8). Green algae were present on both sides of the channel and contributed to 1% of total chlorophyll-a concentration on both the hydro and non-hydro side alike. Cyanobacteria contributed to 44% of total chlorophyll-a concentration on the hydro side and 42% on the non-hydro side (Figure 6.8). Diatom dominance was more pronounced during the September 2014 sampling occasion making up 74% of total chlorophyll-a concentration on the hydro side of the channel and 83% of the non –hydro side (Figure 6.8). No green algae were recorded on the non-hydro side of the channel but green algae contributed to 2% of total chlorophyll-a concentration on the hydro side of the channel (Figure 6.8).

Cyanobacteria dominated on the hydro side of the channel during the August 2015 sampling occasion contributing to 54% of total chlorophyll-a concentration. Yet there was little difference in the relative densities of biofilm components across the hydro and non-hydro side during the August 2015 sampling occasion with cyanobacteria making up 45% of total chlorophyll-a concentration on the non-hydro side of the channel (Figure 6.8). Green algae were recorded on both sides of the channel making up 2% of total chlorophyll-a concentration on the hydro side and 5% on the non-hydro side (Figure 6.8). Diatoms contributed to 44% of total chlorophyll-a concentration on the hydro side and 50% on the non-hydro side (Figure 6.8).

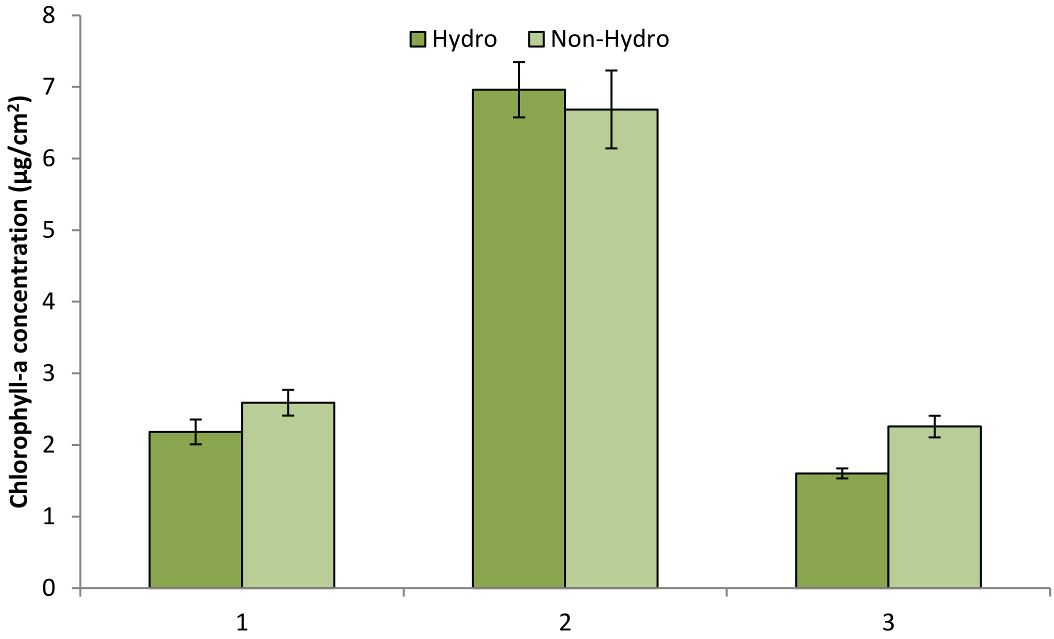

Figure 6.7: Mean chlorophyll-a on the hydro and non-hydro side of the channel across sampling occasions were 1) is the July 2014 sampling occasion, 2) is the September 2014 sampling occasion and 3) is the August 2015 sampling occasion and were error bars represent standard deviation

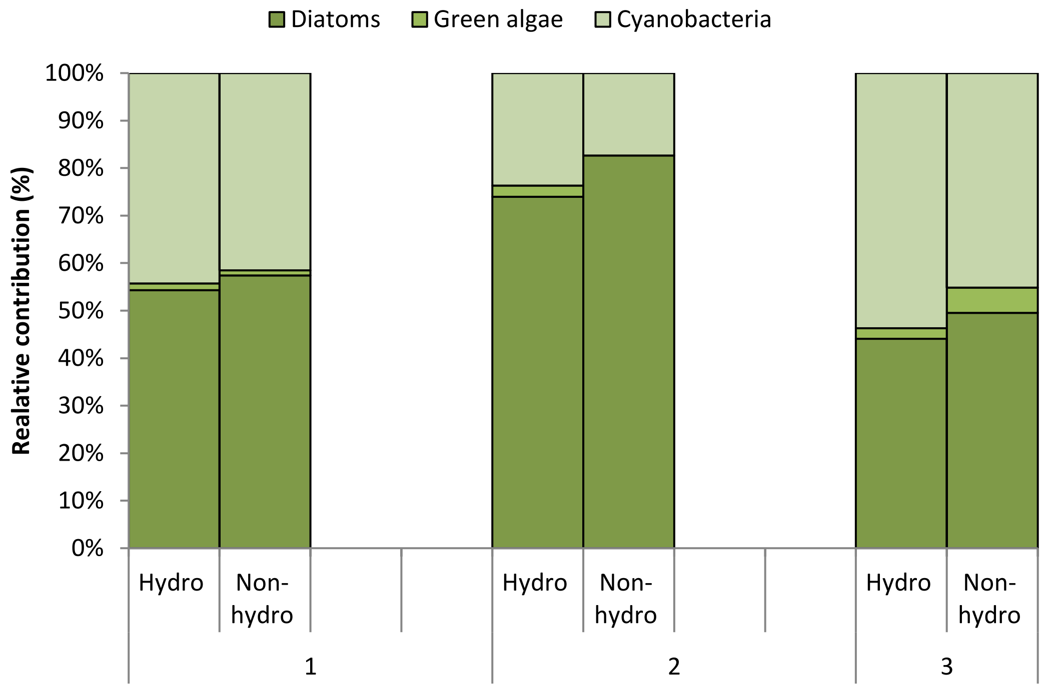

Figure 6.8: Relative contributions of the photoautotrophic components of the biofilm (diatoms, cyanobacteria and green algae) in relation to mean total chlorophyll-a concentration on the hydro and non-hydro side of the channel for 1) the July 2014 sampling occasion, 2) the September 2014 sampling occasion and 3) the August 2015 sampling occasion

Looking at finer scale spatial patterns in flow velocity and chlorophyll-a concentration it is apparent that flow velocity and phytobenthic biomass varied spatially below the scheme on both the hydro and non-hydro side of the channel across all large scale sampling occasions (Figure 6.9). During each sampling occasion an acceleration zone extended from the outlet, there was a separation zone at the outlets downstream junction corner and there was an area of constriction and high flow velocity between the hydro side deposit and the mid-channel island (Figure 6.9).

There was also an area of high flow velocity on the non-hydro side of the channel between the deposit adjacent to the island and the concrete structures (Figure 6.9). Whilst the highest velocities were on the hydro side of the channel the constricted areas on both the hydro and non-hydro side had the highest velocities in general. Even though the acceleration zone extending from the outlet was visible velocities were lower than expected and were lower than velocities recorded in the constriction zones on both the hydro and non-hydro side (Figure 6.9).

Total chlorophyll-a concentration was patchy across all sampling occasions (Figure 6.9). While there was a patch of low chlorophyll-a concentration in the acceleration zone extending from the outlet during the July 2014 sampling occasion linear regression revealed no significant relationship between flow velocity and chlorophyll-a concentration (r-0.031, n-75, p-0.129). However while there appeared to be lower biomass across the hydro side of the channel in comparison to the non-hydro side of the channel during the August 2015 sampling occasion linear regression revealed a weak but significant relationship between flow velocity and chlorophyll-a concentration (r-0.231, f-7.211, p-0.008) with chlorophyll-a concentration reducing with increased flow velocity.

Yet there was no relationship between flow velocity and chlorophyll-a concentration across the September 2014 sampling occasion (r-0.000, n-108, p-0.844) and there was very little similarity in spatial patterns in chlorophyll-a concentration and flow across each of the sampling occasions (Figure 6.9). Even though high levels of chlorophyll-a concentration were recorded during the September 2014 sampling occasion the highest chlorophyll-a concentration was limited to the sheltered area between the hydro side deposit and the island (Figure 6.9).

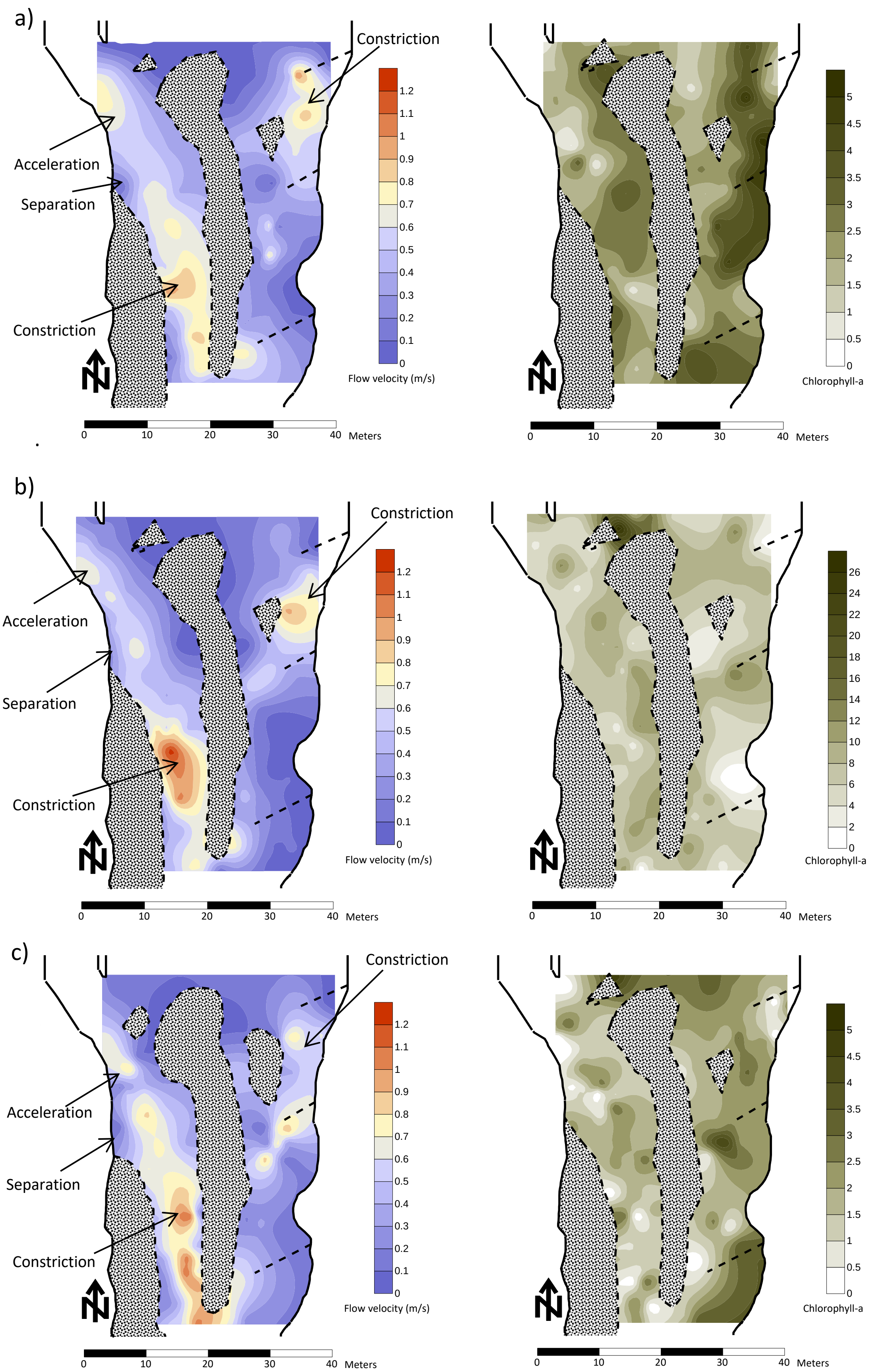

Figure 6.9: Interpolated plots of flow velocity and chlorophyll-a concentration (µg/cm2) from large scale surveys where (a) is the July 2014, (b) is September 2014 and (c) is August 2015 surveys

Figure 6.10 shows the interpolated flow velocity, Ordnance Survey elevations and habitat sketches from the August 2015 sampling occasion where dashed lines represent deposits. The elevation plot shows distinct morphological features including areas erosion and deposition. The island has the highest elevation with measurements up to 54.7m. The bank deposit, hydro side and non-hydro side deposits have similar elevations. A pool with low elevation below the weir extends just above the island (Figure 6.10). An area of low elevation is evident in the turbine forebay below the turbines.

The elevation plot to some extent, particularly on the hydro side of the channel, shows similar patterns to the velocity plot (Figure 6.10). A channel of low elevation extends from the outlet and cuts through the constricted section between the bank deposit and mid- channel island. There are also patches of scour in line with “hot spots” of velocity i.e. where there are areas of high velocity between the bank deposit and island there is also evidence of scour represented by lower elevation measurements (Figure 6.10). The relationship between flow velocity and elevation is less obvious on the non-hydro side of the channel (Figure 6.10).

Distinct hydrological and morphological features are evident in the habitat sketches. A weir pool extends towards a glide on the non-hydro side of the river. An area of stagnation is visible at the upstream junction corner of the outlet. An area of separated flow is visible at the downstream junction corner of the outlet. There is an area of separated flow adjacent to the hydro side deposit at the point where the water from the outlet is discharged back into the main channel. A run extends from the outlet of the hydro scheme towards the end of the island. Riffles extend from the bank deposit on the hydro side of the river and from below the mid-channel island. Glides and pools form the majority of the area on the non-hydro side of the river. A run extends from the first concrete structure on the non-hydro side of the river, beyond the second concrete structure towards the island. Riffles are evident between both deposits on the hydro side and non-hydro-side of the river and the mid-channel island

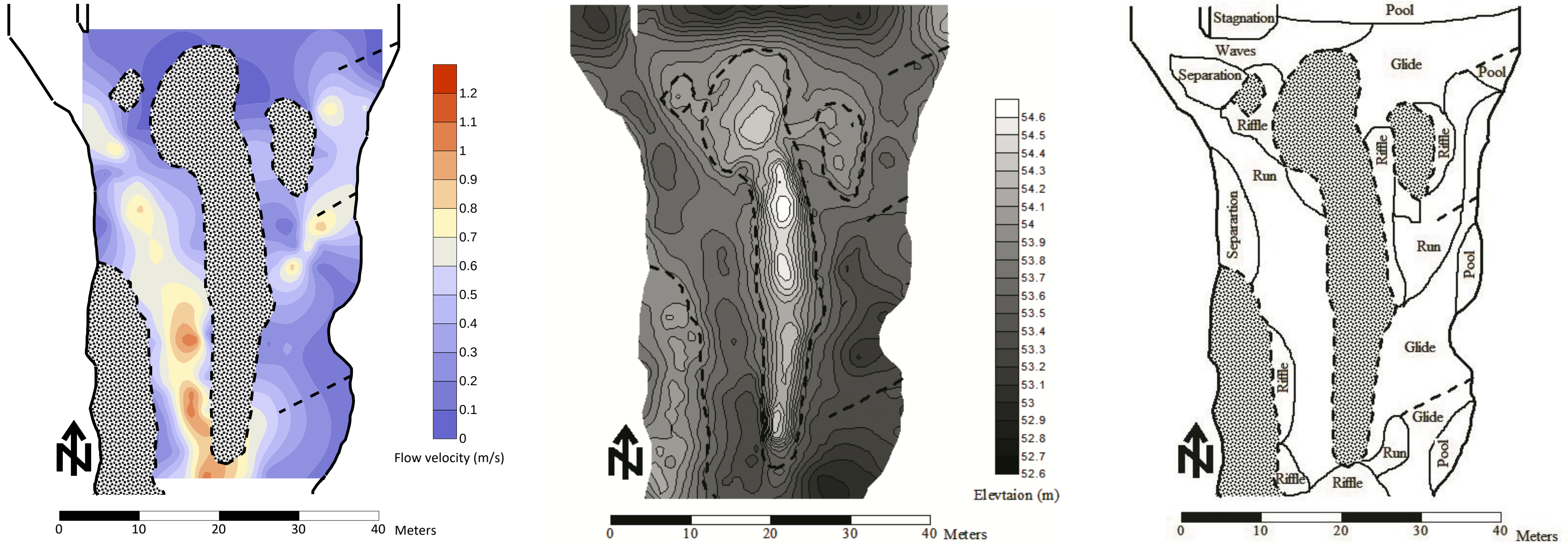

Figure 6.10: Interpolated plots of a) flow velocity and b) elevation measurements from below the hydro scheme and c) habitat sketches from below the hydro scheme during the August 2015 sampling occasion

6.4. Discussion

Results from this study agreed with the hypothesis that flow velocity would be higher on the hydro side of the channel when compared to the non-hydro side. Across all sampling occasions flow velocity was consistently higher on the hydro side of the channel when compared to the non-hydro side. High flow velocities towards the hydro side of the channel supports the Environment Agencies (Mould et al*.,* 2015a) modelling results at Romney weir in the River Thames and findings from Anderson et al., (2015b) below a low head 'mill leat' scheme were higher velocities were found on the hydro-side of the channel and lower velocities were found on the non-hydro side of the channel.

However, in contrast to Anderson et al., (2015b), who found velocities to decrease with distance from the outlet, there was an increase in velocities with increased distance from the outlet across all sampling occasions in this investigation. Looking at interpolated plots it is evident that there is a constricted cross section between the bank deposit on the hydro side of the channel and the mid channel island below an area of separation. This constricted cross-section is likely to be responsible for this increase in velocities.

Separation zones are often found at the downstream junction corner of river confluences. As a result of the lateral flow merging with the main flow, the flow in the main channel can be pushed towards the outer bank. This push creates a recirculation zone or horizontal vortex with low flow velocities near the inner bank of the confluence (Wuppukondor and Chandra, 2017). Sediment can often accumulate in the centre of this zone creating a point bar. As the dimensions of the point bar increase the velocities in the maximum velocity zone also increase as a result of constriction (Ghobadian and Shafai, 2007). Velocities were consistently high in the constricted cross section below the outlet across all sampling occasions. It is reasonable to assume that the bank deposit, evident in the interpolated plots was created as a result of this separation zone and hence was created by the scheme.

While it is difficult to know whether the bank deposit was present before the scheme was installed it is clear that deposits often form in the separation zone at river confluences. The bank deposit below the scheme was situated below a separation zone below the outlet. If the bank deposit was formed as a product of scheme installation the constriction and high velocities could then be attributed to the scheme. This does however highlight the need for conducting before and after installation surveys were possible in a bid to evaluate the impact of 'on weir' hydro schemes and clarify these findings.

Anderson et al., (2015b) also found the extent to which there was a difference in velocities between the hydro and non-hydro side of the channel to increase in line with the proportion of flow diverted through the scheme. This pattern was not echoed in this investigation. However it must be noted that all surveys were conducted during low flow conditions and while the flow split between the weir and the turbine differed between surveys there were only slight differences in the overall discharge across each survey. This suggests that the flow split alone is not enough to explain the difference in velocities between both sides of the channel and that future investigation should concentrate on studying spatial dynamics across a range of flow conditions and flow splits.

Interpolated plots also show a second bar at the point where the two flows collide. It is possible that this deposit is a result of sediment passing through the turbine channel from upstream. This would match the draw down theory presented by Anderson et al., (2015a).
It must also been noted that high flow velocities were also found on the non-hydro side of the channel at the points were the channel narrows but the hydro side of the channel typically had the highest overall velocities. High velocities are evident between the hydro deposit and the river bank, the bank bar and the island and the non-hydro side deposit and concrete structure (Figure 3 and Figure 8). This is not surprising considering that acceleration is typically associated with channel narrowing.

The main morphological features, the scour pool and the mid channel island, identified from the elevation plot, are features typically associated with the aquatic environment below weirs. The water which cascades over the weir causes scouring of the river bed often creating a large scour pool (Mould et al., 2015a). Were the energy in the flow is reduced the scoured material is often deposited forming an island or bar (Mould et al., 2015a). This suggests that the scour pool and mid-channel island found below Stockport Hydro was a feature in the channel before the scheme was installed.

While it was hypothesised that phytobenthic community composition and phytobenthic biomass would differ between the hydro side and non-hydro side of the channel in line with differences in velocities, there were minimal differences in community composition and biomass, derived from the BenthoTorch readings. Even though chlorophyll-a concentration was significantly higher on the non-hydro side of the channel when compared to the hydro side during August 2015 sampling occasion the difference was minimal. This was particularly evident when compared to the difference in chlorophyll-a concentration seen temporally between sampling occasions. This suggests that despite differences in velocities the scheme was having minimal effect of species composition and biomass.

Moreover the phytobenthic biofilm can change according to a number of variables including depth, flow velocity, predation, light penetration, temperature and pH (Law, 2011). While there were minimal differences in the majority of measured river conditions (temperature, pH, dissolved oxygen, turbidity and nitrate concentration) across the hydro and non-hydro side of the channel over each survey, it is possible that the difference in chlorophyll-a concentration during the August 2015 was controlled by something other than flow and something not measured in this investigation. It is possible that light intensity was having a significant effect on biomass. While light intensity was not measured shading by tree coverage during summer months has been known to reduce biomass (Allan, 1995). There was observational evidence of tree coverage on the hydro side which could have been limiting growth.

6.5. Conclusions

Spatial surveys have been used to identify hydrological, morphological and biotic features below a low head 'on weir' hydro scheme. From the analysis of said features a number of points can be summarized;

1. Addition of a hydro scheme to a weir has the potential to change localised flow pattern and distribution.
2. Distinct hydrological and morphological features associated with the collision of two flows are likely to be found below low head hydro 'on weir' schemes.
3. Changes in localised flow pattern and morphology are potentially biologically irrelevant in regards to the phytobenthic biofilm and more pronounced temporally than spatially.

Chapter 7: Synthesis

7.1. Overview

The overall aim of the work presented in this thesis was to advance the understanding of how low head 'on weir' hydropower can influence physical and chemical habitat conditions and the phytobenthic biofilm. In order to achieve this aim this thesis also investigated how weirs themselves change physical and chemical river conditions and the phytobenthic biofilm. This would help in understanding how adding a low head 'on weir' hydro scheme to a weir can either improve the aquatic environment already altered by a weir or cause further detrimental issues.

This chapter synthesises findings of the research by drawing together the linkages between each of the results chapters with particular emphasis on spatial and temporal patterns in phytobenthic biomass and community composition. This chapter begins by bringing together findings from chapters 5 and 6 combining findings in relation to the low head 'on weir' hydro scheme alone. This chapter then goes on to draw comparisons between the influence of the low head 'on weir' hydro scheme to the influence of the low head weir on the phytobenthic biofilm over time. As such this chapter addresses the hypothesis that the hydro scheme will have a greater effect on phytobenthic biomass and community composition as a result of greater increases in velocities created by the outlet.

7.2. Spatial and temporal patterns in phytobenthic biomass and community composition at the low head 'on weir' hydro scheme

Despite hypothesising that there would be differences in in biomass between the hydro and non-hydro side of the channel as a result of differences in flow velocity (Chapter 6) there was limited difference in chlorophyll-a concentration across both sides of the channel (Figure 6.7). Regardless of the fact that measured flow velocities were consistently higher on the hydro side of the channel there was only one occasion when chlorophyll-a concentration was significantly higher on the non-hydro side of the channel. This was during the August 2015 sampling occasion and even though there was a difference between both sides of the channel this was small in comparison to the difference seen temporally across surveys. In addition while there was evidence to suggest that there were hydraulic zones of impact below the scheme similar to those at river confluences, there was also minimal difference in chlorophyll-a concentration across each zone. This suggests that something other than spatial variations in flow velocity were controlling growth for example nutrient concentrations, grazer density or light intensity.

Furthermore it must be noted that all spatial surveys across Chapter 6 were conducted following periods of low stable flow when both abstraction levels and weir levels were low. As such this study did not capture spatial patterns following periods of high abstraction and this could be the reason as to why no differences were observed in phytobenthic biomass between the hydro and non-hydro side of the channel. Yet Anderson et al., (2015b) measured longitudinal velocities below the outlet of a low head 'mill leat' scheme during periods of high flow/high abstraction and found similar patterns in relation to invertebrate communities. Even though this study was focused on invertebrate communities this pattern could also be echoed across the phytobenthic community and in this case it seems like low head 'on weir' hydro schemes are having minimal effect and that current mitigation measures are sufficient.

This pattern was also reflected across the riffle surveys (Chapter 5). Despite the hypothesis that there would be differences in biomass between the riffle below the scheme and riffles upstream and downstream of the scheme as a result of increased flow velocities extending from the outlet there were minimal differences in chlorophyll-a concentration between sites. There was only one occasion when chlorophyll-a concentration differed spatially across sampling locations. This was during the May 2015 sampling occasion when chlorophyll-a concentration was significantly lower below the scheme in comparison to riffles both upstream of the scheme (Figure 5.12). Given that the phytobenthic biofilm can vary spatially as a result of a number of disturbance factors including flow velocity, substrate instability and grazing as well as limitations in resource factors including nutrients and light (Biggs, 2000) it is difficult to understand which is the controlling factor. Yet with the area below the scheme having similar velocities to the areas upstream and downstream of the scheme across all sampling locations it seems unlikely that, on this occasion, the difference was a result of spatial differences in velocities created by the scheme as hypothesised. While this was not expected it again shows how current mitigation measures appear sufficient. The hydro scheme in question, Stockport Hydro, does not appear to be causing any negative effects on the phytobenthic biofilm.

Although the riffle investigated was located approximately 20meters downstream from the outlet. It is plausible that the riffle was too far from the outlet to experience any effects created by the scheme. This is consistent with findings from Mould et al., (2015a) and

Anderson et al., (2015b). Mould et al., (2015a) modelled the changes in velocities below a low head ‘on weir’ scheme in the River Thames and found that changes in velocities were limited to within 20meters of the weir. Anderson et al., (2015b) measured flow velocities below the outlet of a low head ‘mill leat’ scheme and found that while there were increased velocities immediately below the outlet velocities had already decreased 10meters away from the outlet. Moreover when comparing this to the results from Chapter 6, looking at the finer scale patterns in flow, it is apparent that while there where areas of increased flow velocity below the scheme these were often confined to areas of constriction and did not extend to the riffle were the measurements were collected. As such future studies should attempt to collect measurements closer to the outlet. Although this could be difficult in the field due to high water depths and high levels of turbulence.

While temporal patterns were more obvious the main focus of this research was to see whether the hydro scheme was causing an affect spatially so it is unclear as to what the consequence of this pattern was. Although on some occasions, in particular the April 2014 and April 2015 sampling occasions, there were very high levels of chlorophyll-a. Moreover these levels surpassed the concentration commonly used to indicate nuisance growths (Dodds et al., 1997) and as such could cause consequences for ecosystem functioning. Therefore future studies, along the River Goyt, should concentrate on establishing factors that control growth over time.

Similar to biomass there were minimal differences in community composition across the hydro and non-hydro side of the channel (Figure 6.8). It was hypothesised that community composition would differ between the hydro and non-hydro side of the channel as a result of flow velocity but this did not appear to be the case (Figure 6.8). In addition there were minimal differences in community composition across riffles surveys (Chapter 5). Across all sampling occasion there was no difference in community composition between the riffle below the weir and riffles upstream and downstream of the weir (Figure 5.8, Figure 5.9, Figure 5.13, and Figure 5.14). This suggests that any changes created by the scheme were not strong enough to influence community composition and can be related to the fact that communities can tolerate a range of environmental conditions before they alter. For example stalked and short filamentous diatoms can dominate in moderate flow velocities between 0.3-0.7m/s were as mucilaginous diatoms can dominate at high velocities above 0.7m/s (Biggs et al., 1998c).

Essentially the hydro scheme investigated appears to be having little effect on phytobenthic biomass or community composition across a range of seasons. While this could mean that the current mitigation strategies are sufficient hydro developers could argue that they are too strict and that they should be allowed to divert more flow to the turbines to produce more power. As such this study would recommend an investigation where Stockport Hydro is allowed to divert more flow to the turbines over time. This investigation should continue to monitor a range of physiochemical and biotic river conditions but should also think about extending the investigation beyond the phytobenthic biofilm. While this thesis identified that the low head weirs and low head 'on weir' hydropower have limited impact on the phytobenthic biofilm there is no evidence to suggest that this conclusion can be extended to overall ecosystem health and other aquatic communities such as macrophytes, invertebrates or fish.

7.3. Is weir or hydro driving changes in community composition and biomass?

As identified in chapter three, there is similarity between Otterspool weir (hydro scheme) and Stringer's weir (low head weir). As both weirs are situated in the same reach similarities can be drawn across discharge regimes (chapter 3). As such Stringer's weir was considered as a suitable reference weir for assessing the impact of Stockport Hydro. Comparisons were drawn between phytobenthic communities growing in the riffle upstream of the hydro scheme and below the scheme and between communities growing in the riffle upstream of the weir and below the weir (Figure 7.1).

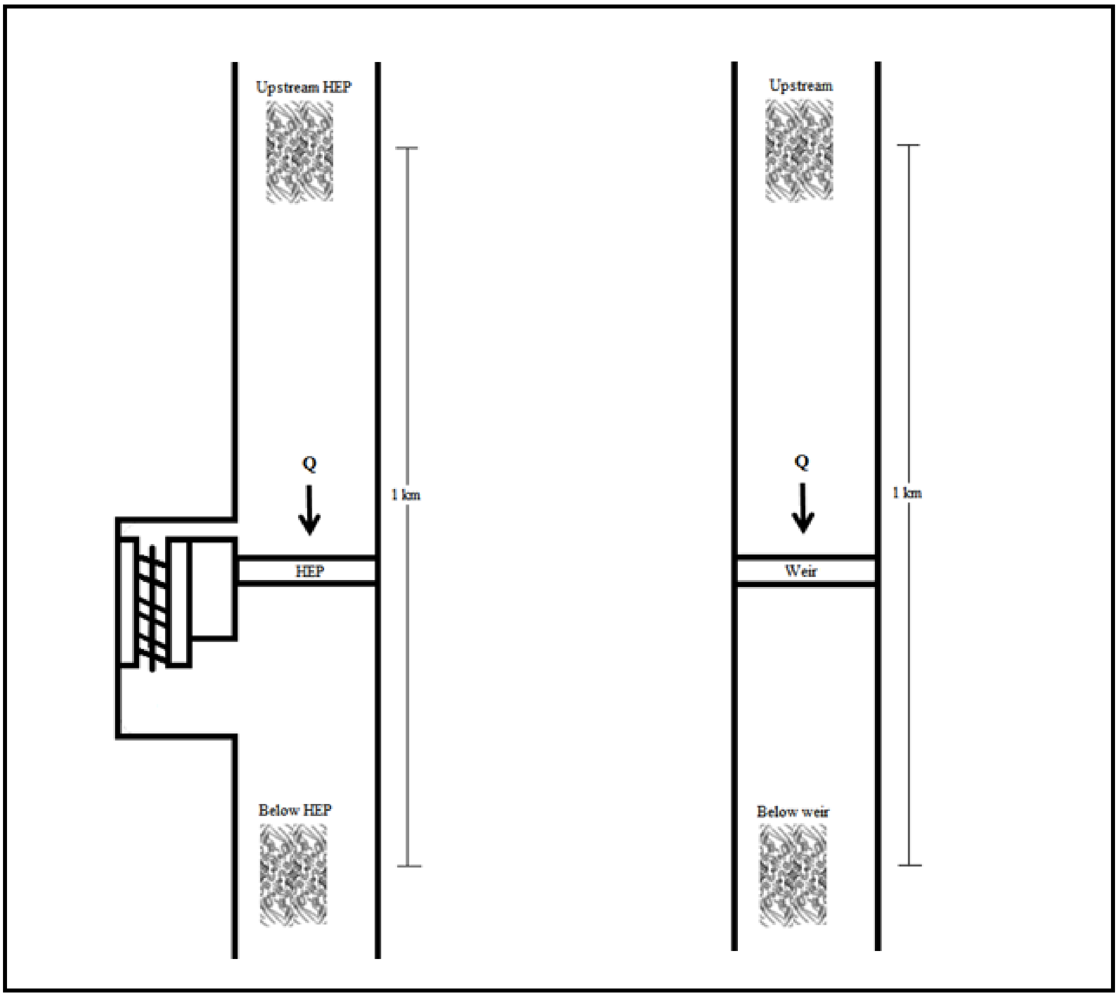

Figure 7.1: Schematic diagram of the sampling design to compare the influence of a low head 'on weir' hydro scheme to the influence of a low head weir on the phytobenthic biofilm

There was no significant difference in flow velocity between the riffle upstream of the hydro scheme and the riffle below the hydro scheme during all 2014 and 2015 sampling occasions. Yet flow velocity was significantly higher below the weir when compared to the riffle upstream of the weir across all 2014 sampling occasions (Figure 7.2, Figure 7.3 and Table 7.1). This does not support the proposed hypothesis that the hydro scheme would cause greater increases in velocities. In fact it appears to support an alternative hypothesis in that the weir is having a greater effect on flow velocities than the hydro scheme.

As identified in chapter two the area below the weir is often associated with complex flow patterns, turbulent flow and high flow velocities (Downward and Skinner, 2005; NSW, 2006; Skalak et al., 2009; Csiki and Rhoads; 2010; Im et al., 2011, Mould et al., 2015a). While increased flow velocities below the weir were not unexpected, they were anticipated to be lower than those below the scheme. At the 'on weir' hydro schemes large volumes of water are constricted through a narrowed turbine forebay. By constricting large volumes of water through a confined forebay there are likely to be increases in velocities.

Despite constriction through the turbine forebay it could be possible that the turbine itself is acting as a barrier and decreasing flow velocities. There could be energy losses as a result of splash, heat, noise, turbulence and from the power in the flow being converted to mechanical and electrical energy. As such the turbine and turbine forebay could be masking the effect of the weir and returning velocities back to more natural levels. Essentially, by limiting the amount of flow over the weir, the scheme could be reducing the effect of the weir and decreasing velocities in turn. If this finding is echoed across numerous 'on weir' hydro schemes and is reflected across aquatic communities, it could have positive effects on hydropower development. If 'on weir' hydropower can have positive effects on ecology and return riverine environments back to more natural conditions whilst also providing renewable electricity this will be deemed as a 'win-win' situation (EA, 2010).

Although these findings must be taken with caution, as they only reflect results from one scheme along one river reach in low flow conditions. More investigations should be carried out across a range of 'on weir' hydro scheme across a range of environments with differing overlying physical, chemical and biotic conditions. They should also be carried out across a range of flow conditions and abstraction regimes to properly quantify flow-related relationships between low head weirs and low head 'on weir' hydro.

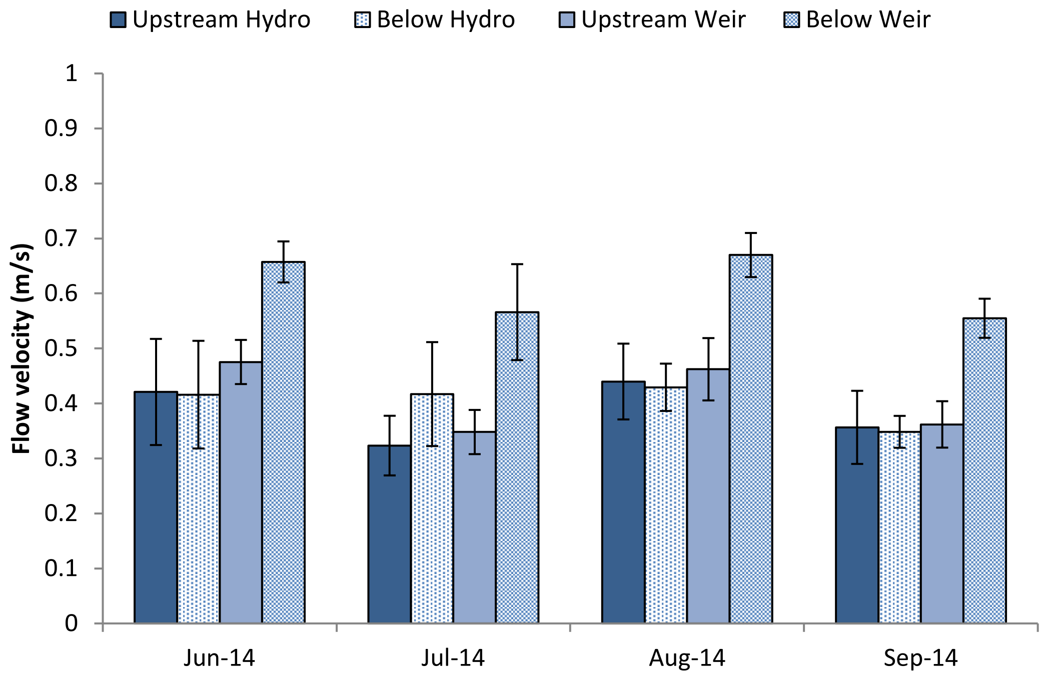

Figure 7.2: Flow velocity in the riffle below the hydro scheme and the riffle upstream of the hydro scheme and the riffle below the weir and the riffle upstream of the weir during each of the 2014 sampling occasions were error bars represent standard deviation

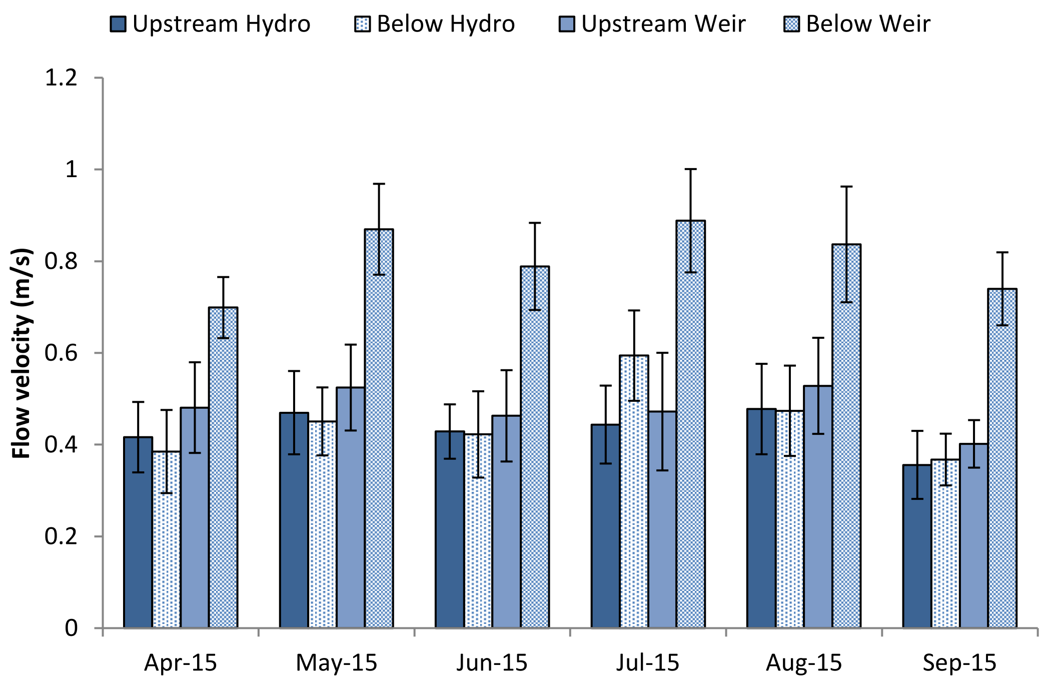

Figure 7.3: Flow velocity in the riffle below the hydro scheme and the riffle upstream of the hydro scheme and the riffle below the weir and the riffle upstream of the weir during each of the 2015 sampling occasions were error bars represent standard deviation

Table 7.1: Two sample t-test comparing flow velocity between the riffle below the hydro scheme and riffle upstream of the hydro scheme and between the riffle below the weir and the riffle upstream of the weir were $p<0.05$ was considered significant and is highlighted in bold

Sampling date	**Comparison**	***df***	***F-value***	***P-value***
Jun-14	Upstream Hydro*Below Hydro	1	0.007	0.933
	Upstream Weir *Below Weir	1	66.236	**0.000**
Jul-14	Upstream Hydro*Below Hydro	1	4.435	0.061
	Upstream Weir *Below Weir	1	29.857	**0.000**
Aug-14	Upstream Hydro*Below Hydro	1	0.100	0.758
	Upstream Weir *Below Weir	1	53.684	**0.000**
Sep-14	Upstream Hydro*Below Hydro	1	0.076	0.788
	Upstream Weir *Below Weir	1	73.413	**0.000**
Apr-15	Upstream Hydro*Below Hydro	1	1.388	0.246
	Upstream Weir *Below Weir	1	66.997	**0.000**
May-15	Upstream Hydro*Below Hydro	1	0.529	0.472
	Upstream Weir *Below Weir	1	128.173	**0.000**
Jun-15	Upstream Hydro*Below Hydro	1	0.061	0.801
	Upstream Weir *Below Weir	1	112.002	**0.000**
Jul-15	Upstream Hydro*Below Hydro	1	2.440	0.127
	Upstream Weir *Below Weir	1	118.929	**0.000**
Aug-15	Upstream Hydro*Below Hydro	1	0.014	0.905
	Upstream Weir *Below Weir	1	70.717	**0.000**
Sep-15	Upstream Hydro*Below Hydro	1	0.313	0.579
	Upstream Weir *Below Weir	1	257.227	**0.000**

While this study always measured during times of low flow conditions and this pattern might not be valid across all flows. Phytobenthic biomass and community composition can be used as an indicator of change over longer periods of time. Hence it is helpful to look at differences across chlorophyll-a concentrations and community composition.

Figure 7.4 and Figure 7.5 show that in most cases there is no difference in chlorophyll-a concentration between the riffle upstream of the hydro scheme and riffle below the hydro scheme. In addition that across the majority of these occasions chlorophyll-a concentration is significantly higher in the riffle below the weir in comparison to the riffle upstream of the weir (Figure 7.4, Figure 7.5 and table 7.2). This in turn supports the alternative hypothesis proposed above and also suggests that the weir is having a greater effect on the biofilm than the hydro scheme. If this finding is echoed across numerous 'on weir' hydro schemes across a range of riverine environments, it could have positive effects on hydropower development. If 'on weir' hydropower can have positive effects on ecology and return riverine environments back to more natural conditions whilst also providing renewable electricity this will be deemed as a 'win-win' situation (EA, 2010).

However there are some similarities between the hydro scheme and weir following periods of high flow and low abstraction. During the May 2015 sampling occasion chlorophyll-a concentration was significantly lower below both the hydro scheme and weir in comparison to riffles upstream. A possible explanation for this is that during low abstraction and high flow events when flow is dominant over the weir due to turbines being at capacity, the masking effect created by the scheme is reduced. This in turn would create higher velocities below the weir and hence would induce scour as a result of increased drag and friction similar to that at a weir without hydropower (Law, 2011). Yet if the hydro developer is allowed install more turbines and divert more flow during these times, the scheme could potentially continue to mask the effect of the weir and produce more power. To test this, an investigation could be carried out at Stockport Hydro, where the regulators allow higher proportions of flow to be diverted to the turbines across a range of flow conditions.

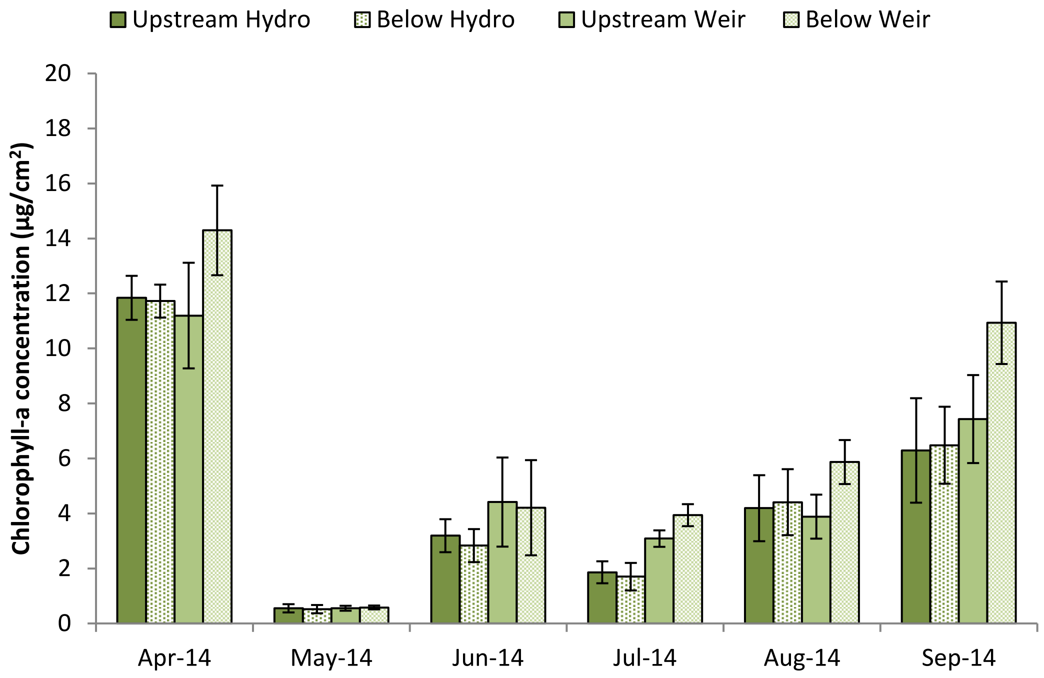

Figure 7.4: Total chlorophyll-a measured in the riffle below the hydro scheme and the riffle upstream of the hydro scheme and the riffle below the weir and the riffle upstream of the weir during each of the 2014 sampling occasions were error bars represent standard deviation

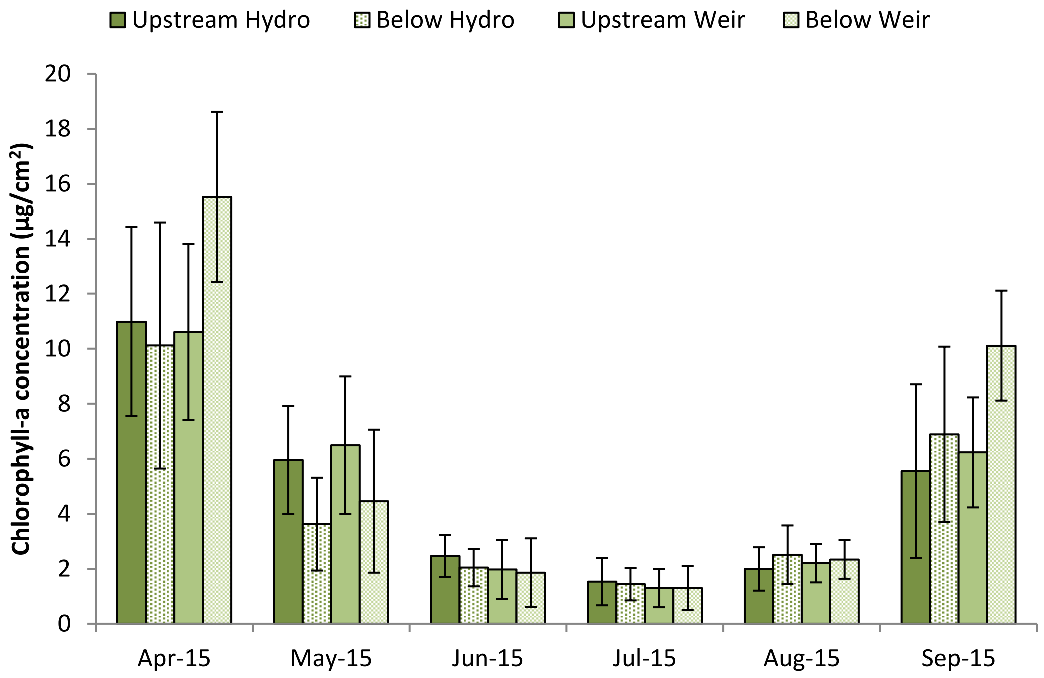

Figure 7.5: Total chlorophyll-a measured in the riffle below the hydro scheme and the riffle upstream of the hydro scheme and the riffle below the weir and the riffle upstream of the weir during each of the 2015 sampling occasions were error bars represent standard deviation

Table 7.2: Two sample t-test comparing chlorophyll-a concentration between the riffle below the hydro scheme and riffle upstream of the hydro scheme and between the riffle below the weir and the riffle upstream of the weir were p<0.05 was considered significant and is highlighted in bold

Sampling date	**Comparison**	***df***	***F-value***	***P-value***
Apr-14	Upstream Hydro*Below Hydro	1	0.084	0.778
	Upstream Weir *Below Weir	1	9.093	**0.013**
May-14	Upstream Hydro*Below Hydro	1	0.112	0.745
	Upstream Weir *Below Weir	1	0.070	0.797
Jun-14	Upstream Hydro*Below Hydro	1	1.047	0.330
	Upstream Weir *Below Weir	1	0.045	0.837
Jul-14	Upstream Hydro*Below Hydro	1	0.342	0.571
	Upstream Weir *Below Weir	1	12.906	**0.005**
Aug-14	Upstream Hydro*Below Hydro	1	0.101	0.757
	Upstream Weir *Below Weir	1	19.358	**0.001**
Sep-14	Upstream Hydro*Below Hydro	1	0.037	0.852
	Upstream Weir *Below Weir	1	14.693	**0.003**
Apr-15	Upstream Hydro*Below Hydro	1	0.477	0.494
	Upstream Weir *Below Weir	1	24.140	**0.000**
May-15	Upstream Hydro*Below Hydro	1	16.197	**0.000**
	Upstream Weir *Below Weir	1	6.498	**0.015**
Jun-15	Upstream Hydro*Below Hydro	1	3.394	0.073
	Upstream Weir *Below Weir	1	0.129	0.721
Jul-15	Upstream Hydro*Below Hydro	1	0.144	0.706
	Upstream Weir *Below Weir	1	0.000	0.990
Aug-15	Upstream Hydro*Below Hydro	1	3.089	0.087
	Upstream Weir *Below Weir	1	0.369	0.547
Sep-15	Upstream Hydro*Below Hydro	1	1.709	0.191
	Upstream Weir *Below Weir	1	37.858	**0.000**

To some extent similar patterns were also evident across species taken from BenthoTorch readings. For example during the August 2014 and September 2015 sampling occasions there was elevated diatom concentrations below the weir (Figure 7.6 and Figure 7.7). In addition there were decreased diatoms below both the weir and hydro scheme during both the May 2014 and May 2015 sampling occasions following periods of low abstraction and high flow. However patterns are much harder to deduce and were not evident across the ecological guilds from species samples (Figure 7.8).

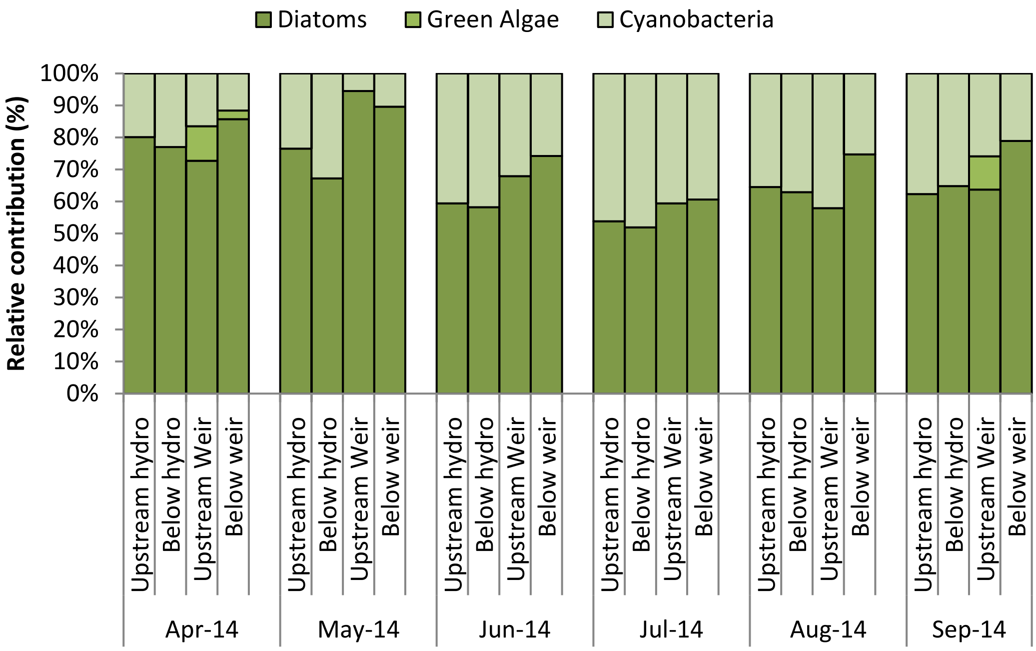

Figure 7.6: Relative contributions of the photoautotrophic components of the biofilm (diatoms, cyanobacteria and green algae) in relation to mean total chlorophyll-a concentration for the riffle upstream of the hydro scheme, riffle below the hydro scheme and riffle upstream of the weir and riffle below the weir during the 2014 sampling occasions

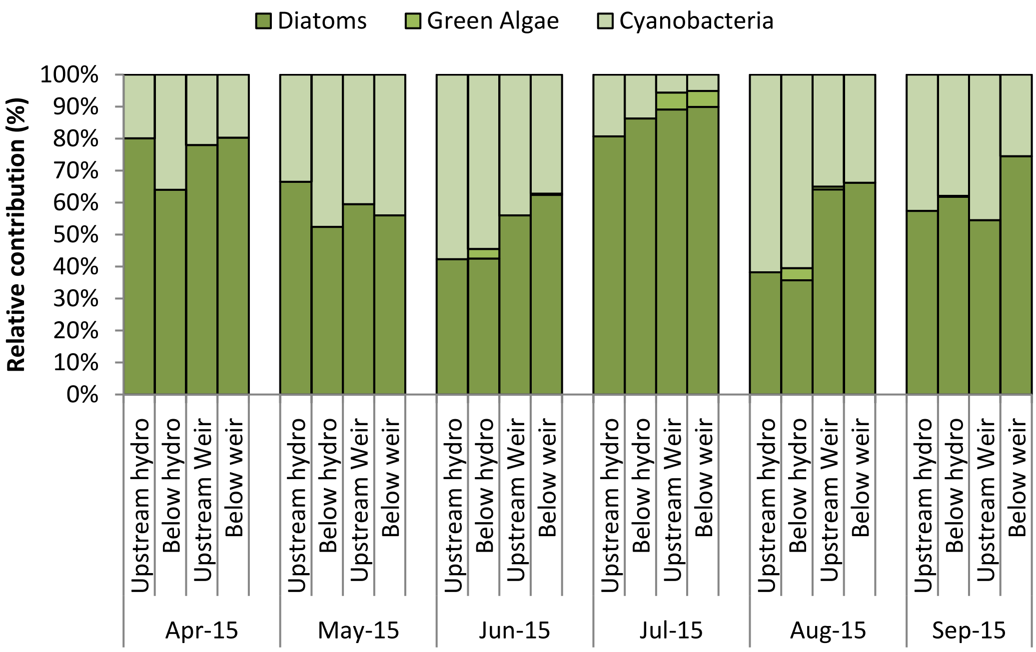

Figure 7.7: Relative contributions of the photoautotrophic components of the biofilm (diatoms, cyanobacteria and green algae) in relation to mean total chlorophyll-a concentration for the riffle upstream of the hydro scheme, riffle below the hydro scheme and riffle upstream of the weir and riffle below the weir during the 2015 sampling occasions

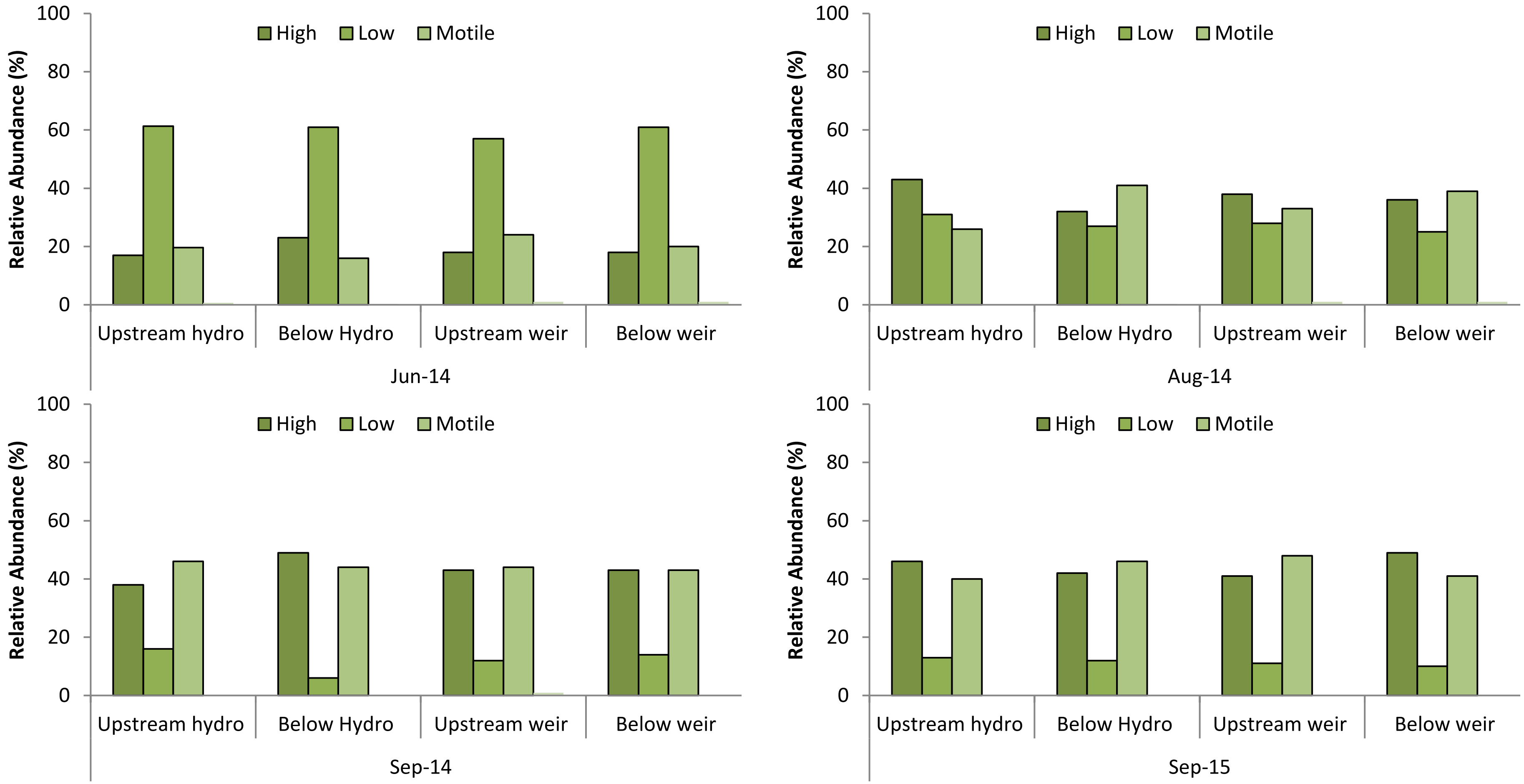

Figure 7.8: Relative abundance of species in each ecological guild in the assemblages collected from the riffle upstream of the hydro scheme, the riffle below the scheme and the upstream of the weir and the riffle below the weir during the June 2014, August 2014, September 2014 and September 2015 sampling occasions

7.4. Conceptual framework

Taking into account the patterns discussed and findings from previous chapters this led to a conceptual framework for how the weir and 'on weir' hydro scheme potentially interacts with the phytobenthic biofilm (Table 7.3). This framework is focused on chlorophyll-a concentration (biomass) as this is where the most significant differences were detected. Patterns in community composition did not appear to be affected by the weir or hydro scheme in this investigation.

This framework is related to the river Goyt, Stringer's weir, Otterspool weir and Stockport Hydro specifically and only currently considers overall discharge alongside abstraction rate. It is likely that different weirs and schemes will have differing effects depending on the size and shape of the weir, the amount of flow diverted and different combinations of environmental variables across sites. Yet more studies need to be carried out to establish better relationships. Across the river Goyt there appeared to be a clear seasonal trend in chlorophyll-a concentration which helped to inform the following framework;

1. Following periods of high flow and low abstraction the benefits of the hydro scheme are likely to be masked by the weir
2. Following periods of moderate flow and moderate to high abstraction the benefits of the hydro scheme and flow diversion are likely to outweigh the negative effects of the weir
3. Following periods of low flow and low abstraction the benefits of the hydro scheme are likely to be masked by the weir

In relation to the hydro scheme patterns appear to be related to the proportion of flow abstracted and overall flow conditions. When overall flow is high, abstraction will be low due to the turbines reaching capacity and the scheme is likely to behave like the weir. Yet when overall flow is moderate and abstraction is moderate to high the scheme could mask the effect of the weir and as a result the scheme could return the environment and aquatic communities back to a more natural condition. When overall flow conditions are low and abstraction is low the scheme is likely to act like a weir.

7.5. Conclusion

This thesis provides the first in field investigation at a low head 'on weir' hydro scheme and is to the best of my knowledge the only investigation that has carried out detailed spatial surveys below a low head 'on weir' scheme. There was evidence across this study to suggest that low head 'on weir' hydropower is having minimal effects of phytobenthic biomass and community composition. While there was evidence of hydraulic zones of impact below the outlet these appeared to have limited impact on phytobenthic biomass and community composition. Moreover changes in biomass and community composition were more obvious over time than spatially across sampling locations. Furthermore, low head weirs appear to be having a greater effect on phytobenthic biomass and there is evidence to suggest that low head 'on weir' hydro schemes can mask the effects of weirs by reducing the proportion of flow over the weir. This is most apparent following periods of moderate flow with high abstraction but could be increased if regulators allow the developers to install more turbines/divert more flow. In turn this could have positive effects on future hydro development. If 'on weir' hydro installation provides both benefits for ecology and meaningful amounts of renewable electricity this will be seen as a 'win-win' situation (EA, 2010).

7.6. Implications for developers and regulators

This thesis provides basic empirical evidence for decision making. This thesis provides the initial framework, on which, the regulators can build on, and expand on to collect more evidence. Regulators could use results from this thesis to inform survey design i.e. where and when to collect samples. Going forward regulators could monitor the impacts of the scheme closer to the outlet i.e. within at least 10meters of the scheme. They could also explore the impacts of low head weirs and low head 'on weir' hydro across a variety of flow conditions and abstraction regimes. Given that the effects of the scheme investigated were minimal and that in some instances the scheme appeared to mask the effect of the weir this study could be used help to solve conflict between environmental and renewable energy targets. If future investigations validate findings from this study hydro development will increase and renewable energy targets will be met.

7.7. Limitation and further work

This investigation did however, collected measurements at a point in time. More continuous measurements would provide more robust results. Especially considering that the biofilm can follow patterns of accrual and loss over shorter time scales than is measured in this study. Moreover this study only considered a 6 month period over two years and hence did not capture all seasonal trends. It is possible that the weir and/or scheme are having an effect over periods that were not measured i.e. the winter period. This investigation was also carried out at one scheme and one weir and hence it is unknown if this pattern is echoed across other schemes and other rivers with different combinations of environmental variables. Going forward studies could consider a variety of schemes across rivers with different nutrient and flow regimes. As stated previously, if findings from this study are validated this could have positive effects on future hydro development. If regulators allow higher proportions of flow to be diverted to the turbines, across a range of flow conditions at Stockport Hydro a series of experiments would need to be conducted.

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