Conservation of barbel (*Barbus barbus*) in the River Great Ouse

being a Thesis submitted for the Degree of
Doctor of Philosophy

in the University of Hull

by

Karen Gemma Twine
BSc (Hons), Msc

October 2013

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ACKNOWEDGEMENTS

I would first like to thank my supervisors Professor Ian Cowx and Dr Ian Hirst for providing me with the opportunity to undertake this research. My gratitude to the Environment Agency for funding the project, and the working parties involved in analysing the diatom and water quality samples. I am extremely grateful to the teams at Hull International Fisheries Institute and Fisheries and Biodiversity for their help, support and advice during the field work and write up stages. Thank you to the sampling and collection team of the Environment Agency at Brampton, Chris Gardner and Ian Welby for the safe capture and tagging of adult barbel. Martyn Lucas and the University of Durham, for the use of their radio tracking equipment. Mark Ives (Cefas) and Luke Mitchell (Unversity College London) for their assistance with the collection of freeze core samples, and Hull University Institute of Esturine and Costal Studies for their help in analysing the samples. My appreciation goes to the land owners, Angling Clubs and Associations for allowing access to the river banks, giving their continual support to the project. In particular, Mr and Mrs Tusting for letting us camp in their field during the spawning season, Milton Keynes Angling Association, Newport Pagnell Angling Club, Verulam Angling Club, Upper Great Ouse Fisheries Consultative Association and The Barbel Society for their support and funding contributions. My thanks and best wishes go to Roy Bates, for sharing his extensive knowledge of the river and area. Last and definitely not least, special thanks and appreciation to my friends and family Natalie Angelopoulos, Adam Barton, Aimee Collins, Jonathan Gilby, Kye Jerrom, Simon Kelsey, Claire Mansell, Ryan Oakley, Sarah Padfield, Marie Taylor, Lauren Tewson, Gemma Waghorn, Ann, Rick and Jennifer Twine, who all went above and beyond to help and support me.

ABSTRACT

CONSERVATION OF BARBEL IN THE RIVER GREAT OUSE

There have been growing fears relating to the distribution and a perceived lack in natural recruitment of barbel in European rivers. This project reviewed existing literature, examined the suitability of Environment Agency data to assess barbel populations and designed investigations to identify possible bottlenecks in recruitment focusing on all life history stages and environmental influences, with the intention of developing a practical management plan for the River Great Ouse fishery that can be applied to other rivers.

This study examined seasonal movements of 20 wild barbel via radio telemetry in a nine kilometre river stretch on the upper Great Ouse, recording weekly movements over an 18 month period. The project aimed to ascertain the effects of environmental influences on movement and habitat use. Radio tracking over 100 consecutive days throughout the spring periods in 2010 and 2011 gave an understanding of their daily movements, identified barriers limiting longitudinal movements and located active spawning gravels. Health of spawning gravels was assessed by monitoring changes in diatom growth and hyporheic water quality during the embryonic development stage. Representative freeze core samples from spawning gravels were used to assess fine sediment infiltration. Larval drift measured the number of larvae leaving the spawning grounds, a range of methodologies were used to capture 0+ to 3+ barbel. Habitat and feeding preferences were then evaluated.

It was found that temperature and flow impacted movement, individuals moved through the entire river stretch, despite the presence of a weir that was previously thought of as impassable. Variations in sediment loading were found between spawning habitats, but fine sediment and organic matter were improved with gravel jetting. Larval drift and electric fishing were found to be the most effective methods for catching young barbel, but the necessary habitats to support these young fish were not readily available within the study stretch.

1. GENERAL INTRODUCTION

Barbel (*Barbus barbus* (L.)) is an aggregative, lithophilous and rheophilous species, widely distributed in central Europe (Lucas & Batley 1996) and a component of fish communities in middle and lower reaches of temperate rivers (Huet 1949; Lucas & Frear 1997). In some rivers throughout central Europe, such as Poland (Witkowski 1991) and Czech Republic (Penaz *et al.* 2005) the barbel is regarded as a threatened species. In the United Kingdom (U.K), there is anecdotal evidence from anglers of a decline in barbel numbers in rivers such as the Great Ouse and the Thames, but the species continues to thrive in the Rivers Severn and Kennet.

In England, it is believed that barbel are native to only to these eastern rivers (Wheeler & Jordan 1990), including the Yorkshire Ouse, Derwent, Wharfe, Aire, Swale, Don, Trent, Witham, Welland, Great Ouse, Thames, and a number of their tributaries (Figure 1.1a). The distribution of barbel was restricted by the limitation of suitable habitats and the vulnerability of the species to environmental changes (Wheeler & Jordan 1990). The occurrence of barbel in some rivers is due to stocking occurrences from the 1950s onward, specifically the River Severn in western England (Figure 1.1b), where barbel populations grow in strength and number. The success of such movements has been attributed to the existence of vacant niches present within the receptor systems (Churchward *et al.* 1984; North & Hickley 1989).

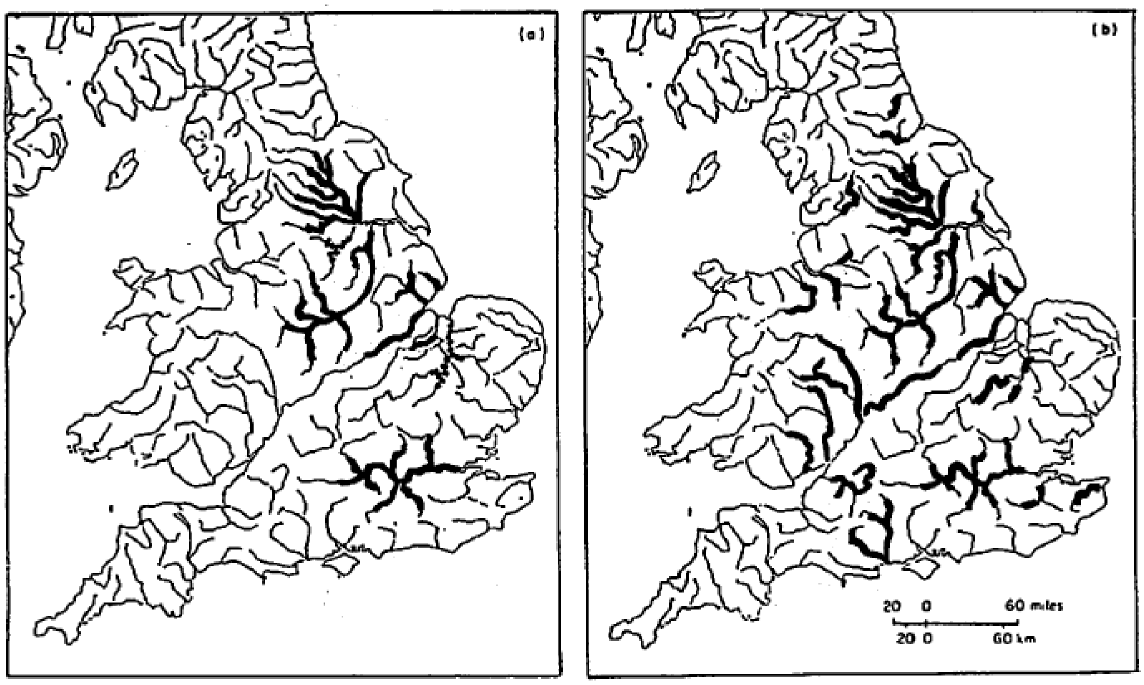


Figure 1.1. Deduced natural occurrence (a) and distribution in 1989 (b) (Wheeler & Jordan 1990).

In England and Wales between the mid-1980s and 2010, 8924 barbel were caught during Environment Agency surveys (National Fisheries Population Database). A total of 711 of these were from the Anglian Region, and 506 from the Great Ouse, accounting for 6% of the national and 71% of the regional population (Figure 1.2). According to data available, barbel populations follow a cyclical pattern in growth and decline. In recent years in the Great Ouse, barbel catches have been at their lowest recorded. The sampling methodologies used to collect these population data are known to be biased towards barbel of certain sizes, this is also shown in Environment Agency data (Figure 1.3). Fewer individuals between 210 and 400 mm have been caught using electric fishing and seine netting techniques; this may be due to sample sites non representing habitat preferences of barbel in that size range. The apparent recent decline in barbel numbers is supported by angler word of mouth and reports in the media, including: angling and barbel specific internet forums and magazines.

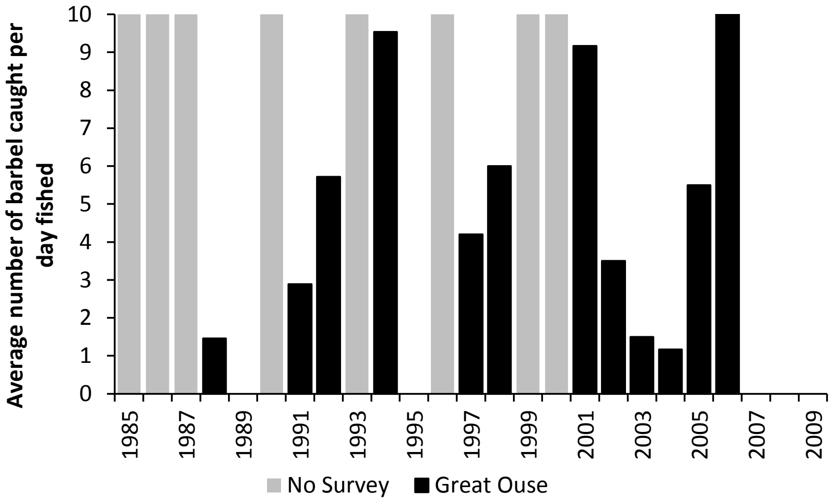


Figure 1.2. Trends in barbel catches by the Environment Agency in the Great Ouse catchment, using seine netting and electric fishing methodologies.

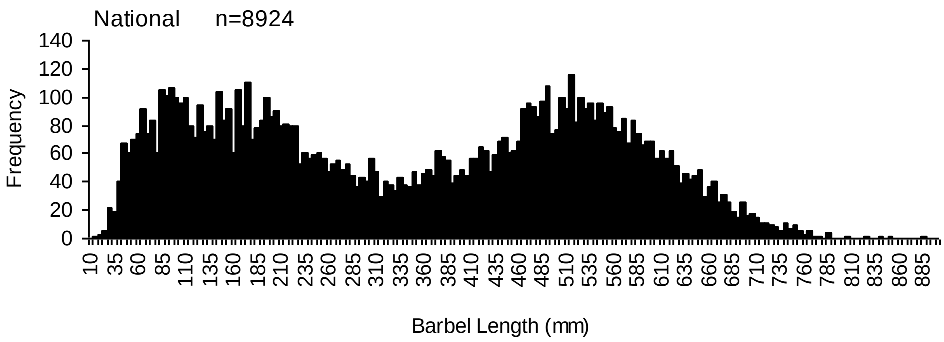


Figure 1.3. National length frequency distribution of barbel between 1986 and 2008, using seine netting and electric fishing methodologies.

During the first half of the 20th Century, the Great Ouse was regarded as one of the premier mixed recreational fisheries in England (Pinder *et al*. 1997) with over 30 species of freshwater fish being recorded in the catchment (Mann 1997; Bass *et al.* 1997). Now, it is dominated heavily by small roach (*Rutlus rutilus* (L.)), and many species, notably common bream (*Abramis brama* (L.)), have declined substantially in abundance (Pinder *et al*. 1997) with concerns over other charismatic fish species such as barbel.

In recent years it has become apparent that it is important to address the issues that influence fish populations rather than artificially recover species diversity and individual numbers by stocking. The shift within fish communities from rheophilic taxa to eurytopic species (Pinder *et al*. 1997) is mainly due to human impacts (Jurajda 1995). Barbel is a long lived species that matures late and as a result, changes in its population structure caused by habitat pressures can take many years to become apparent. Populations are sensitive to anthropogenic influences and pressures such as:

- fragmentation of the longitudinal corridors by dams, navigation weirs (Baras *et al.* 1994; Lucas & Bately 1996; Ovidio & Philippart 2002), which limits the species ability to colonise new areas and utilise necessary habitats for their altering needs;
- discharge regimes that are subjected to regulation (Faulkner & Copp 2001; Cattaneo *et al.* 2001) such as in the River Great Ouse, which alter the environmental cues related to spawning activity;
- destruction of essential habitats for all life stages (Copp 1992; Jurajda 1999), which creates population bottlenecks at multiple stages, as barbel go through a number of habitat shifts (Watkins 1997; Bischoff & Freyhoff 1999);
- elevated levels of nutrients (Pilcher & Copp 1997), affecting hyporheic water quality and supporting the growth of biofilms on spawning gravels, reducing the successful hatching of larvae;
- compromised water quality with treated domestic effluents contaminated with endocrine disruptors (Penaz *et al.* 2005; Vilizzi *et al.* 2006) can result in intersex individuals and reduced sexual function in adults. The larval and juvenile development stages of barbel are most susceptible;
- climate change (Baras &Philippart 1999) affects river temperature, and can also cause dramatic fluctuations in both river level and flow. This is particularly

influential on barbel populations during the spawning season, when an increase in flow can wash the eggs and larvae away, or a decrease in river level can leave eggs stranded on exposed spawning gravels;

- predation of all life stages (Degerman *et al.* 2007) creates population bottlenecks at multiple stages;

Despite improvements to rivers deriving from the European Union (EU) Water Directives and the EU Water Framework Directive (WFD, EU 2000/60/EC), anglers have noticed a decline in barbel catches since the ‘hay days’ of the 1970s and 80s. In the 1990s the River Great Ouse was regarded as one of the best barbel fisheries in the country. It is undetermined whether these barbel were natural in size and abundance or whether they were the result of previous stockings, but poor barbel catches have led to anglers altering this target species or ceasing their involvement in the sport (Environment Agency 2007b).

The barbel is of particular interest, due to its value as an angling amenity. The species is considered to be elusive and difficult to catch, due to its habitat preferences and it can reach a large size, with individuals reaching weights >8 kg. These attributes attract high numbers of specialist anglers, particularly in rivers or sections of rivers where there are known to be large specimens (Wheeler & Jordan 1990; Taylor *et al*. 2004). Ecosystem services such as recreational angling provide important income for the economy of the UK. A report on the economic evaluation on inland fisheries (Environment Agency 2007b) stated that gross expenditure on coarse fishing in 2005 was close to £1 billion, based on 26,386,734 angler days. A total of 36% of course anglers fished river water bodies and 75% of anglers spent between £5 and £50 on each occasion totalling ~£700,000. Coarse fishing accounted for ~88% of fishing effort in that year, 10.1 % of this effort was on river water bodies. In the same year coarse fishing effort in Anglian Region, accounted for 2.3 million angler days. If angler barbel catches decline, it is likely that they will change their target species. This would not necessarily impact on rod license sales, but it could change target rivers and regions.

Thesis scope

Due to its popularity, barbel is a much studied species but its biology is still insufficiently understood (Penaz *et al.* 2002; Britton & Pegg 2011). Over 90% of studies regarding this species have focused primarily on movements and habitat use (Britton & Pegg 2011), and few have researched population structure and recruitment success. Barbel is native to the Great Ouse and an important biological and economic component of the region. It is unknown what pressures are most influential on the decline in barbel numbers, if the barbel is naturally recruiting, or whether its population consist primarily of stocked individuals. It is also unknown if naturally recruited or stocked barbel are surviving to an age where they are either caught by anglers or able to reproduce. Scientific evidence is needed to gain a greater understanding into the anthropogenic impacts on the recruitment and survival of barbel, evaluating the current population status with the perspective of habitat availability and environmental influences.

Thesis objectives

1) To review existing literature to identify what work has previously been undertaken, what gaps exist in barbel research and what research would best benefit the Great Ouse barbel population. This will enable appropriate decisions regarding what research is possible within the three year timeframe and available budget.

2) To consider the biological, chemical, morphological status of the Great Ouse catchment and identify the most likely pressures on barbel recruitment with a view to use this information to design studies to target specific issues.

3) To assess daily and seasonal movements, habitat use of adult barbel and the species ability to pass barriers. This will give evidence that barbel migration is hindered by weirs and that movement and habitat use are affected by environmental characteristics. This research will also identify specific habitats to target in rehabilitation projects, spawning gravel use and fidelity.

4) To assess barbel spawning habitat in the River Great Ouse. This will provide previously unknown information on the quality of gravels available for this and other lithophilic species as well as provide data for comparison with similar studies in the future.

5) To assess the population of young barbel (0 to 3 years of age) and habitat use, to be compared with research in other rivers. This will demonstrate that young barbel inhabit sections of river that are not routinely surveyed and numbers of this age range are

therefore underestimated in population calculations. It will also identify habitat types to target for rehabilitation projects to increase the survival rate of young barbel.

6) To provide land owners, angling clubs, consultatives and other stakeholders with a number of options to improve their fisheries with ‘stand-alone’ enhancement projects, and also to provide the Environment Agency with management options they can build into their framework to improve rivers on a larger scale whilst delivering the objectives of the Water Framework Directive.

Chapter 2 reviews historical and current literature documenting the life history of *Barbus barbus* throughout Europe including its distribution, habitat preferences, seasonal behaviours, reproductive strategy, physiology, food preferences and growth rates in England. It evaluates historical data on national and regional barbel populations. Information gathered in this review forms the basis for investigations designed in this research project, and identifies what research is possible within the three year timeframe and available budget.

Chapter 3 reviews data and information available, relating to concerns for the local barbel population over the biological and chemical status of the Great Ouse catchment, river fragmentation, flow regulation, physical habitat, predation and parasites. This evaluation highlights pressures at each life history stage of the species. Information gathered in this review forms the basis for investigations designed in this research project, and helps ascertain what research is most relevant to the Great Ouse catchment and would most benefit the barbel population.

Chapter 4 investigates the seasonal movements of 20 wild barbel via radio telemetry in a nine kilometre stretch of the upper River Great Ouse, documenting weekly movements over an 18 month period and movements over 100 consecutive days during the spawning periods of 2010 and 2011. The project aimed to ascertain the effects of environmental characteristics (such as flow, river level and temperature) on movement and habitat preferences. It considers the passability of weirs and identifies spawning habitats currently used by barbel, which can be used for further investigation. It is predicted that habitat use will alter on a seasonal basis that environmental variables will influence movement, and that major weirs will act as barriers to migration.

Chapter 5 Investigates and compares the quality of four currently used spawning gravel habitats identified in Chapter 4, by assessing hyporheic water quality at 2, 5 and 10 cm within the spawning gravel, periphytic diatom growth, fine sediment infiltration and organic content. Comparing fine sediment infiltration and organic content before and after gravel rejuvenation work. It provides previously unknown information on the quality of gravels available for rheophilic species in field conditions and provides data for comparison with similar studies in the future. It is predicted that the habitat quality would be a main pressure for the natural recruitment of barbel.

Chapter 6 Investigates the juvenile barbel population in the River Great Ouse using a series of fishing methods including; drift of larvae from spawning gravels identified in Chapter 4, micromesh seine netting at locations that anglers have identified spawning had previously occurred, continuous electric fishing, point abundance sampling and hoop netting in the study section used for the radio telemetry study in Chapter 4. This will establish habitat types to target for rehabilitation projects with an aim to increase the survival rate of young barbel. Chapter 6 also investigates the feeding preferences of larval and juvenile barbel, and compares the growth rates of barbel in the first 2 years based on data collected nationally, regionally, locally to the River Great Ouse and known stocked fish reared at Calverton Fish Farm. It is predicted that growth rates in the first two years would be different between naturally recruited and captive bred barbel and that habitat preferences will alter with development from larval to juvenile stages.

Chapter 7 Surmises the information gained from Chapters 4 to 6, and thus offers possible rehabilitation methods based on the outcomes from the investigations, providing land owners, angling clubs, consultatives and other stakeholders with a number of options to improve their fisheries with ‘stand-alone’ enhancement projects. It also provides the Environment Agency with further research and management options that can be built into a framework to improve rivers on a larger scale whilst delivering the objectives of the Water Framework Directive.

2 THE ECOLOGY OF BARBEL AND POPULATION TRENDS IN THE UNITED KINDOM

2.1 Introduction

The diversity of fish fauna throughout many large European rivers has shown evidence of a structural shift from rheophilic taxa to eurytopic species (Cattanéo *et al.* 2001) and a stabilisation of limnophilic species (Wolter & Vilcinskas 1996). This shift is mainly due to human impacts (Jurajda 1995). One of the most abundant groups of riverine fishes is the family Cyprinidae, a diverse freshwater group that is widely distributed throughout Europe (Lucas & Batley 1996) and are often, a major component of fish communities in the middle and lower reaches of temperate rivers (Lucas & Frear 1997).

The genus '*Barbus*' is the largest of the Cyprinidae family. Species belonging to this genus are widely distributed throughout the world; but, barbel (*Barbus barbus* (L.)) is the only species that inhabits British inland waters. It is a shoaling, lithophilic and rheophilous species, of particular interest because of its value as an angling amenity. Due to its popularity, barbel is a much studied species (Britton & Pegg 2011), but its biology is still insufficiently understood (Penaz *et al.* 2002). Studies on its life history have been carried out in the rivers Ourthe (Baras & Cherry 1990) and Meuse (DeVocht & Baras 2003) (Belgium), Jihlava (Penaz 2005) (Czech Republic), Severn (Hunt 1974a; 1974b; 1975), Thames (Tyler & Everett 2005; EA 2007a), Lee (Copp *et al.* 2002), Nidd (Lucas & Batley 1996) and Great Ouse (Copp 2006) (England) and Rhone (Penaz *et al.* 1992) (France).

This Chapter aims to review historical and current literature documenting the life history of *Barbus barbus* throughout Europe including its distribution, habitat preferences, seasonal behaviours, reproductive strategy, physiology, food preferences and growth rates in England. Also, recognise research previously undertaken and identify gaps in research regarding the species that could be incorporated into this research program. This chapter additionally aims to compare historical data on the United Kingdom's national and regional barbel populations. Information gathered in this review was used to form the basis for investigations designed in this research project.

2.2 Species distribution

The barbel is a characteristic species in the middle reaches of many rivers (Huet 1959), widely distributed throughout western and central Europe (Wheeler 1977), including the Rhone and Danube in the south, as well as the Dneiper and Neman in the north and east. In these rivers, barbel has previously formed the highest biomass within the fish community (Huet 1949; Baras 1992a).

Analysis of native freshwater fish distribution in the British Isles was first attempted by Regan (1911) who identified that the eastern rivers possessed a much richer fauna than the western rivers of the British Isles. In England, it is believed that barbel is native to only to these eastern rivers (Wheeler & Jordan 1990), including the Yorkshire Ouse, Derwent, Wharfe, Aire, Swale, Don, Trent, Witham, Welland, Great Ouse Thames, and a number of their tributaries (Figure 2.1a). The distribution of barbel was restricted by the limitation of suitable habitats and the vulnerability of the species to environmental changes (Wheeler & Jordan 1990) such as poor water quality and unsuitable refuge or spawning habitats.

The increased distribution of barbel (Figure 2.1b) is a result of introductions of barbel into southern and western UK rivers that were carried out in the latter half of the 20th Century (Wheeler & Jordan 1990). The species was successfully translocated into several rivers, specifically in 1956 when 509 fish were moved from the River Kennet to the River Severn. The success of such movements has been attributed to the existence of vacant niches present within the receptor systems (Churchward *et al.* 1984). Another 102 barbel were moved from the River Swale into the Warwickshire Avon, but this attempt was not as successful as the River Severn translocation (Wheeler & Jordan 1990).

In recent years the translocation of this species has become increasingly important in conservation and commercial aquaculture (Griffith *et al.* 1989). The translocation of fish species for conservation purposes includes (Hodder & Bullock 1997):

- reintroductions in regions where the species is extinct;
- reinforcements of declining populations;
- habitat restoration;
- relocations to rescue individuals or small populations.

Between 2001 and 2012, 164,000 juvenile barbel were stocked by the Environment Agency in the rivers and associated on line still waters of England and Wales with lengths ranging between 1 and 25 cm. Barbel catch data from the mid-1990s to 2008 show a similar distribution throughout the UK (Figure 2.2) to that previously recorded by Wheeler and Jordan (1990) (Figure 2.1 a and b).

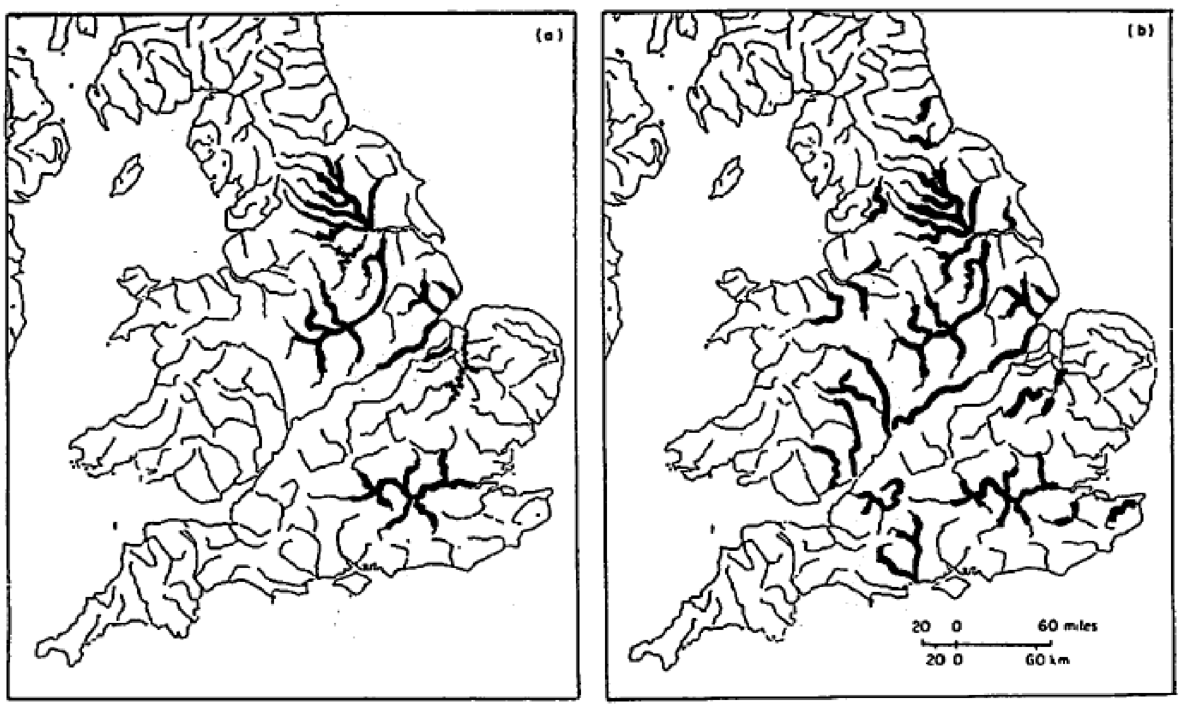


Figure 2.1. Deduced natural occurrence (a) and distribution in 1989 (b) of barbel in the British Isles (Wheeler & Jordan 1990).

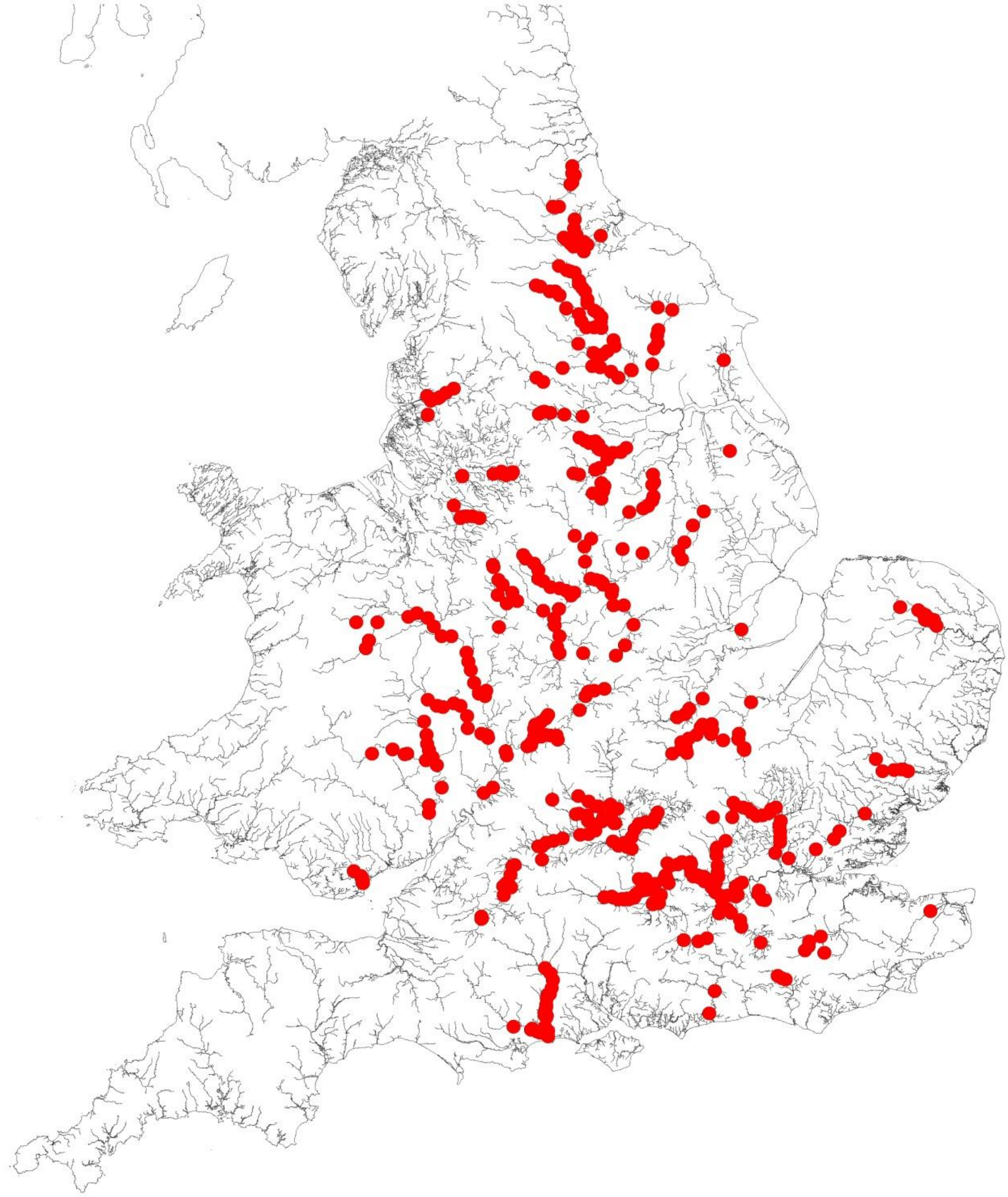


Figure 2.2 Distribution of barbel catches in EA monitoring (1990-2012).

2.3 Environmental requirements for barbel

2.3.1 River flow

Hydraulic variables play a central role in the distribution of fish as they are directly affected by flow regulation as spatial and temporal alterations in the habitat use of fish is a response to seasonal environmental factors such as river discharge, temperature and water quality (De Vocht & Baras 2003). Marked changes in river levels and discharge have resulted in the decline in the number of diadromous (Philippart *et al.* 1994) and potamodromous species such as barbel (De Vocht & Baras 2003) as these species show preferences to certain velocities, local depths and substrate composition (Lamouroux *et al.* 2002).

Flow regulation affects all life history stages, removing appropriate conditions for gonad maturation, migrations, pre spawning and spawning interactions, altering environmental conditions needed for larval and juvenile stages (Baras & Nindaba 1999; Humphries & Lake 2000). Changes in river level and flow leave eggs, larvae and juveniles at risk from being stranded on gravel bars or being washed down the river channel (Humphries & Lake 2000), individuals in poor condition are more likely to be swept away (Reichard *et al.* 2004). There is evidence that fish forage more efficiently when dispersed (Pilcher & Parish 1993) and so behavioural responses to environmental factors, such as water velocity can disrupt their foraging efficiency and enhance their predation risk, therefore decreasing growth and survivorship (Vizilli & Copp 2001).

Rivers and streams suffering from low flows can suffer from the deterioration of water quality, increased water temperatures, hypoxia and show a dramatic reduction in habitat space, which also increases competition and predation (Lake 2000). In general, recovery from drought and extreme low flows takes more time than recovery from floods for invertebrate and fish species (Boulton & Lake 1992a).

2.3.2 Water quality

Larval and juvenile stages of fish development are more sensitive to extreme chemical conditions (Mann 1996). Oestrogens play an important role in reproduction and development (Jobling *et al.* 1998) so when high levels of these chemicals enter a water system they result in impaired reproductive function in adult species of either sex resulting in irreversible abnormalities that form during their development (Jobling *et al.* 1998). Although effluent characteristics change with annual and seasonal variations, exposure during sexual differentiation (Yeoh *et al.* 1996) can induce sex reversal and/or intersexuality (Jobling *et al.* 1998). Exposure during sexual maturation (Bohemen & Lambert 1981) can inhibit gonadal growth and development (Jobling *at al.* 1996).

Barbel spawn in late spring, and so the sexual differentiation of the juveniles occurs during the summer months when effluent concentrations will be at their highest, as a result of reduced summer flows. During years of severe low flow, a large proportion of the young of year could, as a consequence, be sterile and not be able to contribute to recruitment in the future when they themselves would be becoming sexually mature.

2.3.3 Physical habitat

The surrounding habitat for barbel, is vital to their survival. It needs to offer suitable spawning, feeding and refuge areas to support all life stages through varying conditions. The limitations on populations of barbel are generally related to decreasing habitat diversity and land-use practice has led to a degradation of spawning areas (Zeh & Dönni 1994; Baras *et al.* 1994). It is also believed that these limits reduce the possibly of barbel inhabiting new sites and river systems, for example the tributaries of the Great Ouse (Copp 1992a, b).

Studies on fish communities have identified relationships between fish species community traits and their habitat requirements (Merigoux *et al.*2001; Lamouroux *et al.* 2002; Goldstein & Meador 2004). Bottom dwelling species such as barbel have the ability to maintain their place by physical contact with the substratum (Hynes 1970), but adult fish often make use of areas that provide cover, for example, weed beds, over hanging willow trees and root masses. Heut (1949) defined barbel to be benthopelagic, inhabiting the middle reaches of rivers with medium to strong flow and high oxygen concentrations. They prefer faster than average flow velocities (Lucas & Batley 1996) and are able to decrease swimming costs by using micro turbulences behind coarse stones (Freyhoff 1996) resting in deep, lentic habitats or by utilising obstructions to flow for cover. The practice of seeking refuge increases as the barbel matures and in winter, barbel use structures such as boulders once plant cover has disappeared. Pool and riffle river channel characteristics are very important to adult barbel Penaz *et al.* (2002).

2.4 Seasonal behaviour of adult barbel

Migratory behaviours are an adaptive response to buffer the adverse environmental conditions that can be experienced (Baras 1995). For example, between October and March inclusive, when there is loss of cover, reduction in food availability there is a need for different habitat types. This results in net movements of barbel to alternative habitats that offer other refuge such as boulders that provide shelter from predation and high flows at times when barbel energy is lowest. Seasonal fish diversity changes within a river channel (e.g. as found by Wolter & Bischoff 2001), can reflect the shift between winter and summer habitats.

River fish movements are significantly constrained by the spatial structure of their environment (Daufresne & Boët 2007). Impoundments limit or prevent upstream migration to spawning grounds and can limit genetic diversity or cause injury to fish moving downstream (Lucas & Frear 1997). Studies have shown that in some instances, barbel have been unable to clear these obstacles and as a result individuals will go back down stream and wait until conditions improve, possibly waiting days or months, before passing successfully (Lucas & Frear 1997; Ovidio & Phillippart 2002). The success of fish passes to overcome problems to migration depend on the species physiological capability (Lucas & Frear 1997), individual size, swimming/jumping capacities, health and muscular efficiency and temperature. Lucas and Batley (1996) found that barbel used high flows to help them get successful passage over obstructions and that night or twilight were also when individuals were most successful at ascending weir, possibly related to predator avoidance.

All major movement of barbel, occur when temperatures range from 10˚C to 22˚C (Baras & Cherry 1990), but seasonal movements are related to several environmental factors (Lucas & Batley 1996), induced not only by temperature changes (Baras 1995; Baras & Philippart 1999) and flow rates (Cattaneo *et al.* 2001) but also by light intensity (Poncin 1989; Baras & Philippart 1999). The overriding effect of sun rise and sun set on fish behaviour was emphasised by Helfman (1993), the natural alteration of light and dark on daily cycles offers a range of available temperatures.

2.4.1 Winter

In winter months there is a net downstream movement of both females and males (Lucas & Batley 1996). Baras and Cherry (1990) believed that barbel move downstream during winter because they are unable to sustain their position in residence areas under the higher discharge conditions and that the foraging energy cost is too high. This would be particularly true when temperatures fall below 10 ^{o}C, as fish mobility is subsequently reduced. This reduction in mobility accounts for the 20% reduction of activity in winter, recorded by Lucas and Batley (1996).

Lower fish abundances in general are usually recorded from shoreline surveys over winter (Wolter & Bischoff 2001), possibly due to the fish seeking refuge in deeper parts of the river channel. During winter months the survival instinct of fish species is to avoid predation using the least amount of energy possible. Diel behaviour patterns of barbel exhibit single peaks toward dusk (Lucas & Batley 1996) and there is no activity below 4°C (Baras 1995) as the energy costs of foraging are potentially not compensated by feeding. Towards the end of winter, there is an emergence of diurnal activities, followed by crepuscular activities and then daylight activities as water temperatures increase (Baras 1995).

2.4.2 Spring

Wolter and Bischoff (2001) found that, a higher number of individual barbel were recorded during spring. The increasing day length in this season stimulates upstream movement, possibly due to spawning preparations for the early summer months from May to July. Spring activities are also dependent on temperature, especially for the hyperactive spawning period, when exploratory activities and changes of residence areas are most frequent (Baras & Cherry 1990; Baras 1993*a*). In late spring, barbel are most active for several hours at dawn and dusk (Baras & Cherry 1990; Baras 1995; Lucas & Batley 1996).

2.4.3 Summer

In the summer months, barbel remain in individual activity areas (Baras 1993*b*) or their chosen spawning ground. In these months there is typically a bimodal pattern of diel activity peaking early morning and late evening (Lucas & Batley 1996; Baras & Phillipart 1989; Pelz & Kastle 1989; Baras & Cherry 1990) during the periods of rapidly changing light intensities (Baras 1995). At this time of year, the role of temperature would be limited as it sits in the ‘comfort range’ for barbel (10 to 20°C) and therefore, light intensity is suggested to be the prominent variable modulating activity rhythms (Baras 1995).

Around sunset, barbel activity includes individuals leaving their resting place to travel to riffles and other high food availability sources where they exhibit feeding behaviour (Baras 1995). At sunrise, feeding activities resume, before individuals return to their resting place. This behaviour is delayed at high temperatures above 20°C (Baras 1995) when instead, individuals rest in deep pools.

Bischoff & Scholten (1996) found that barbel had more ability to migrate to other areas with higher water velocities in warmer months. This illustrates that behavioural patterns will alter between river systems, and is under the influence of river regimes (natural or a result of anthropogenic activities), food availability and predation (Copp & Juraja 1999).

2.4.4 Autumn

Baras (1995) found that in early autumn when temperatures were around 10°C, barbel activity exceeded that observed in summer and decreased again as winter approached. The increase of activity may be the result of increased feeing and improve body conditioning, in preparation for winter dormancy phases (Baras 1995).

2.5 Reproduction

Baras and Philipart (1999) believed that identifying the seasonality of reproduction and the environmental synchronisers responsible for the initiation of spawning is a key step to understanding the life histories of barbel and all other fish species. The initiation of spawning is under the control of an endogenous cycle of gonadal development and of an internal mechanism that synchronises with environmental cues (Wootton 1990), such as those used for seasonal migrations. For barbel, gonadal maturation occur in spring (Fredrich *et al.* 2003), a process that is induced by increasing day length (Poncin 1989; 1992)**.** In the same year, male barbel mature at 3 to 4 years of age, a number of weeks before female barbel of 5 to 8 years of age mature (Hunt & Jones 1974).

Poncin (1989, 1992) conducted studies under constant photoperiod and suggested that the role of day length or day length variation was minor during the barbel spawning season. Under increasing photoperiod and other environmental variables, spawning showed less consistency (Baras & Philipart 1999). A number of other studies have highlighted the fact that the mechanism governing the timing of reproduction in barbel is temperature (Ovidio *et al.* 2007). Baras and Philippart (1999) found that, based on evidence that for 8 consecutive years, spawning was initiated as soon as the daily minimum temp reached 13.5˚C; any decrease of temperature below this value later in the spawning period caused spawning to be suspended (Baras & Philipart 1999). Temperature is an important influence on spawning and the period of gestation, it regulates chemical reactions and other metabolic pathways, as well as triggering the migration to spawning grounds. These spawning movements are more erratic than those recorded post spawning and in the summer (Baras & Cherry 1990).

Most non salmonid fish species have been regarded as non-migratory up until the last couple of decades, but it has since been viewed that fish are the most mobile component of the permanent aquatic community (Lucas *et al.* 1998). There is evidence from mark - recapture studies and tracking programmes (Baras & Cherry 1990; Baras 1993a; Baras *et al.* 1994; Lucas & Batley 1996; Lucas & Frear 1997; Baras 1998), that barbel are one of the most migratory UK cyprinid fish species. The distance that this species can travel between its residence area that it occupies and its chosen spawning ground has varied from 0.25 to 22.7 km (Ovidio *et al.* 2007), with mobility patterns proportional to the fish size (Baras & Cherry 1990; Baras 1992, 1997; Lucas & Batley 1996). Lucas (2000) demonstrated that upstream migrations in barbel are mainly linked with elevated discharge events to aid the passage over weirs.

For many cyprinid species, migration may be the most vulnerable part of the life cycle (Smith 1991). The process of migration allows the colonisation of alternative feeding or nursery areas. The site chosen for spawning needs to fit the profile of ecological demands of the embryos during the intra gravel stage of life (Ovidio *et al.* 2007) and be suitable for free embryos and young larvae (Kryzhanovsky 1949). to increase survival and growth, maximises fitness (Mann & Mills 1986; Jonsson 1991; Braithwaite & Burt de Perera 2006). The final selection of the spawning site is done by the females (Hancock *et al*. 1976; Baras 1994). Males and females move up stream in spring to reach gravel beds (Lucas & Batley 1996), but barbel does not spawn systematically at the site nearest to the resting place occupied before migration (Ovidio *et al.* 2007).

Spawning occurs during daylight from April to July; males already occupy the spawning ground vicinity when the mature females reach the site. This earlier migration may be related to demographic constraints imposed by the sex ratio of the population (Baras *et al.* 1994). Spawning of barbel is a long-lasting process; females can produce 8,000 to 12,000 relatively large eggs (1.95-2.37 mm) per kg of body weight. Calta (1998) reported a negative correlation between fecundity and egg size at the interspecific level. The eggs are shed in the gravel (Kryzhanovsky 1949) and the interstitial spaces between gravels ensure sufficient oxygen delivery to eggs. Typical spawning sites measure a few m^2 in depths of water between ranging from 15-50 cm, in moderate to fast flowing areas of clear water (Hancock 1976; Baras 1994).

Males spend longer near to spawning grounds as they search for receptive females (Lucas & Batley 1996). Although hundreds of individuals can be observed simultaneously on the same spawning bed (Hancock *et al.* 1976), too many males per female or sub optimal habitat conditions reduce spawning success because there is an increased risk of damage to eggs, resulting in a high mortality rate. Where-as, a higher number of receptive females increase the reproductive potential of a male (Hancock *et al.* 1976), therefore females are the true limiting factor of barbel populations (De Vocht & Baras 2003).

Hancock *et al.* (1976) found that with regards to multiple males attending a single female, two or three were present during the most successful spawning attempts whereas attempts with six or more males, which were seen less often were not as successful in terms of releasing eggs and milt. During all attempts, Hancock *et al.* (1976) reported that males continuously changed position in the spawning group, suggesting an absence of a dominance hierarchy, but the observations of chase-away interactions between courting males is a characteristic of spatial competition and defence (Hancock *et al.* 1976; Baras 1994; Poncin *et al.* 1996). Post spawning, barbel exhibit no tendancies to hide or guard their eggs, nor any kind of parental care after hatching (Penaz *et al.* 2002). Females exhibited a quicker downstream movement than males over the summer months after spawning (Lucas & Batley 1996; Lucas & Frear 1997).

After spawning, high waters or increased flow can displace eggs from intra gravel spaces, but low waters expose eggs harden the cases and ultimately reduces successful hatching (Mann 1996). As well as this threat to survival, eggs and newly hatched larvae are at high risk from predation, directly affecting recruitment success.

2.6 Juvenile barbel

Most evidence suggests that the recruitment bottlenecks in most non-salmonid fish populations is poor spawning success and survival or growth of newly hatched larvae (Mills & Mann 1985). In temperate regions, recruitment is intimately dependent on reproductive success and environmental conditions faced by 0+ group fish until exogenous feeding, when vulnerability to lethal factors and environmental stressors is at its highest (Penaz 2001). This is a longer development process for barbel than most other cyprinids leaving them more vulnerable, influencing their chances to survive the first winter (Baras & Philipart 1999). Not a lot is known about the density-dependence of post-emergence behaviour in European cyprinids but there is some evidence to suggest that it exists in barbel populations (Penaz 2001). Incubation times are controlled by temperature and barbel larvae hatch after 5.4 days at 16˚C or 3 days 18 hours at 20.52˚C. There is poor hatching below 14˚C and turbidity also impedes gaseous exchange of eggs, therefore affecting hatching success (Mann 1996).

Once released from the protection of the egg, fish enter a new environment where oxygen demands are higher than at any other stage in their life history (Penaz 2001). Functioning sensory organs start to inform them about their environment which, induces specific behavioural patterns and spatial shifts, such as photophobia and orientation within the water column, associated with the search for dark interstices safe from predators (Penaz 2001) as initially, the larvae are photophobic (Balon 1975).

After hatching, the larvae initially resist displacement by the flow of water currents within the channel and attach themselves to vegetation using adhesive glands (Mann 1996; Penaz 2001). The drift of young fish from spawning grounds to nursery sites and those used for overwintering located downstream is important in the early ontogeny of riverine fishes such as barbel as it ensures their dispersal (Baras 1995; Penaz *et al.* 1992). In river systems, the dispersal of most fish species is greater for juveniles as they are less able, than older and larger species, to maintain their position in elevated water velocities (Lightfoot & Jones 1996). There are three recognised forms of downstream migration;

- passive – no orientation to current, most common form. Connected to either the physical inability of young fish to resist a current, or loss of orientation due to low visibility;
- active-passive – orientation to current;
- active – swim to chosen areas of the river channel.

The distribution and timing of fish larvae already drifting are influenced by secondary flow patterns, turbulence and buoyancy (Pavlov 1994) as well as temperature, velocity and light (Copp *et al.* 2002). Compared with other larvae, barbel exhibit the greatest tendency to aggregate (Bischoff & Freyhoff 1999). A study in the River Lee on downstream drift behaviour of fish found that a greater density of fish larvae were caught in areas where water velocities were highest and barbel drifted predominantly at night (Copp *et al.* 2002).

Species habitat relationships are an important aspect of community ecology and fish life history, particularly in early ontogeny (Copp 1992). The preferred habitats of 0 group fish are different for each species (Mann 1996) with shallow rivers the most important habitats for barbel larvae (Bischoff & Freyhoff 1999). Young barbel (<20 mm) are associated exclusively with the marginal zones and shallow bays with low flow, submerged and overhanging vegetation and no water current (Watkins *et al.* 1997; Bischoff & Freyhoff 1999). These offer refuge to larval and juvenile barbel from both high flows and predation present in the mid channel (Power 1987; Copp 1992a; Copp & Jurajda 1993). This change in habitat preference from marginal zones and slack waters to the centre of the channel with submerged vegetation supports the findings of Garner (1999) who found that 0 group cyprinids occupied larger areas of the river channel as they develop and are able to swim more efficiently. Alternately, Copp (1992) observed that microhabitat overlap between different larval stages increased at lower velocities in the upper River Rhone, concluding that water velocity was not a key determinant of larval distribution unless it was sufficiently high to displace larvae.

Other authors (Murphy & Eaton 1981, 1983; APEM 2009) suggested that vegetation cover, specifically water crowfoot may be an important factor governing mortality rates in juvenile fish. Watkins *et al.* (1997) revealed that bank slope, submerged vegetation, specifically water crowfoot, and cannel width were prominent variables influencing microhabitat use.

0+ fish during their first year of life go through a series of anatomical and corresponding physiological changes resulting in a shift in resource uses, and the potential to go through several meso-habitat shifts during their first summer (Bischoff & Freyhof 1999; Balon 1984). The movement of 0+ barbel juveniles to gravel bank habitats coincides with the completion of the fin apparatus which enables the fish to move more swiftly (Bischoff & Freyhoff 1999; Krupkra 1988).

Older (>0+) barbel prefer deeper waters over gravel bottoms further away from the bank without submerged vegetation (Watkins *et al*. 1997). The maximum sustainable swimming speed of barbel is a direct function of length (Bischoff & Freyhof 1999; Webb & Weihs 1986 & Mills 1991), Bischoff and Freyhoff (1999) found that almost all juveniles >59 mm were caught in riffle habitats and that individuals between 70-89 mm preferred discharge of up to 120 cumecs.

0+ and 1+ fish are infrequently encountered during sampling (Copp & Bennetts 1996), and studies on 0+ age class recruitment has revealed that barbel is under-represented in day time samples (Copp *et al.* 2002; Copp 2005). This is possibly due to dispersal behaviour under conditions of reduced light (Vizilli & Copp 2001), with the highest numbers found foraging close to the shore at dawn, dusk and night (Copp *et al.* 2005; Vizilli & Copp 2001) as predation risk from pike (*Esox Lucius* (L.)) and chub (*Leuciscus cephalus* (L.)), for example, is relatively high. The behavioural mechanisms of aggregation and dispersion play important roles in species-specific responses to variations in the altering environmental conditions and pressures (Pilcher & Parish 1993).

2.7 Physiology, morphology and anatomy

According to Philippart and Vranken (1983) barbel has an affinity for high-temperature with optimal growing temperatures between 14–23 ˚C. Below 13.5˚C, 0+ barbel stop growing (Baras & Philippart 1999), their first summer is therefore critical for survival. Calta (1998) noted that with barbel skeletal development, no calcification of vertebra was observed until day 4 of post hatch and with regards to gill development; lamellae were observable at day 3, the number increasing with age and size. Furthermore newly hatched barbel are considerably larger than chub (Calta 1998), the largely passive benthic mode with exclusively endogenous nutrition lasts longer with barbel than any other lithophilous species (Penaz 1973).

Adult barbel typically range between 50 and 100 cm (fork length), weighing between 1 and 3 kg. Larger adult fish can grow up to 1.2 m in length with weights rarely exceeding 6.4 kg. The species is slightly laterally compressed, lacking an adipose fin. The colouring of the fish is a dark brown or grey mottled appearance with a light coloured underside, the fins have a reddish tinge. The mouth of this fish has four large, long barbules and a down-turned gape, used to feel for food in the river bed. Sex of barbel cannot be determined externally, Lucas and Batley (1996) used a dental inspection mirror and minimal manipulation of the viscera, to inspect the gonads and determine the sex of the fish.

2.8 Food and feeding

Diurnal activities have a great influence on the feeding behaviour of individual barbel; a river temperature of 15˚C is ideal for foraging (Baras 1992, 1995a, 1995b; Lucas and Batley 1996). At temperatures greater than 20˚C activities are determined by behavioural thermoregulation and fish feed nocturnally to avoid the higher temperatures (Baras 1992).

Localised activity varies greatly on both diel and seasonal scales and is mainly associated with foraging (Lucas & Batley 1996). The movement of juvenile barbel to high velocity areas and profitable feeding positions may be adaptive behaviour (Bischoff & Freyhoff 1999). Foraging in riffles is cost effective for 0+ barbel because those habitats are highly productive and are used by many bottom dwelling and drifting benthic organisms, specifically Ephemeroptera nymphs, chironomid larvae and algae are the most important insect orders in the diet of 0+ barbel (Bischoff & Freyhoff 1999). As with other species, diet of barbel usually becomes more diverse as fish size increases (Mills 1985). Adults feed on benthic organisms including crustaceans, insect larvae, worms, elvers and lampreys. They find their prey in deeper areas of rivers with a rocky gravel or silt substrates and in vegetated areas, where the probability of finding macro-invertebrate prey items is higher. Baras and Cherry (1990) noted that feeding activities began around sunset, when fish left their resting place and travelled through pools and glides to close riffles or rapids, where they developed activities identified visually as feeding behaviour.

2.9 Growth

Determining the age of barbel and back calculating the length at age (Figure 2.3) has revealed that growth varies widely between river systems and female fish have been shown to grow faster than males (Hunt & Jones 1975; Hancock 1976; Philippart 1977).

Growth is density dependent, as illustrated by the rapid initial and subsequent slowing of growth of River Severn barbel (Churchward *et al.* 1984). Ultimate length also varies greatly between river systems: e.g. Bristol Avon - 776 mm; Hampshire Avon -1241 mm; Kennet -1366 mm; Stour - 854 mm; Thames - 844 mm; Severn - males 606 mm, females - 648 m (Craig Goch Research Team 1980). Age determination from scale readings from young fish is more reliable than older fish due to the closeness and poorly defined checks older samples (Hunt & Jones 1974).

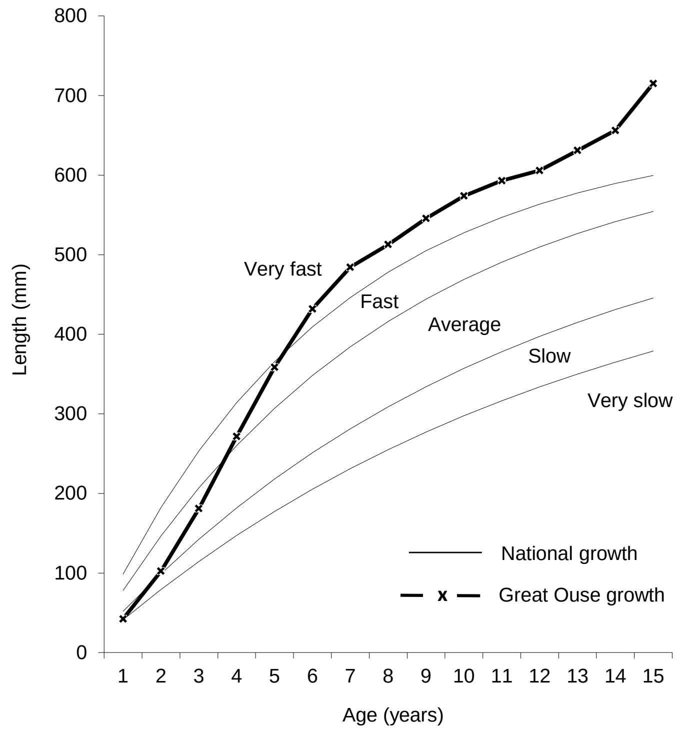


Figure 2.3. Curve to show variation in growth of barbel in the British Isles (Britton, unpublished data). Lines show the limits of ‘very fast’, ‘fast’, ‘average’, ‘slow’, and ‘very slow’ growth.

2.10 United Kingdom barbel population information

Information on the UK barbel population has been derived from data held in the Environment Agency’s National Fisheries Population Database (NFPD), the most comprehensive data set available derived from seine netting and electric fish sampling techniques. These data have been used to establish national and regional length frequency distribution, barbel catches and stocking events so that the population of barbel in Anglian region can be compared to the other regions supporting barbel populations within the UK.

2.10.1 National and regional length frequency distribution

Numbers of barbel (n) used to calculate the length frequency distribution graphs are not suitable for comparison due to differences in sample numbers and techniques. Nationally, individuals range from 14 to 885 mm (Figure 2.4). Regional length frequencies of barbel show similar length distributions (Table 2.1 and Figure 2.4). Wales, Anglian, Thames and North East Dales Regions had records of the smallest barbel, whereas Thames and Anglian Region had the longest lengths recorded. Few barbel between 250 and 400 mm in length have been caught in any of the regions assessed, suggesting an inefficiency in the fishing technique and/or location to capture a truly representative sample of the barbel population.

The occurrence of barbel in some rivers is due to stocking of farmed fish, specifically those in western England (Wheeler & Jordan 1990). Barbel have been stocked in large numbers since the 19th Century, usually between 10 to 20 cm in length, but in some cases they can be much smaller. Therefore, the presence of smaller fish is not necessarily an indication of natural recruitment. Between 2001 and 2009, the Midlands and North West of England have had the most barbel stocked into their rivers with over 58,000 individuals (Figure 2.5).

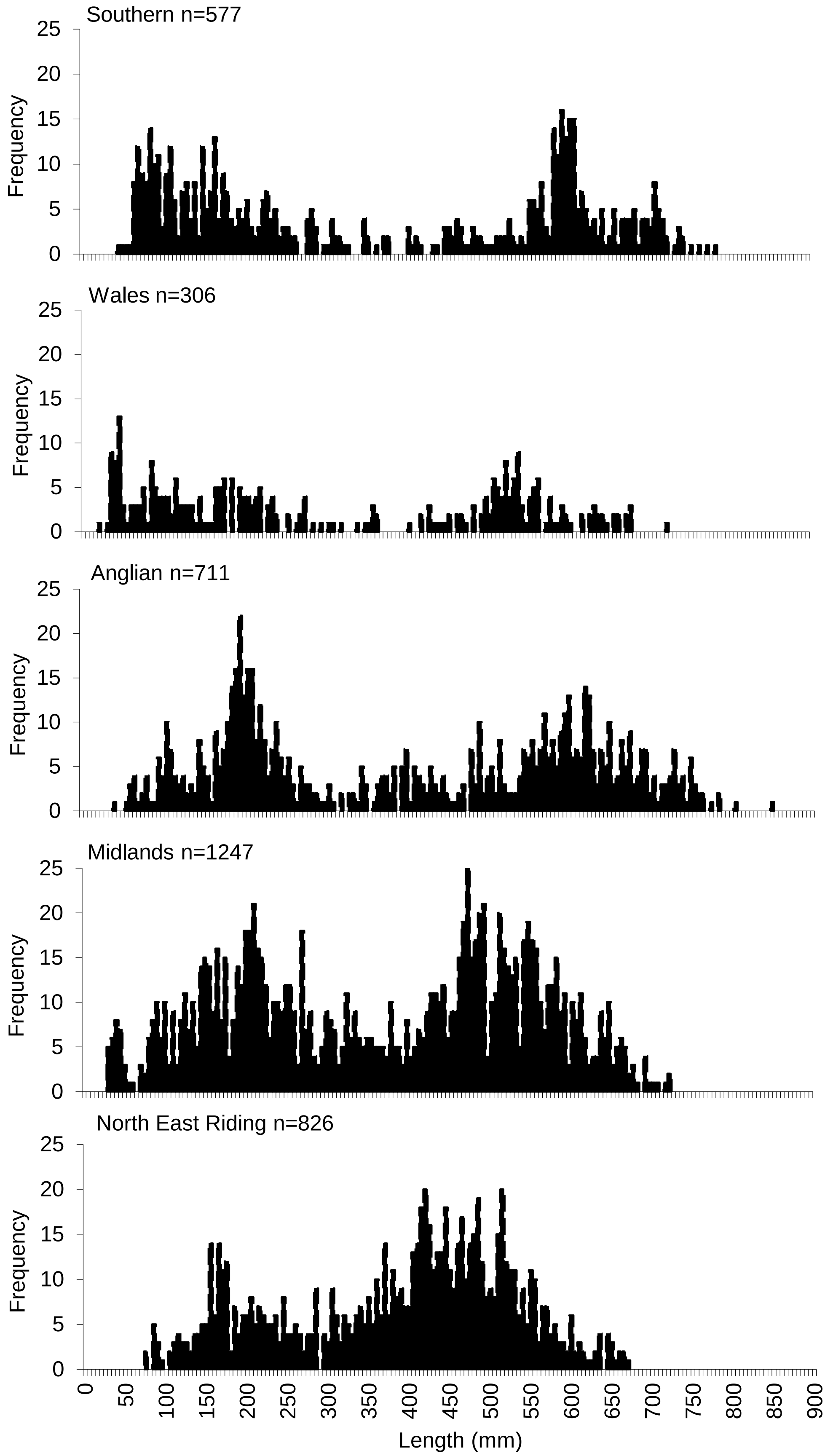


Figure 2.4. Length frequencies of barbel caught regionally in the Environment Agency fishing surveys from 1986 to 2010.

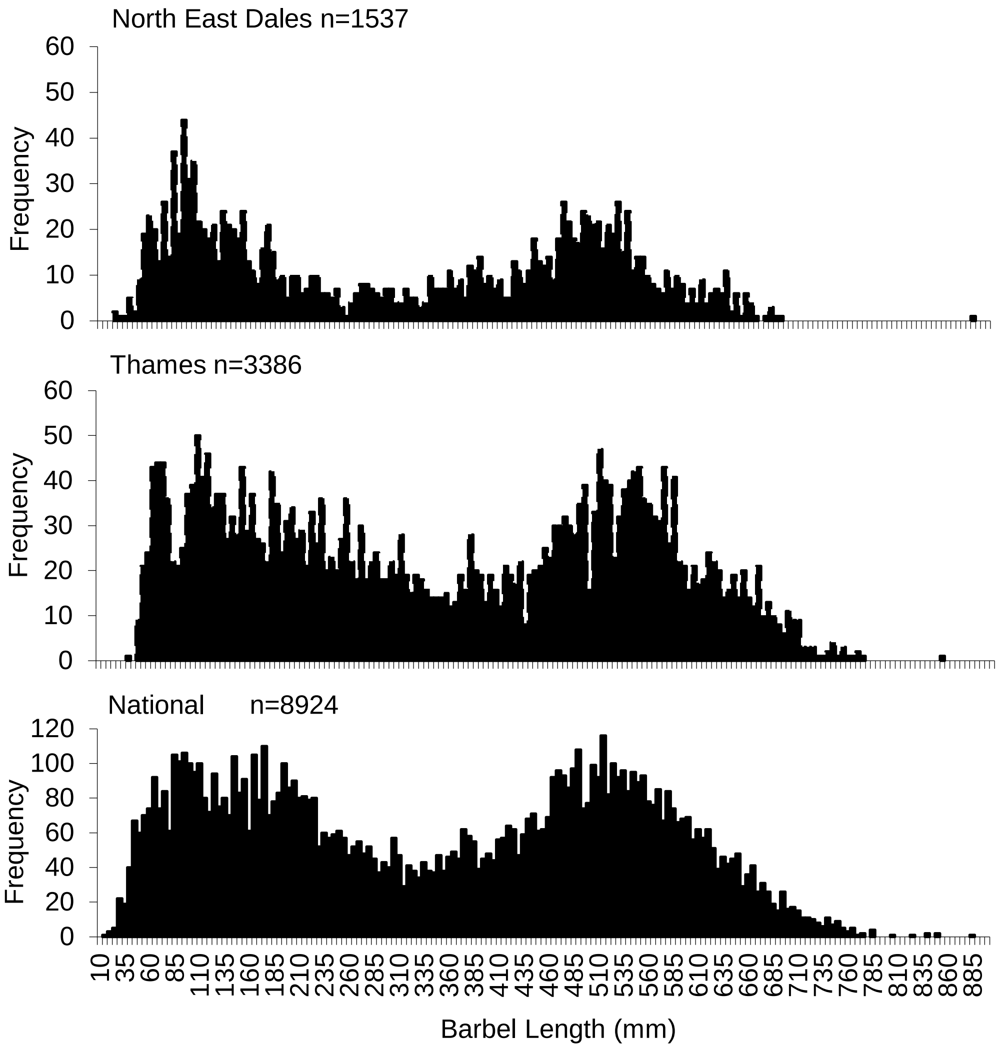


Figure 2.4 (continued). Length frequencies of barbel caught regionally in the Environment Agency fishing surveys from 1986 to 2010.

Table 2.1. Rivers included in each Regions fishing surveys from which barbel data was used, number of barbel caught and maximum and minimum lengths of barbel.

Region	Rivers	n	min – max (mm)
Southern	Medway	8924	14-885
	Bristol Avon	131	43-682
	Avon	303	47-785
Wales	Wey	167	45-725
	Wye	139	17-680
Anglian	Great Ouse	465	58-805
	Stour	130	108-728
	Wensum	47	36-850
	Witham	69	54-684
Midlands	Warwickshire Avon	283	70-710
	Dover Beck	74	81-264
	Derwent	185	42-700
	Meden	62	95-665
	Soar	74	137-703
	Trent	283	88-722
	Severn	286	28-721
North East Riding	Wear	57	92-669
	Calder	151	134-515
	Dearne	166	82-664
	Don	161	103-660
	Rother	291	75-650
North East Dales	Wharfe	378	42-660
	Ure	149	38-885
	Tees	299	26-635
	Swale	342	4-690
	Nidd	134	36-630
	Derwent	235	31-672
Thames	Colne	457	39-705
	Lee	1355	38-744
	Wandle	84	142-500
	Loddon	284	58-732
	Mole	127	62-684
	Thames	1079	29-847

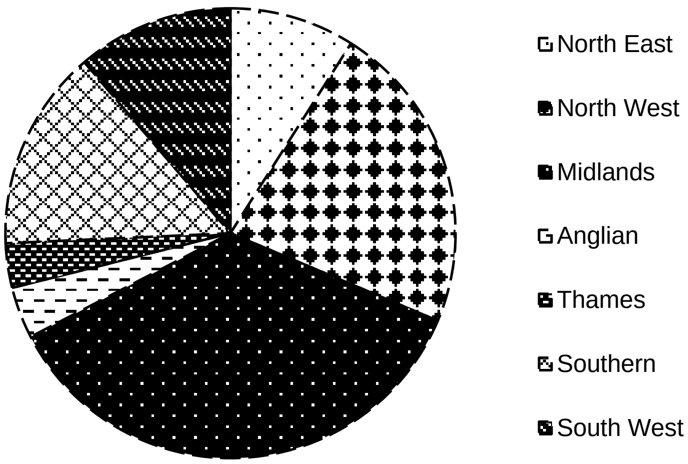


Figure 2.5. Regional percentages of barbel stockings into rivers 2000-2012.

2.10.2 National and regional barbel numbers

To standardise Environment Agency survey data, information from the National Fisheries Population Database (NFPD) were converted to average number of barbel caught per day fished. Data from some regions wasn't available until the mid 1990s, for example, in Southern and North East Dales. Southern, Wales, Anglian, Midlands, North East Riding and North East Dales barbel populations appear to fluctuate in a cyclical pattern (Figures 2.6), but there is not enough long term evidence to support this.

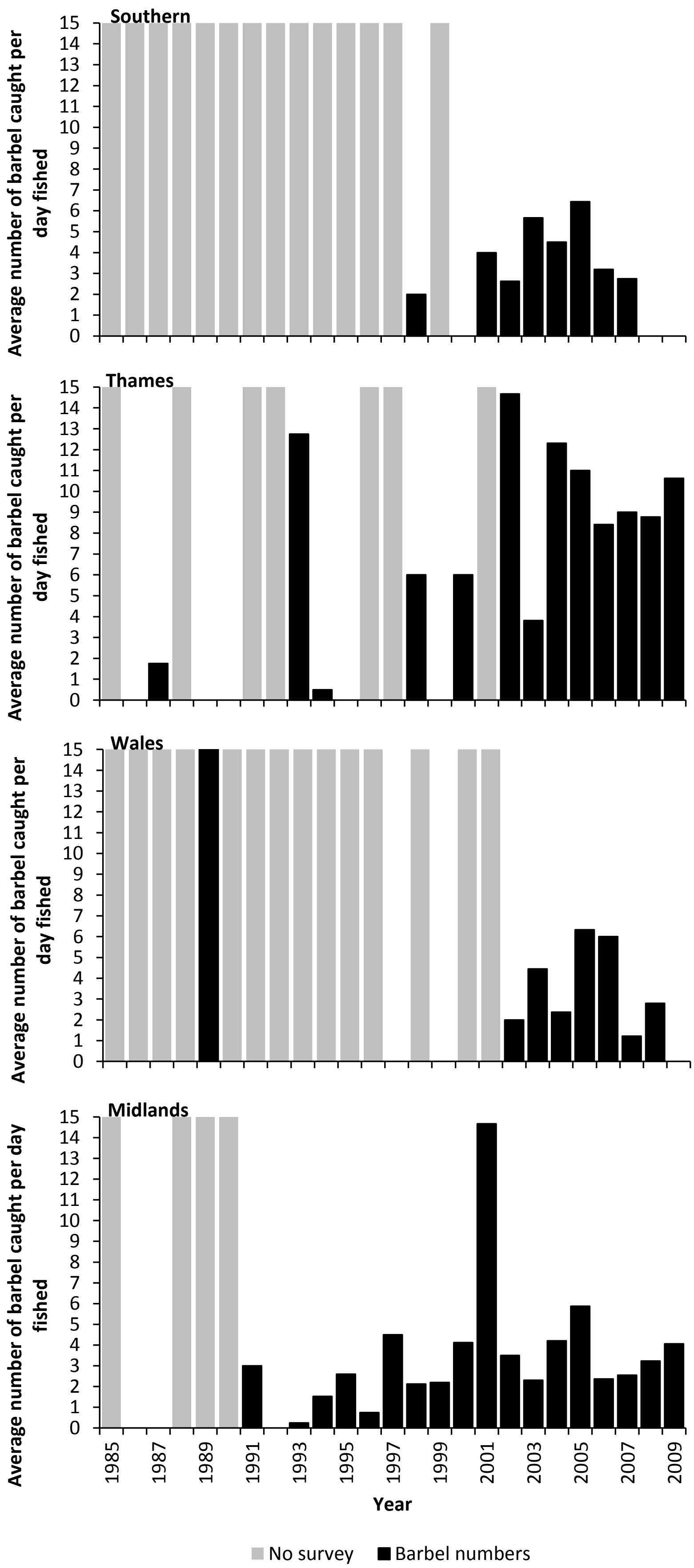


Figure 2.6. Average number of barbel caught per day electro-fished in each region during Environment Agency surveys.

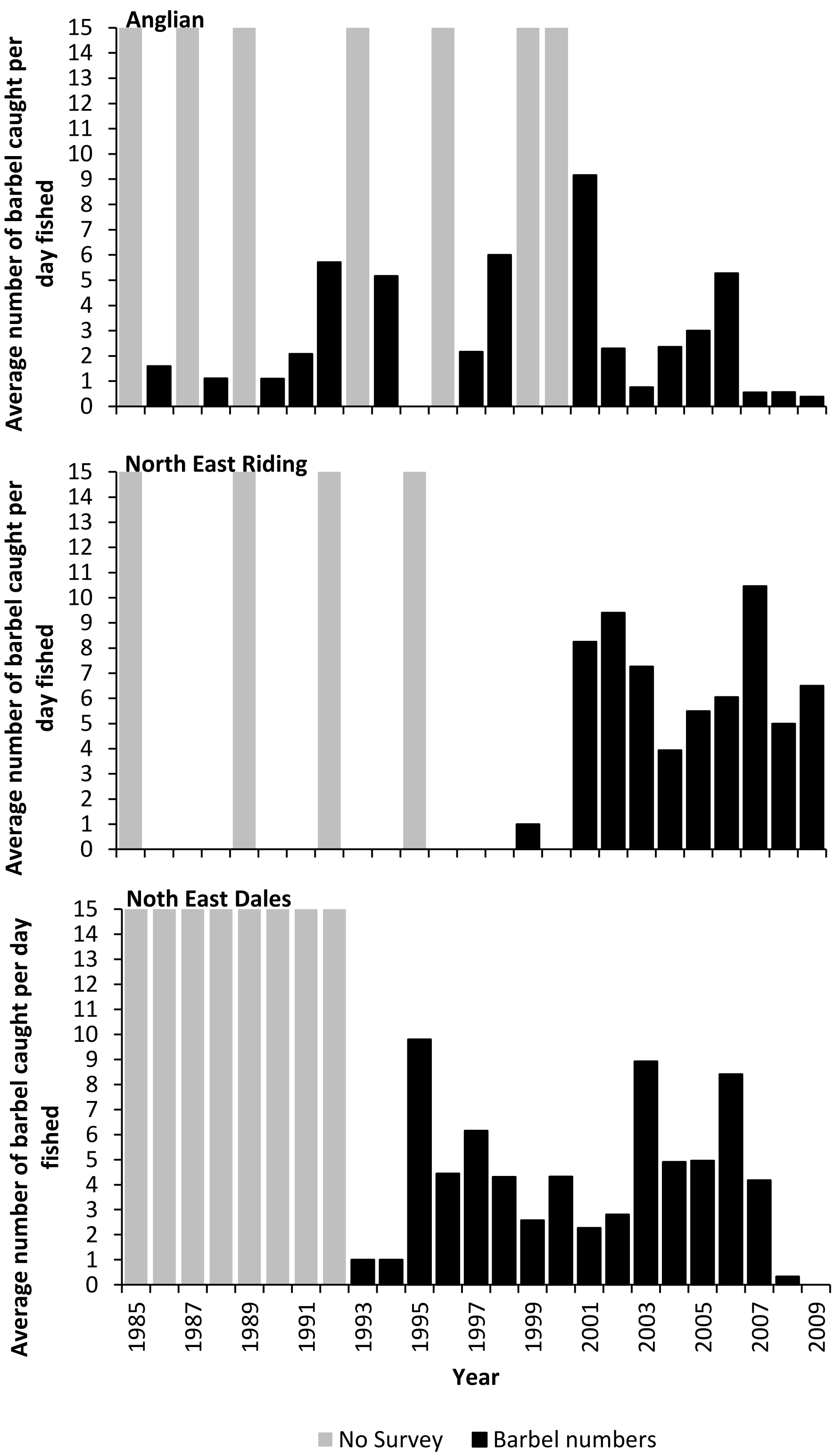


Figure 2.6 (Continued). Average number of barbel caught per day electro-fished in each region during Environment Agency surveys.

2.11 Great Ouse barbel population, length frequency distribution and species density

Information on the Anglian region barbel population has been derived from data held in the Environment Agency's National Fisheries Population Database (NFPD), the most comprehensive data set available. These data have been used to establish differences in length frequency distribution, barbel catches and stocking events so that comparisons can be made between the populations in Anglian rivers and between sites on the Great Ouse. Annual changes in length frequency and average densities have also been considered.

Compared to the other catchments within the Anglian region, the Great Ouse has the largest range of lengths and multi modal distribution (Figure 2.7). Within the Great Ouse catchment, the Upper Great Ouse and its two tributaries; Ivel and Ouzel, all had barbel ranging from approximately 55 to 810 mm in length. The New Cut, a site located near Bedford, lacked barbel greater than 500 mm according to surveys conducted there (Figure 2.8).

Average density (ρ) per year has been calculated to standardise electric fishing and seine netting. On occasions where triple run surveys were conducted, only run one data were used. In 82 electric fishing and seine netting surveys conducted by the Environment Agency on the Great Ouse, Ouzel and Ivel over a 23-year period, 506 barbel were caught. No data were collected in 1989, 1991, 1993, 1995, 1996 and 1998-2000 making it difficult to establish whether a definite cyclical pattern in barbel density exists. Data available suggest that there were peaks previous to 1988, in 1992 and 2002, following these years average densities have reduced (Figure 2.9).

Barbel has much lower average species density each year, compared with other major species (Figure 2.10): roach, which had the highest average density all years except 2001; perch and bleak, although average densities of this species were lowest between 2009-2011. Other rheophilic and or lithophilic species such as: chub; gudgeon (with the exception of 2006 and 2010), bullhead and dace, also have lower average densities than the dominant species. Compared with the rest of the fish community, average densities of barbel are notably lower in 1988, 1991 and 1997; and higher in 1992, 2001, 2003 and 2005 (Figure 2.10).

Annual changes in length frequencies for the whole of the Great Ouse Catchment show that although found in low numbers in 1988, from 1997 onwards barbel ranging from 300 to 400 mm were either missing or underrepresented in catch data (Figure 2.11), these size ranges correlate to individuals of four to five years of age.

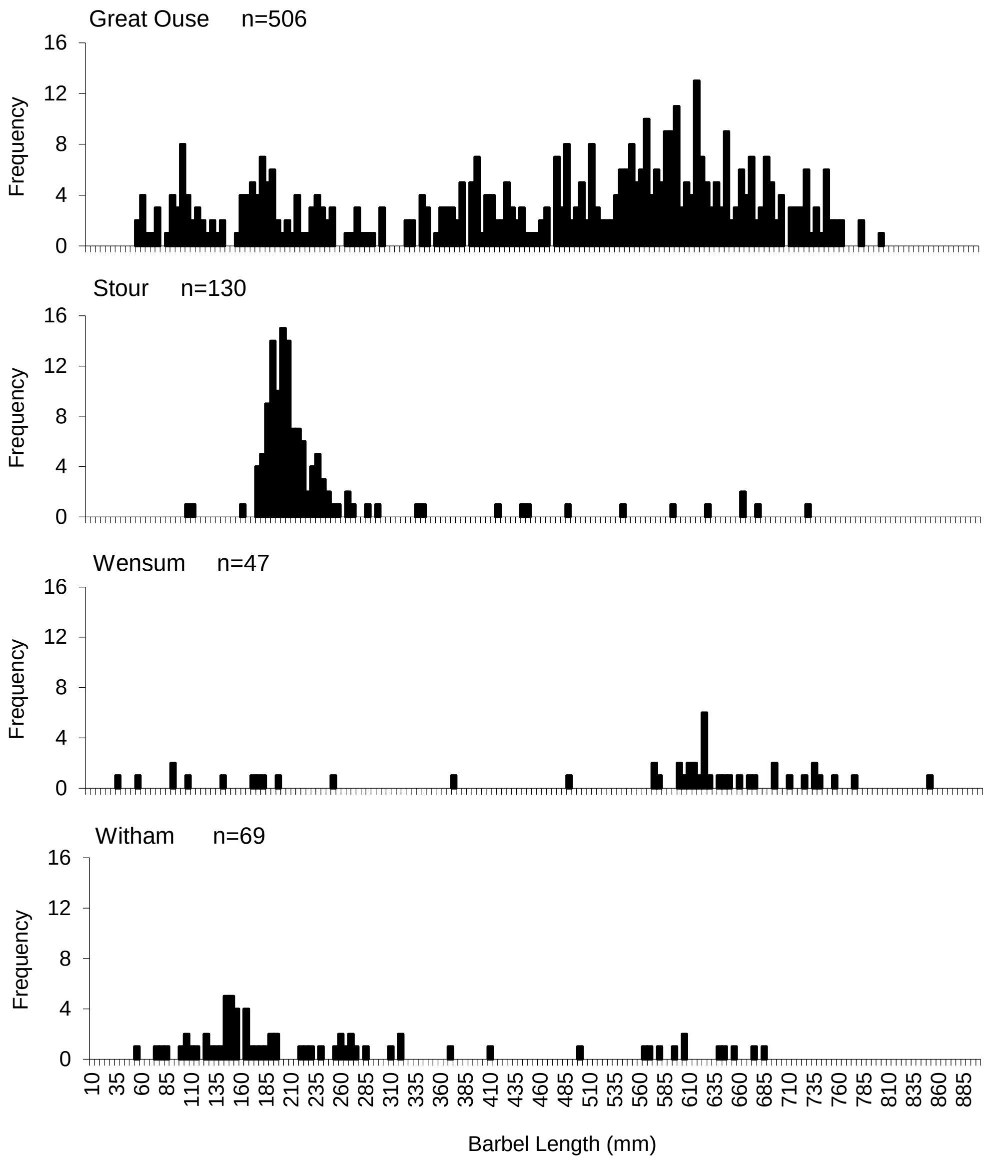


Figure 2.7. Length frequency distribution of barbel in each catchment in the Anglian Region.

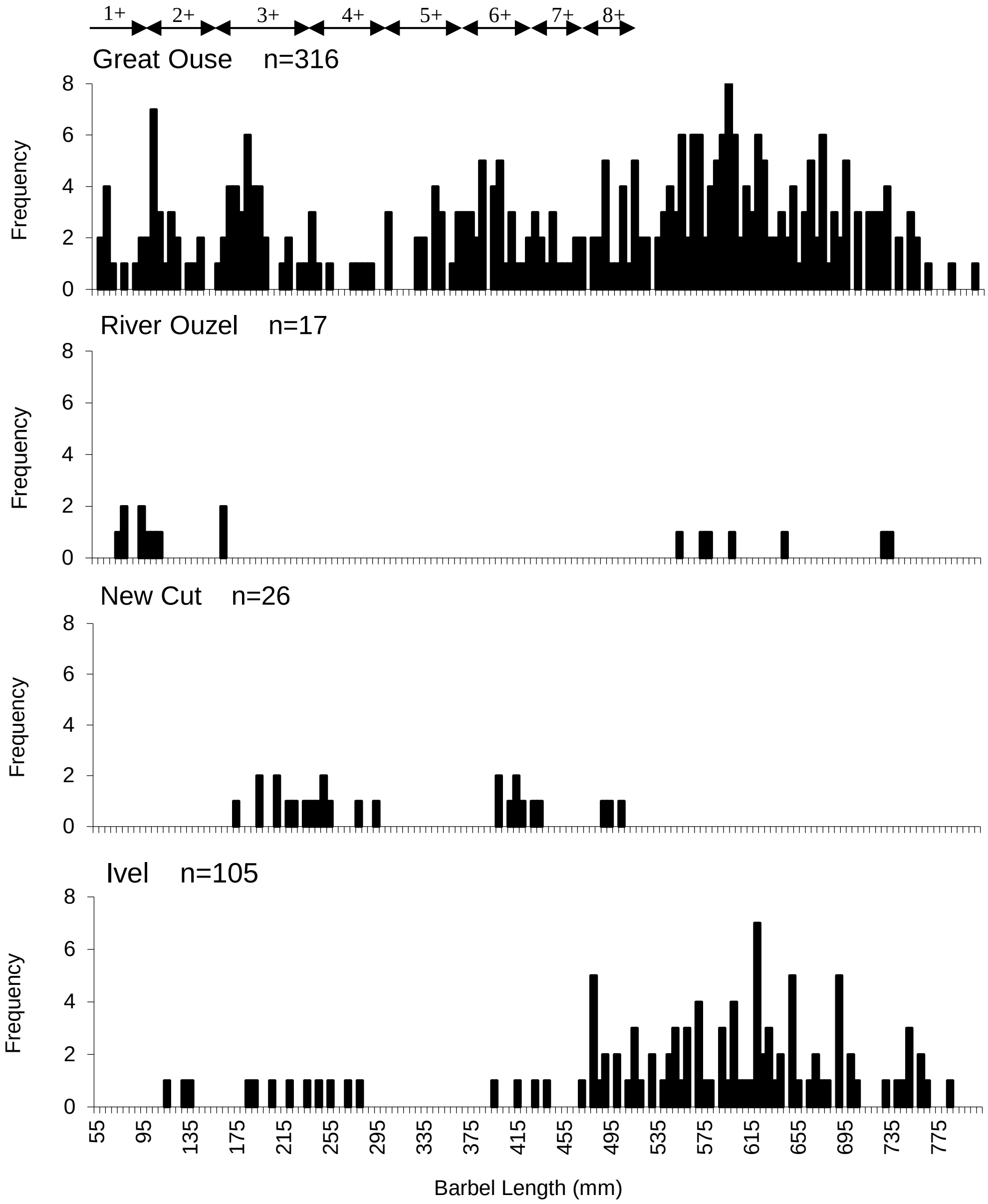


Figure 2.8. Length frequency distribution of barbel in the Great Ouse and its tributaries. 0+ to 8+ age ranges depicted by arrows.

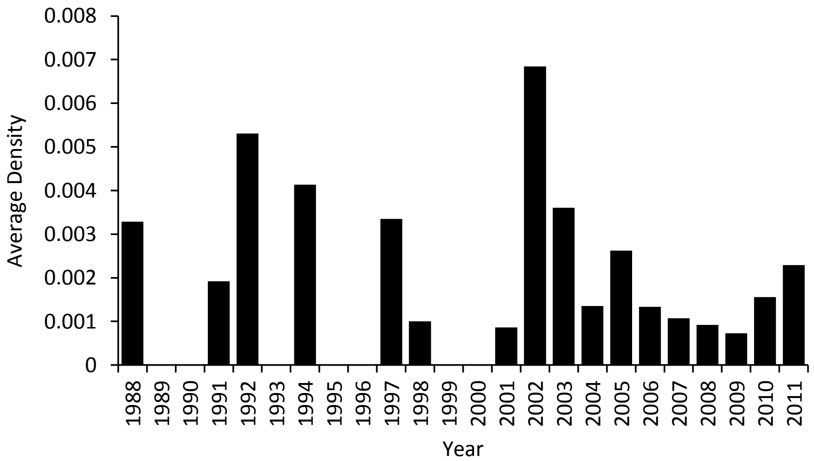


Figure 2.9. Annual average densities of barbel caught by the Environment Agency 1988 - 2011.

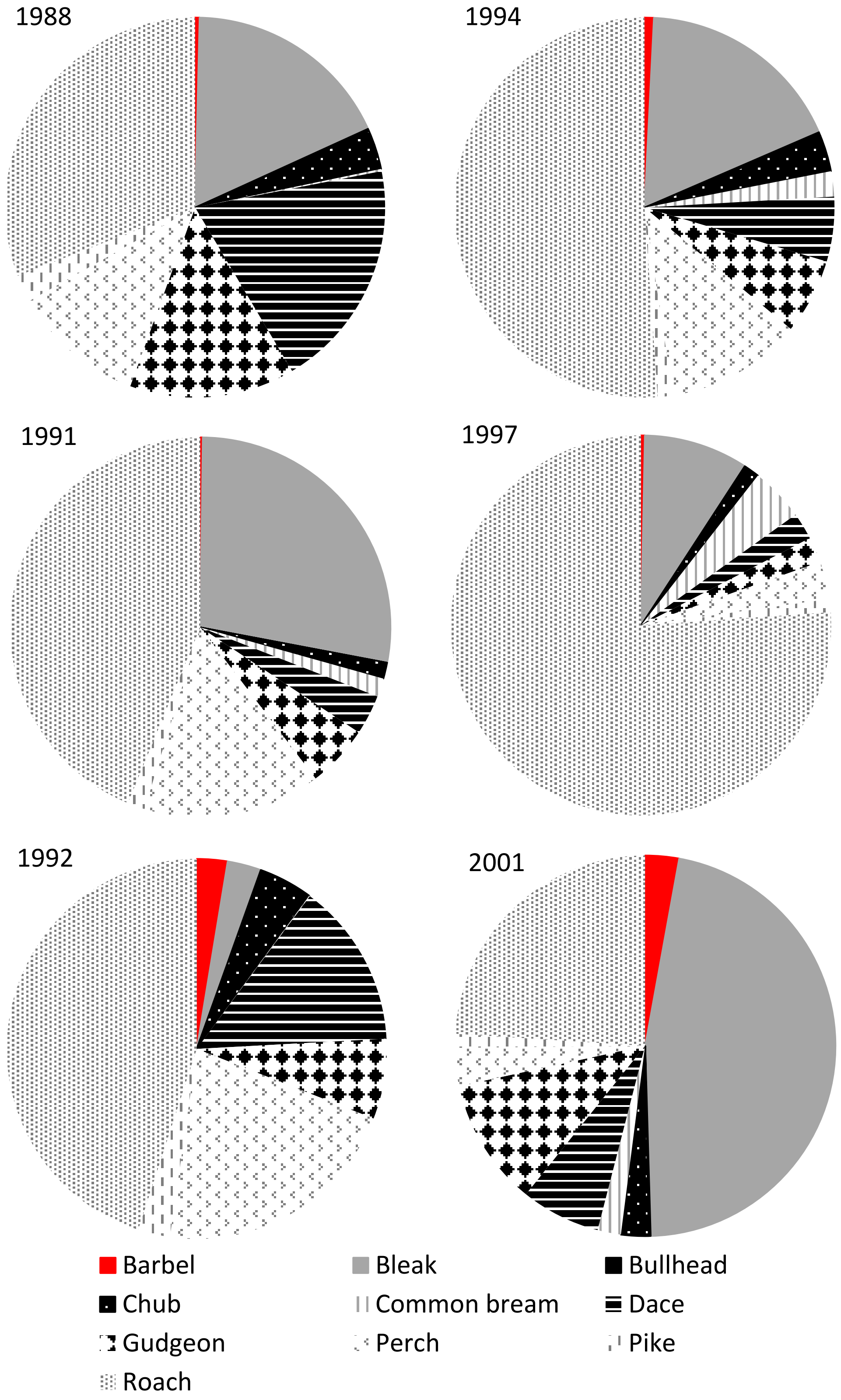


Figure 2.10. Average densities of major fish species caught in the upper Great Ouse between Newport Pagnell and Bedford.

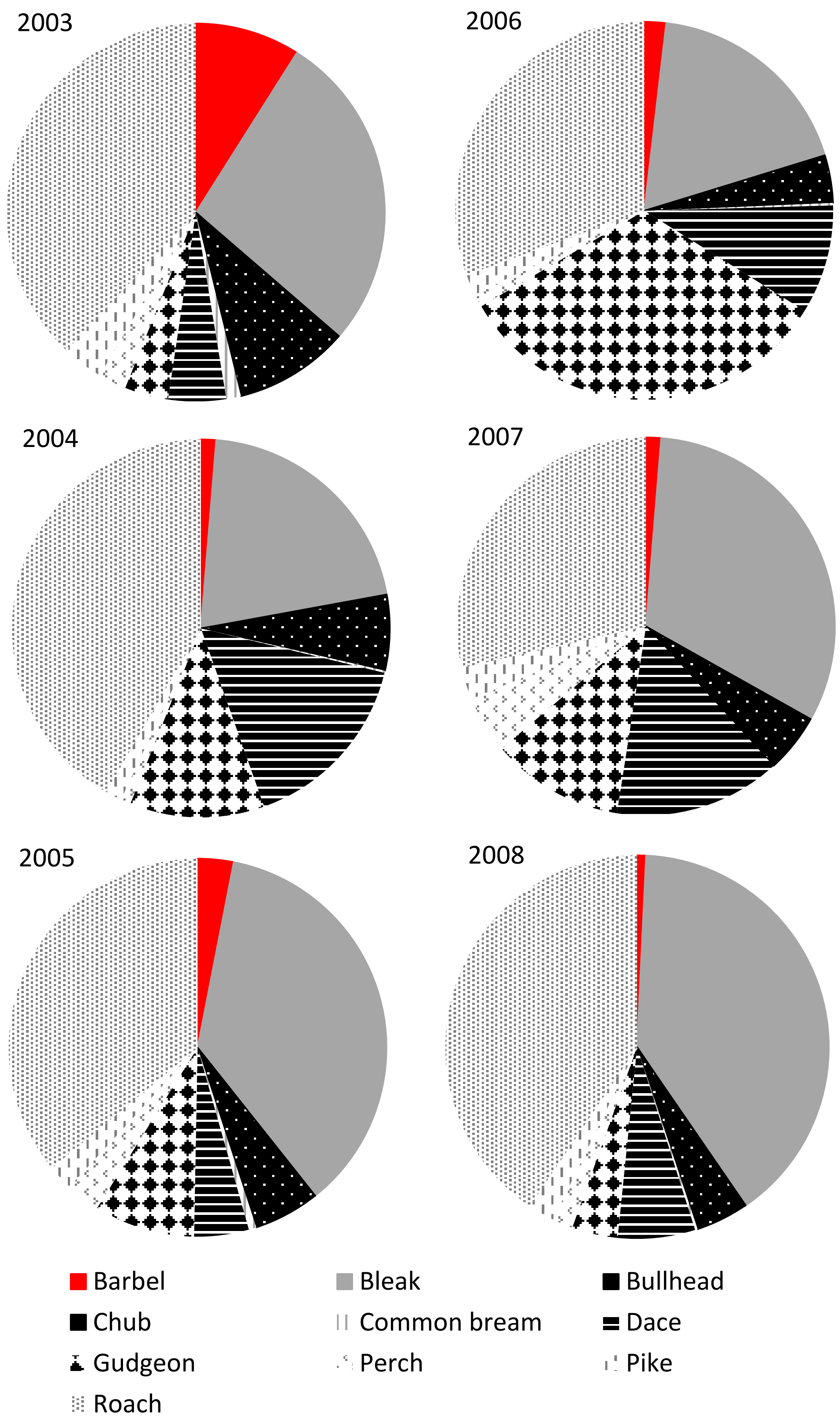


Figure 2.10 (continued). Average densities of major fish species caught in the upper Great Ouse between Newport Pagnell and Bedford.

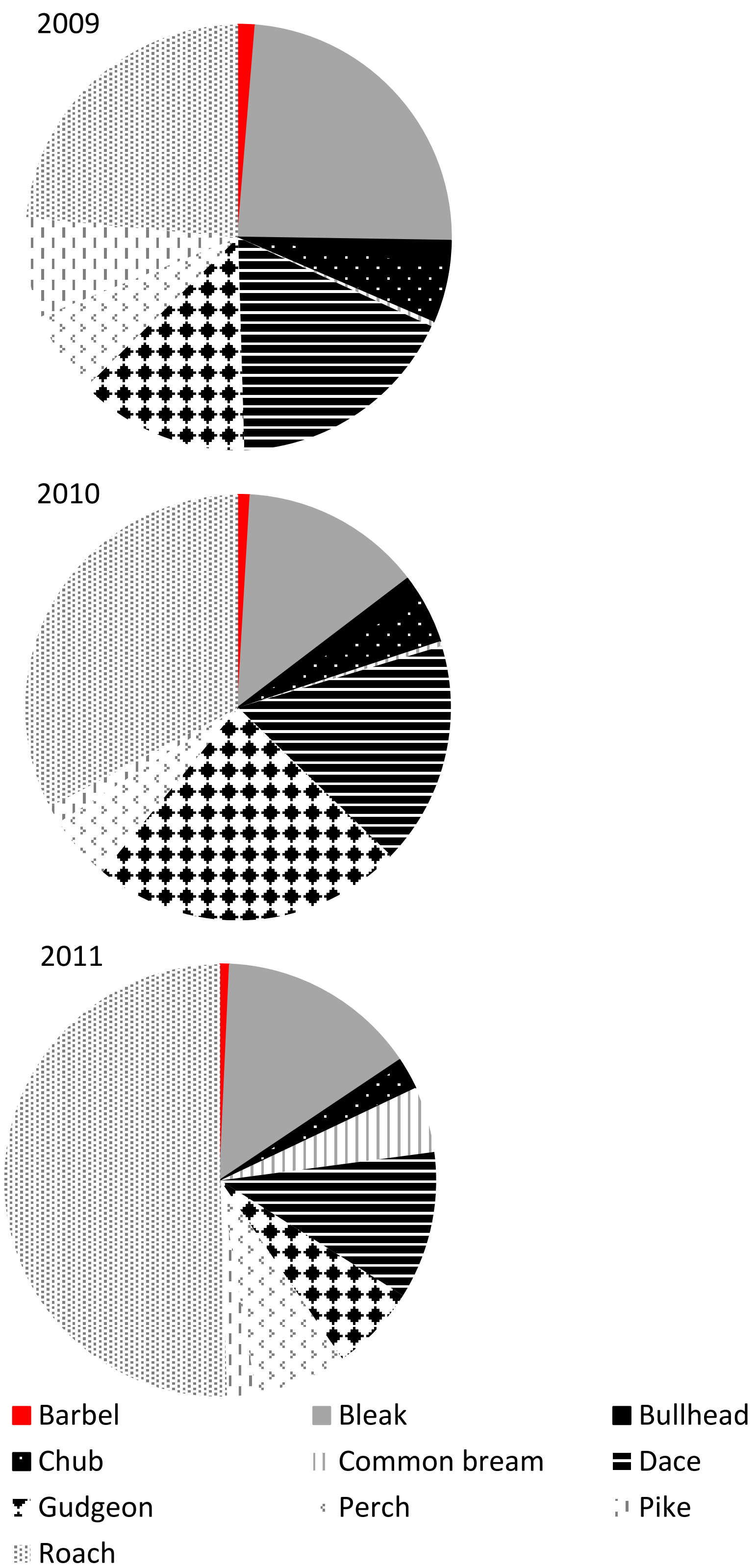


Figure 2.10 (continued). Average densities of major fish species caught in the upper Great Ouse between Newport Pagnell and Bedford.

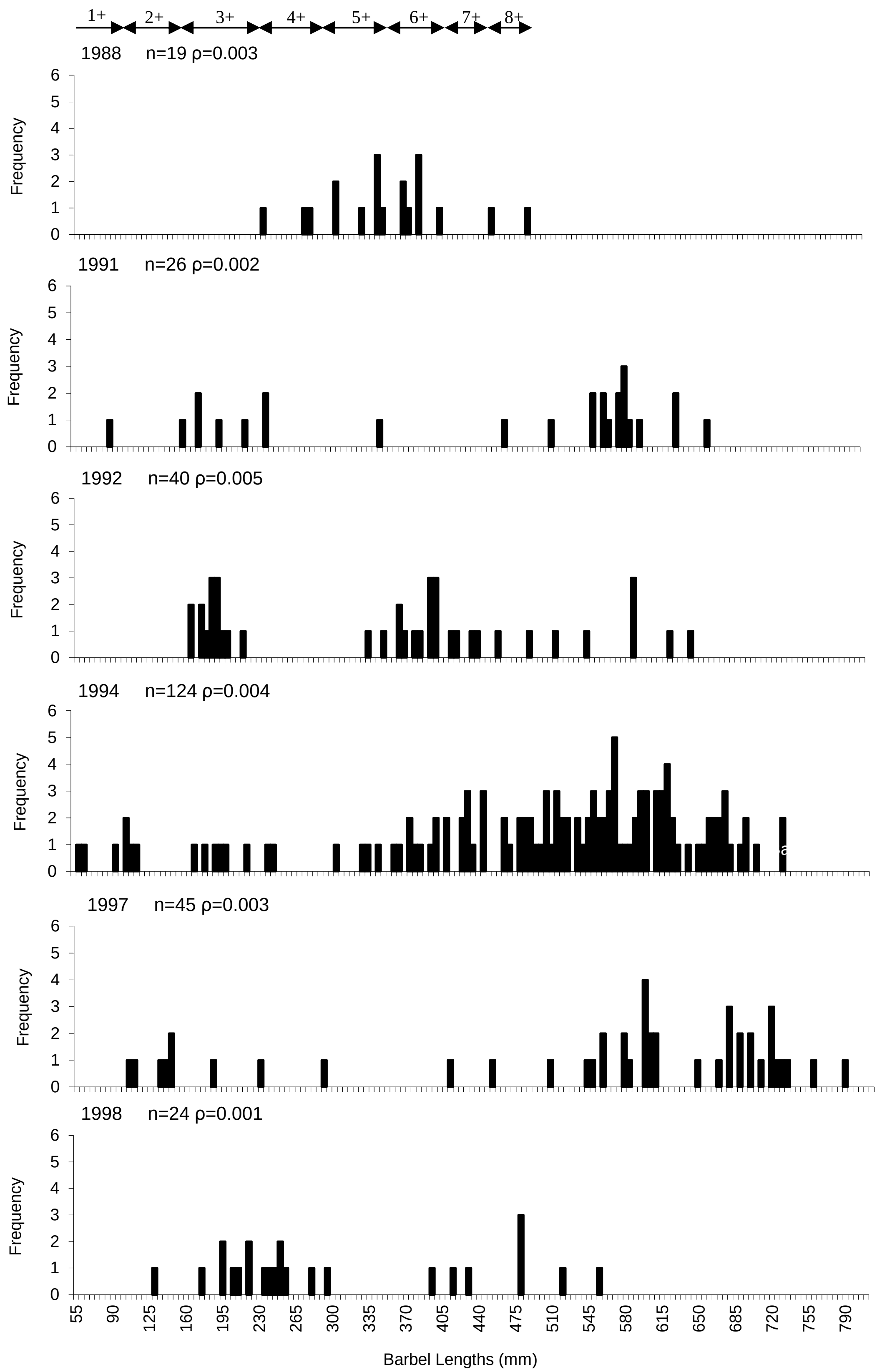


Figure 2.11. Annual Length frequency distributions of barbel in the Upper Great Ouse, between 1988 and 1998. 0+ to 8+ age ranges depicted by arrows.

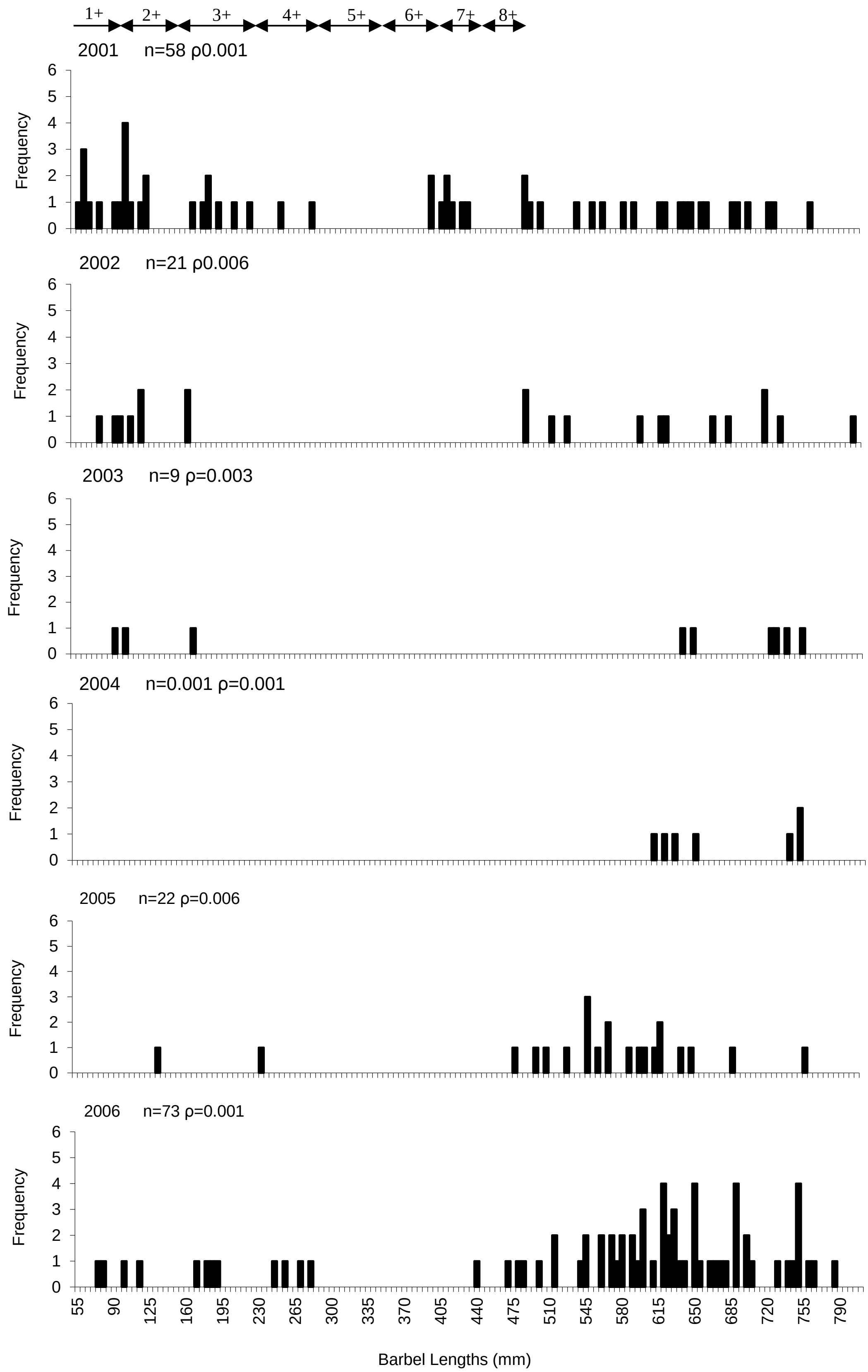


Figure 2.11 (Continued). Annual Length frequency distributions of barbel in the Upper Great Ouse, between 1999 and 2006. 0+ to 8+ age ranges depicted by arrows.

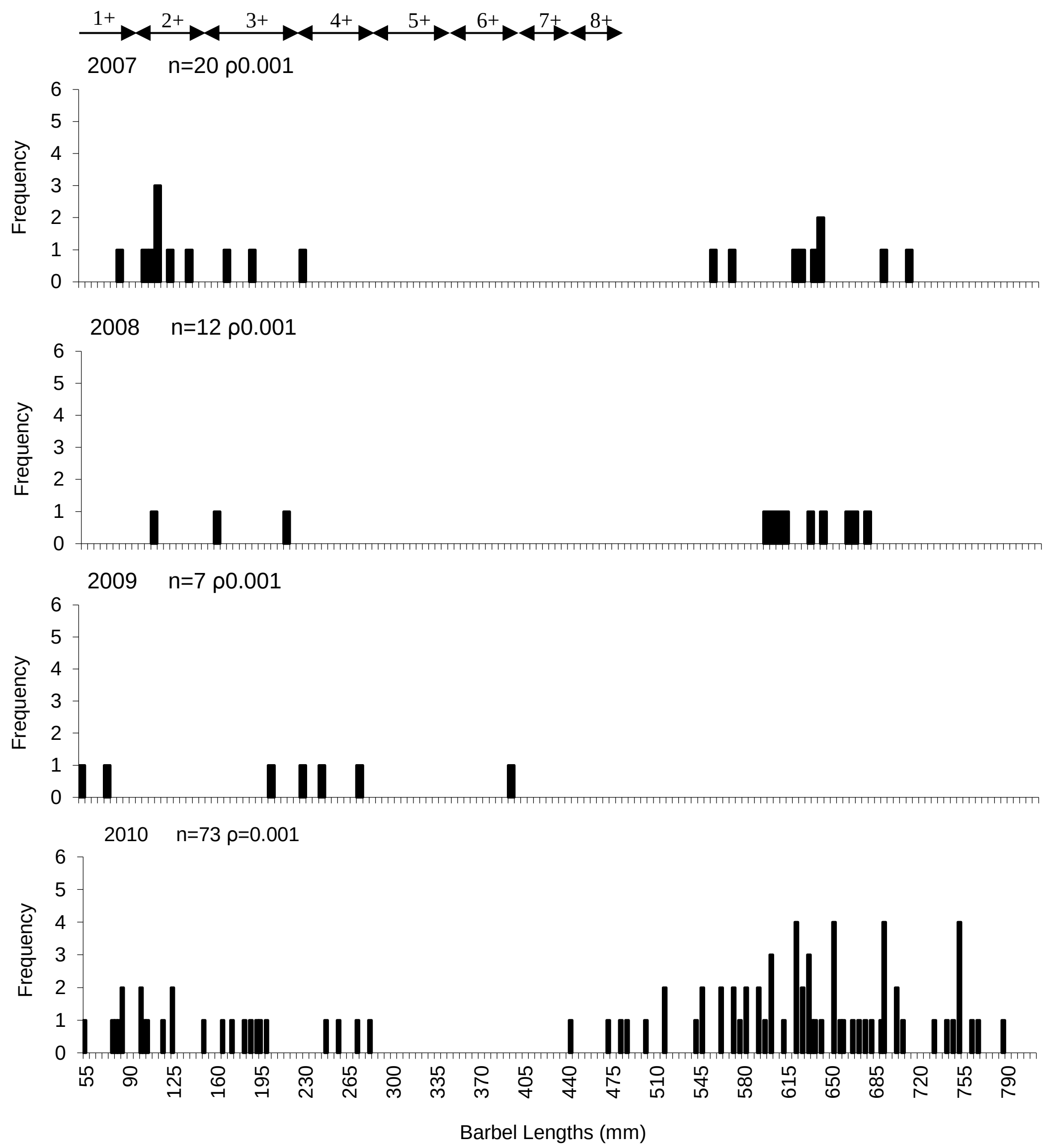


Figure 2.11 (Continued). Annual Length frequency distributions of barbel in the Upper Great Ouse, between 2007 and 2010. 0+ to 8+ age ranges depicted by arrows.

Inter-site differences in length frequency (Figure 2.12) and average density (Figure 2.13) of barbel in the Great Ouse are visible. Mill Farm and Newport Pagnell had size ranges from 50 to 805 mm, Radwell had the lowest average density. Odell had the second highest average density, but with no barbel larger than 600 mm and Radwell had the second lowest average density, with no fish smaller than 540 mm. Turvey had the highest average density and a unimodal distribution of barbel around a mode of 600 mm.

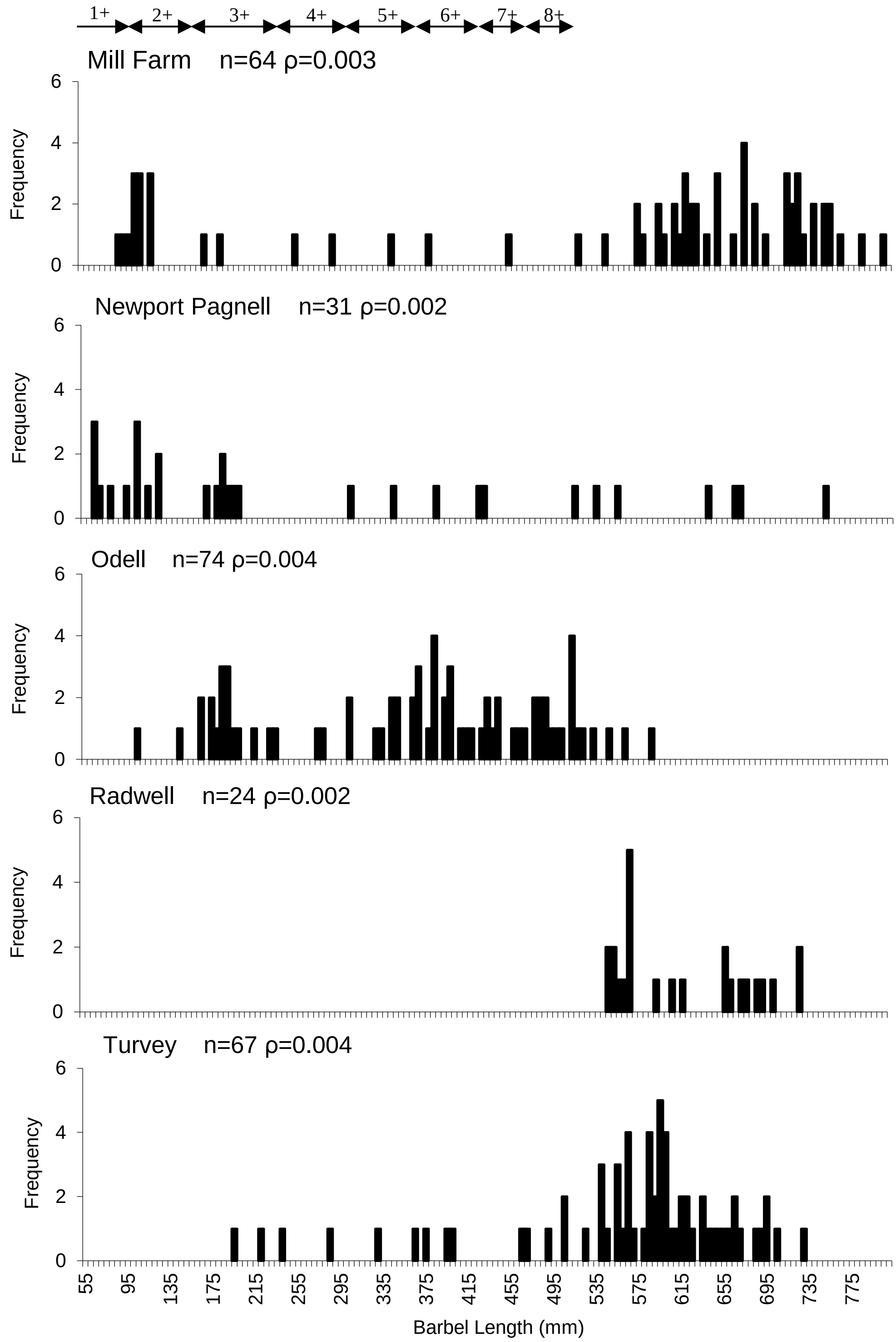


Figure 2.12. Length frequency distribution of barbel in the Great Ouse and its tributaries. 0+ to 8+ age ranges depicted by arrows.

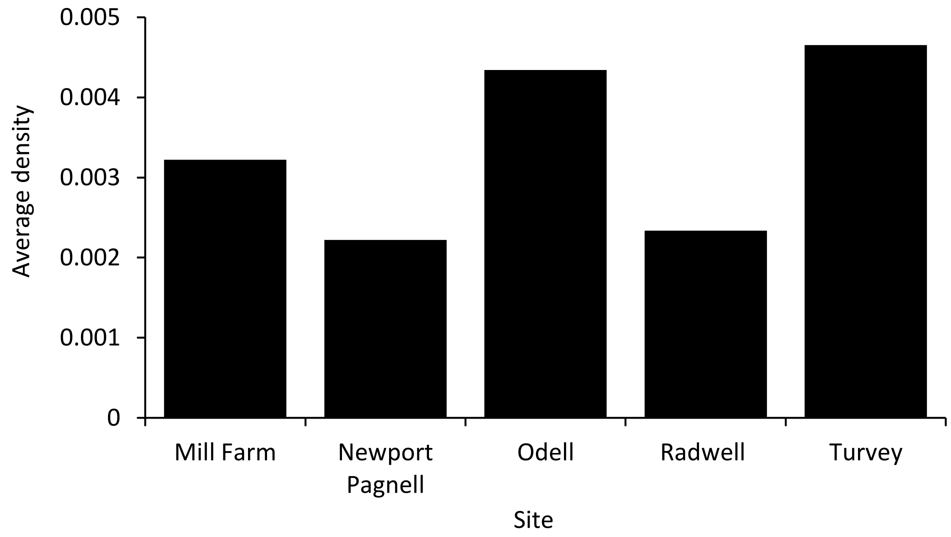


Figure 2.13. Average desity per site on the River Great Ouse from 1988 to 2011.

2.12 Recommendations

From this review of literature, it is recognised that methodologies previously used with regards to barbel ecology in European rivers, such as radio telemetry, larval drift and habitat use (Hunt & Jones 1974; Baras & Cherry 1990; Baras 1997; Vilizzi *et al.* 2006; Ovidio *et al.* 2007; Copp *et al*. 2002) could be applied to the Great Ouse to increase the understanding of barbel ecology specifically in this river. The literature review also identified a number of gaps in the knowledge of barbel ecology, which would help with the conservation of the species. Some of these, such as predation at different life stages are recommended for further research:

- **Predation on eggs and larvae by crayfish** – radio tracking crayfish during the weeks before the barbel spawning season will show if their movements are synced with the increased availability of food resources (Bubb *et al.* 2002; Bubb *et al.* 2006). It may also be possible to use RNA-DNA analysis for the stomach content of locally caught crayfish to establish the percentage composition of barbel in their diet (Scalici & Gibertini 2007).
- **Predation by cormorants –** analysis diet selection of cormorants to understand the impact that they are having on the local barbel population, using the methodologies of Sutter (1997), Wolter & Pawlizki (2003) or Stewart *et al*. (2005).

Selected topics are discussed in the thesis, such as the ones listed below:

- **Quality of available spawning habitat** – analysis and comparison of spawning habitats, this could include the use of experiments to assess biofilms, hyporheic water quality and fine sediment infiltration more commonly associated with salmonid species.
- **Sampling strategies targeting young barbel** – comparison of a range of fishing methodologies currently used by and novel to the Environment Agency, that have proved successful elsewhere.
- **Prey selection of young barbel** – assessment of the diet of young barbel in the wild, on: spatial; temporal and developmental scales.
- **Climate –** assessment of the effects of temperature on the behaviour and biology of barbel.

3. THREATS TO THE GREAT OUSE BARBEL POPULTATION

3.1 Introduction

The presence of barbel in rivers indicates high quality river habitat (Environment Agency 2007b) and although natural fluctuations may account for some of the variability of barbel populations over time (Frear & Cowx 2003), the species is under pressure from a range of factors and they are becoming increasingly threatened (Penez *et al.* 2002).

Barbel are a long lived species that mature late and as a result, changes in their population structure caused by habitat pressures can take many years to become apparent. The decline of barbel numbers in rivers has been noticed in UK rivers such as the Great Ouse and the Thames, where although not on the UK biodiversity priority list (UK BAP 2001), they are "considered by the Environment Agency to be of local biodiversity importance" (Vizilli *et al.* 2006). In some rivers throughout central Europe, such as Poland (Witkowski 1991) and Czech Republic (Penaz *et al.* 2005) the barbel is also regarded as a threatened species. Concerns about the species population arise from the fact that it is sensitive to pollution and to physical alterations of the stream ecosystem. This is especially true for rivers that have been and still are, affected by: fragmentation; regulation; water quality; habitat quality and climate change, all previously mentioned in Chapter 2.

This Chapter aims to review available information and consider the biological, chemical, morphological status of the Great Ouse, to identify the most likely pressures on barbel recruitment with a view to use this information to design studies to target specific issues relevant to the catchment. In addition, this chapter gives the relevant background information relating to these pressures on the study sites selected for this research.

3.2 The River Great Ouse

With an approximate area of 8600 km^2, the catchment of the River Great Ouse is one of the largest in the country (Pinder *et al.*1997), draining approximately 7% of England (Cowx *et al.* 2004), covering most of Bedfordshire and Cambridgeshire and parts of seven other counties (Neal *et al.* 2000). The Great Ouse has a total length of approximately 250 km flowing through low lying land. The river rises in the Jurassic limestone of central England (Pinder *et al.* 1997), 7 km northwest of Buckingham and 150 m above Ordnance Datum (Cowx *et al.* 2004). It flows in a general north east direction through Bedford, Huntingdon and Earith where it has been divided into two flowing sections, one artificial and one natural. The New Bedford and the Old Bedford Rivers collectively known as the Ouse Washes, maintain the drainage of the Fens and prevent the majority of the water flowing towards the City of Ely. The natural channel flows eastward past Ely, and the channels re-join at Downham Market and flow to the Wash at Kings Lynn and into the North Sea. The major tributaries of the Great Ouse are: the Ivel, Cam, Little Ouse, Lark, Thet and Wissey (Figure 3.1).

The major towns and cities along the length of the Great Ouse and its catchment include; Buckingham, Bedford, Cambridge, Thetford and Kings Lynn (Figure 3.1). Major roads such as the M1, M11 and the A1, A1 (M), alongside rail links, all allow easy access between locations. Nonetheless, the distribution of towns has been influenced by river access at a time when water travel was heavily relied upon. Nowadays these waterways are still used for recreational boating.

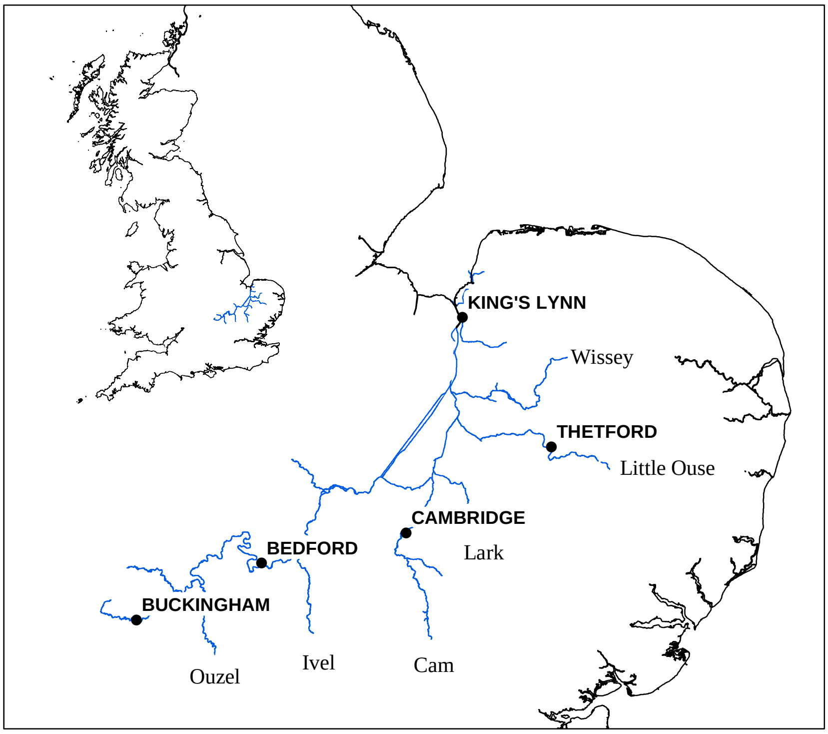


Figure 3.1. The location of the River Great Ouse in the UK and the major towns (●) and tributaries along its length.

During the first half of the 20th Century, the Great Ouse was regarded as one of the premier mixed recreational fisheries in England (Pinder *et al.* 1997) with over 30 species of freshwater fish being recorded in the catchment (Mann 1997; Bass *et al.* 1997). Now, it is dominated heavily by small roach, and many species, notably common bream, have declined substantially in abundance (Pinder *et al*. 1997) with concerns over other charismatic fish species such as barbel.

3.3 Concerns for barbel in the River Great Ouse

The Water Framework Directive (WFD, EU 2000/60/EC) established a strategic framework to enhance the status and prevent further deterioration of aquatic ecosystems. Classification for the WFD takes into consideration the biological status (inclusive of: fish, invertebrates, phytobenthos and macrophytes) and chemical status (inclusive of: dissolved oxygen, ammonia, phosphate and pH) to determine the ecological status of rivers. According to the WFD fish classification, some reaches of the Great Ouse and tributaries have been classified as having ‘high’ ecological status but the majority of the Great Ouse main channel is classified as having ‘moderate’ to ‘good’ ecological status. The study reach used for this project has been classified as having ‘good’ (Figure 3.2). Invertebrates are an important food source for species such as barbel. The WFD classification for invertebrates in the Great Ouse is ‘High’ and ‘Good’, with many of the tributaries ‘Moderate’ and relatively few considered to be ‘Poor’, these are in the upper reaches of tributaries (Figure 3.3).

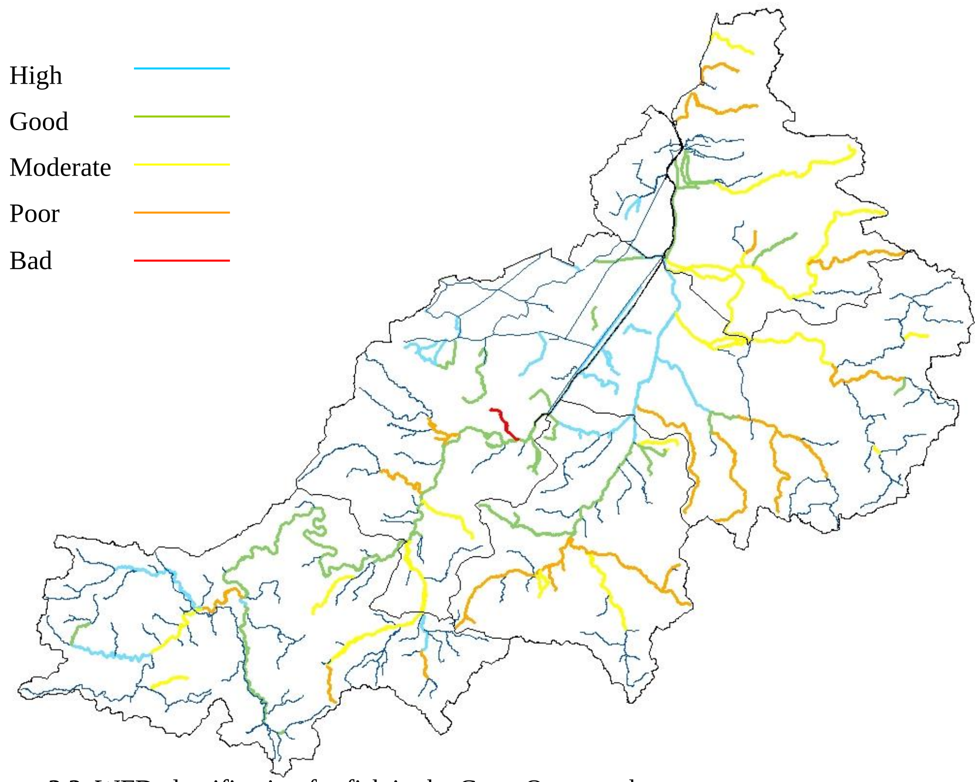


Figure 3.2. WFD classification for fish in the Great Ouse catchment.

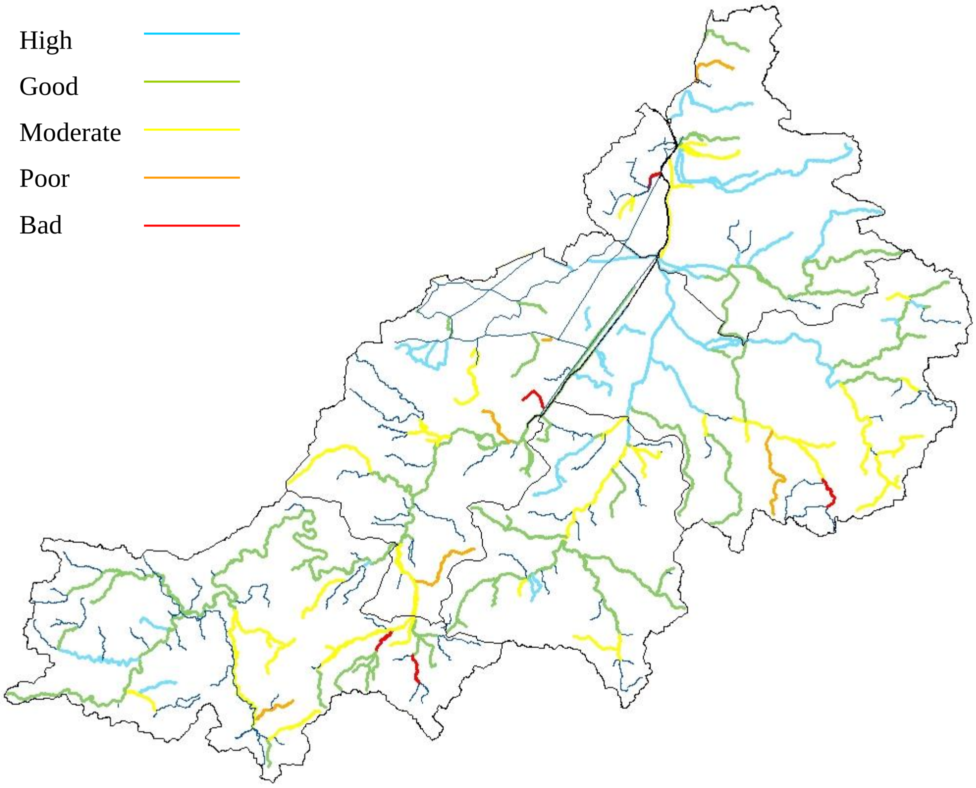


Figure 3.3. WFD classification for invertebrates in the Great Ouse catchment.

3.3.1 Fragmentation of longitudinal connectivity and flow regulation

Considerable morphological pressures have occurred over the previous centuries within the Great Ouse catchment such as land claim, physical barriers, aggregate dredging and canalisation associated with navigation, drainage and flood control (Linfield 1981; Ward *et al*. 1983; Pinder *et al.* 1997). Examples of these alterations can be found on the Bedford Ouse, from upstream of Newport Pagnell to Earith, where the river has been progressively impounded, regulated and canalised to facilitate navigation, land drainage, flow control and to provide a water supply for the many mills that the river once supported (Pinder *et al*. 1997). There are very few river stretches in the catchment that are not considered to be at risk from morphological pressures (Figure 3.4).

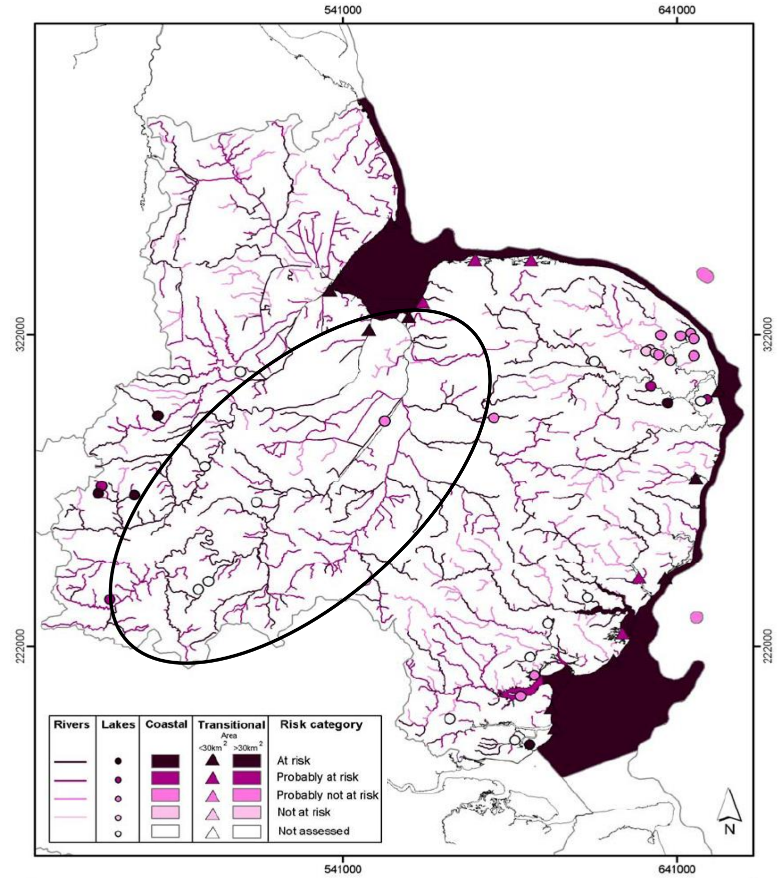


Figure 3.4. Morphological pressures in the Anglian region, circled area identifies the Great Ouse catchment.

There are a high number of barriers to fish migration throughout the Great Ouse catchment, along the main river and the tributaries. On the Upper Ouse, from the headwaters to St Ives, where the majority of barbel inhabit there are approximately 80 barriers (Figure 3.5). The negative effects of such impoundments are magnified by further reductions in water quality, habitat disruption (Ovidio & Phillippart 2002), and altered flows.

The Great Ouse catchment is one of the driest catchments in the United Kingdom, receiving relatively low amounts of rainfall (Neal *et al.* 2000) to replenish ground water and reservoir storage, resulting in more water abstraction from the river (Figure 3.6). Water is for the most part abstracted for domestic usage in addition to vegetable washing, food processing, concrete/brick manufacture, irrigation of neighbouring farmland, sand and gravel washing (Cowx *et al.* 2004). Water removed from this system is also transferred into neighbouring catchments (Neal *et al.* 2000).

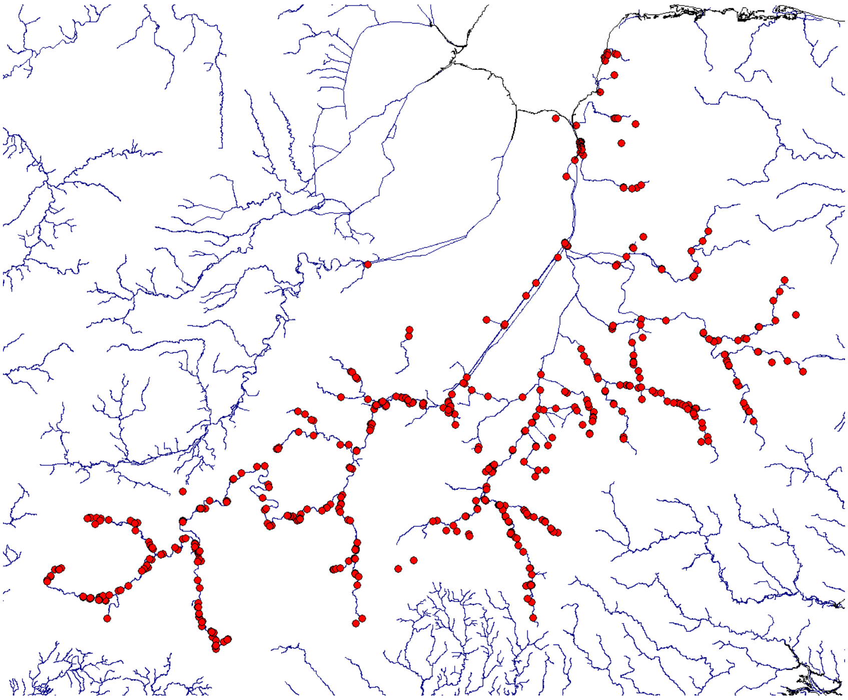


Figure 3.5. Barriers in the Great Ouse catchment.

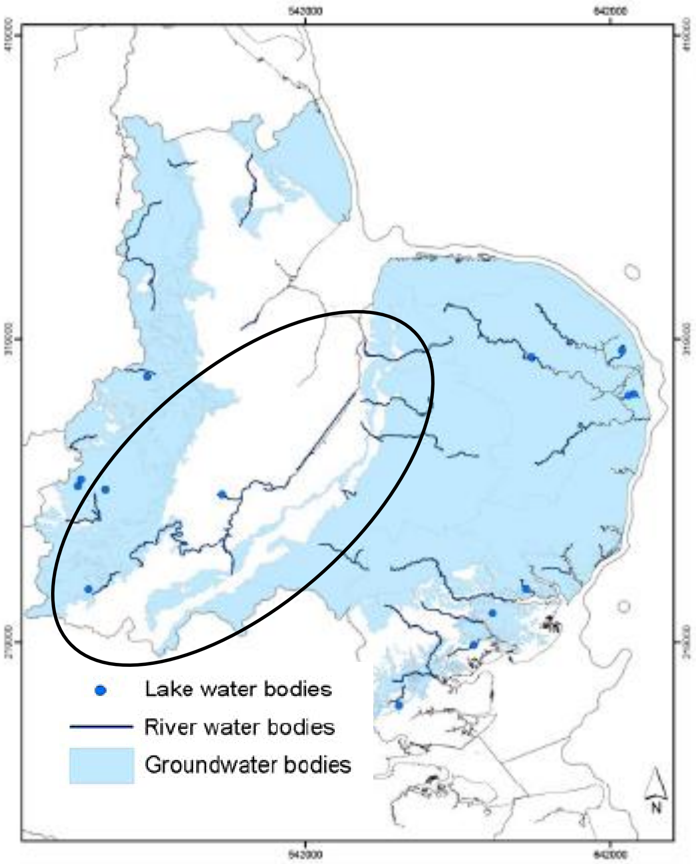


Figure 3.6. Waters used for the abstraction of drinking water in the Anglian region. The circled area highlights the Great Ouse catchment.

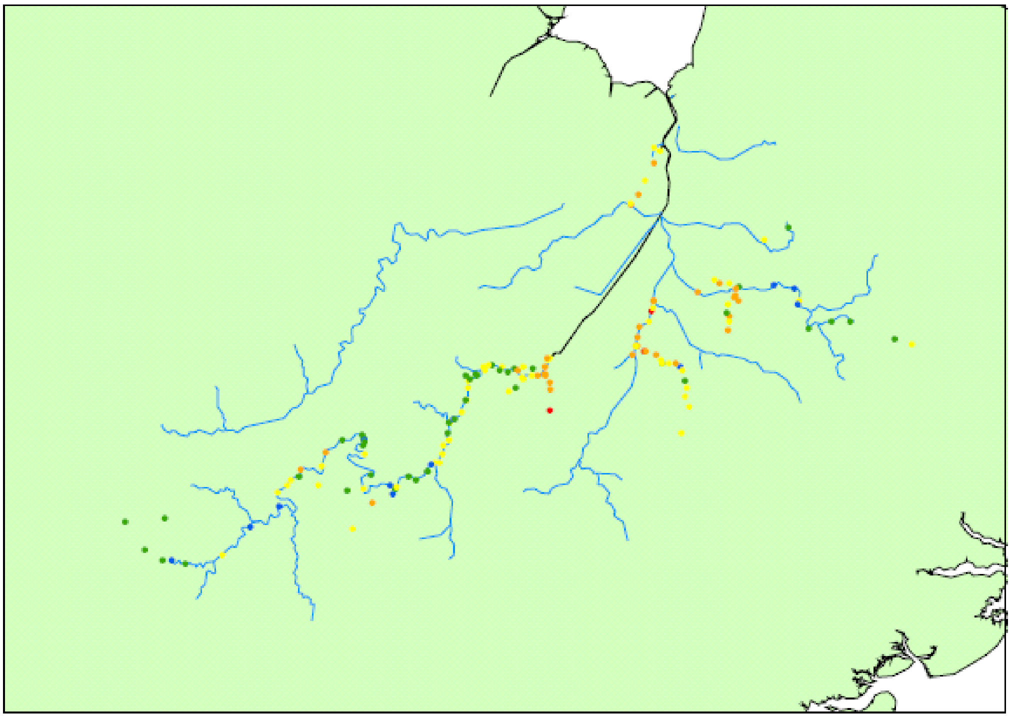
3.3.2 Physical habitat

It is important to understand the needs of the species within the river, species habitat relationships are an important aspect of community ecology and fish life history, particularly in early ontogeny (Copp 1992). For barbel, good spawning, hatching, nursery and appropriate flows are important for successful recruitment and strong year classes. These habitats are detailed in Chapter 2.

The Habitat Quality Assessment (HQA) aspect of the River Habitat Survey (RHS) data collected for the EU funded STAR Project includes a systematic framework for the collection and analysis of rivers. Information recorded is based on;

- Channel substrate
- Habitat features
- Aquatic vegetation types
- Complexity of bank vegetation structure
- Point bars
- Land use
- Trees
- Associated features
- Riffles
- Pools
- Special features

The upper Ouse has the highest habitat quality in the catchment, with the exception of some of the tributaries in the east (Figure 3.7).



High = ● Good = ● Moderate = ● Poor = ● Bad = ●

Figure 3.7. Habitat Quality Analysis output for the Great Ouse catchment.

3.3.3 Water quality

As with elsewhere in north-western Europe, the British landscape has changed dramatically over the past century, largely through the intensification of agriculture (Pretty *et al.* 2003). The Great Ouse continues to be subjected to inputs of discharge from industry, agriculture and sewage treatment works. As a result there are numerous influxes of poor water quality and chemical imbalances that are a consequence of these facilities, and as a result there is an absence of older fish (Ovidio & Philippart 2002).

The Great Ouse system is majorly impacted by agriculture (Neal *et al.* 2000), primarily arable farming (Figure 3.8) for products such as wheat, sugar beet, barley and oats, in addition to market gardening nearer the coast. The lower part of the Great Ouse catchment is low-lying fenland and, as a consequence of drainage work that took place during the 17th Century, the Fens have been transformed from wetland with raised islands of clay, into some of the most productive arable land in the UK. There is also light industry in the major towns of Bedford, Cambridge and Milton Keynes (Neal *et al.* 2000). Unfortunately, it is widely acknowledged that in general, intensive farming reduces habitat diversity and quality to the detriment of some terrestrial and aquatic wildlife (Benton *et al*. 2002; Robinson & Sutherland 2002).

High concentrations of pollutants decrease with increasing flow in response to dilution of point and groundwater sources by rainfall. However, for elements and compounds such as barium and nitrate, concentrations increase with flow, indicative of increased surface runoff from agriculturally impacted soils (Neal *et al.* 2000). After floods, as the flood waters recede, nutrients and organic matter from the floodplain are funnelled back into the main channel, side channels and back waters along with newly produced biomass such as fry, larvae, invertebrates and plant matter.

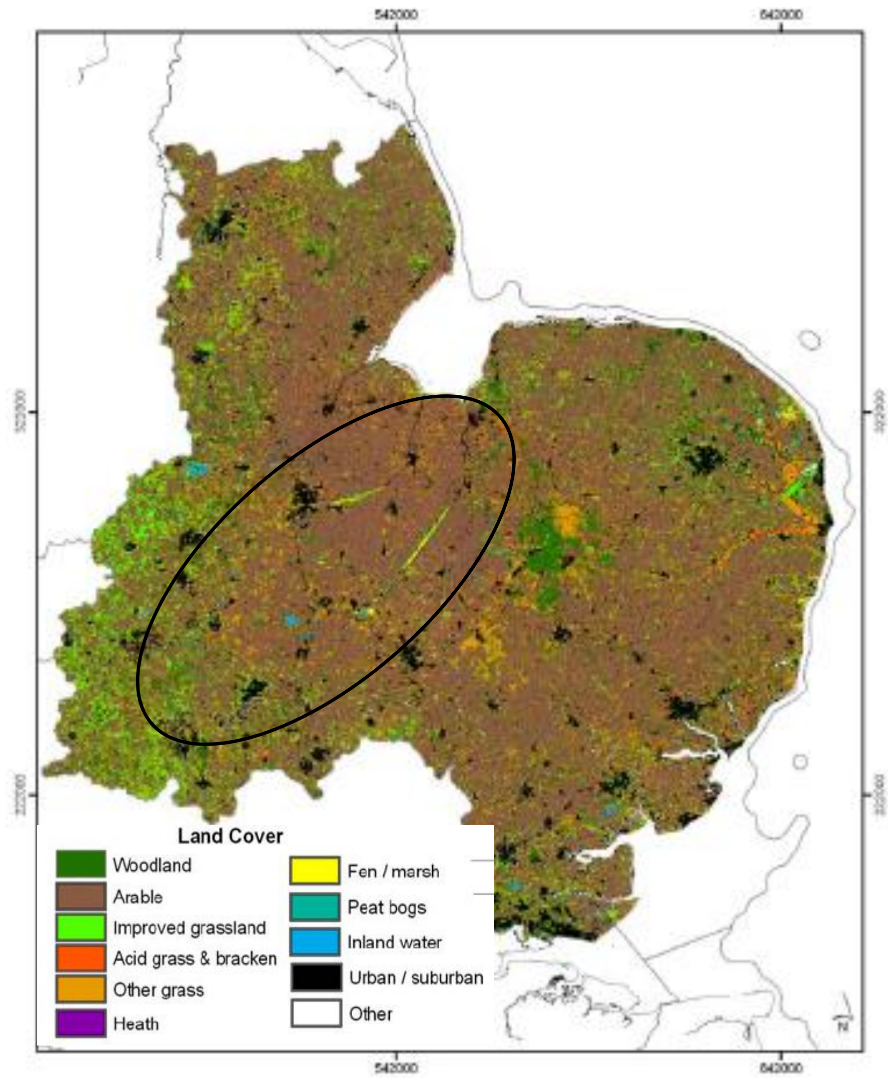


Figure 3.8. Land use in the Anglian region. The circled area highlights the Great Ouse catchment.

The main point source pollution localities are associated with major urban centres and associated discharge from sewage treatment works. The majority of the River Great Ouse is either 'at risk' or 'probably at risk' from point source pollution, the Ivel and the Ouzel are also 'at risk' (Figure 3.9). Diffuse pollution includes the input of nutrients (particularly nitrogen and phosphorus) from agricultural runoff, and industries that produce highly eutrophic conditions in the river (Pinder *et al.* 1997). The whole of the Great Ouse catchment is 'at risk' from diffuse pollution (Figure 3.10).

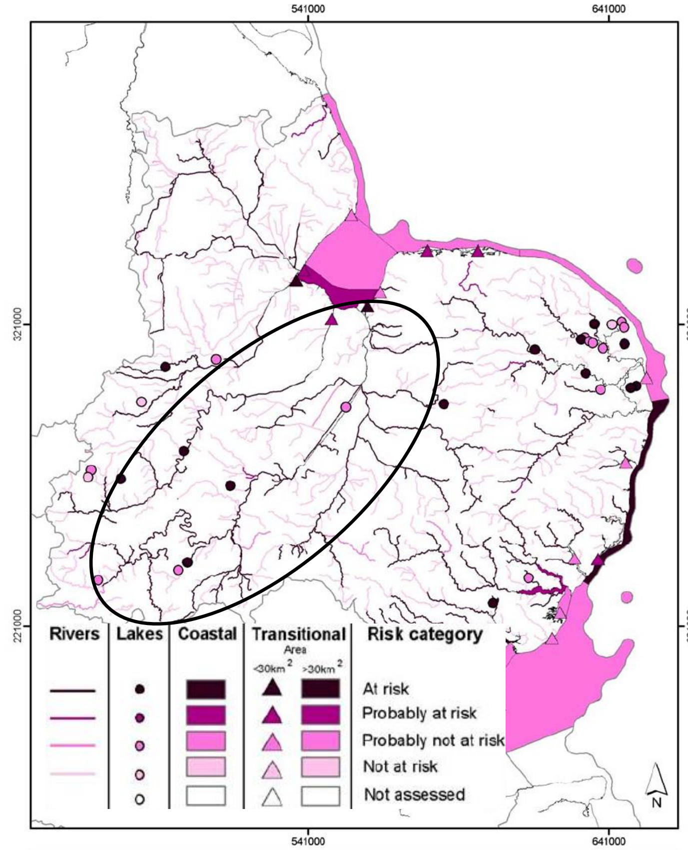


Figure 3.9. Surface water bodies in the Anglian region at risk from point source pollution pressures. The circled area highlights the Great Ouse catchment.

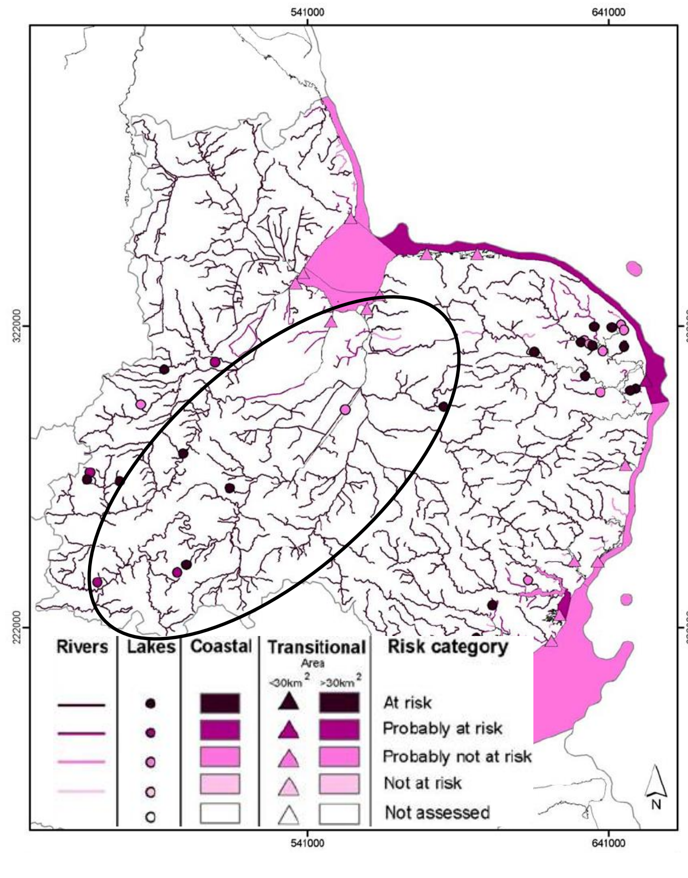


Figure 3.10. Surface water bodies in the Anglian region at risk from diffuse pollution pressures. The circled area highlights the Great Ouse catchment.

Nitrate pollution is of concern because it has to be removed before water can be supplied to consumers, and it can harm aquatic environments. Over 60% of nitrate enters water from agricultural land (Defra), of which there is a large percentage within the Anglian region. Nitrate concentrations in the Great Ouse and its tributaries fluctuate and show strong seasonal trends, generally being low in the summer months and increase during winter. Nitrogen is soluble so it is more readily lost from a wet soil than a dry soil; therefore nitrate concentrations are classically greater during times of high runoff after a dry summer when nitrogen has built up in the soil from fertiliser, deposition from the air and nitrogen fixing plants. Nitrates and phosphates in a body of water can contribute to high Biological Oxygen Demand (BOD) levels as they have the ability to enhance the growth rate of plant life and algae.

Over the catchment, phosphate levels are considered to be 'Moderate' to 'Poor', with tributaries in the north east of the catchment rated as 'High' and 'Good' with levels between 0.05 mgL^{-1} (Table 3.1 and Figure 3.11). Land use in this area is arable, but there are fewer urbanised areas. Phosphate levels in the river reach used for this investigation are considered 'Poor' with over 1 mg/l^{-1}. Dissolved oxygen (DO) levels in the upper Great Ouse are considered to be 'High' with over 70% DO saturation a few tributaries rated as 'Moderate' to 'Bad' with less than 50% SAT (Table 3.1 and Figure 3.12).

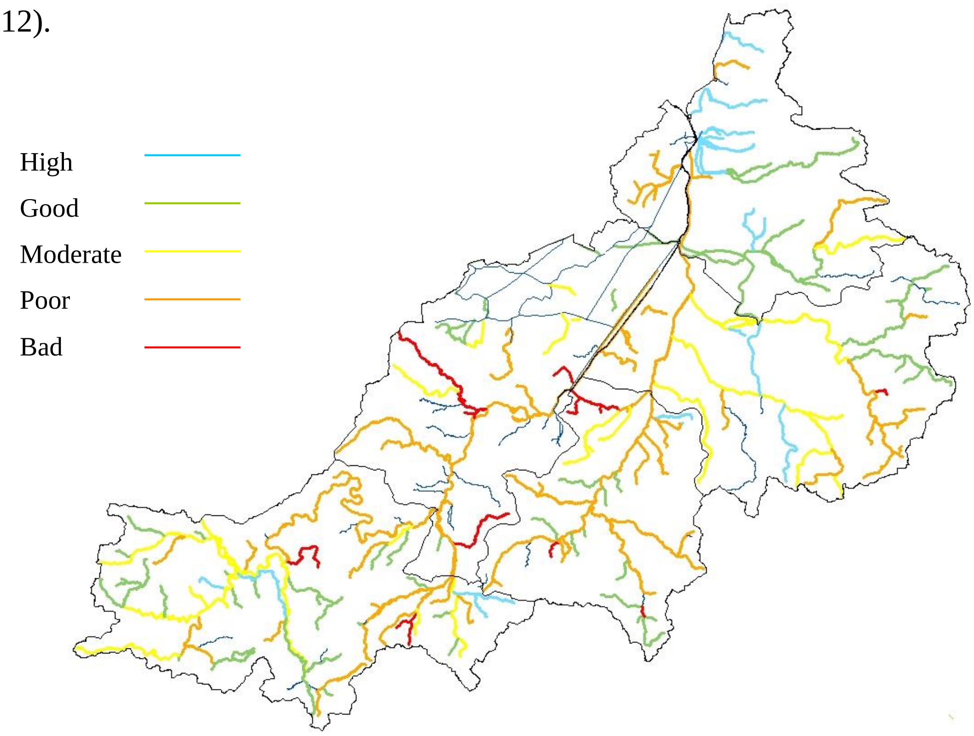


Figure 3.11. WFD classification for Phosphate levels in the Great Ouse catchment.

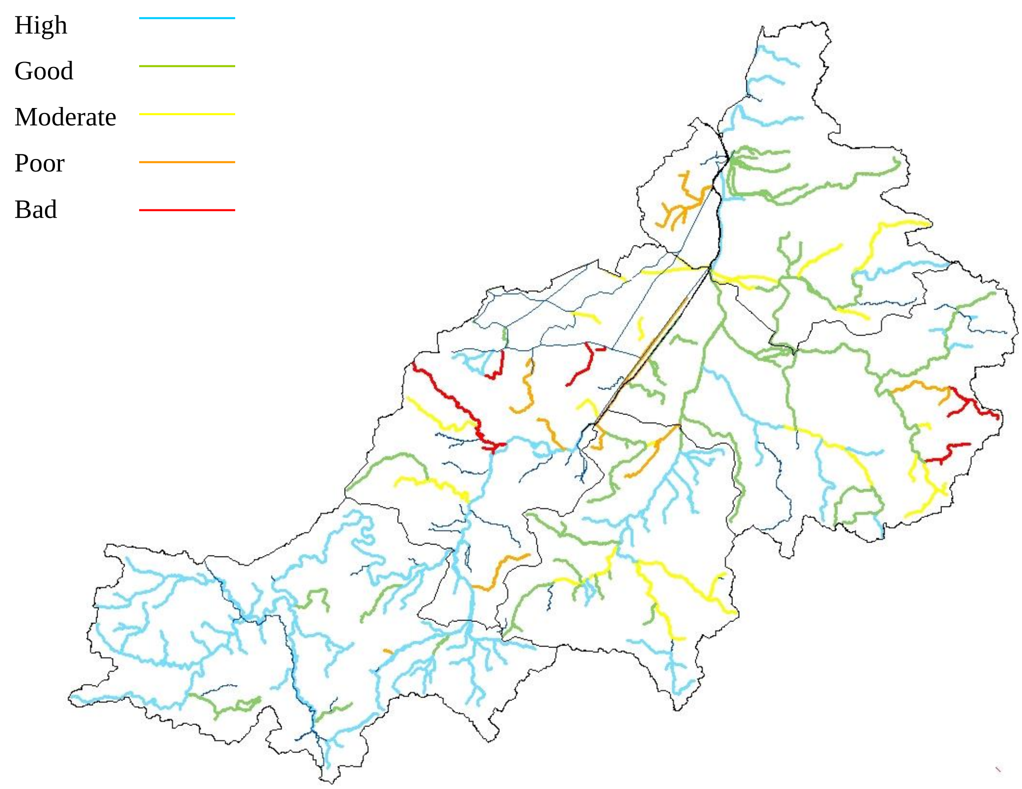


Figure 3.12. WFD classification for dissolved oxygen in the Great Ouse catchment.

3.3.4 Catchment Climate

During the last 40 years, there has been a clear north west and south east division in temperatures in England and the Great Ouse catchment has experienced some of the highest spring and summer temperatures within the UK (Figures 3.13 to 3.15), influencing the ecology of rivers. There has been no significant increase in temperature over the last 17 years (Regression analysis, R^2=0.0003 $p>0.05$) (Figure 3.16). However since 2007, there has been an increase of the number of degree days above 13.5°C (Figure 3.17), a critical temperature threshold for the reproduction of barbel and the survival of larvae.

The river flow of the Great Ouse at Bedford ranges between 0.008 and 278 m^3/s averaging 10.6 m^3/s. The largest peaks in river flow have occurred during the winter months and also spawning months for barbel (Figure 3.18). The highest velocities recorded in recent years were in April 1998, at 219 m^{-3}. The river level measured at Bedford ranges between 24.78 and 26 mAOD, averaging 24.9 mAOD. River level is generally higher in the winter months (Figure 3.19A and B), lower levels throughout the year were recorded between 2003 and 2007.

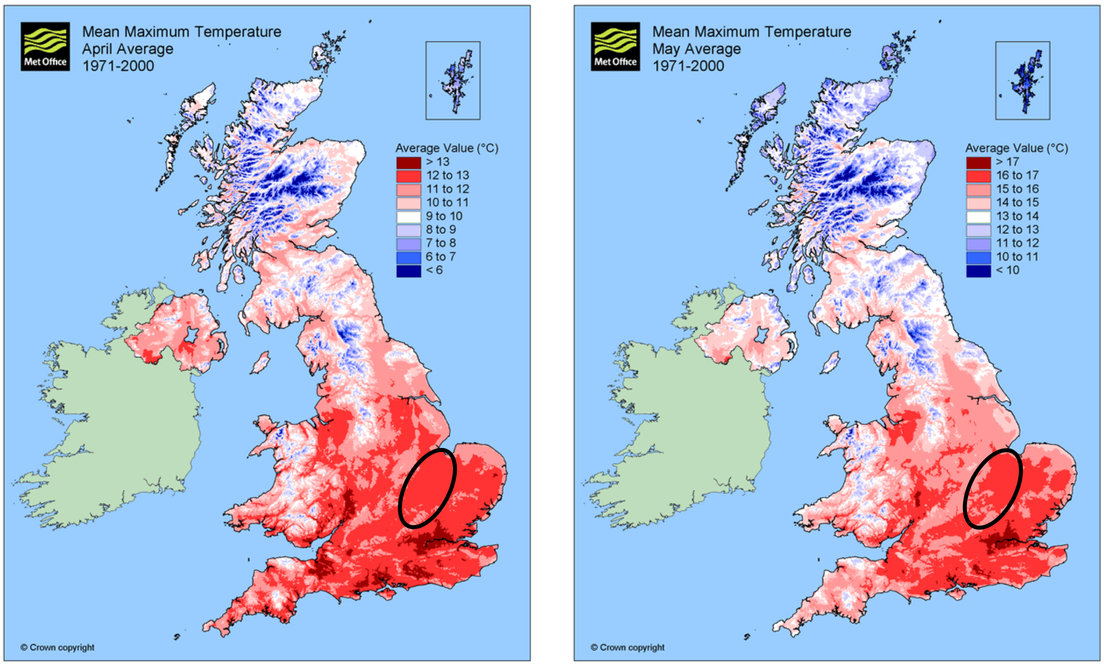


Figure 3.13. Mean April and May temperatures in the UK between 1971 and 2000 (Met Office). Circled area highlights the Great Ouse catchment.

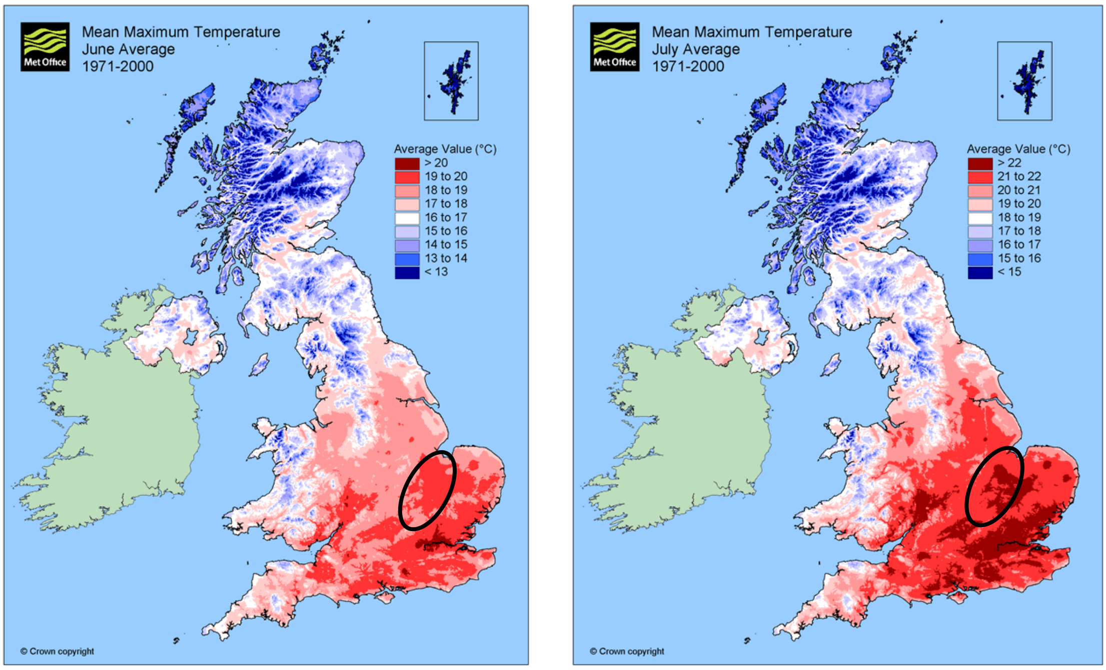


Figure 3.14. Mean June and July temperatures in the UK between 1971 and 2000 (Met Office). Circled area highlights the Great Ouse catchment.

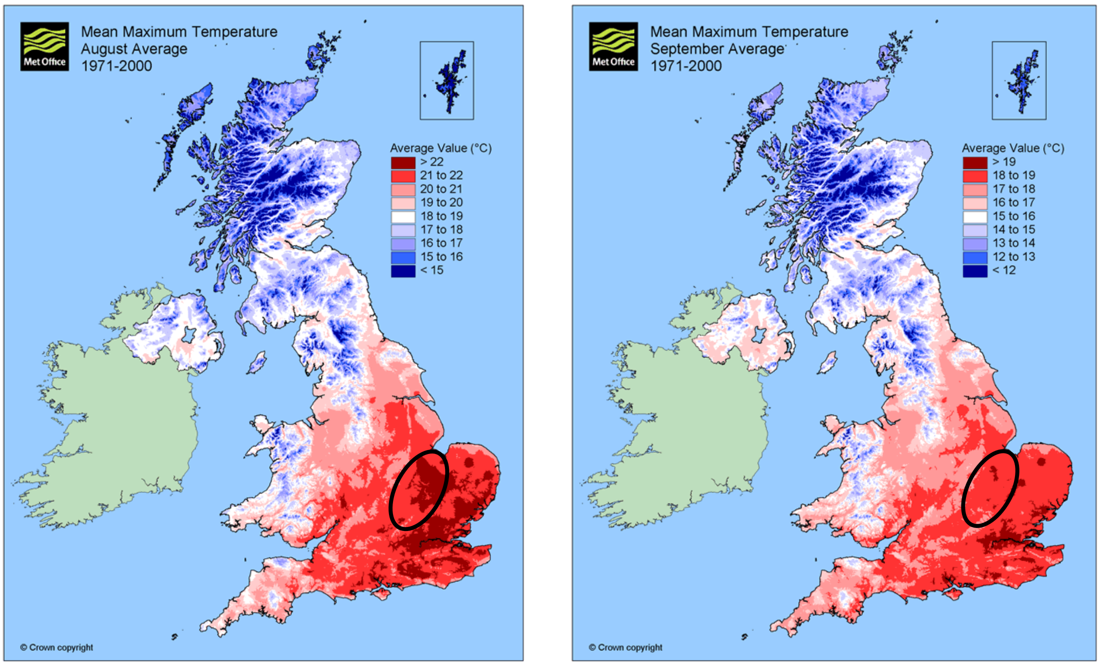


Figure 3.15. Mean August and September temperatures in the UK between 1971 and 2000 (Met Office). Circled area highlights the Great Ouse catchment.

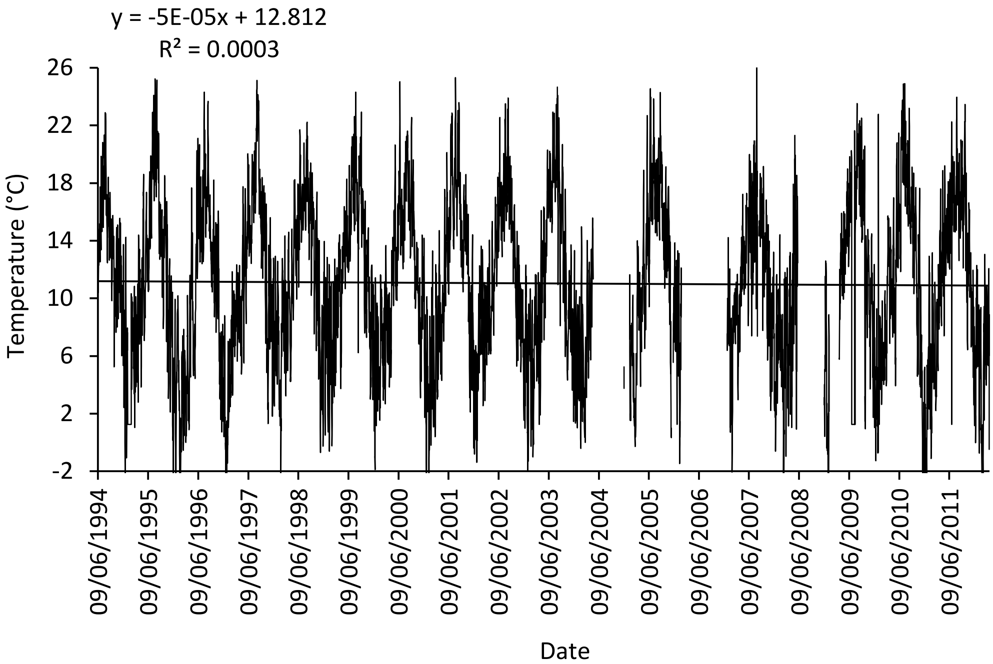


Figure 3.16. Daily water temperature at Odell over an eight year period.

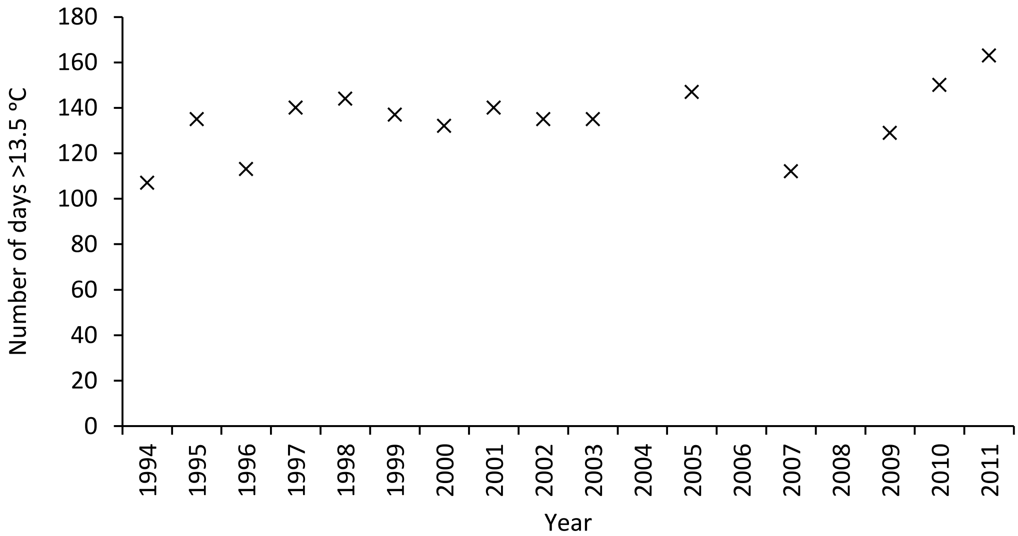


Figure 3.17. Annual number of degree days above 13.5 °C, Odell.

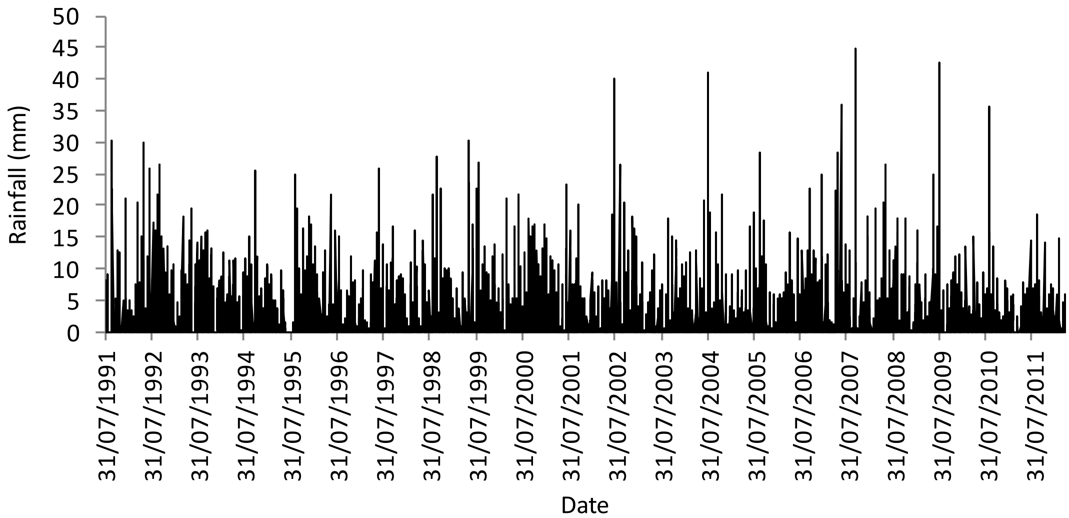


Figure 3.18. Daily rainfall recorded at Bedford.

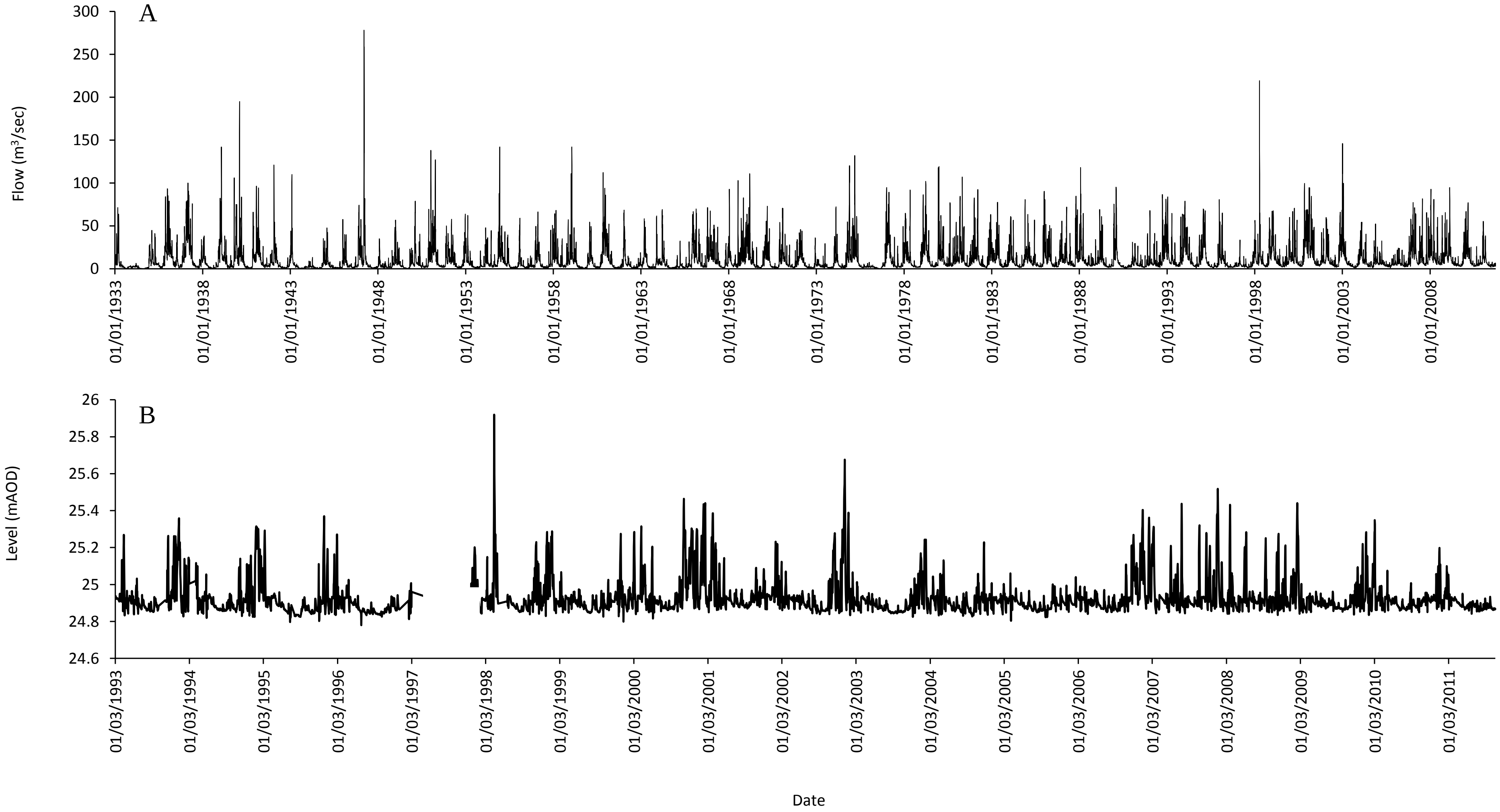


Figure 3.19. Mean daily Flow (A) and Mean daily river level (metres above Ordinance Datum) (B) at Bedford gauging weir.

3.3.5 Predation

Due to the decline in otter populations between 1950 and 1970, there were re-introductions of otters between 1983 and 1999. None of these individuals are alive today and only a small proportion of the current otter population in England consists of descendants of the released otters. Natural recovery of otter populations has followed a ban of toxic pesticides. There has been natural immigration of otters into the Great Ouse catchment, including the Rivers Cam and Ivel (Copp & Roche 2003) and therefore predation of barbel by otters within this region is possible.

The River Great Ouse has a higher density, biomass and production of signal crayfish than other reported figures for this species elsewhere (Guan 2000), it is a particular issue on the upper Great Ouse where there is growing concern regarding the impact on fish stocks by predating on fish and their eggs after spawning. Anglers have seen numbers of signal crayfish increase in this area, particularly in the last 20 years (*Pers. Comms.*). There are no definitive population estimations for crayfish in any river catchment, but the number of crayfish trap consents issued between January 2002 and June 2013 increased from 2 to 55 (Figure 3.20), allowing for multiple traps under each license.

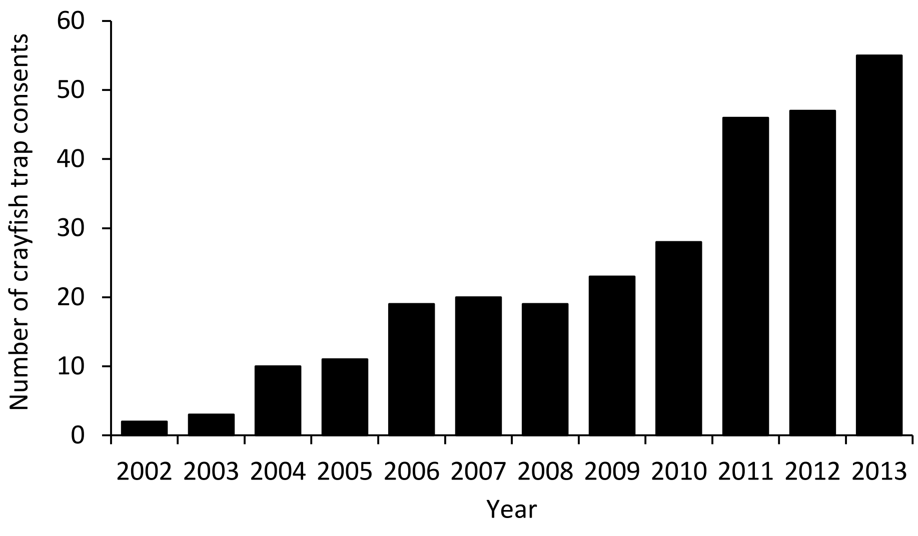


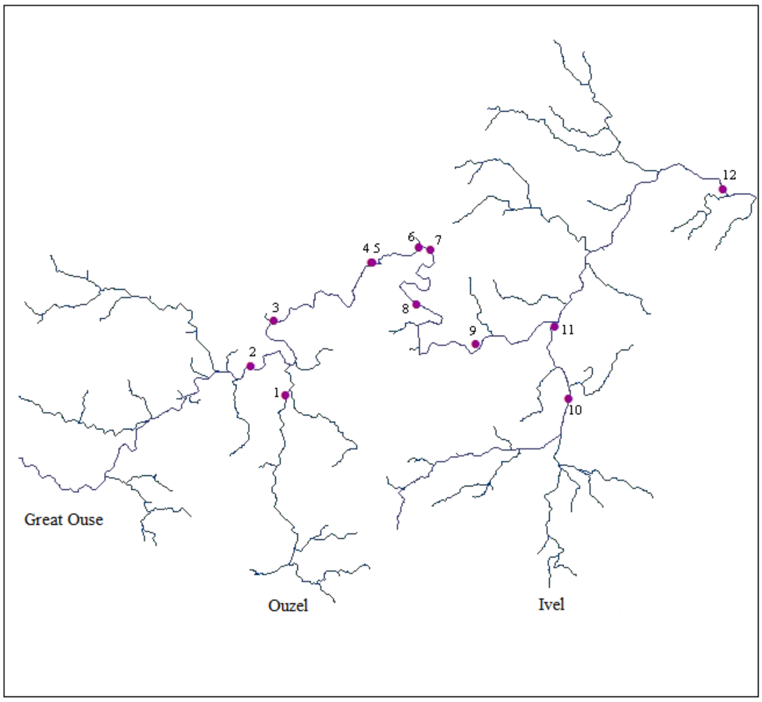
Figure 3.20. Number of crayfish trap consents issued by the Environment Agency for the River Great Ouse between January 2002 and June 2013.

3.4 Study areas

The study sites for this project cover parts of the upper and middle Great Ouse from Milton Keynes to St Ives (Cambridgeshire), and includes two of its major tributaries (Figure 3.21) where barbel spawning has been witnessed over recent years. A more detailed series of studies designed to assess population bottlenecks were conducted between Harrold weirs at a site known as 'Aquarium' (Site 4) to Sharnbrook weir (Site 7) (Figures 3.21 and Figure 3.22).

The upper and middle Great Ouse are heavily impounded and under morphological pressure. The main river channel is at risk from both point source and diffuse pollution, with moderate to poor water quality. Phosphate levels are considered 'Poor' with over 1 mg L^{-1}. Dissolved oxygen levels in the upper Great Ouse are considered to be 'High' with over 70% DO saturation. This main channel is also used for abstraction, but the tributaries are not. The surrounding land is primarily arable farming and grassland, owing to the issues with water quality. River and riparian habitat varies from good to poor.

The study reach is characteristic of the upper Great Ouse, surrounded by agricultural land use and rural villages. The river habitat is hetergogenous with patchy riffle-pool-raceway sequences, undercut banks and varied riparian vegetation providing shelter and woody debris. Other than the section between Harrold weirs and the mill channel, there was fully natural and stabilised river bed and banks, although the river channel had moved since parish boundaries were established. Three weirs act as limits to the study reach, two at the upstream end and one at the downstream end, there are also weirs at Harrold Bridge. There are no tributaries in this section of the Great Ouse; there are three mill channels that do not allow the possibility of the barbel moving out of the stretch. Drainage ditches cut into the agricultural land remained dry for the majority of the study.



1. d/s Willen sluice
2. Haversham weir
3. Ravenstone Mill
4. Aquarium
5. d/s Harrold weir
6. Pinchmill Island
7. Sharnbrook weir
8. Oakley
9. New Cut
10. Biggleswade Common
11. d/s Tempsford saw Mill
12. St Ives Sluice

Figure 3.21. Study sites for the project in the Upper and Middle Great Ouse.

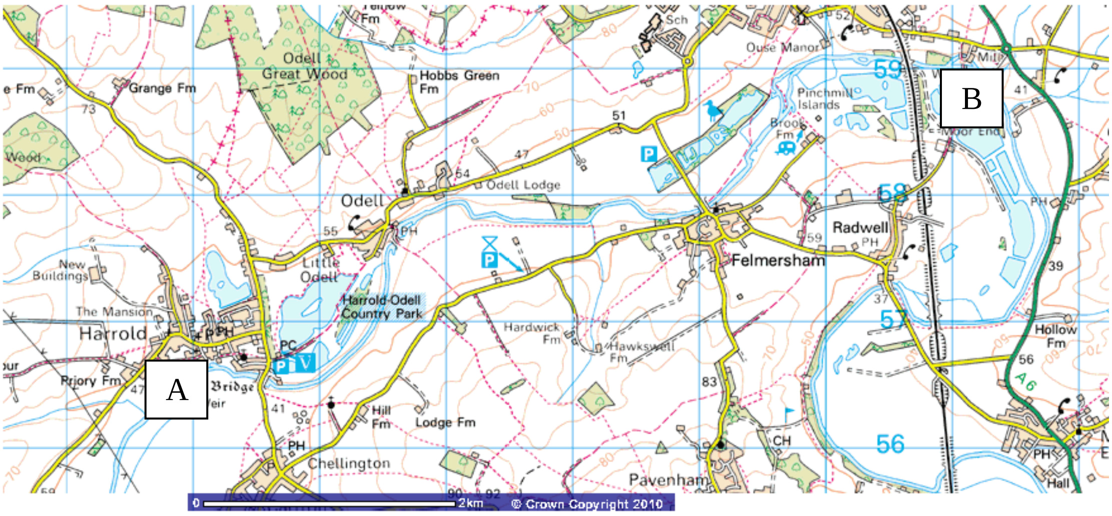


Figure 3.22. Study reach between Harrold weirs (A) and Sharnbrook weir (B).

4. SEASONAL AND DIURNAL MOVEMENTS AND HABITAT USE OF ADULT BARBEL

4.1 Introduction

Of all the cyprinids that inhabit UK rivers, barbel exhibits one of the largest seasonal home ranges (Lucas & Baras 2001). This is defined as the distance between the upstream most and downstream most locations (De Vocht & Baras 2003) and during the spawning period; the species shows its highest mobility (Baras 1992, 1993a, 1998; Lucas & Batley 1996). Migratory behaviour of barbel in the Great Ouse are largely unknown other than anecdotal evidence from experienced anglers relating to multiple catches of individuals and preferred spawning grounds in spring. The Great Ouse is a highly regulated river in (Pinder 1997; Copp 1998) and one of the driest in the UK (Neal *et al*. 2000). Therefore barbel in this river may behave differently to the findings of studies (Baras and Cherry 1990; Lucas 2000; Lucas and Frear 2005).

The aim of this Chapter was to investigate the natural behaviour of wild mature barbel in the Great Ouse and to identify bottlenecks to the recruitment of the species related to the adult life history stage; including appropriate habitat and environmental cues, so that appropriate mitigation measures could be considered. This was achieved by radiotracking 20 barbel of varying length and weight, over a 73 week period, recording habitat use and collecting environmental data such as river temperature and flow. The specific objectives were to: 1) examine the movements of barbel at a diurnal and seasonal scale; 2) ascertain the effects of specific environmental influences on movement and habitat use: 3) identify barriers to longitudinal movement; 4) locate active spawning gravels.

It was predicted that habitat use would alter on a seasonal basis, that environmental variables would influence movement and that major weirs would act as barriers to migration and make the colonisation of new habitats outside of the study section impossible. The identification of active spawning gravels was crucial for planning further studies relating to other chapters within this thesis. The information gathered on the behaviour and habitat use of barbel is important for the understanding of how barbel react to changes in their environment, such as drought and low river level events, or increases in flow and river level, and how best to target habitat enhancement projects to improve refuge areas for these conditions.

4.2 Methodology

4.2.1 Sampling sites

Four representative sampling sites (approximately 300 m long), between Harrold weirs and Sharnbrook weir, comprising riffle, glide and pool habitats with instream and riparian vegetation, were selected for electric fishing to collected 20 mature, wild barbel (Figure 4.1). Three of these sites were known to support high numbers of large barbel suitable for radio tracking (EA 2009), tagged barbel represented ~ 40% of adult barbel seen during the sampling.

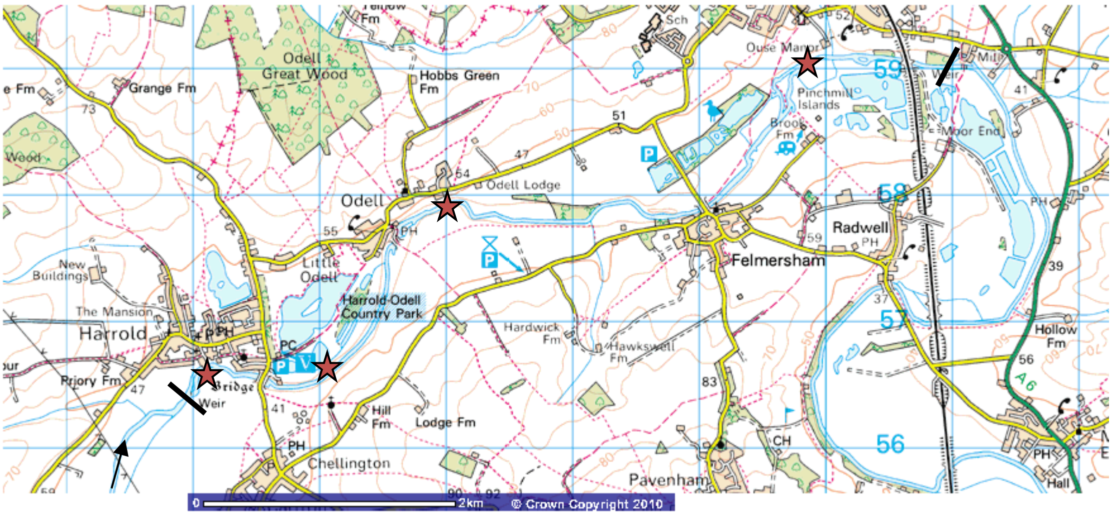


Figure 4.1. ★ Locations of electric fishing sites. From upstream site; Aquarium (SP9501456480), Harrold Country Park (SP9559756519), Odell (SP9717357916) and Pinchmill (SP9971858725). Arrow indicates direction of flow and bars indicate the location of weirs acting as the limits to the study stretch.

4.2.2 Sampling and tagging procedure

Wild fish were obtained using a standard Environment Agency 'two boat' electric fishing technique used by Central Area. In this operation, two boats were joined, one boat carried the electric fishing box, and the other held the aerated tank in which to keep the captured barbel. Two persons operating anodes and long handled nets were positioned on each boat to capture fish. Ropes were attached on the outer ends of each boat and held by one or two persons on the river bank to manoeuvre the boats from bank to bank in wider stretches and to hold the boats in position if necessary (Figure 4.2).

Captured fish were held in the aerated tank with systematic water changes and removed one at a time to be anaesthetised before undergoing surgery. Once out of the tank, body weight (kg) and fork length (mm) were recorded (Table 4.1) and scales were removed from all fish for later analysis in the laboratory. The fish also underwent a visual health check.

All fish were treated in compliance with the UK Animals (Scientific Procedures) Act 1986 Home Office licence number PPL 80/2390. Prior to tagging in the field, fish were anaesthetised one at a time in a solution of buffered tricaine methanesulphonate (MS-222, 0.1 mg L^{-1}) which is rapidly absorbed through the gills. This was done with caution, as anaesthesia is dependent on immersion time, size of fish, water temperature, water hardness and oxygen concentration. Fish were submerged until the operculum beat continued but the fish was non responsive.

Each barbel was then transferred to an operating table consisting of half a pipe that was cushioned to protect the fish. The fish was placed ventral side up and covered with wet material to keep the gills moist and strapped into the pipe with elastic to avoid movement or reflexes whilst under the anaesthesia.

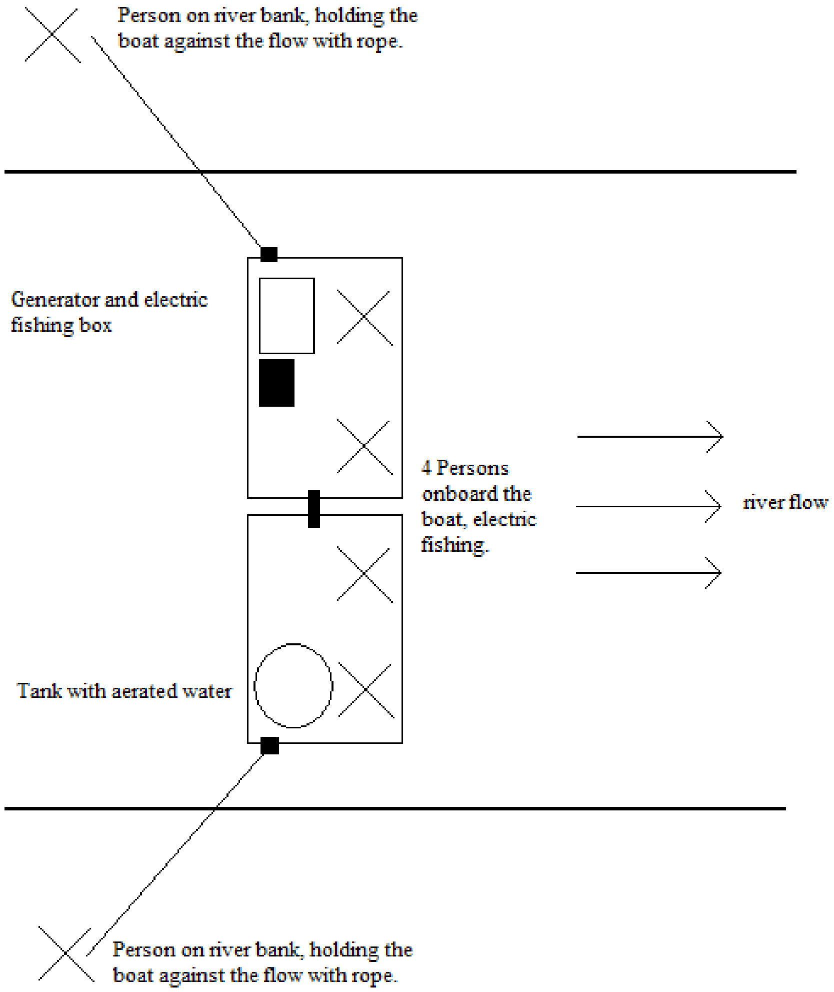


Figure 4.2. Central Area's standard Environment Agency 'two boat' electric fishing technique.

Radio transmitters (Biotrack, Dorset, England) measuring (15 x 40 mm) were sterilised using a diluted solution of Dettol (25%) and distilled water and then rinsed in distilled water before implantation. Iodine was applied to the area and scales were removed to enable a tidy incision that would heal quickly. Tags were inserted into the body cavity through a 13 mm ventro-lateral incision made with a scalpel. After insertion of the radio tag, a single stitch was used to close the wound, which was then sprayed with G7, an acriflavin-based antiseptic/disinfectant and covered with orahesive powder, to form a barrier and bind the G7 to the wound. The application of G7 and orahesive powder was repeated to ensure the protective barrier. Finally, each fish was injected with the antibiotic, Baytril.

Each fish was then moved into an aerated recovery tank until consciousness and responsive behaviour were regained, at which point fish were moved into a keep net, anchored to the riverbed in the centre of the river channel to maximise flow availability. Once natural capacities had been regained (Ovidio *et al.* 2007), barbel were released within 200 m of the capture site, at a location with low flow and cover from riparian vegetation, optimal conditions for resting.

4.2.3 Monitoring

Barbel were tracked weekly from April 14 2010 to October 7 2011 and in both years daily radio tracking continued for 100 consecutive days from April 14 to July 22. The latter incorporates the spawning period and the beginning of the coarse fishing season. Tracking was conducted between 0700 and 2000, but generally between 0800 and 1500.

Tracking was mostly carried out on foot, using a Yagi antenna. Range was approximately 100 m under field tracking conditions in the Great Ouse, with the antennae held 2-5 m above water level (Lucas & Batley 1996). The location of individual fish was determined from the bank (avoiding disturbing the fish) to within 1 m by reducing the gain on the receiver to localise the fish from either bank. When fish were located, their position was recorded with a TOPCON positioning system (accurate to 0.5 m). On each tracking occasion the presence (1) or absence (0) of each occupied habitat type: instream vegetation, emergent vegetation depth (< 1 m was recorded as absent, > 1 m was present), flow (visible flow was recorded as present, slack waters were recorded as absent) and overhang from trees or undercut banks. The presence and absence scores for each habitat type of all 20 barbel on each of the 73 weeks tracked, were summed and converted to a percentage using the number of barbel located on each day, to create the daily percentage use of each habitat type. In addition to the microhabitat monitoring, available habitat was scored in 50 m transects for the 8.2 km stretch of river. Visual estimations of habitat features important to barbel were recorded as percentages, these included:

- fine sediment (<1 mm);
- gravel (>1 mm <64 mm);
- boulders (>64 mm);
- in-stream vegetation;
- emergent vegetation;
- woody debris and overhang;
- riparian vegetation.

Fish that were not located, continued to be searched for on each tracking event. Additional measures including the use of extra receivers on both banks, altering frequencies during the search in case of frequency shift, a boat and searching upstream and downstream of the study reach until the next impoundment were also undertaken on more than one occasion. The distances were 8 and 20 km respectively.

4.2.4 Data analysis

Fish movements were calculated using ArcGIS, Linear Referencing Tools. The daily position of each barbel from the upstream weir of the study reach was then used to calculate daily and weekly movements.

The relationship between daily mean in river temperature recordings from a data logger positioned at Odell (n = 275), and air temperature recorded at the nearest weather station in Cambridge was determined. The resulting equation (y = 0.9967 x -1.2425), was used to transform historical air temperature data into river temperature data.

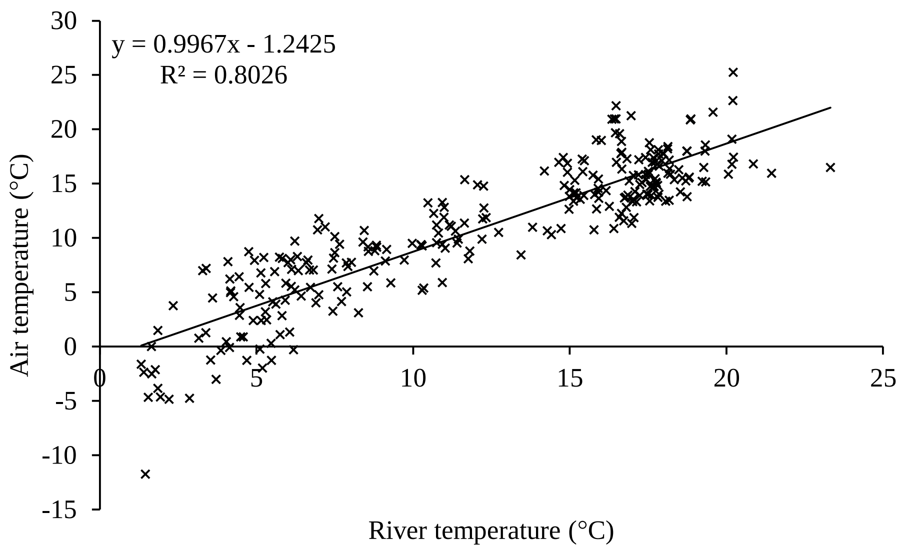


Figure 4.3. Scatter plot and regression analysis of air temperature (°C) and river temperature (°C).

Environmental (temperature (°C), river level (mAOD) and flow (m^3s^{-1})) and movement (distance moved (m)) data were tested for normality using Kolmogorov-Smirnov test and all results were extremely significant ($p < 0.001$) and therefore not evenly distributed. Data were then transformed using Log10 and then retested. A constant of +1 was added to rainfall data to remove zero values. Regression analysis was also implemented to assess the influence of environmental variables such as weather, moon phase and day length on movements. Weather data were represented by numerical values with the following descriptions: 1) sunny, 2) sunny with cloud, 3) overcast, 4) overcast with light rain and 5) heavy rain. Moon phases were represented by numerical values with the following descriptions: 0) new moon, 0.25) waxing and waning crescent, 0.5) first and last quarter, 0.75) waxing and waning gibbous, 1) full moon.

Paired t-tests were performed to: 1) test for differences in length of fish between sites and 2) determine whether there was a significant difference in movements for individual fish between 2010 and 2011, which may have been a result of the tagging procedure (SPSS, version 19.0). Mann Whitney U was used to test for differences between mean range per day tracked and mean daily distance moved, in 2010 and 2011 (SPSS, version 19.0). Generalised Linear Models (GLM) with gamma log link function were constructed to examine the influence of environmental factors on fish activity (SPSS, version 19.0). Distance moved per day was used as the response, and flow, temperature and flow and temperature as predictors into the model.

Graphical representation of movement, environmental and micro habitat data was produced in Microsoft Excel. Brodgar (v 2.7.2) was used to perform Canonical Correlation Analysis (CCA), a multivariate method to describe the potential relationships between adult barbel assemblages and their physical environment on a meso-habitat scale.

4.3 Results

In April 2010, 20 barbel were tagged at 3 sites (Table 4.1) as no barbel were caught at the Odell site. Not all fish caught were tagged, the first eight from the catch at Aquarium and the first 10 from the catch at Harrold Country Park were tagged. Between April 2010 and October 2011, barbel were monitored using radio telemetry. Tracking ceased on 7 October 2011, when a number of the tags showed signs of reduced signal strength. Data collected on this date have not been used. Large variations in movements were identified between individuals and fish origin.

During 2010, barbel 2 (B2) could not be located on several occasions for long periods of time. Due to missing data, B2 was not used for the analysis of daily movements in 2010 or weekly movements between 2010 and 2011. Barbel 4 (B4) could not be located after the daily tracking in 2010 were completed. Barbel 1 (B1) could not be located after day 43 in the 2011 daily tracking, for this reason B1 was excluded from 2011 daily movement analysis. There was no significant difference between the lengths of fish from each of the capture sites (t = -0.18, df = 1 16; P>0.05).

Of the seven morphological disorders mentioned by Tyler & Everette (1993), B5 and B11 suffered from ocular pathology with opaque lenses and B1, B12 and B17 had obvious fin damage. In addition, B11 had dislodged scales from netting, B7 had a lesion on its snout, B12 had a lesion on its left flank and B3, B5, B6, B11, B15, B16 and B17 suffered from black spot.

Table 4.1. Information recorded on the 29 adult barbel captured by electric fishing for the radio tracking sample..

Site	Fish Number	Length (mm)	Weight (kg)
Pinchmill Islands	1	755	7.11
Pinchmill Islands	2	748	6.35
Aquarium	3	600	3.23
Aquarium	4	715	4.81
Aquarium	5	619	2.97
Aquarium	6	700	5.44
Aquarium	7	618	3.31
Aquarium	8	587	2.89
Aquarium	9	643	3.74
Aquarium	10	672	4.08
Aquarium	Not tagged	655	3.88
Aquarium	Not tagged	600	3.43
Aquarium	Not tagged	639	4.25
Aquarium	Not tagged	346	5.18
Harrold Country Park	11	715	5.47
Harrold Country Park	12	628	3.03
Harrold Country Park	13	592	3
Harrold Country Park	14	690	5.04
Harrold Country Park	15	583	3.40
Harrold Country Park	16	724	5.01
Harrold Country Park	17	718	5.27
Harrold Country Park	18	576	2.94
Harrold Country Park	19	585	3.14
Harrold Country Park	20	678	4.30
Harrold Country Park	Not tagged	603	2.97
Harrold Country Park	Not tagged	618	3.34
Harrold Country Park	Not tagged	289	No data
Harrold Country Park	Not tagged	239	2.72
Harrold Country Park	Not tagged	726	5.30

4.3.1 Home ranges

The home range of each barbel can be defined as the length of river between its most upstream and most downstream recorded locations. These movements should be considered as minimum values for distances actually travelled by the barbel as out and home movements could take place between the daily fixes (Baras & Cherry 1990).

Home ranges measured in this study ranged from 645 to 6842 m, averaging 2187 m out of a possible 8200 m between Harrold weirs and Sharnbrook weir (Figure 4.4). Overall, individuals from Pinchmill had the largest average home range (n=2, average homerange = 6140 m), despite both fish being missing for part or most of the study. Barbel from Harrold Country Park had the second largest average home range (n=10, average homerange = 2130 m) followed by barbel from Harrold (n=8, average homerange = 1269 m). Differences in home ranges were significant between Pinchmill and Aquarium (t=6.5, df=1, $P<0.05$) and Aquarium and Harrold Country Park (t=-2.5, df=15, $P<0.05$), but not between Pinchmill and Harrold Country Park (t=-2.5, df=15, $P>0.05$).

B1, had the largest home range of 6842 m using 83% of the available river length; B6 had the smallest home range of 645 m using 8% of the available river length. B1, B2 and B20 had the largest measured home ranges and were the three largest barbel that were tagged. There was a significant relationship between fish length and home range (R^2=0.1896, $P<0.05$) (Figure 4.5), corresponding with the findings of Baras and Cherry (1990); Baras (1992, 1997); Lucas and Batley 1996), but B1 and B2 levered this relationship and when removed the relationship became insignificant (R^2=0.002, $P>0.05$).

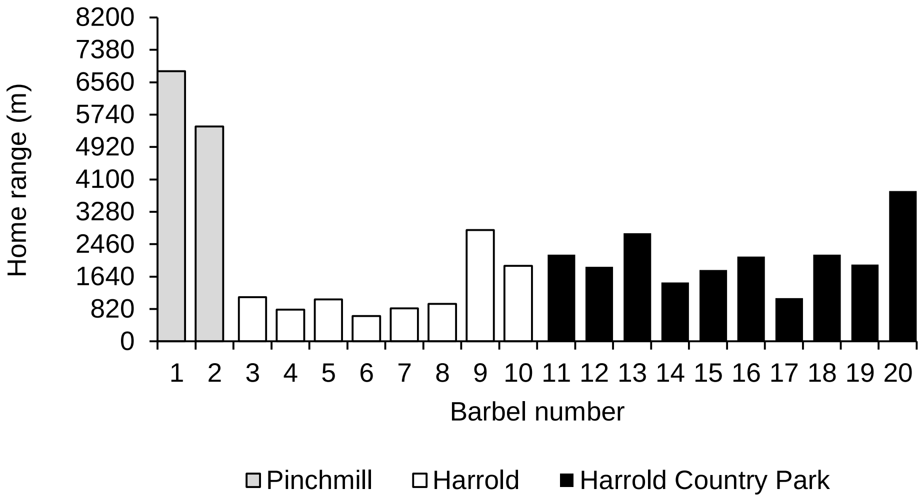


Figure 4.4. Total home range of tracked barbel based on all location data collected after the first week and over the 73 week period.

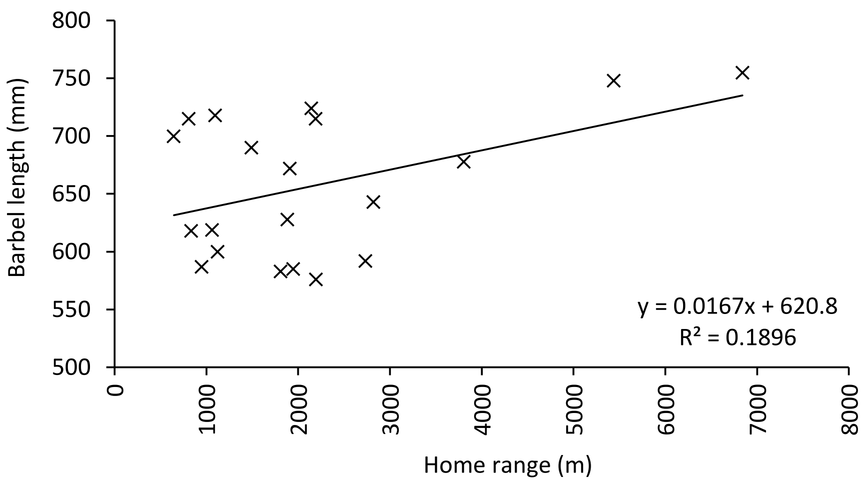


Figure 4.5. Regression analysis of individual home range against length of fish.

4.3.2 Weekly movements: April 2010 to September 2011

Weekly movements were used to identify seasonal movements over a 73 week period. The behaviour of barbel varied between sites. Barbel from Pinchmill had the highest weekly movements (Figure 4.6A), but these were mostly recorded in high activity seasons and individuals were not recorded each week. Of the individuals that were present over the entire study period (individuals from Aquarium and Harrold Country Park), those from Harrold Country Park had the highest average weekly movements ($t=-4.18$, $df=14$, $P<0.005$) (Figure 4.6B and 4.7). In both years, average weekly movements were highest in spring (March, April and May) than the other months, although some large movements were found in other months (Figure 4.6). In 2010, the summer season had the lowest movements recorded and movements peaked in weeks 39 and 40 (winter). Movements in 2011 exhibited less of a seasonal pattern, with peaks in spring, summer and autumn (Figure 4.8).

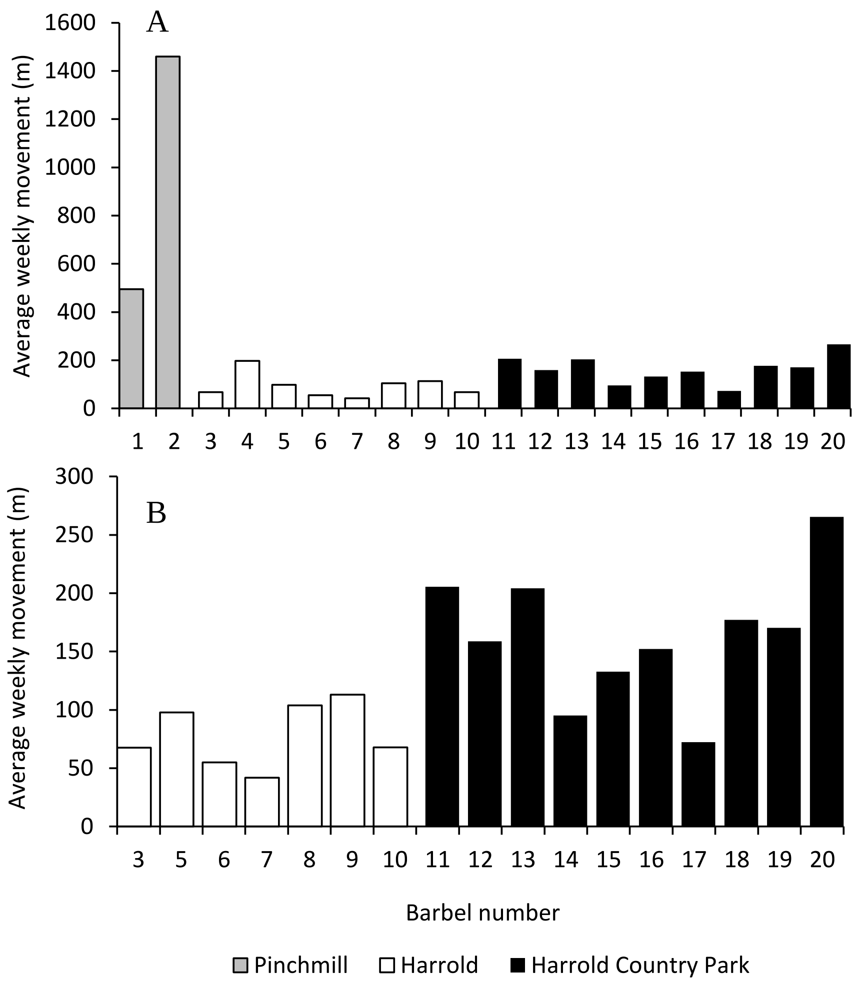


Figure 4.6. (A) Average weekly movements for each barbel. (B) Average weekly movements for all barbel tracked for the entire 73 week period.

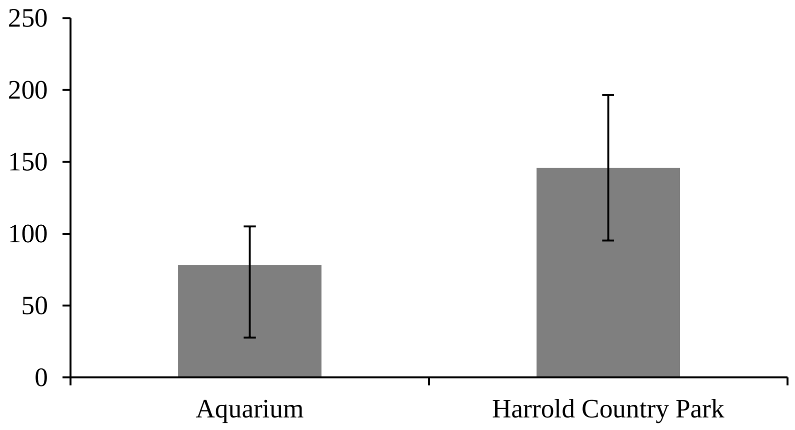


Figure 4.7. Average weekly movements and Standard Deviation for barbel from Aquarium and Harrold Country Park.

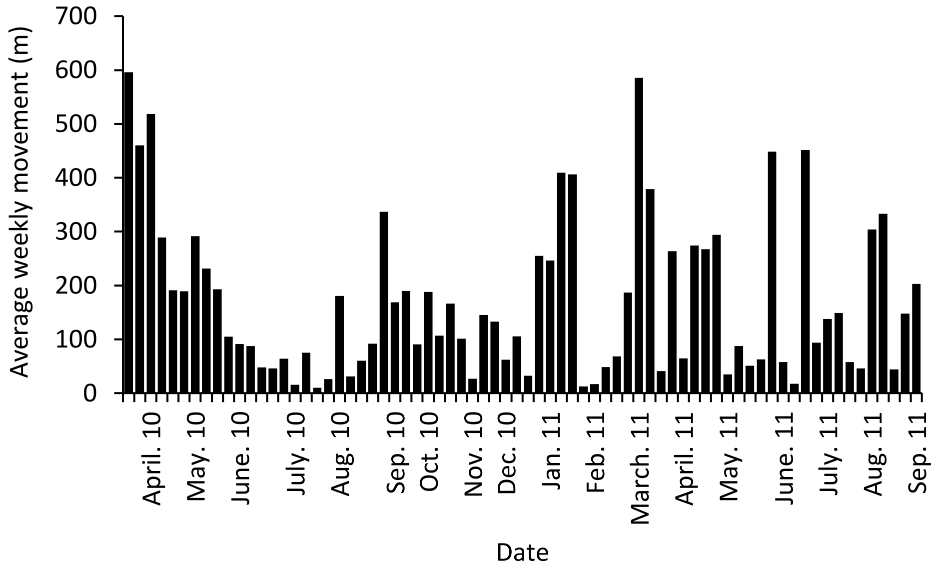


Figure 4.8. Average weekly movements of all barbel over the 73 week tracking period.

Of the barbel tagged from Harrold, all fish moved both downstream and upstream on several occasions between tagging and spawning. Over the 73 weeks, B3 had separate summer and winter residence areas and also occupied the same residence area in spring and autumn. B9 never returned to the capture site, but kept separate summer and winter residence areas, as did B10. The other barbel from this capture site remained in the same locality, resulting in their smaller home ranges (Figures 4.9 and 4.10).

Despite the movements into different seasonal residence areas, B3 had a low average weekly movement compared with the barbel that remained in the same residence area throughout the study (Figure 4.6). Of the 8 barbel from Harrold, B4 and B9 had the highest average weekly movement, although B4 went missing after week 15 (Figure 4.9 and Figure 4.10).

Of the barbel captured at Harrold Country Park, B11 moved upstream after tagging, all others moved downstream for up to 2 weeks before moving upstream (Figures 4.11, 4.12 and 4.13). Barbel from this section had more defined seasonal movements than those from Harrold. Barbel remained near spawning grounds until September, when the majority of individuals travelled downstream moving upstream again in March. B13 travelled upstream to its winter resting area, and downstream in March. B14 and B17 had the lowest average weekly movements, despite having similar seasonal movements to the other barbel (Figure 4.11 and 4.12).

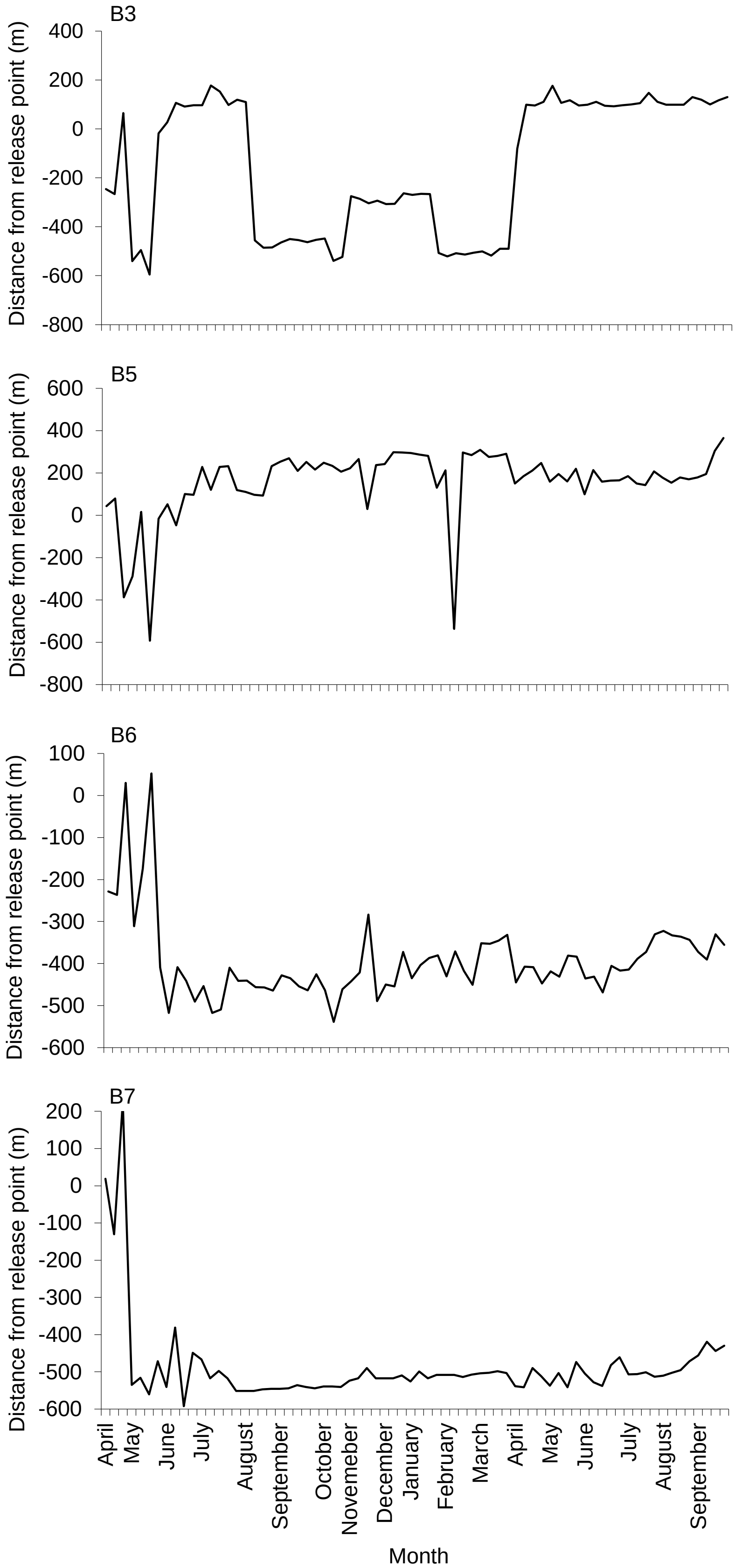


Figure 4.9. Weekly distance of B3, B5, B6 and B7 from release site (0). Landmarks; Harrold Bridge 84 m, Aquarium -564 m.

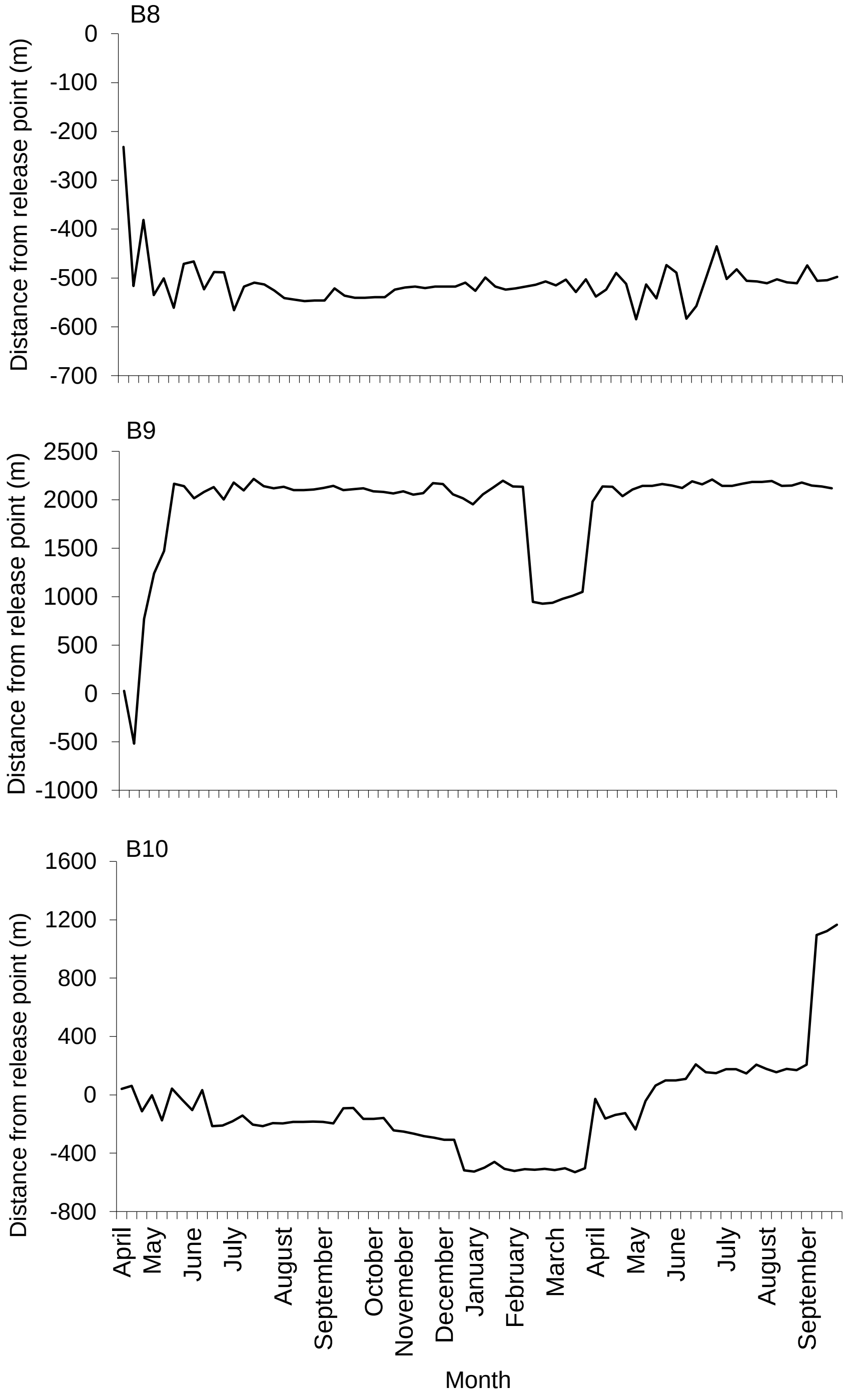


Figure 4.10. Weekly distance of B8, B9 and B10 from release site (0). Landmarks; Odell 2002 m, Harrold Bridge 84 m, Aquarium -564 m.

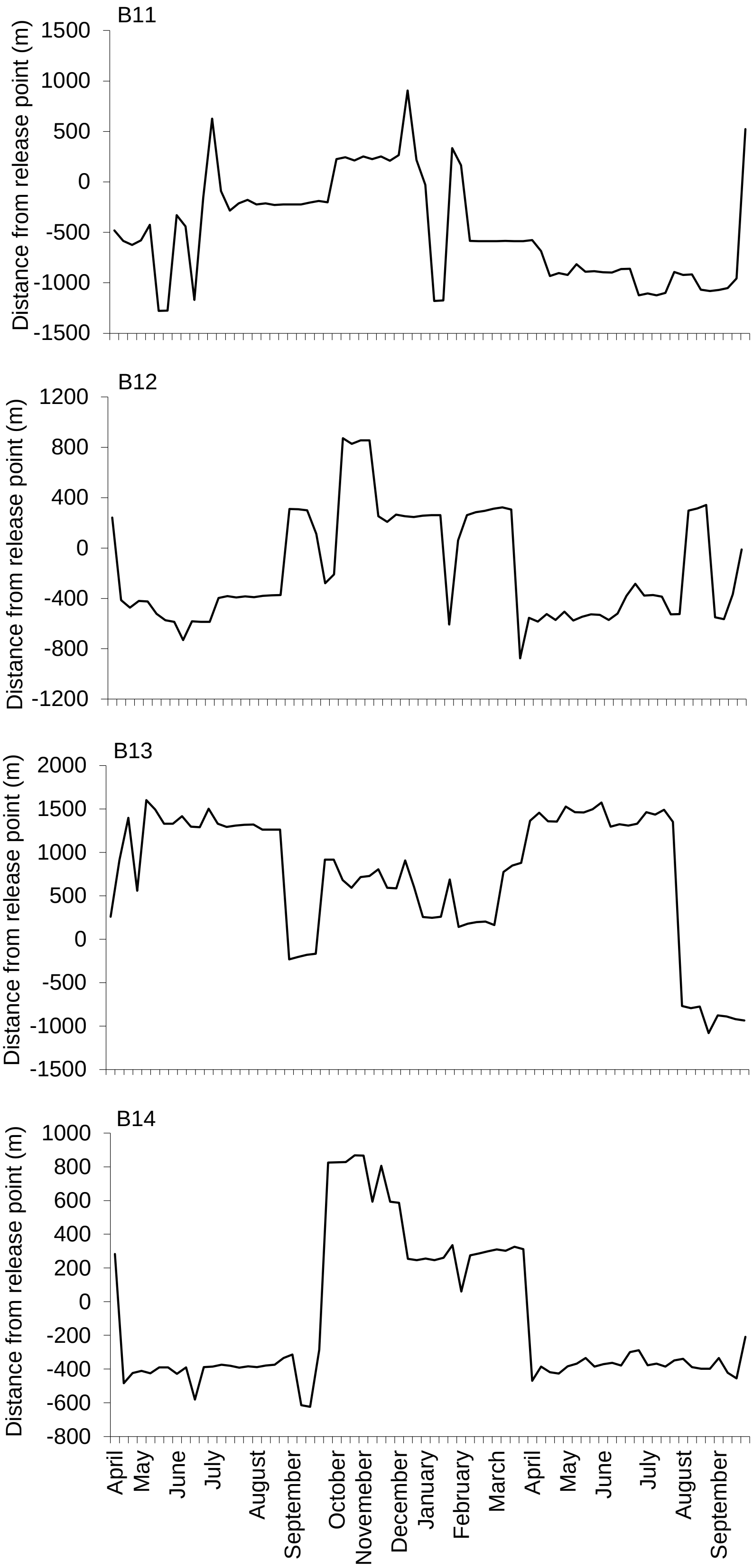


Figure 4.11. Weekly distance of B11, B12, B13 and B14 from release site (0). Landmarks; Odell 1319 m, Harrold Bridge -598 m, Aquarium -1247 m.

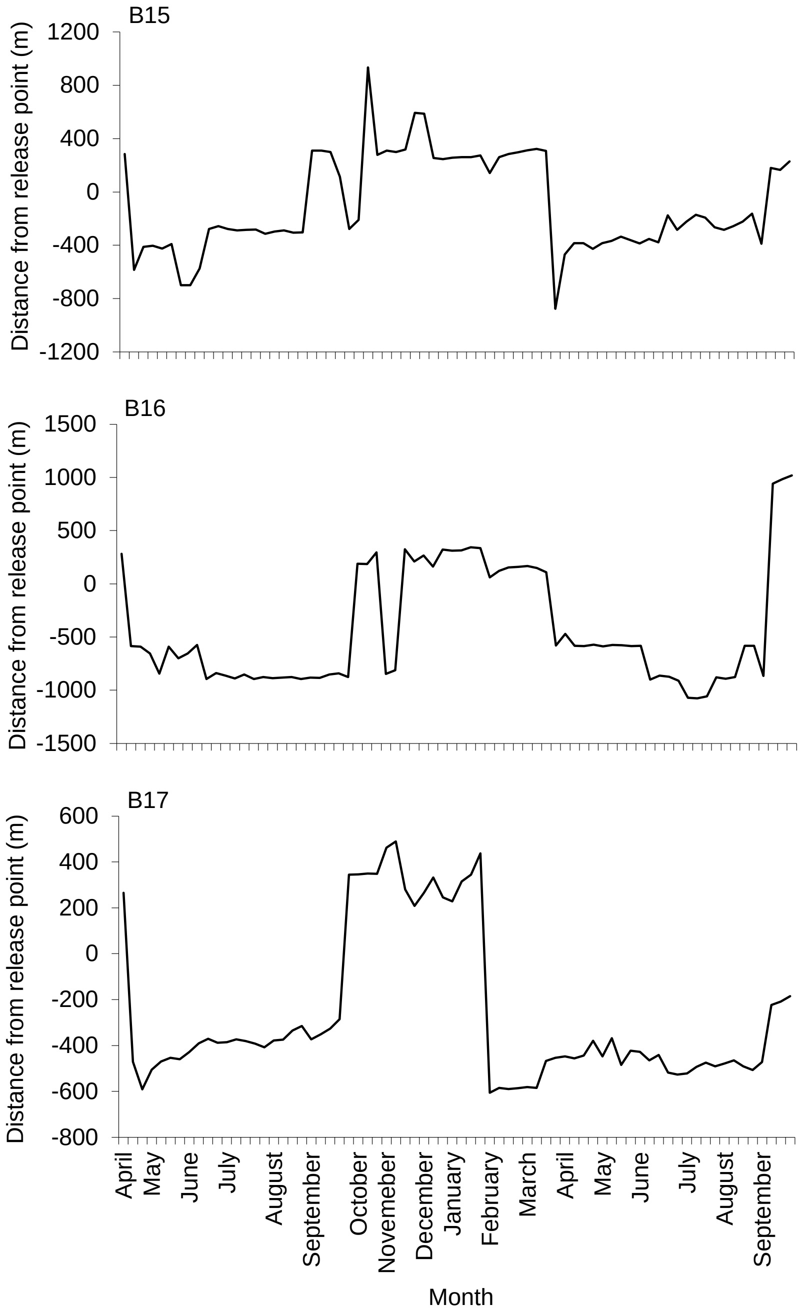


Figure 4.12. Weekly distance of B15, B16, and B17 from release site (0). Landmarks; Odell 1319 m, Harrold Bridge -598 m, Aquarium -1247 m.

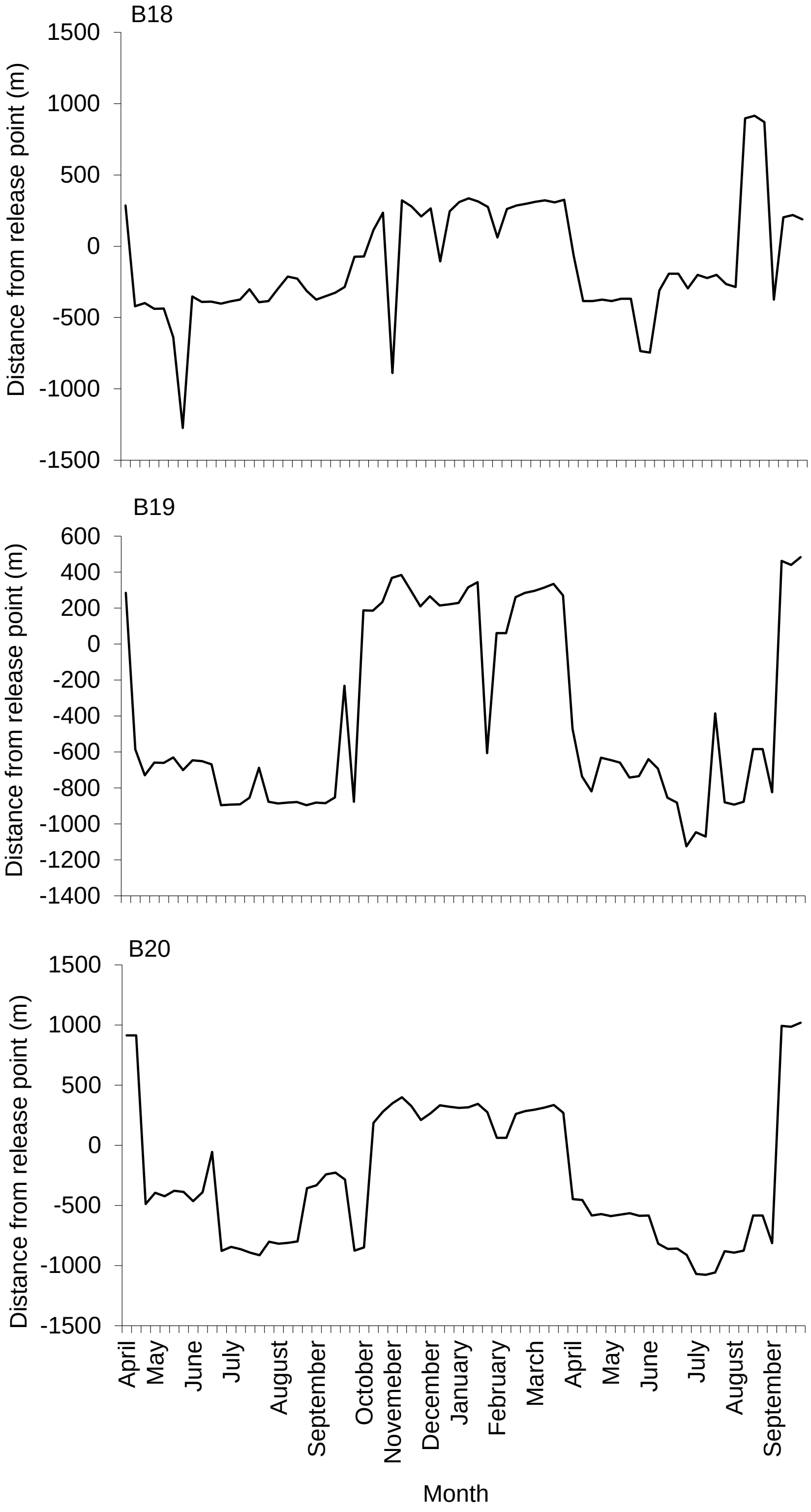


Figure 4.13. Weekly distance of B18, B19 and B20 from release site (0). Landmarks; Odell 1319 m, Harrold Bridge -598 m, Aquarium -1247 m.

4.3.3 Daily movements: 2010 and 2011

There were significant differences in daily movements (distance moved per day (m)) between 2010 and 2011 for all fish except B8, B9 and B18 based on all 100 consecutive tracked days (Table 4.2). There were significant differences in the daily movements between 2010 and 2011 for all fish except B8, B9, B17, B18 and B20 based on the last 93 consecutive days tracked, after the first week's data had been removed from the sample. There were no significant differences in the first 7 consecutive days tracked between 2010 and 2011, suggesting that there may have been an effect from the tagging procedure on daily movements.

Table 4.2. T-test results comparing 2010 and 2011 daily movements.

Barbel	100 consecutive days			Last 93 consecutive days			First 7 consecutive days		
	df	t Stat	P Value	df	t Stat	P Value	df	t Stat	P Value
B3	99	2.6299	<0.01	92	2.5436	<0.01	6	2.2809	>0.05
B5	99	5.671	<0.001	92	5.5389	<0.001	6	1.1759	>0.05
B6	99	5.3094	<0.001	92	5.2581	<0.001	6	1.7417	>0.05
B7	99	3.0304	<0.01	92	2.8308	<0.01	6	2.9693	>0.05
B8	99	1.6452	>0.05	92	1.6307	>0.05	6	0.8895	>0.05
B9	99	0.2925	>0.05	92	0.2075	>0.05	6	1.7741	>0.05
B10	99	3.821	<0.001	92	4.4317	>0.05	6	0.1352	>0.05
B11	99	2.6084	<0.01	92	2.7128	<0.001	6	-1.592	>0.05
B12	99	2.8692	<0.01	92	2.5478	<0.01	6	2.0980	>0.05
B13	99	2.5006	<0.01	92	2.4033	<0.01	6	0.6401	>0.05
B14	99	2.2999	<0.05	92	3.5658	<0.01	6	0.8768	>0.05
B15	99	2.7645	<0.01	92	3.2665	<0.001	6	0.9078	>0.05
B16	99	3.1018	<0.01	92	2.8776	<0.001	6	1.1533	>0.05
B17	99	2.0872	<0.05	92	1.966	<0.001	6	2.1535	>0.05
B18	99	1.8113	>0.05	92	1.5079	>0.05	6	1.0142	>0.05
B19	99	2.0655	<0.05	92	2.1991	<0.05	6	-1.098	>0.05
B20	99	2.2276	<0.05	92	1.8319	>0.05	6	2.6353	>0.05

P<0.05 significant, P<0.01 highly significant, P<0.001 extremely significant.

Analysis of spatial behaviour of daily tracking was based on two descriptors of the pattern and extent of movements: range per day tracked and daily distance (Bolland 2007).

- Range per day tracked was calculated by dividing the linear range (the difference between the maximum distance upstream and downstream recorded throughout the tracked period) by the number of days the fish was tracked (Figure 4.14). This describes the extent of river used, standardised for the period of tracking;
- daily distance for each fish was calculated by dividing the total distance moved (calculated from the position recorded every day) by the period over which the fish was tracked, and reflects the overall level of movement (Figure 4.15).

In 2010, barbel exhibited significantly larger mean ranges per day tracked (2010 = 17.36 m day^{-1}, 2011 = 7.34 m day^{-1}: Mann Whitney *U*-test: Z = 3.497, n=34, P<0.001) and mean daily distances (2010 = 103.38 m day^{-1}, 2011 = 50.71 day^{-1}: Mann Whitney *U*-test: Z=-3.634, n=34, P<0.001) than in 2011 (Figure 4.13 and 4.14).

In 2010 year, B2 had the highest average daily movement recorded. In both years, B7, B10 and B14 had the lowest. In 2010, daily average movements for all fish peaked on day 4 (Figure 4.16), coinciding with B2's first major movement after the tagging process. Following this, there were 4 cycles of movements; between days 5-28, 29-51, 52-78 and 79-95 with peaks on days 23, 37, 49, 51 and 60. In 2011, daily average movement peaked on day 11, due to B2's movement from its capture site and winter residence area. There were 7 cycles of movement; between days 1-14, 15-26, 27-40, 41-57, 58-70, 71-87 and 88-100 with peaks on days 11, 20, 21, 28, 34, 38 (Figure 4.16).

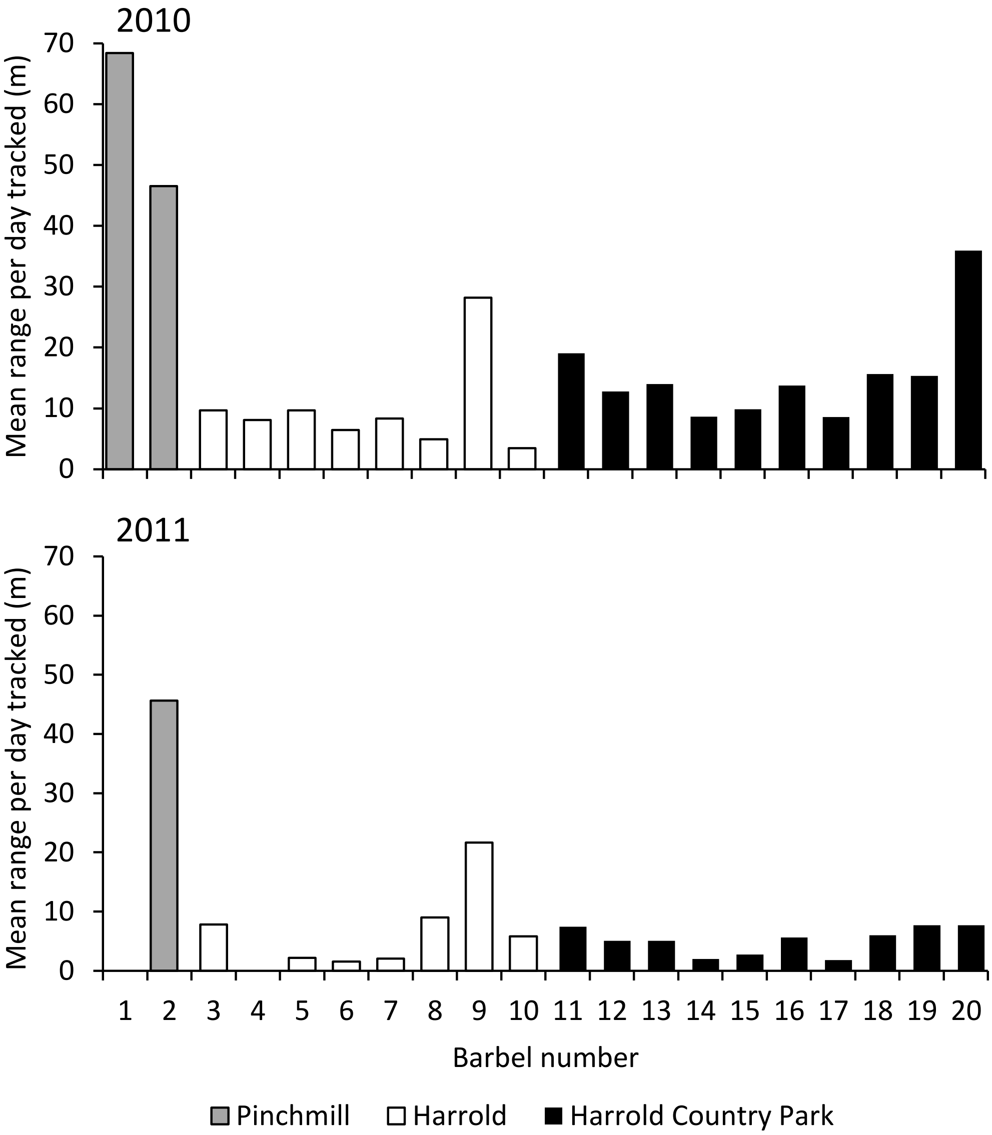


Figure 4.14. Mean range per day tracked for each barbel in 2010 and 2011.

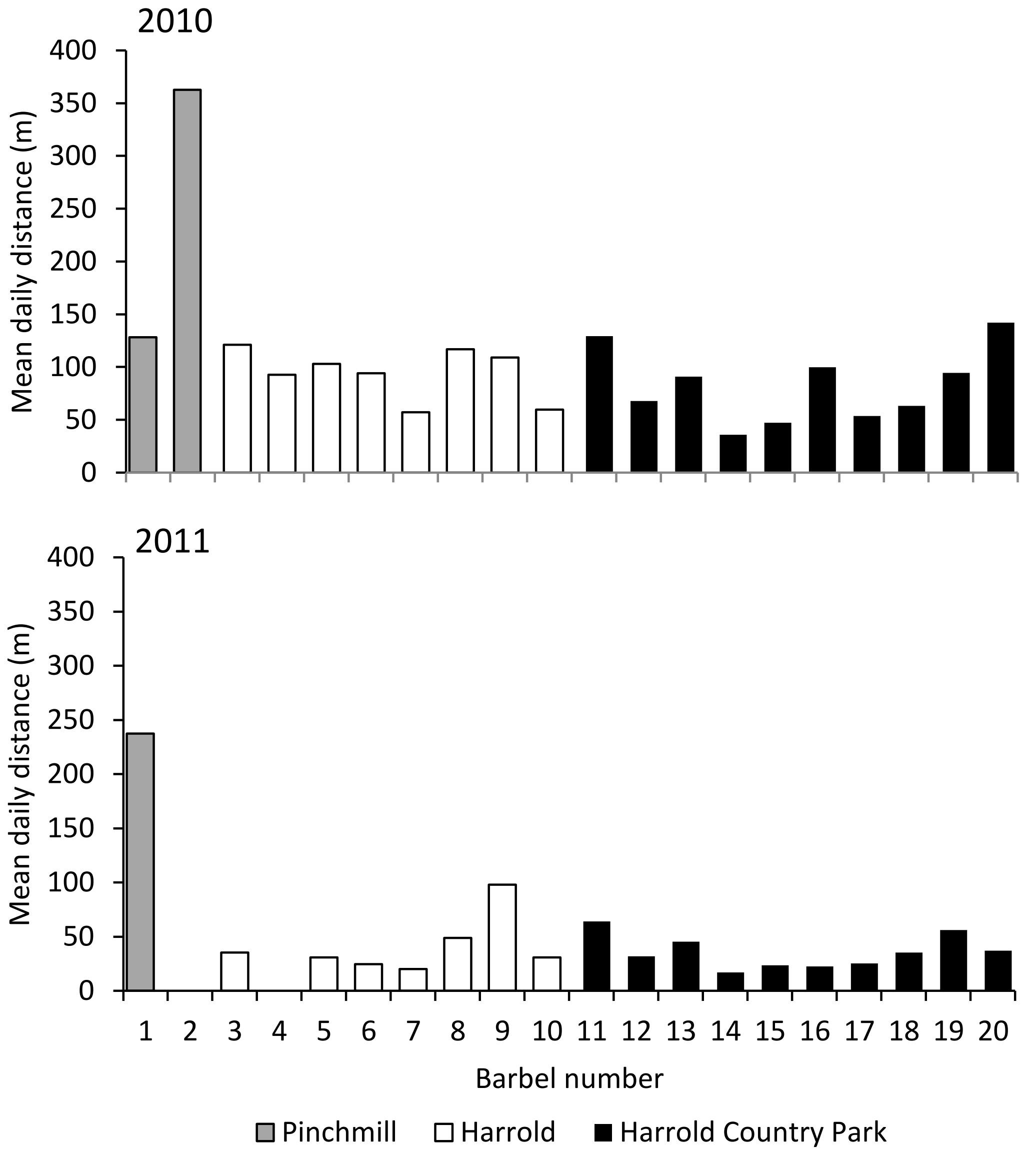


Figure 4.15. Mean daily distance travelled by each barbel in 2010 and 2011.

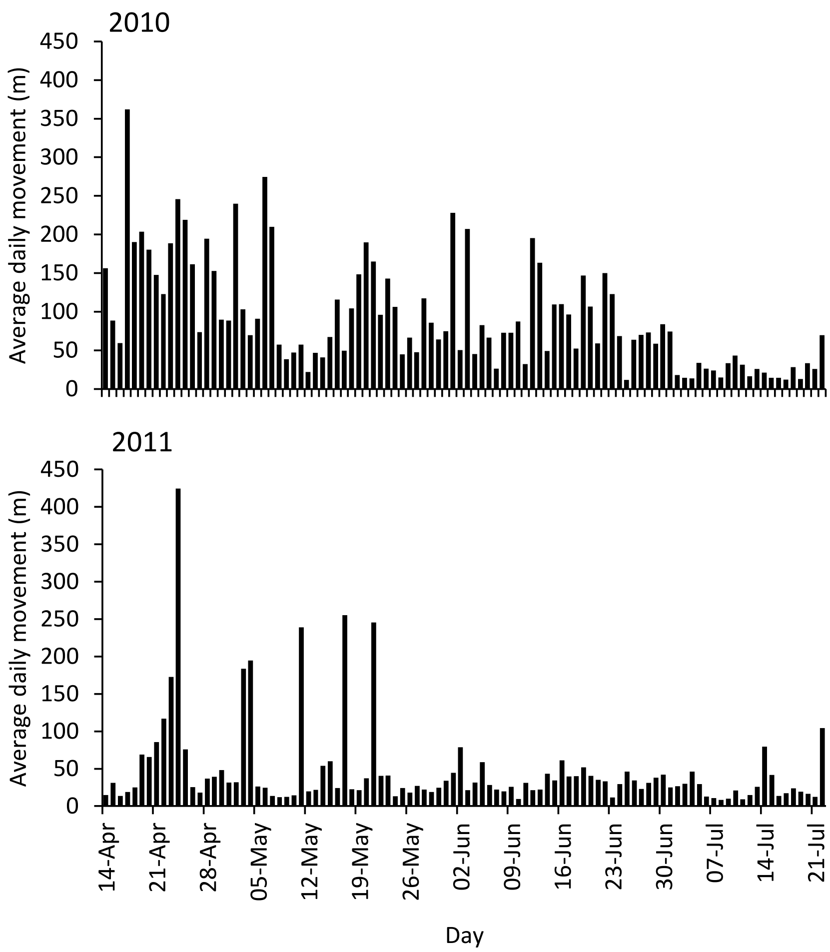


Figure 4.16. Average daily movements in 2010 and 2011.

B1 did not go back to its capture site at Pinchmill during the 100 days that it was tracked in 2010. B2 moved between Pinchmill and Odell throughout both years (Figure 4.17). B3 and B6 were at different locations during the daily tracking in 2010 and 2011 (Figure 4.18). B7, B8 and B9 never returned to their release site, but they remained in the same residence area for the rest of the study (Figure 4.19). B10 remained in a similar residence area from days 1 to 60 each year, but in 2010 and 2011 resided on different sides of Harrold Bridge (Figures 4.19).

B11 showed big differences between residence area preference in 2010 and 2011. B12 (Figure 4.19), B13, B14, B15, B17, B18 and B20 never returned to their release site. B15 and B16 remained in the same residence areas each year with the exception of the days between day 37 and 57, 50 and 100, respectively (Figures 4.20 to 4.22).

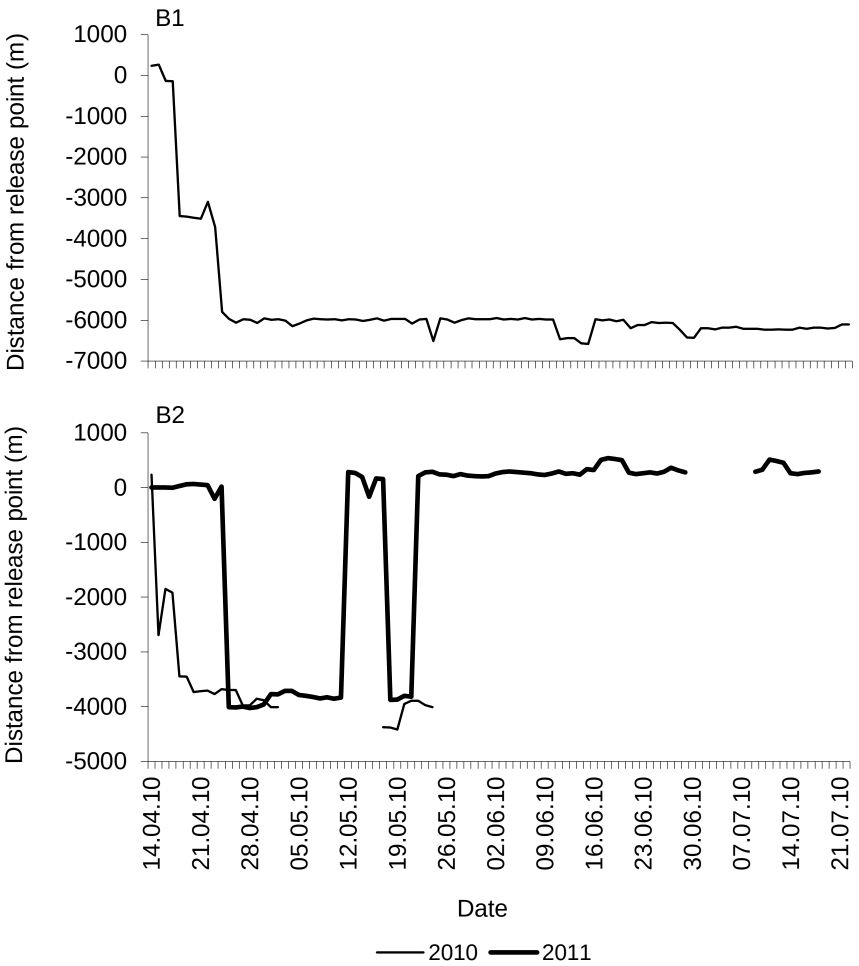


Figure 4.17. Daily distance of B1 and B2 from release site (0 m) over 100 consecutive days tracked in 2010 and 2011. Landmarks; Odell -4015 m, Harrold Bridge -5933 m, Aquarium -6581 m.

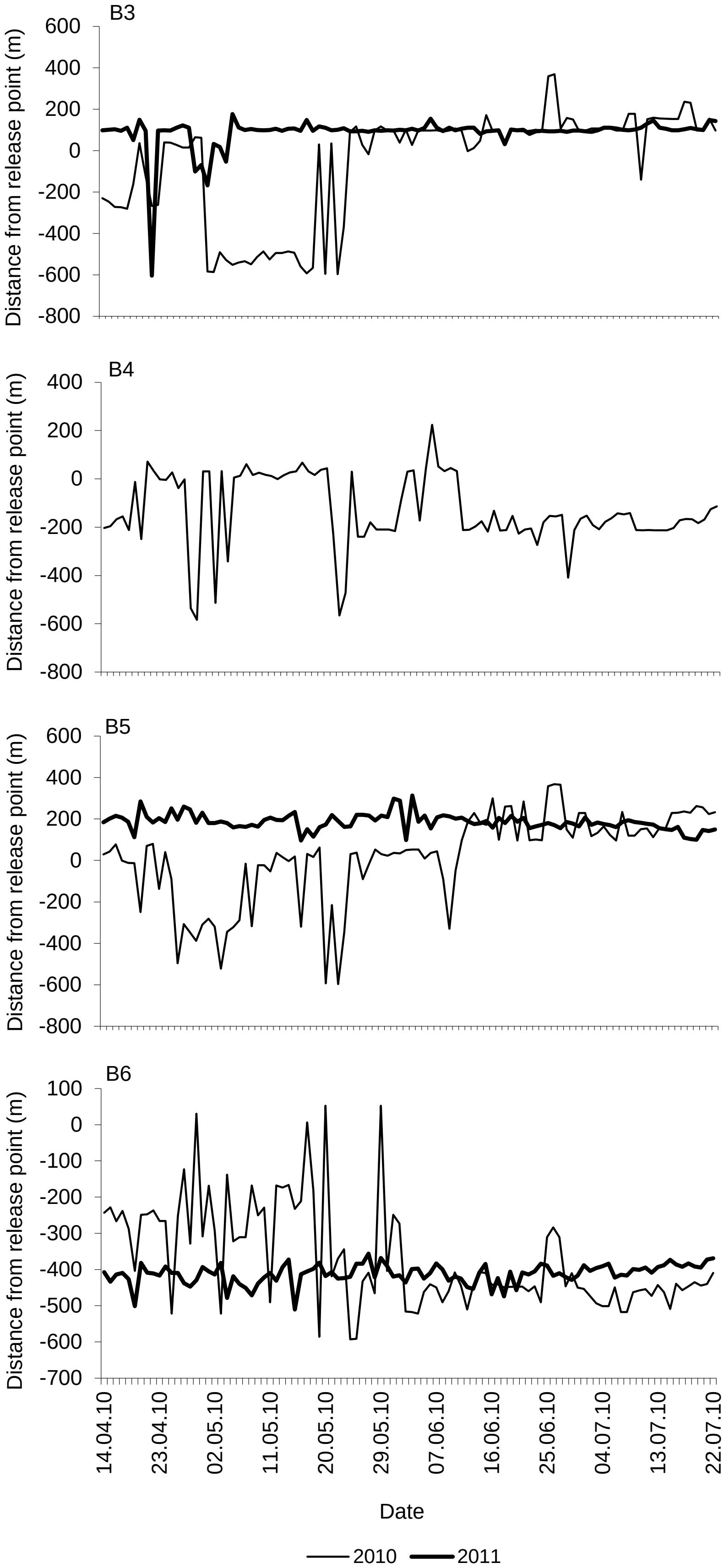


Figure 4.18. Daily distance of B3, B4, B5 and B6 from release site (0 m) over 100 consecutive days tracked in 2010 and 2011. Landmarks; Harrold Bridge 84 m and Aquarium -564 m.

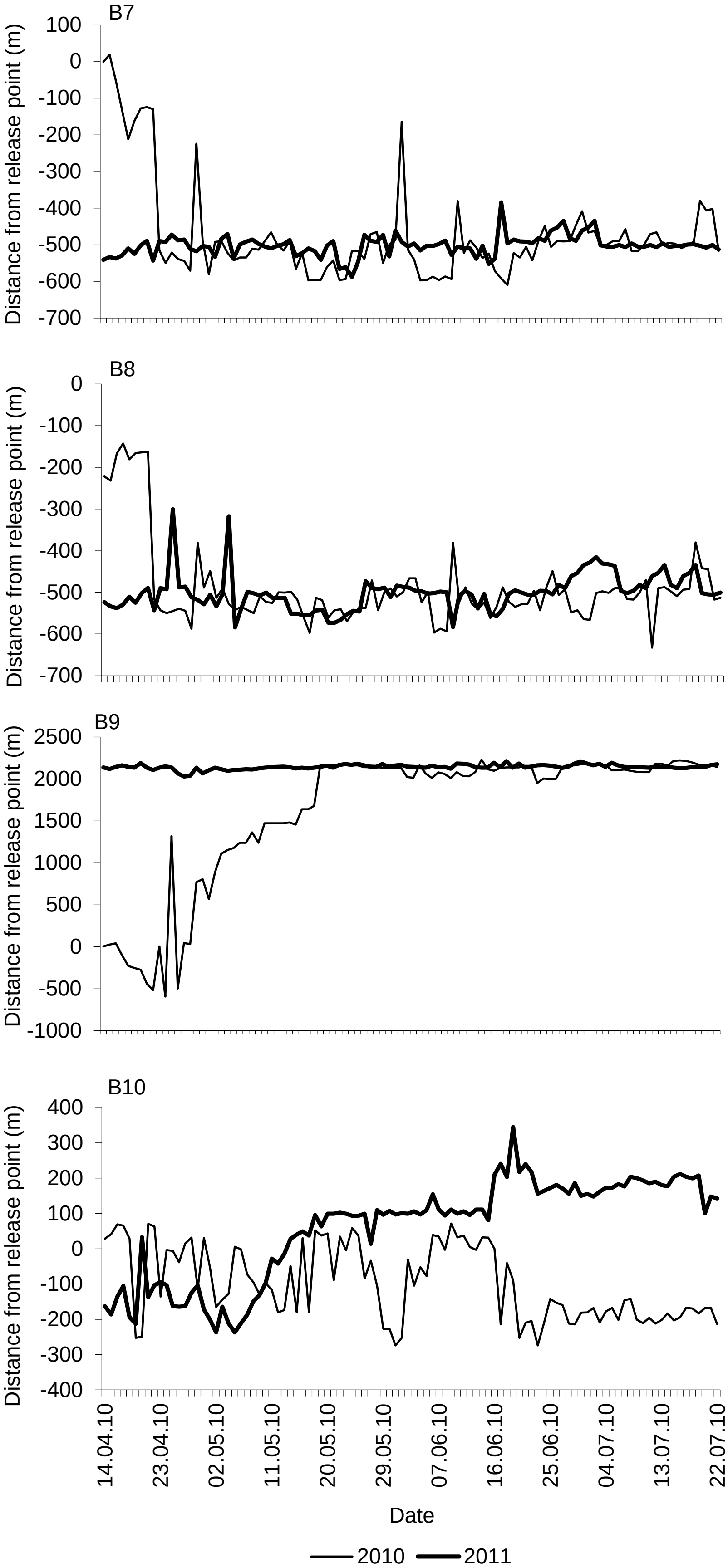


Figure 4.19. Daily distance of B7, B8, B9 and B10 from release site (0 m) over 100 consecutive days tracked in 2010 and 2011. Landmarks; Odell 2002 m, Harrold Bridge 84 m and Aquarium -564 m.

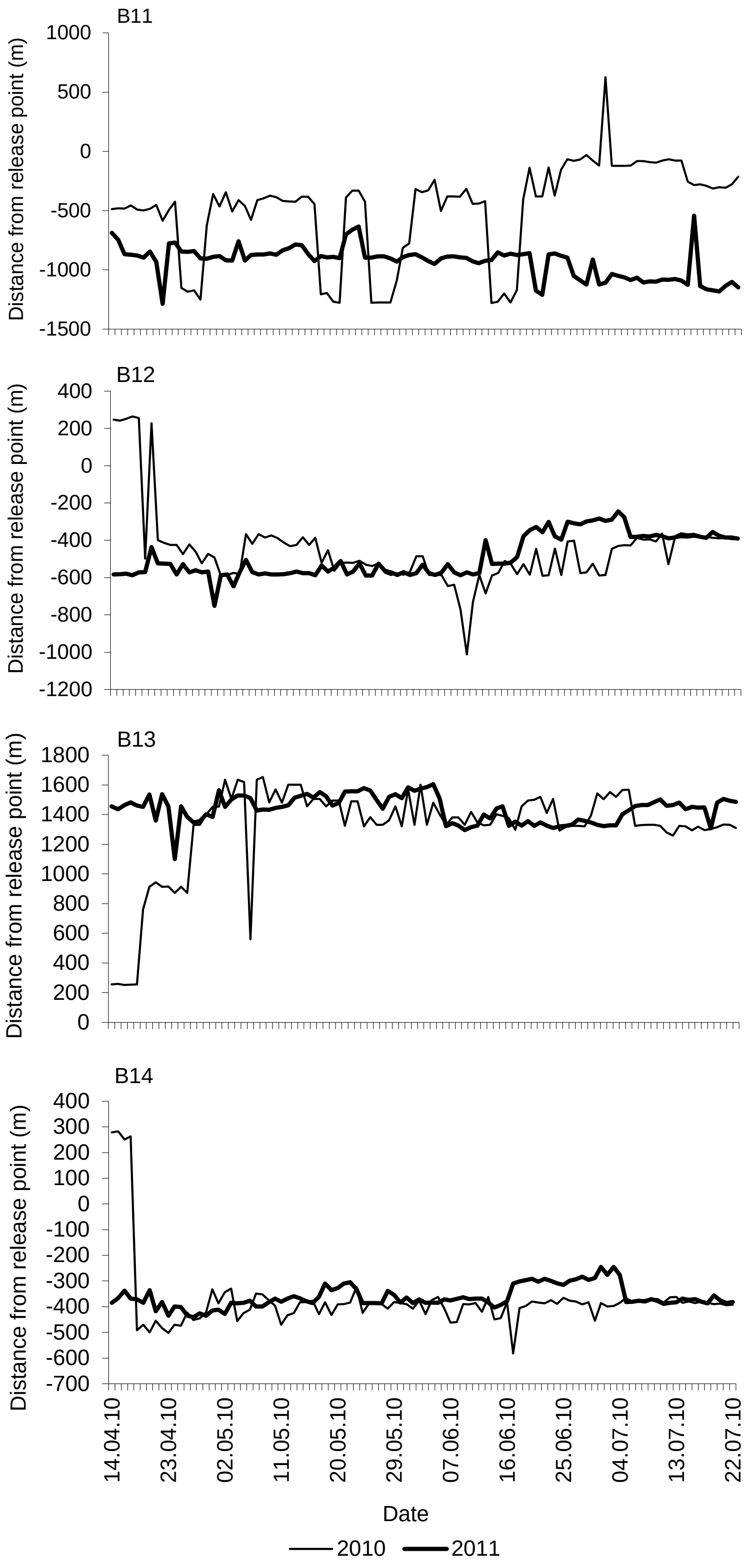


Figure 4.20. Daily distance of B11, B12, B13 and B14 from release site (0 m) over 100 consecutive days tracked in 2010 and 2011. Landmarks; Odell 1319 m, Harrold Bridge -598 m and Aquarium -1247 m.

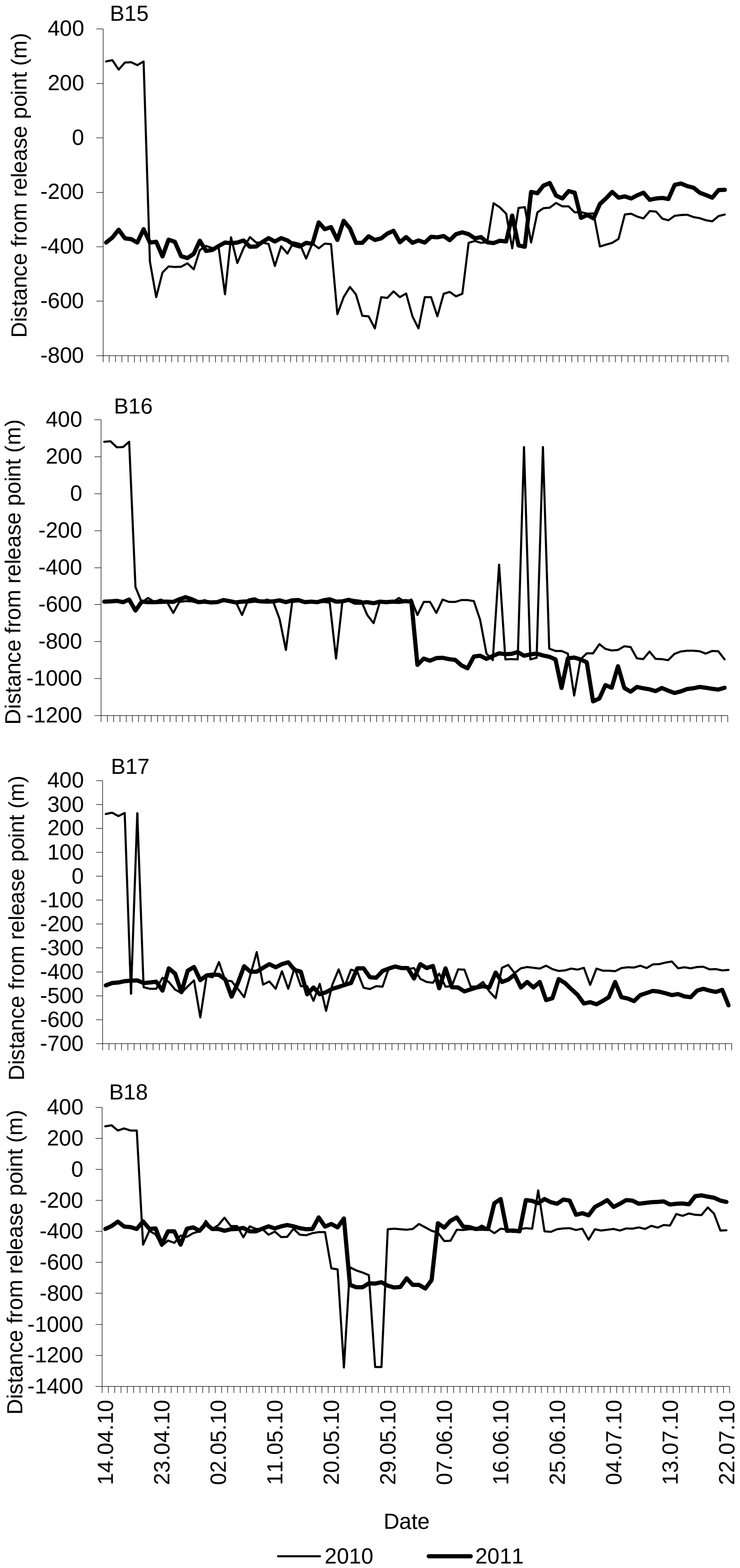


Figure 4.21. Daily distance of B15, B16, B17 and B18 from release site (0 m) over 100 consecutive days tracked in 2010 and 2011. Landmarks; Harrold Bridge -598 m and Aquarium -1247 m.

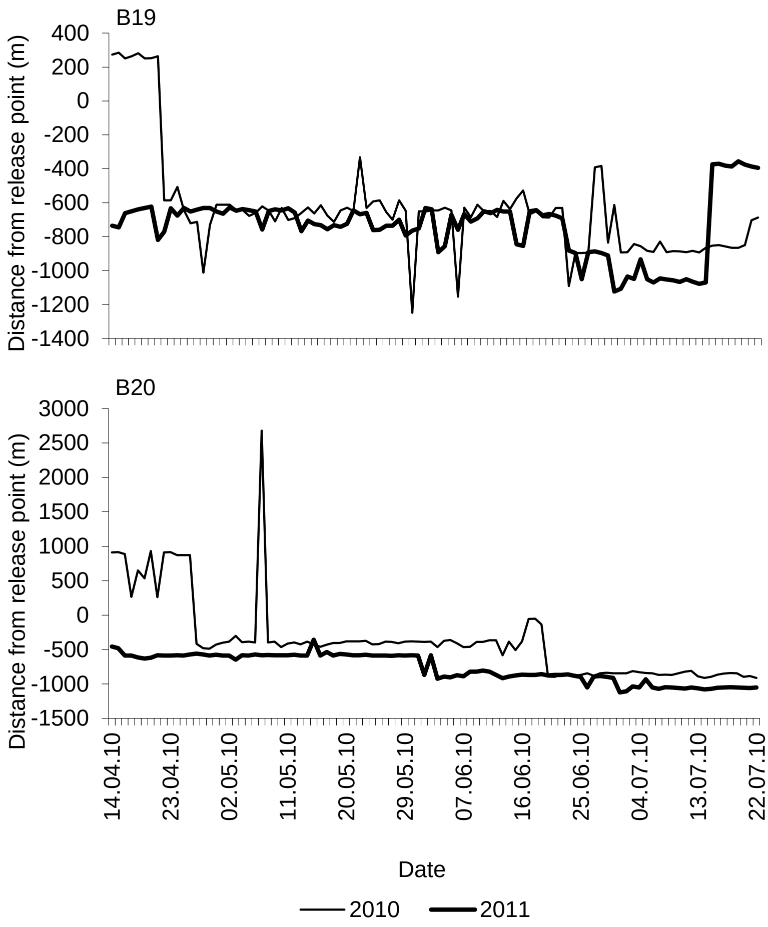


Figure 4.22. Daily distance of B19 and B20 from release site (0 m) over 100 consecutive days tracked in 2010 and 2011. Landmarks; Odell 1319 m, Harrold Bridge -598 m and Aquarium -1247 m.

4.3.4 Spawning activities

Of the 20 barbel tagged, only B9 and B13 migrated in a downstream direction during the spawning period (Figures 4.19 and 4.20). Visual observations of tagged and non-tagged barbel identified seven spawning gravels over the two spawning seasons (Figure 4.23). Two spawning habitats were used by tagged barbel and one was used exclusively by non-tagged barbel. B1, B2, B3, B5, B9, B10, B13, B16, B18, B19 and B20 all bypassed one or more spawning gravels.

Due to the clear and shallow waters it was possible to count individuals by visual observations. Spawning attempts were made by several tagged and non-tagged barbel between 27 April and 1 May 2010 after 5 days of pre-spawning activity including chase away interactions and remaining in the same position over the spawning gravel. B3 was seen at Harrold Bridge spawning gravel exhibiting chase away interactions with B1 and two other non-tagged individuals. B9 and seven non-tagged barbel were seen at the

Odell spawning gravel forming two groups, in both groups one barbel, presumed to be female, was pursued by two and three individuals, presumed to be male. The group of three fish appeared to spawn successfully, after which prolonged rain over several days caused the river level and flow to increase, the water temperature to drop and spawning activities were suspended (Figure 4.24).

On 16 May 2010, when the river temperature was ~12°C, barbel activity on the spawning gravel began for a second time. This involved the same stationary and chase away behaviours observed on the first spawning attempt. Three barbel were observed at Aquarium, four barbel observed at Odell and 12 barbel at Harrold Bridge, where the release of milt and eggs was observed first-hand. Despite daily surveillance, no barbel spawning activity was witnessed at Pinchmill. No tagged barbel were observed on the spawning gravels during this second attempt, but all were in close proximity to a spawning gravel. On this occasion, B4, B5, B9 and B13 had moved to a position downstream of their release site. B2 and B5 in 2010 and B2 in 2011 could not be localised by any spawning gravels. B7, B8, B12, B13, B14, B15, B16, B17 and B18 were in the vicinity of the same spawning gravel in 2010 and 2011, but no pre spawning or spawning behaviour of tagged or non-tagged barbel was seen at any of the spawning gravels in the study reach in 2011. One barbel was observed on two occasions on the spawning gravel directly downstream of Odell Bridge.

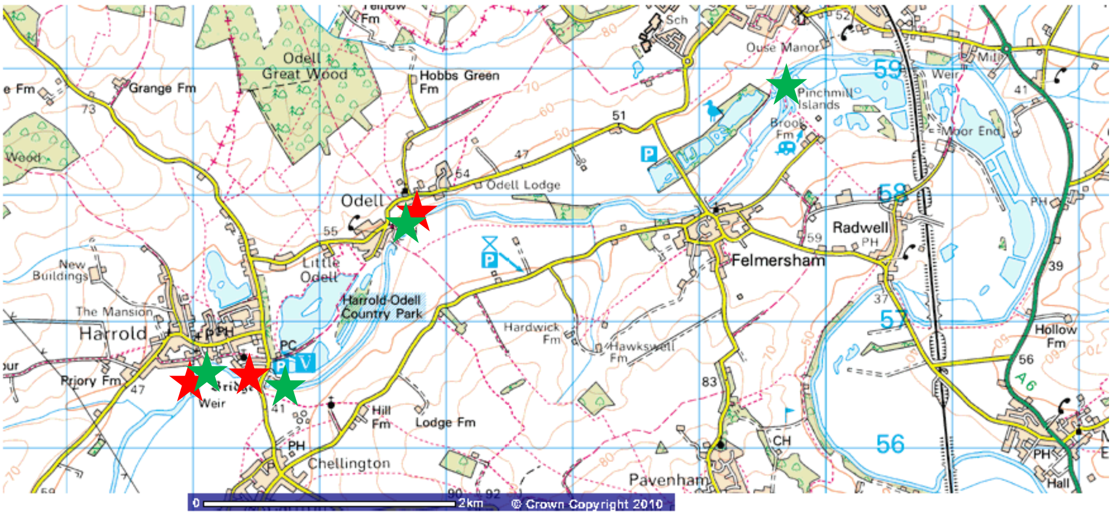


Figure 4.23. Map of study site illustrating the locations of spawning gravels used by barbel in 2010 (★) and chub (★) in 2011.

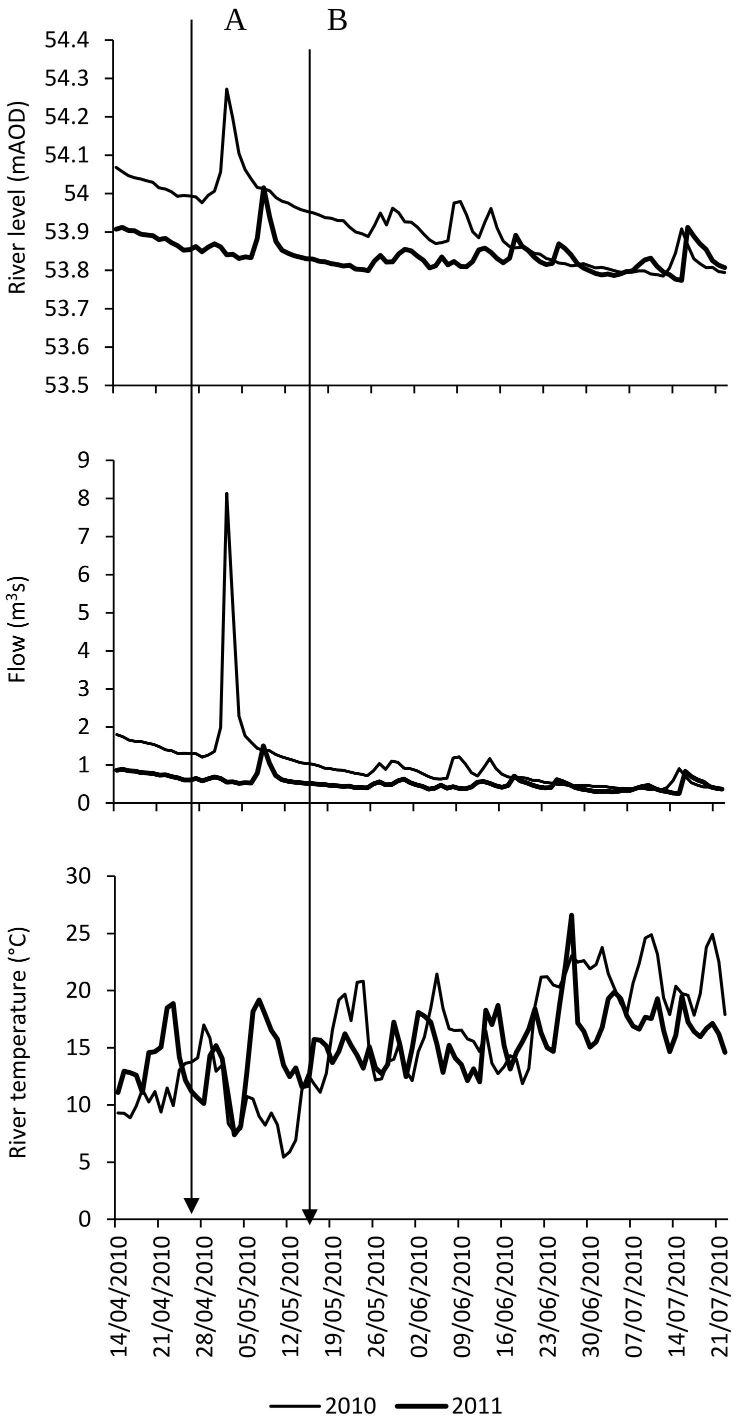


Figure 4.24. River level (Newport Pagnell gauging station), flow (Newport Pagnell gauging station) and temperature (Odell) during the 2010 and 2011 spawning period. (A) first spawning attempt, (B) second and successful spawning attempt.

After 25 May 2010, interactive behaviours on the spawning habitat stopped and barbel left the spawning gravels. This happened at different times for each of the locations identified: Odell after 21 May Aquarium after 24 May and at Harrold Bridge after 27 May. Post spawning movements of barbel can be grouped into 3 groups: B2, B3, B4, B5, B6, B10 and B18 moved downstream after spawning; B12 and B15 moved upstream after spawning; and B1, B7, B8, B9, B13, B14, B16, B17, B19 and B20 stayed in the vicinity of the spawning gravel until the end of the daily tracking. B11 did not fit any of these categories, as it travelled upstream and downstream on multiple occasions for three weeks after spawning had finished.

Visual observations of recreational activities, such as canoeing/kayaking and swimming that utilise the riverine habitat during the barbel spawning season showed that the general public had little knowledge and/or consideration for the natural processes that were occurring during this time. The shallow gravels that were accessible to the public, were used as launch sites, paddling and barbeque areas, they were therefore unavailable for use by the barbel and other lithophilic species. It was also noticed that some of the spawning habitats used by tagged and non-tagged barbel ranged in quality; with regards to fine sediment infiltration and compaction.

4.3.5 Environmental influences on daily movements

There were no relationships between Moon phase, weather, day length and daily movement in 2010 or 2011 (Figure 4.25). During 2010 and 2011, pooled daily movements of wild barbel were significantly influenced by temperature, flow, temperature and flow combined (GLM: deviance = 8.50, d.f. = 196, P ($\chi2$) <0.001). In 2010 specifically, movements were also significantly influenced by temperature, flow, temperature and flow combined (GLM: deviance = 2.74, df = 96, P ($\chi2$) <0.001), whereas in 2011, movements were not significantly influenced by temperature, flow, temperature and flow combined (GLM: deviance = 4.57, df = 96, P ($\chi2$) >0.46).

4.3.6 Ability to pass weirs

60% of tagged barbel could move past Harrold weir in both directions throughout the 73 week tracking period and in low flow conditions in this study (Figure 4.26). This includes multiple occasions during each of the 100 consecutive tracked days (Figure 4.27). None of the 20 tagged barbel were able to pass the gauging weirs at Sharnbrook or Harrold. No barbel moved towards Sharnbrook weir, but several barbel were recorded close to Harrold weir #2 for days at a time and on more than one occasion (Figure 4.28). None of these barbel were recorded upstream of Harrold weirs, highlighting the possibility that it may be impassable to barbel and therefore other cyprinid species with poorer swimming capabilities.

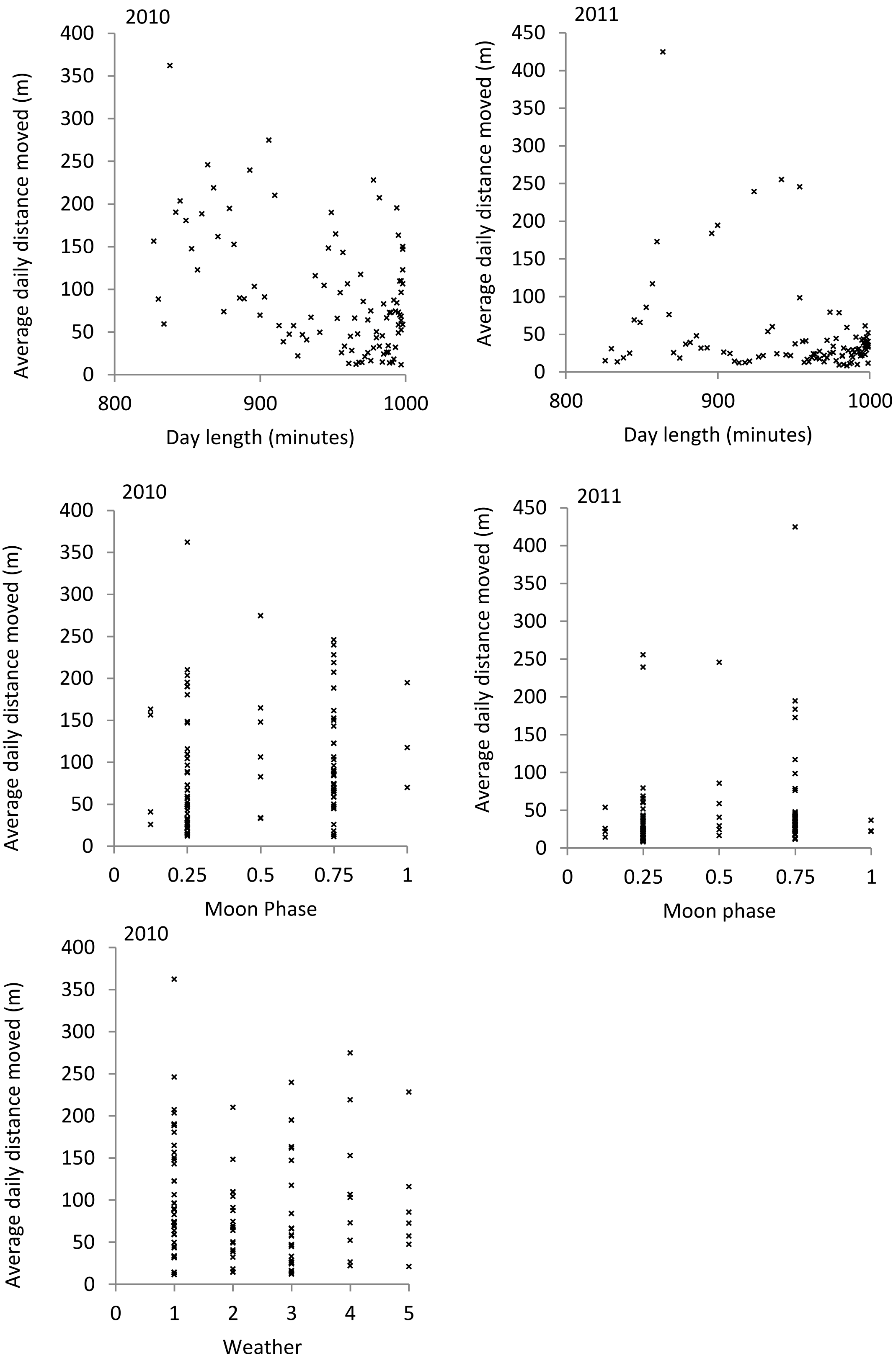


Figure 4.25. Regression analysis of average barbel movement and environmental influences in 2010 and 2011.

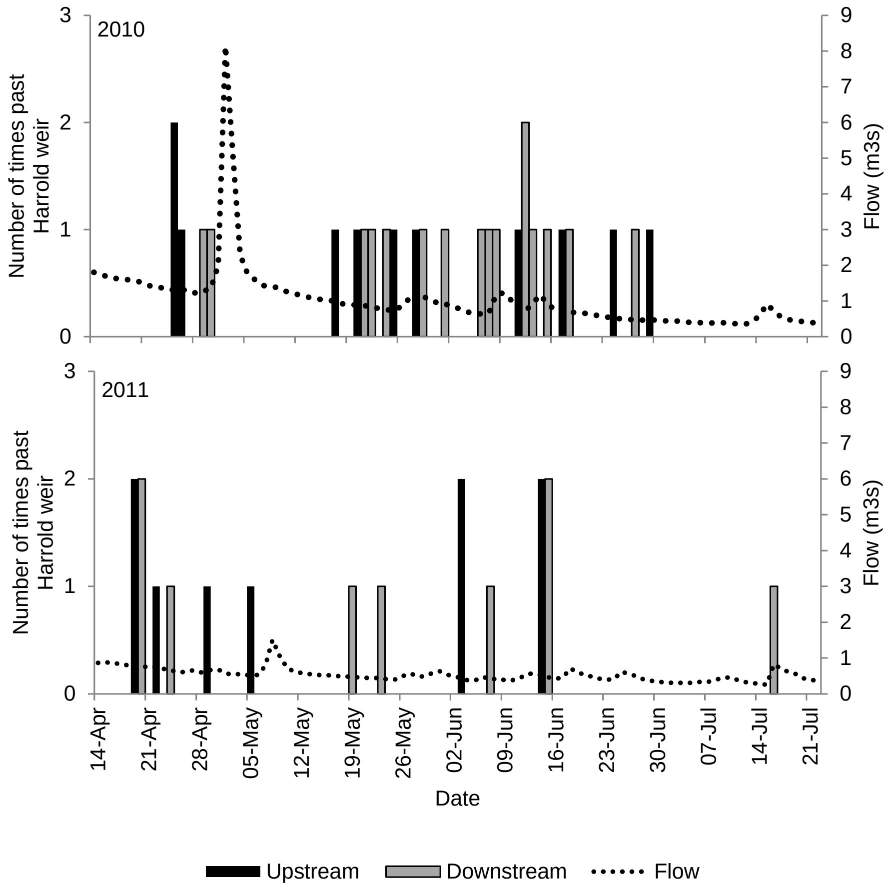


Figure 4.26. Number of barbel that travelled upstream or downstream of Harrold Bridge weir and mean daily flow on each of the 100 consecutive tracked days.

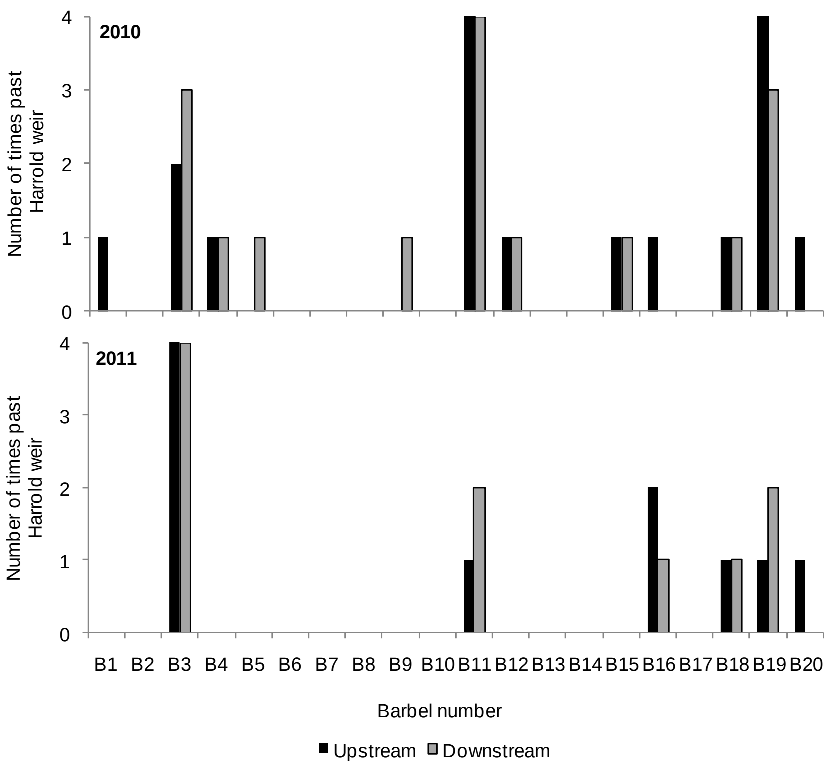


Figure 4.27. Number of times each barbel moved upstream and downstream of Harrold Bridge weir.

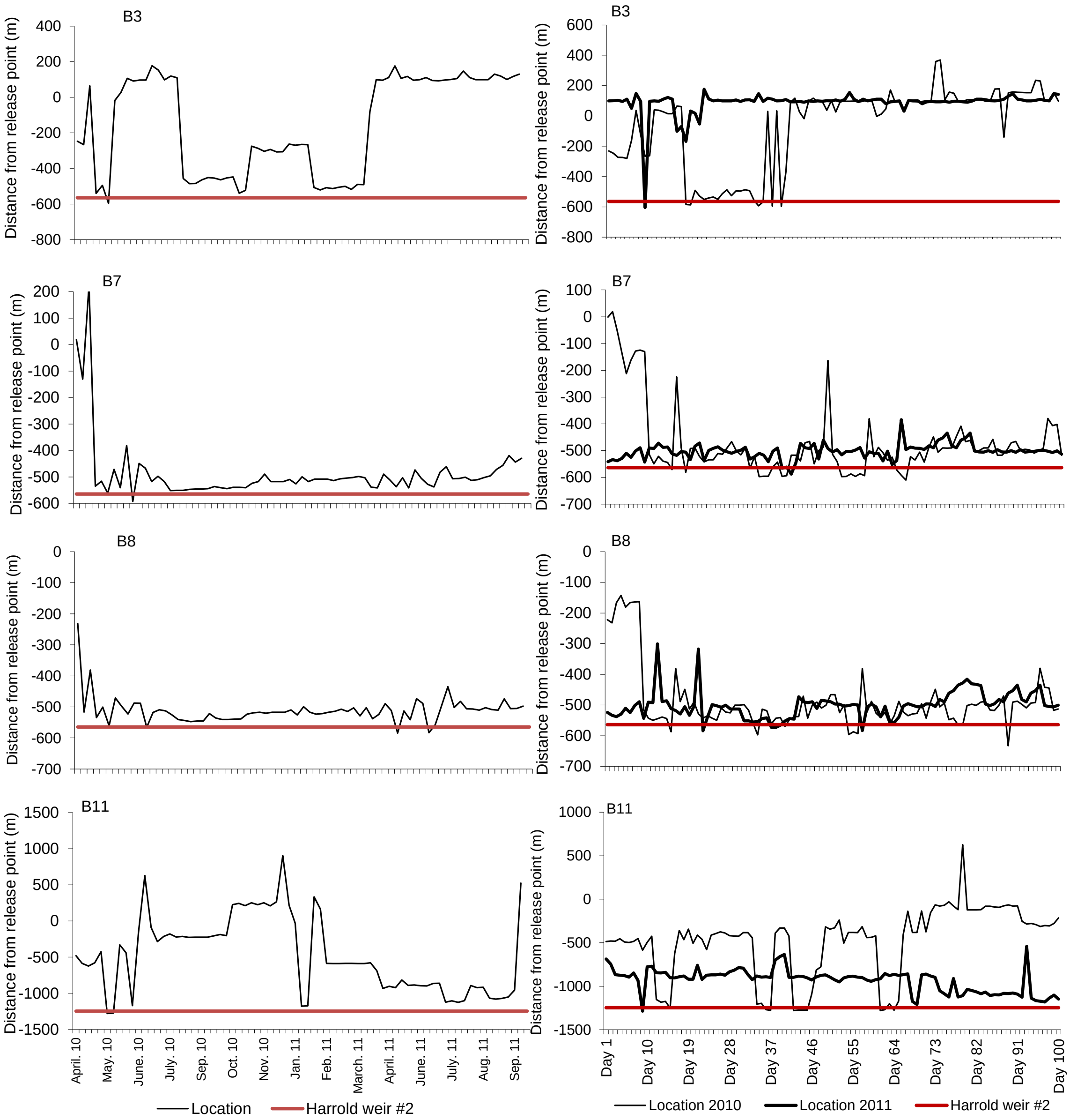


Figure 4.28. Movements of barbel towards Harrold weir #2 recorded with weekly tracking and daily tracking in 2010 and 2011

4.3.6 Meso and Micro scale habitat use

Analysis of habitat scores from 100 m transects and all located barbel positions (n= 4500) showed that each barbel had different habitat use over the 73 week tracking period (Figure 4.29), highlighting that there is not one specific habitat type preferred by barbel. B13 and B9 had the highest affinity to gravel, as did B5 to a lesser extent. This individual, along and B17 used habitats where emergent vegetation was present. B3, B6, B7 and B8 had a high affinity to habitats with riparian overhang and large substrate material (>64 mm) the river bed. B1, B4, B10, B11, B16, B19 and B20 used areas of the river with a high percentage of in stream vegetation, B2, B12, B14, B15 and B18 had high affinity to emergent vegetation.

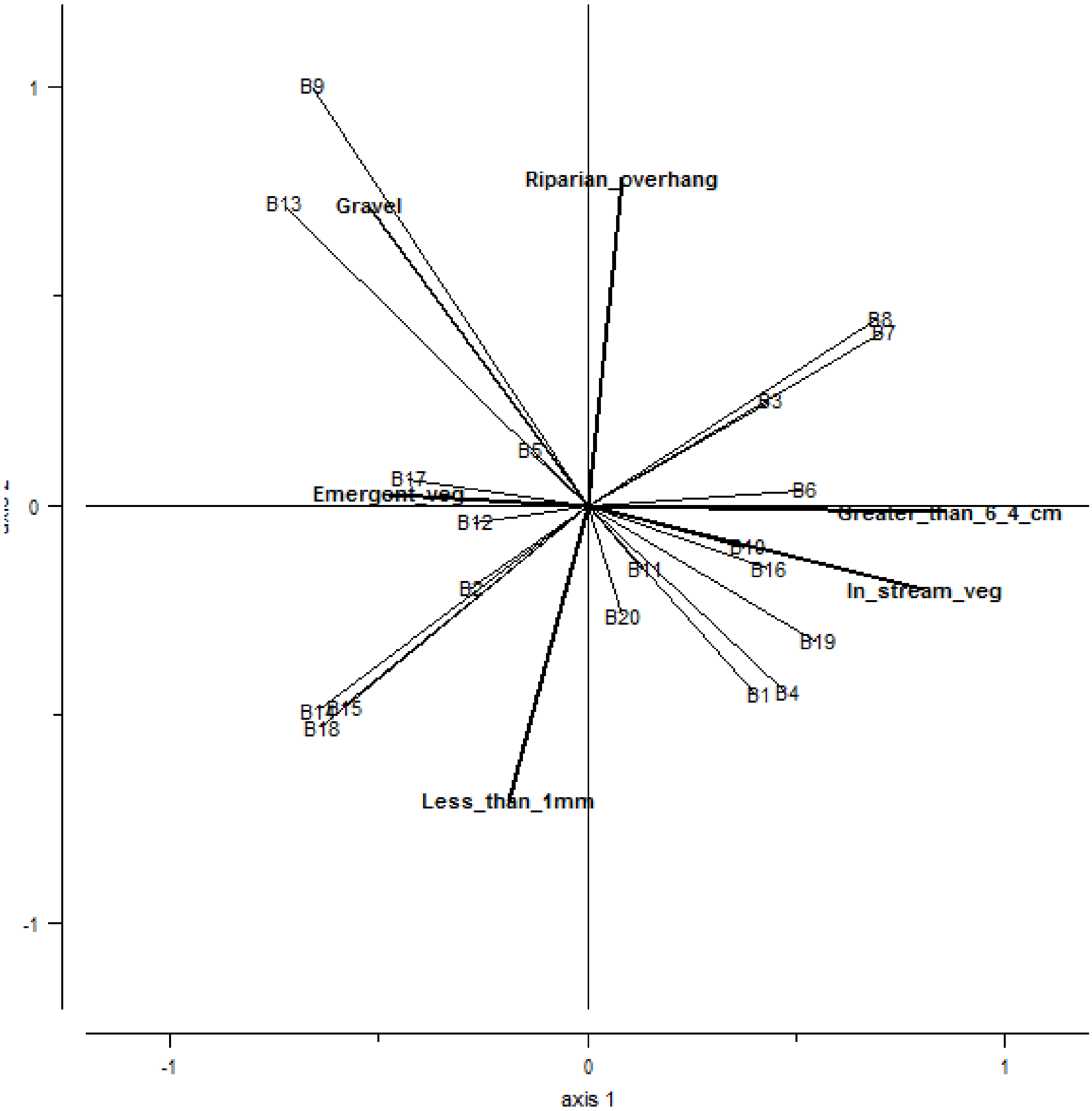


Figure 4.29. Canonical Correspondence Analysis for meso-habitat use of all barbel during the 73 week radio telemetry study.

Analysis of habitat use from daily tracking data in 2010 and 2011 showed that some barbel had some similarity in habitat use in each year and others differed (Figure 4.30 and Figure 4.31). For example, in 2010, B2, B9, and B13 used gravel habitats and in 2011 B9 and B13 remained in similar habitats but in 2011, B2 used habitats with a presence of emergent vegetation associated with fine sediment (<1 mm). This habitat type was also used by B5, B12, B17, B18, (Figures 4.30 and 4.31). Similar changes in habitat use were found with B11. In 2010 this individual used habitats associated with emergent vegetation and cobbles (>64 mm) as did B1, B4, B10, B16, B19 and B20, in 2011, B11 was more closely associated with emergent vegetation. B19 used habitats with instream vegetation and cobbles (>64 mm) in both years.

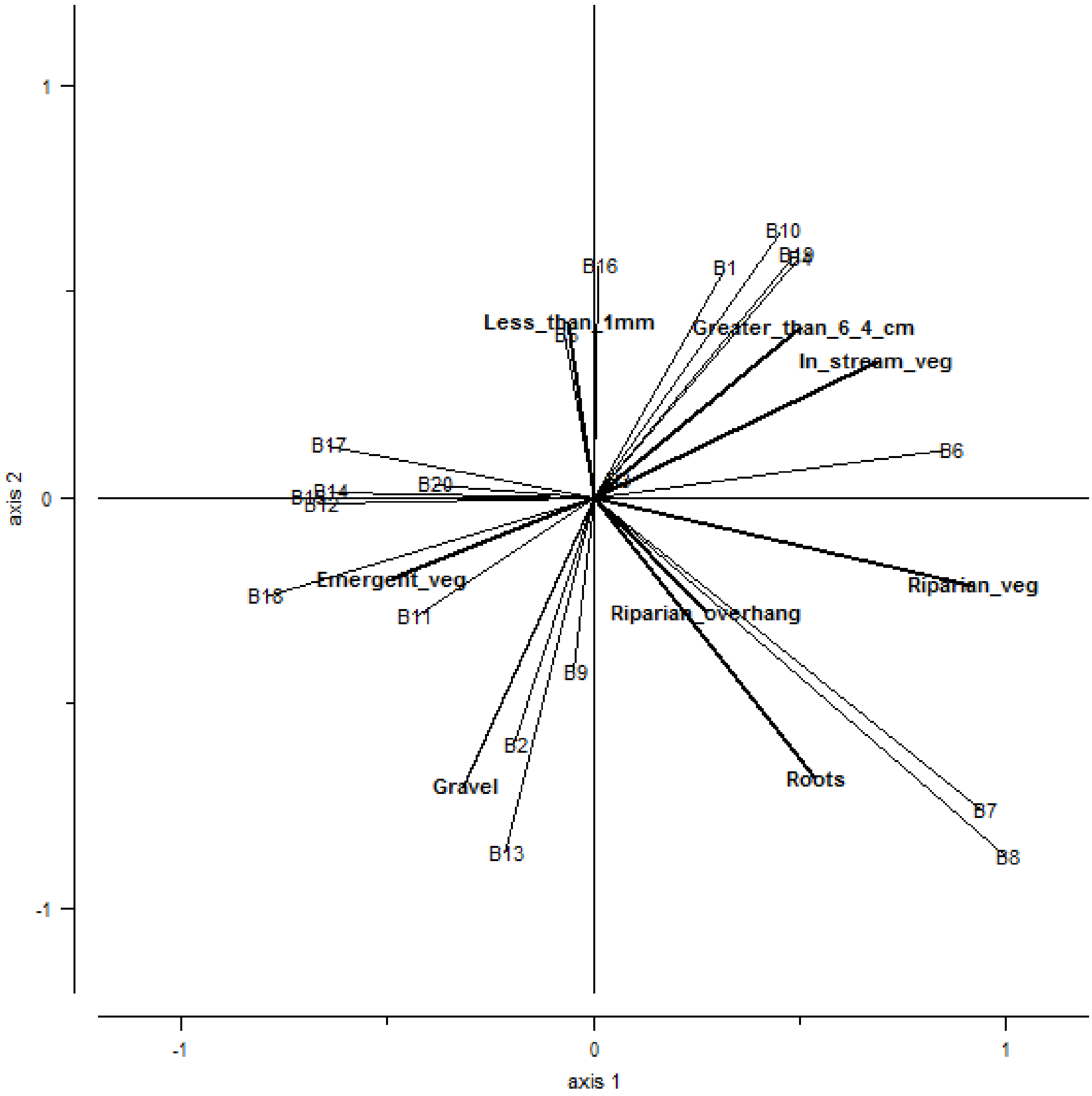


Figure 4.30. Canonical Correspondence Analysis for meso-habitat use of all barbel during daily radio tracking in 2010.

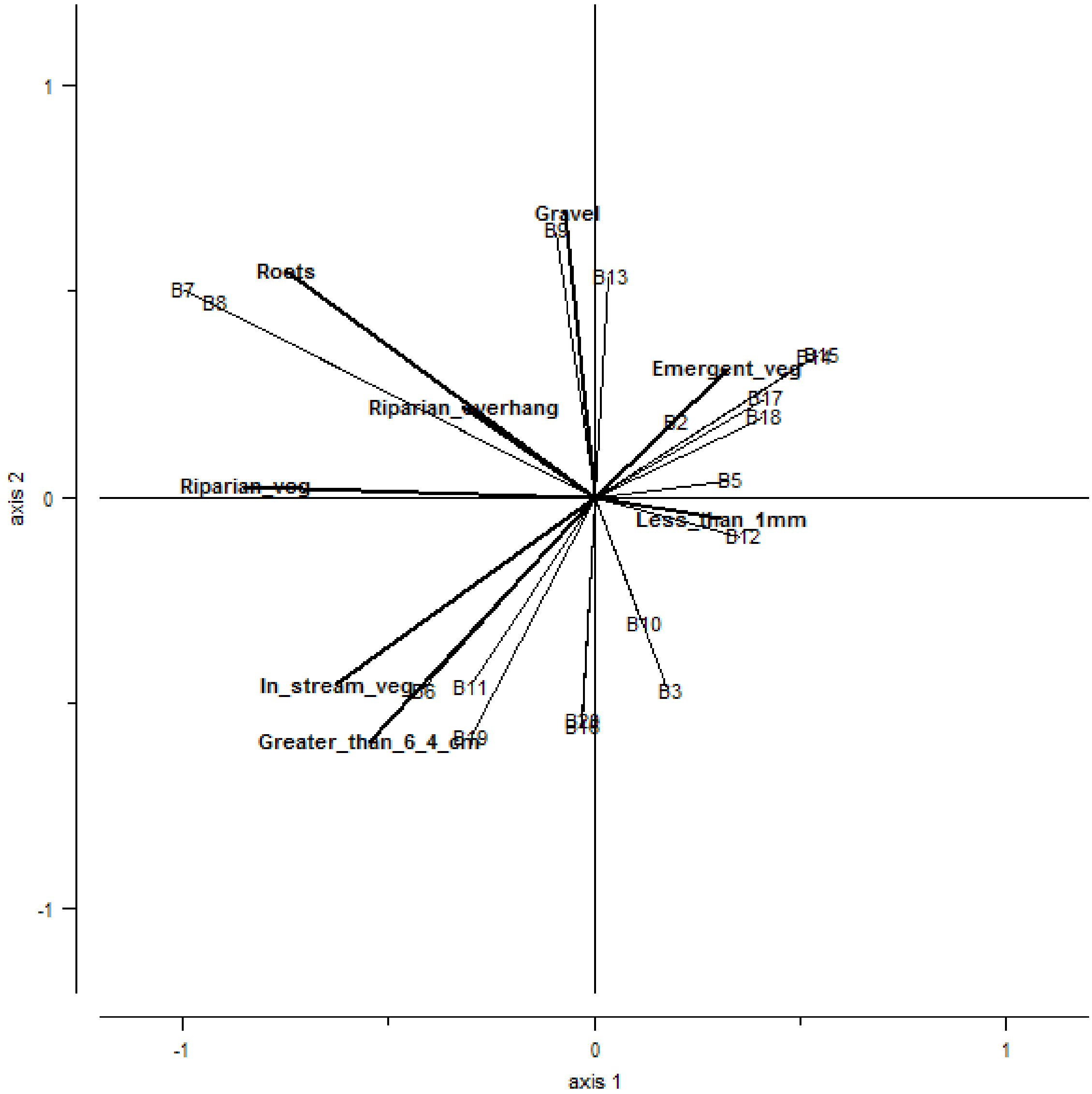


Figure 4.31. Canonical Correspondence Analysis for meso-habitat use of all barbel during daily radio tracking in 2011.

Seasonal trends in habitat use were found (Figures 4.32 to Figure 4.35). In winter (December, January and February), the majority of barbel were in vegetated areas (in stream and emergent) with a high presence of fine sediment (<1 mm) (Figure 4.30). In spring (March, April and May), B2, B11, B12, B13, B14, B15, B16, B17, B18 and B20 all used areas where there was a high percentage of gravel (Figure 4.33). In summer (June, July and August), B5 and B9 we also inhabiting sections of channel with a greater abundance of gravel (Figure 4.34). In autumn (September, October and November), gravel stretches were used less by barbel and emergent and in stream vegetation were important habitat types during this season (Figure 4.35). Pooled daily tracking data from 2010, for all barbel showed that there was little association between weather and habitat use on a daily basis (Figure 4.36).

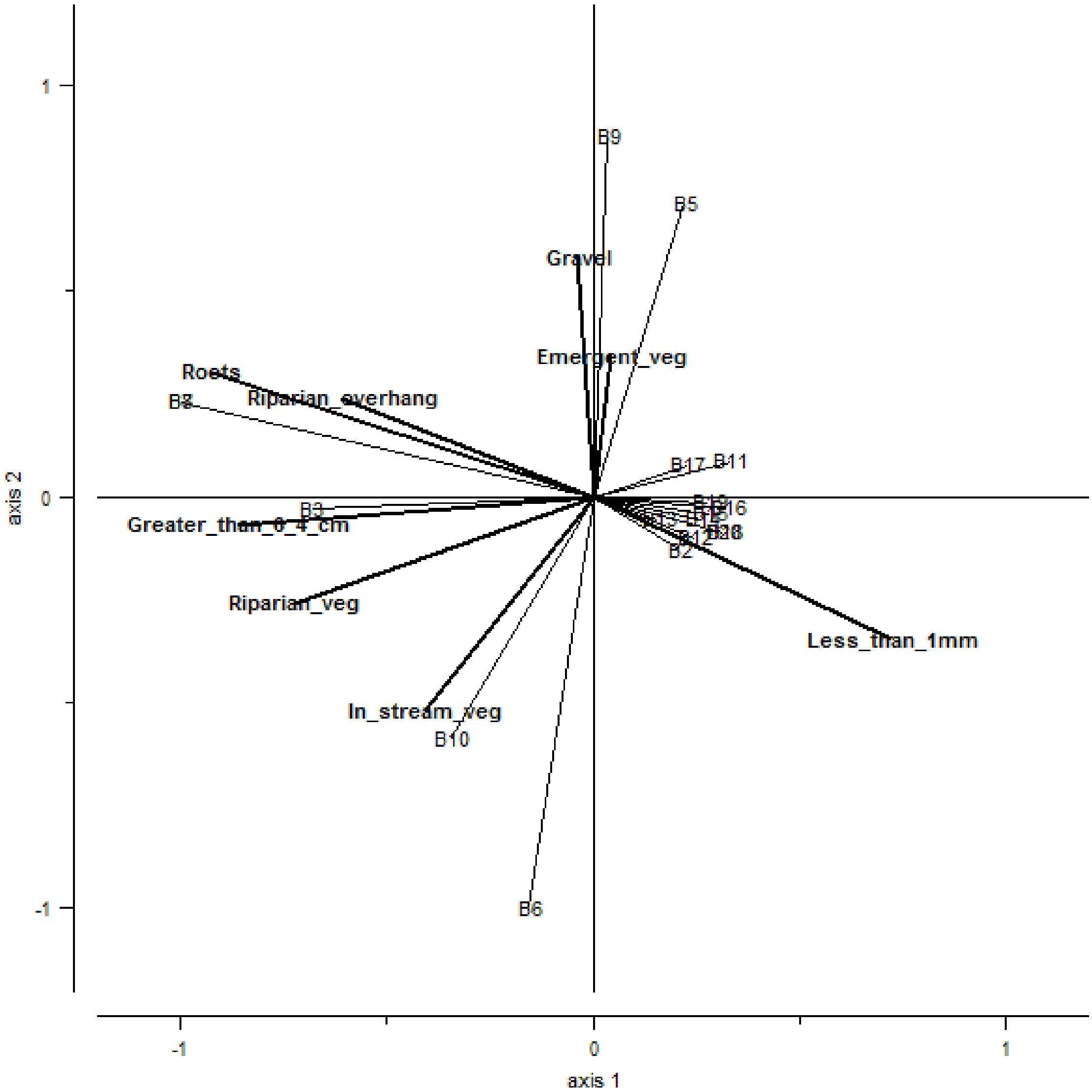


Figure 4.32. Canonical Correspondence Analysis for meso-habitat use of all barbel during winter (December to February).

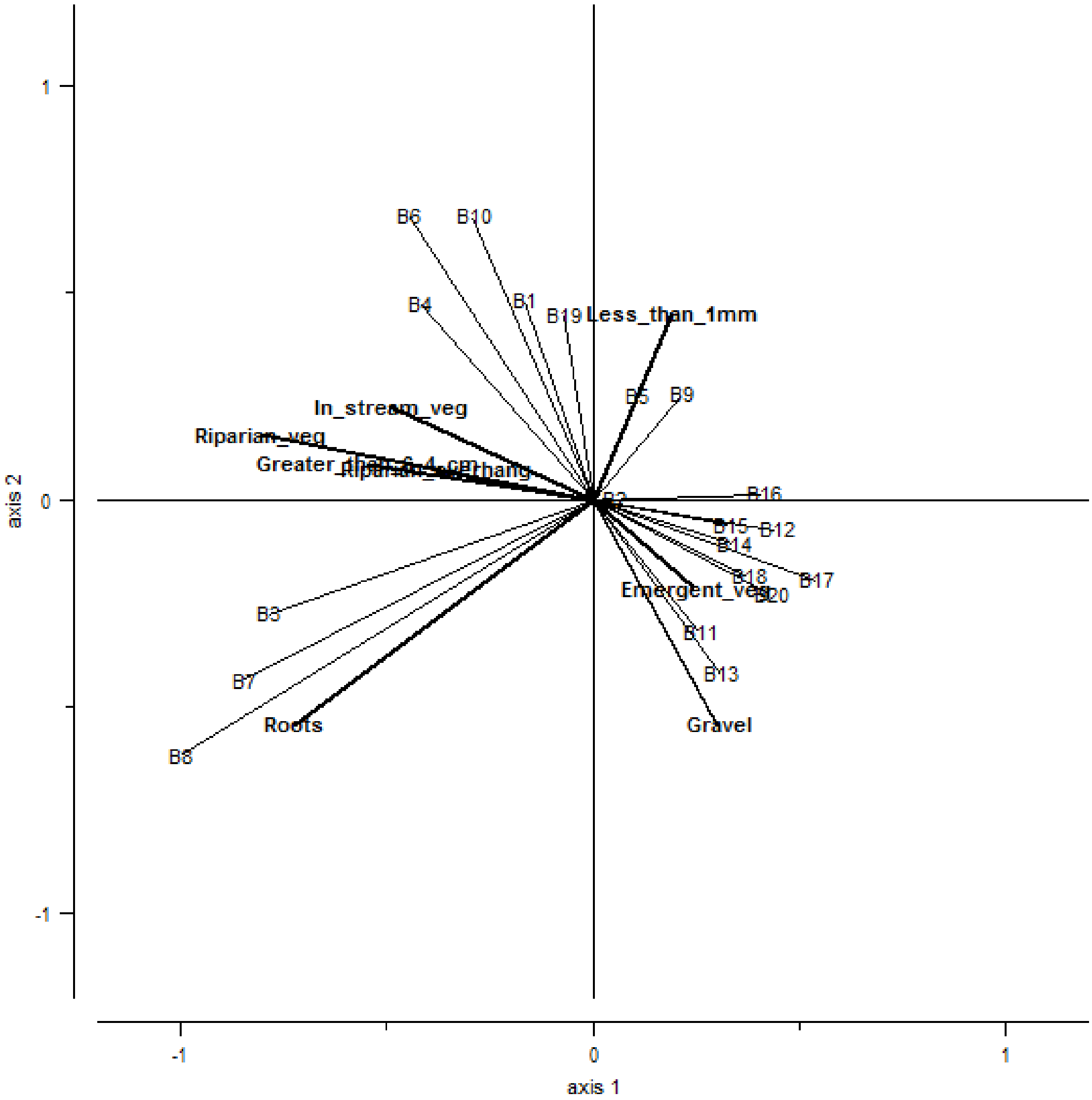


Figure 4.33. Canonical Correspondence Analysis for meso-habitat use of all barbel during spring (March to May).

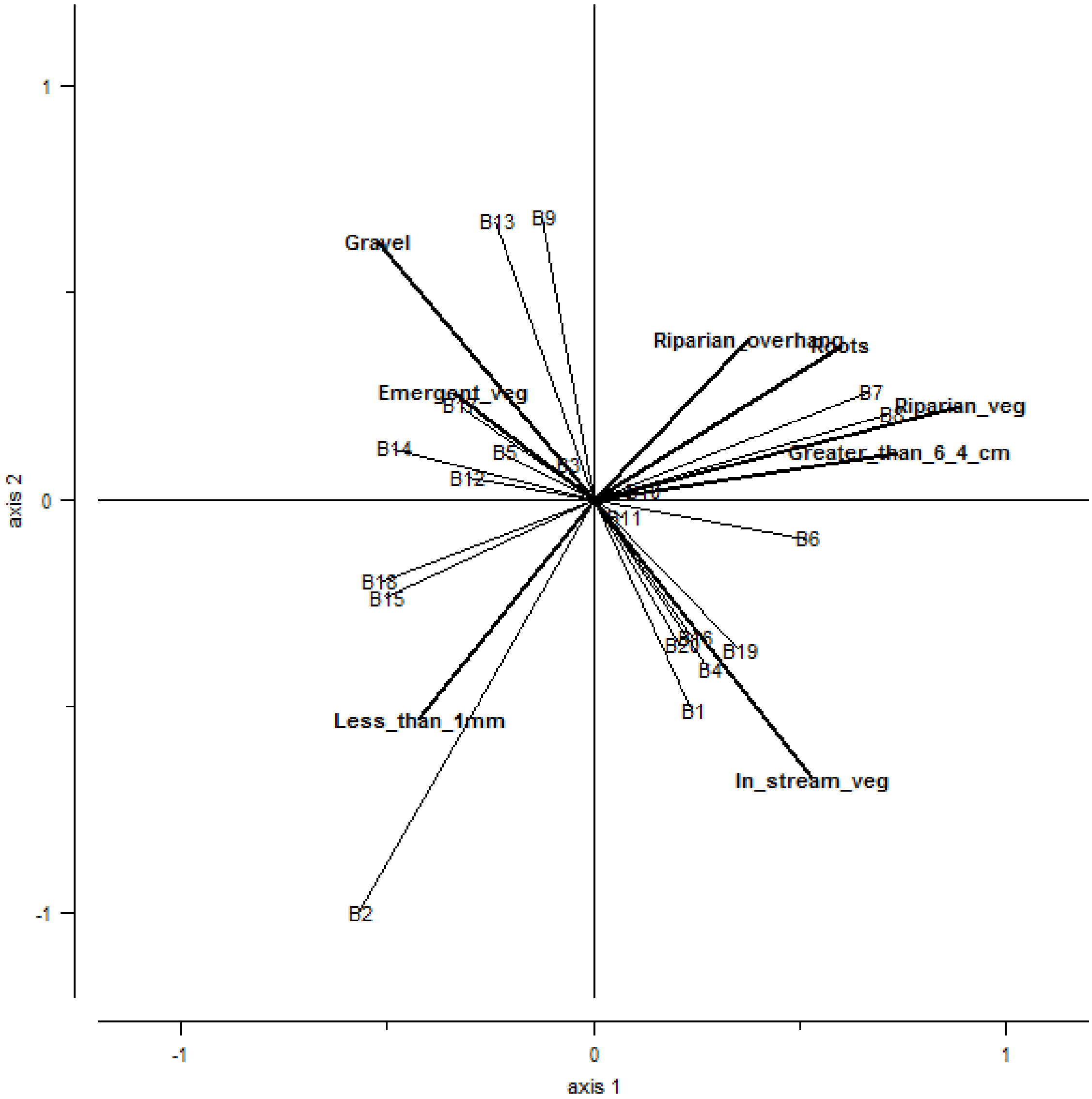


Figure 4.34. Canonical Correspondence Analysis for meso-habitat use of all barbel during summer (June to August).

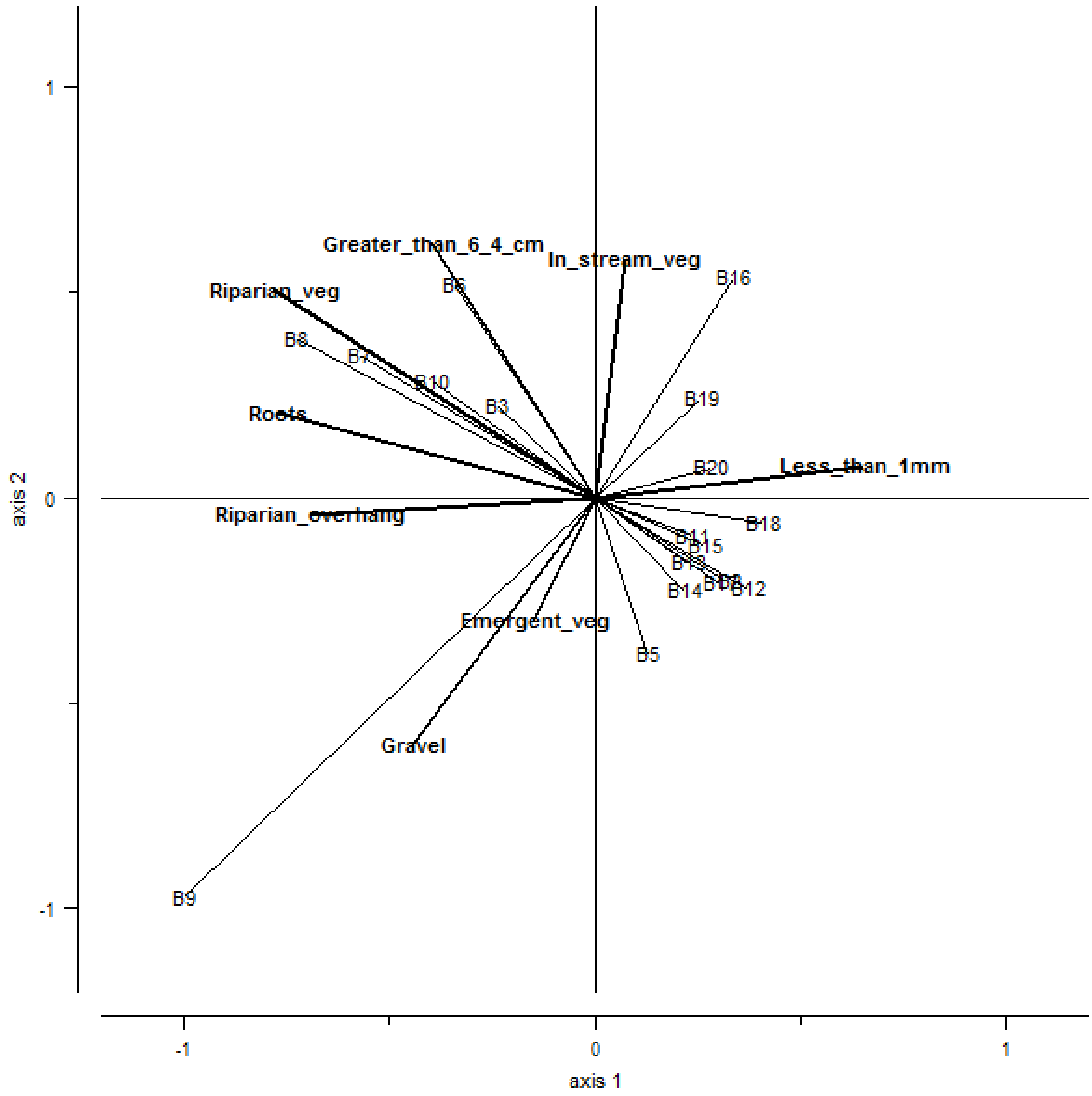


Figure 4.35. Canonical Correspondence Analysis for meso-habitat use of all barbel during autumn (September to November).

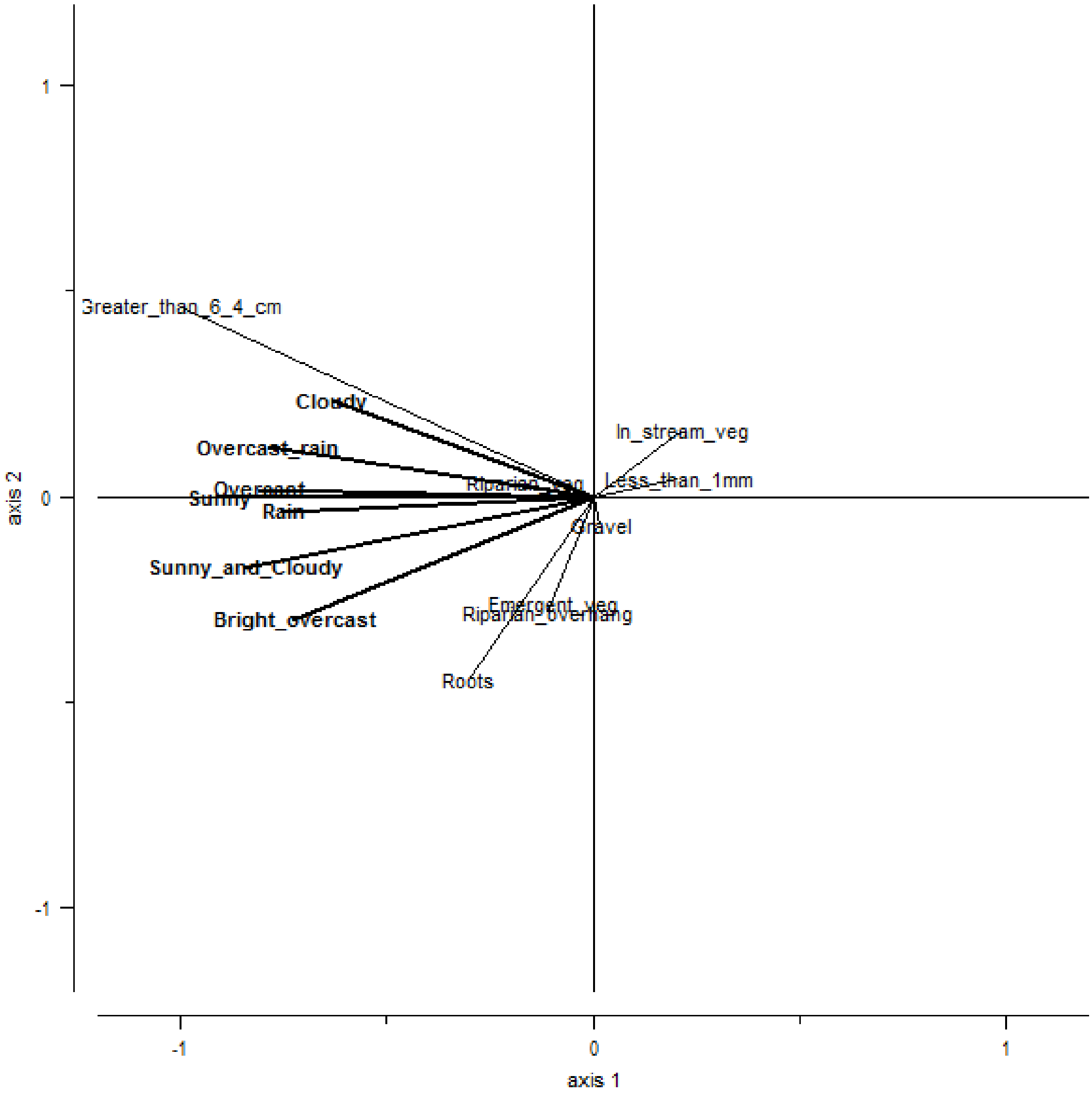


Figure 4.36. Canonical Correspondence Analysis for meso-habitat use during different weather recorded.

Seasonal alterations in depth and flow preferences occurred during the study period (Figure 4.37). From May to July in both years, barbel inhabited shallower sections of the river, coinciding with the spawning activities, including the post spawning residence areas. Low flow habitats were used from October 2010 to March 2011. There were no distinct seasonal variations in the use of channel sections where in stream vegetation, emergent vegetation or overhang were present. Of these three variables, overhang was the most prominent habitat feature being used on average for 64% of tracked occasions. Instream and emergent vegetation were used 30 and 13% of the time respectively.

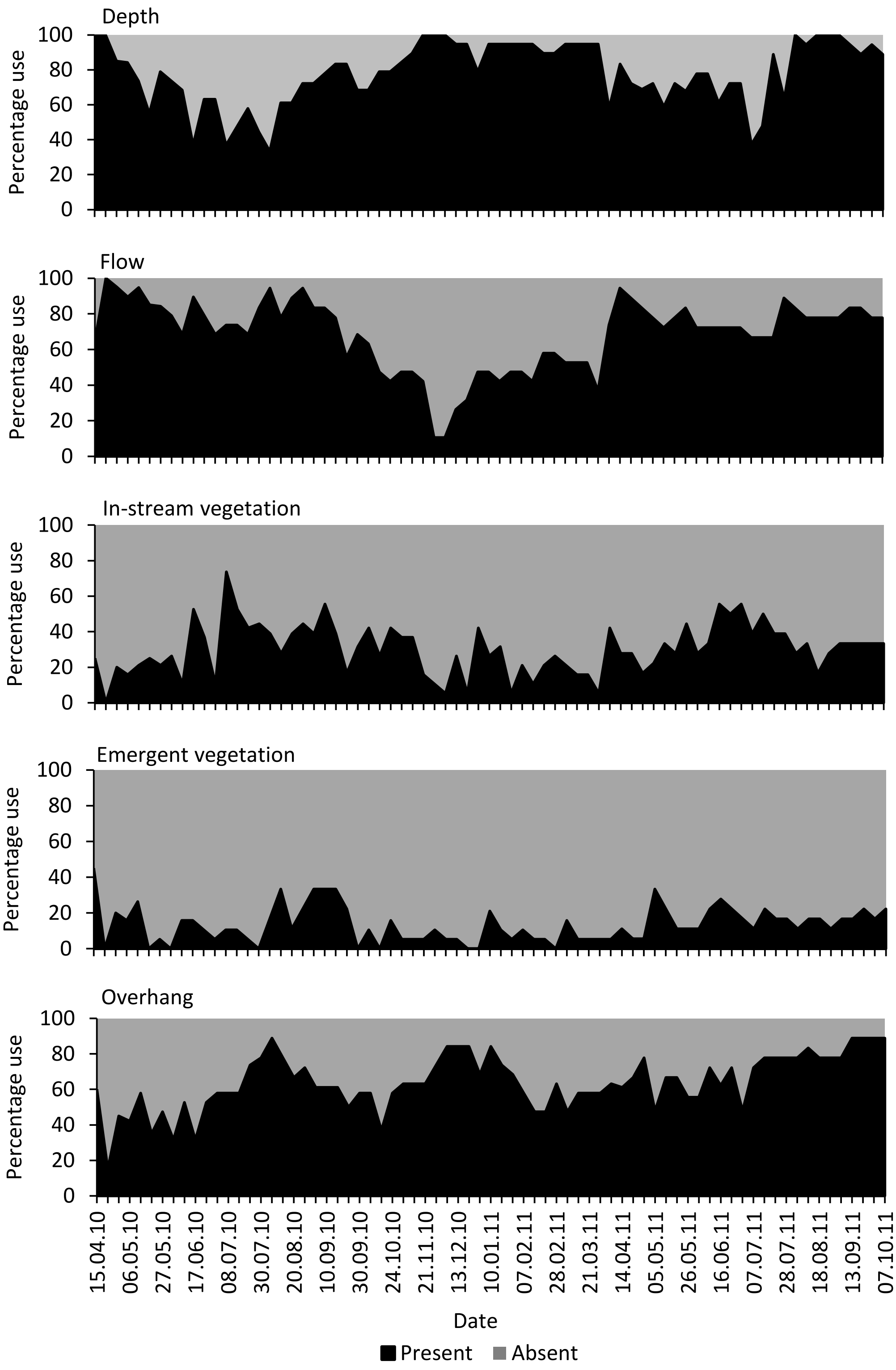


Figure 4.37. Percentage use of each habitat type over the 73 week tracking period

4.4 Discussion

Telemetry of barbel using electronic tags, has been used as a tool to investigate the species population densities (Hunt & Jones 1974; Vilizzi *et al.* 2006), residence area selection (Baras 1997; Ovidio *et al.* 2007), movements (Hunt & Jones 1974), seasonal activities including migration (Baras & Cherry 1990; Baras *et al.* 1994; Baras 1995; Lucas & Frear 1997; Lucas & Baras 2000; De Vocht & Baras 2003) and the effects of barriers on these processes (Lucas & Frear 1997; Ovidio & Philippart 2002). This study investigated the environmental influence on seasonal and diurnal movements and habitat use of wild adult barbel in an 8.2 km stretch of river on the River Great Ouse to gather information on movements, habitat use, the effect of environmental influences and spawning habitat use specific to this river. These studies were used to identify bottlenecks to the recruitment to barbel at the adult life history stage, and gain the evidence necessary to improve the population with a targeted approach.

Barbel were not tagged in equal numbers throughout the study reach. It was intended that barbel be caught and tagged at both ends and Odell which is central and is a known stronghold for mature barbel. Only two barbel were caught at Pinchmill and no barbel were caught at Odell during this specific survey, but Harrold Country Park was a successful second option, contributing the ten barbel needed to complete the tagging of 20 barbel. It was also noted that further to those that were caught, approximately 45 barbel were stunned during the electric fishing exercise but not tagged. Although the majority of barbel was caught and tagged in the upper section of the study reach from Harrold weirs to Harrold Country Park, it was noted that B1 and B2 both left their residencies in the lower section to reach habitats available upstream. Due to the method of continuous electric fishing to catch the barbel, it was impossible to return the barbel to the exact location where they were caught, but 80% of the barbel were released within their home range. Those that were not returned to their release site during the 73 week study possibly returned to their normal home range by spawning time.

There were no running sexual products to determine the sex of each barbel caught (Penaz 2002). Incisions would have to have been larger to inspect the gonads and determine the sex of each fish, with increased risk of infection and recovery time; thus it was decided that this risk was too great.

Fish were lost during the radio telemetry study, but all efforts were made to relocate these individuals during the daily or weekly tracking on foot. 8 km upstream and 20 km downstream were searched on a boat and from both banks where possible, with additional antenna. Frequency shift did occur, particularly in the winter months when temperatures were low. No fish losses could be attributed to the tagging procedure. The reason for the disappearance of B1 and B4 is unknown, and it is also unknown where B2 went on the occasions when it could not be located.

Movements

One person radio tracking limited the amount of radio tracking that could be accomplished within the study. Tracking at six-hourly intervals was attempted on two occasions, but on each occasion it took approximately that amount of time to locate and record each individual and allowed little time to rest. Although it is unknown how much the barbel moved each night and how their habitat use altered from dusk until dawn, the data provided from the radio tracking were sufficient to meet the objectives of the study.

Minimum home ranges identified in this investigation ranged from 0.65 to 6.84 km, larger than Baras and Philippart (1989) (2.2 km); Baras and Cherry (1990) (1.6 km) and Baras (1997) (0.2 - 2.4 km), but much smaller than Lucas and Baras (2001) (>30 km) and Ovidio *et al*. (2007) (20 km). Movements of barbel in this section of the Great Ouse were restricted by Harrold weirs and Sharnbrook weir, so these large home ranges were not possible. Home range was not significantly related to fish size, the two larger fish were tagged at Pinchmill, the furthest site downstream that had the poor habitat heterogeneity suggesting that B1 and B2 travelled furthest to reach more varied habitat in Spring, although B1 went missing in 2010, B2 made these movements over both years.

Each fish had distinctive behaviours, but could not be grouped into sedentary and mobile individuals as was found by Hunt & Jones (1974b). In 2010, on average: B7, B10, B12, B14, B15, B17 and B18 were less mobile and B2, B3, B5, B6, B8, B9, B11, B13, B16, B19 and B20 were more mobile; but due to the significantly smaller movements in 2011 compared to 2010 there was no strong correlation between the two years, with the exception of B2 (Figure 4.38). In 2010 the distribution of summed daily movements was bimodal at 6000 and 10000 m, whereas in 2011 there was a single mode at 4000 m (Figure 4.39). Short movements of adult barbel reportedly coincide with high habitat diversity, where fish have access to habitats suitable for spawning, feeding and resting (De Vocht & Baras 2005). River habitat upstream of Harrold Bridge was the most diverse in terms of depth, flow, river bed substrate instream vegetation and provided two of the six spawning gravels throughout the 8.3 km section of river, used by lithophilic spawners.

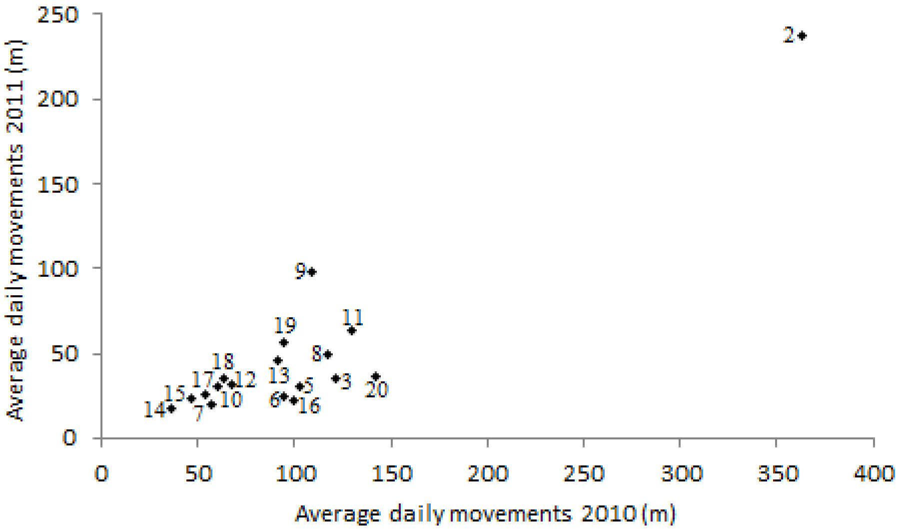


Figure 4.38. Correlation of average daily movements of each barbel in 2010 and 2011.

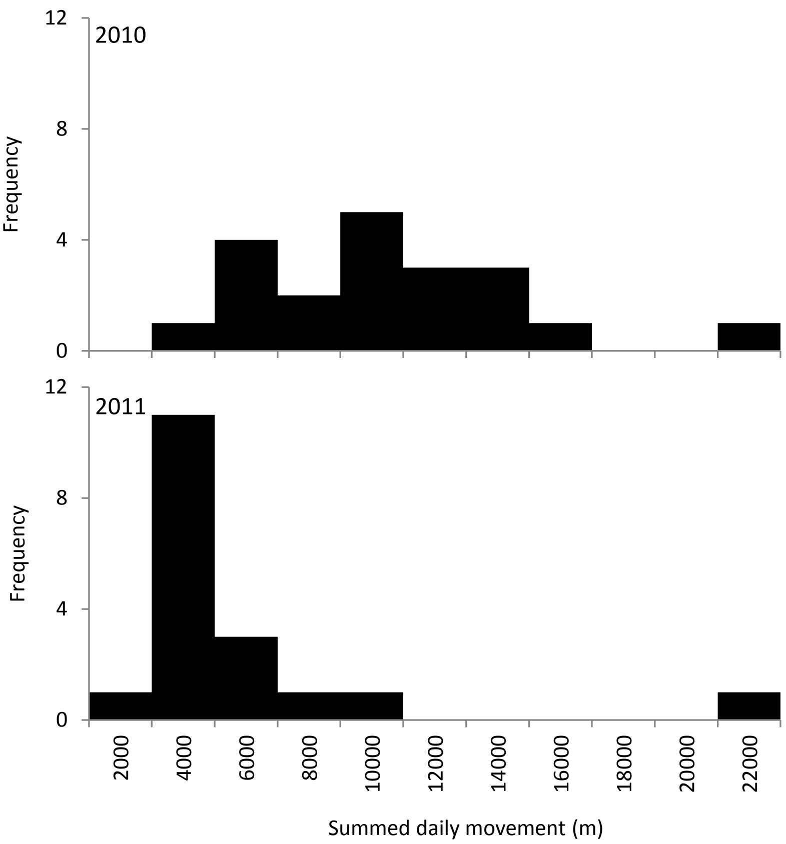


Figure 4.39. Frequency of summed daily movements of each barbel in 2010 and 2011.

Seasonal habitat use

Overhang from riparian vegetation and woody debris was an important habitat on average 64% of the time. Instream and emergent vegetation were present 30 and 13% of the time respectively. These findings match those found by Lucas and Batley (1996). Seasonal alterations in depth and flow preferences occurred during the study period (Figure 4.36). Low flow habitats were used from October 2010 to March 2011, presumed to be a mechanism to keep out of main flow and reduce energy costs, as found by Freyhoff (1996). During the spawning season, barbel would use deep waters with high flows before moving onto the spawning habitat. Where cover from riparian overhang or woody debris was available, it was also used (*pers. Obs.*). From May to July in both years, barbel inhabited shallower sections of the river, coinciding with the spawning activities, including the post spawning residence areas.

Overall, tagged barbel used a wide range of habitats throughout the year, including: gravel, riparian overhang, woody debris and emergent vegetation, deep pools, riffles, slack water areas and on occasion areas with a high percentage of silt. Therefore, a high variety of habitat types need to be maintained to benefit the species throughout the year.

Environmental influences

The use of a scatter plot to determine the river temperature from historical air temperature data was not ideal, but it has been successful in other studies (Nunn *et al.* 2003). Recording river temperature had been attempted during the research, temperature loggers (EL-USB-1 data-logger) placed in the river in accordance to their depth range. One of these recorded six weeks of temperature data, one was lost and the waterproof seals on the remaining three loggers failed, resulting in the equipment flooding and data being irretrievable.

Discharge and temperature are known to influence the movements of barbel (Baras & Cherry 1990; Lucas & Batley 1996; Lucas 2000). Daily movements were significantly related to temperature and discharge in 2010 and 2011 pooled, and 2010 as an individual year. The combined effect of temperature and flow on barbel movement was also significant for these years. Flow, temperature and the combined effect, did not have a significant influence on barbel movements in 2011. This is possibly due to the significantly lower flows and higher temperatures in 2011 compared to 2010. There was no correlation with movement and other environmental cues such as moon phase.

Weather at the time of tracking did not influence habitat use, but there were changes in seasonal habitat use. Most barbel movement occurred between 10 ºC and 15ºC, corresponding with findings from Baras and Cherry (1990) and Lucas and Batley (1996).

Barriers to longitudinal connectivity

The increased fragmentation of the riverine ecosystem is likely to have impacted migration processes, prevented natural reproduction (Arnekleiv & Ronning 2004) and therefore the population structure (Labonne & Gaudin 2005). To protect barbel populations it is important that habitat diversity is preserved (De Vocht & Baras 2003). Barbel tend to select habitats that are as close as possible to their preferences (Chapter 2; Baras 1992, 1995).

Of the 20 barbel tracked, none were located upstream of Harrold weirs or downstream of Sharnbrook weir that acted as the boundaries for the study reach. An unexpected finding from the research was the ability of barbel to pass the smaller weirs at Harrold Bridge (Figure 4.40) during normal and low flow conditions. It had previously been thought that individuals from Harrold weirs and Harrold Bridge were from an isolated population, resulting in a low genetic diversity. It is now known that this is not true, and that barbel have access to the whole river stretch and multiple spawning gravels. B1, B3, B5, B9, B11, B12, B15, B16, B18, B19 and B20 were all capable of overcoming the barrier at Harrold Bridge, resulting in their increased mobility and larger home ranges.

Lucas and Batley (1996) found that barbel used high flows to help them get over obstructions, this study found that tagged barbel could get over Harrold weir (Figure 4.40) in low flow conditions (Figure 4.26) on multiple occasions during each of the 100 consecutive tracked days (Figure 4.27) and throughout the 73 week tracking period. Number of crossings were higher in 2010 than 2011, related to the reduced mobility in the latter year.

Figure 4.40. Harrold Bridge weirs at normal flow conditions, photograph taken from a downstream position.

Observations of active spawning habitats

Six spawning gravels between Aquarium and Sharnbrook were identified as used by lithophils in 2010 and 2011 (Figure 4.41). In 2010: B1, B2, B3, B5, B9, B10, B13, B16, B18, B19 and 20 all bypassed one or more spawning gravels before settling in close proximity to a 'final' spawning habitat, matching findings by Braithwaite and Burt de Perera (2006) and Ovidio *et al.* (2007). In 2011, no pre spawning or spawning behaviour of tagged or non-tagged barbel was observed at any of the spawning gravels in the study reach, suggesting that the reduction in flow and level from 2010 to 2011 inhibited the ability of the species to spawn, as there was a weak environmental cue. Additionally at Harrold Bridge, as a result of the low flows spawning gravels were above the surface of the river level (Figure 4.42).

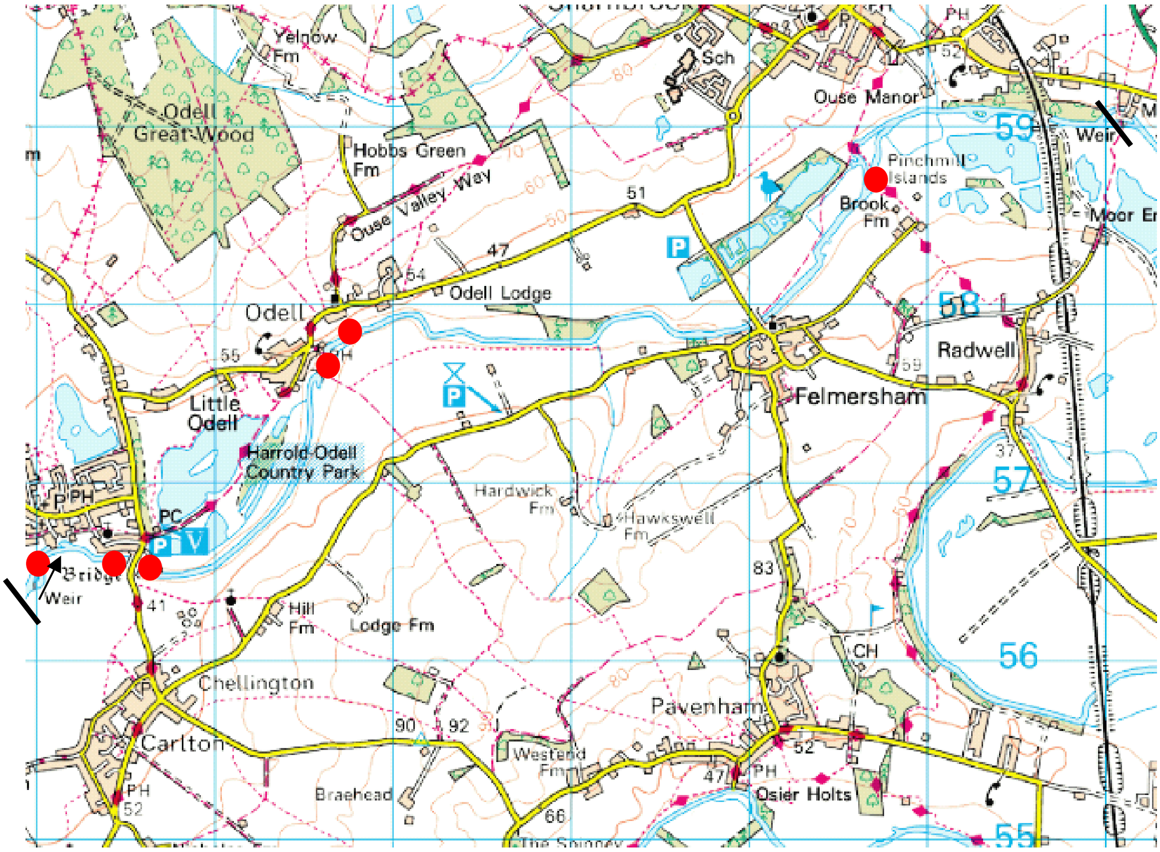


Figure 4.41. Map of study section highlighting identified spawning gravels (●) on the River Great Ouse between Harrold and Sharnbrook. Arrow represents the direction of flow, bars represent the barriers that act as limits to the study section.

Figure 4.42. Exposed spawning habitat as a result of reduced river level, Harrold Bridge 2011.

Bottlenecks to barbel recruitment at the adult life history stage

This Chapter aimed to investigate the natural behaviour of wild mature barbel in the Great Ouse. Movements of adult barbel were examined on a diurnal and seasonal scale and the extent to which environmental variables impacted on this behaviour and habitat were calculated. Passable and impassable barriers were identified, and spawning gravels were recognised in 2010; meeting the objectives of the research. The identification of active spawning gravels was crucial for planning further studies relating to Chapter 5 and 6. The observed lack of spawning in 2011 prevented the identification of spawning gravel fidelity.

Two bottlenecks to the recruitment of barbel related to the adult life history stage have been identified. These are:

- Home ranges and therefore longitudinal movements were limited by the presence of gauging weirs that appear to act as barriers to migration, as barbel approached them multiple times but did not pass them. Adult barbel were therefore not able to colonise other habitats outside of the study section for feeding, refuge or spawning
- Low flows and high temperatures significantly affected behaviour of barbel, specifically the movements made in 2010 but it is also likely that the reduction in flow was responsible for the lack of spawning in 2011.

Mitigation

- The removal of, or bypass for one or both of the gauging weirs acting as the limits of the study section or on a wider scale throughout the upper Great Ouse would improve longitudinal connectivity and enable the movement of fish.
- The creation of deep pools for refuge and an increasing riparian overhang to shade the river would reduce the rate of temperature increase and extend the time that the river temperature remains in the comfort range of barbel.

5 SPAWNING GRAVEL QUALITY ON THE RIVER GREAT OUSE

5.1 Introduction

Considerable research has been conducted regarding the intragravel conditions and the survival and development of salmonid embryos (Crisp 1996; Shackle *et al.* 1999; Kondolf 2000; Milan *et* al. 2000; Hendry 2003; Kondolf *et al.* 2008; Meyer *et al.* 2008). There have been very few investigations relating to coarse fish, specifically barbel, a species that is dependent on high quality substratratum as a key habitat for the egg and larval development stages in its life history. Hyporheic water quality, algal growth and fine sediments can all alter these environments individually or as a combined affect. The survival of embryos can be variable for gravel spawning fish species, as the hyporheic zone strongly influences the incubation success.

The hyporheic zone is defined as an active ecotone between the surface stream and deep ground water (Boulton *et al*. 1998) (Figure 5.1). The upwelling process supplies nutrients, (Thorley & Malcolm 2009) while downwelling of stream water provides dissolved oxygen and organic matter to the hyporheic zone (Gilbert *et al*. 1990; Vervier *et al*. 1992). These processes are influenced at a number of scales by water movement, permeability, substrate particle size, biofilms and physiochemical water quality (Boulton *et al*. 1998). Barbel typically do not cut deep into the gravel when they spawn, but deposited eggs lay on the gravel surface, so there is reason to believe that hyporheic health is a concern to successful hatching of this species in the Great Ouse. Of the 3 spatial scales of the hyporheic zone described by Boulton *et al*. (1998), this study will concentrate on the sediment scale gradient (Figure 5.2).

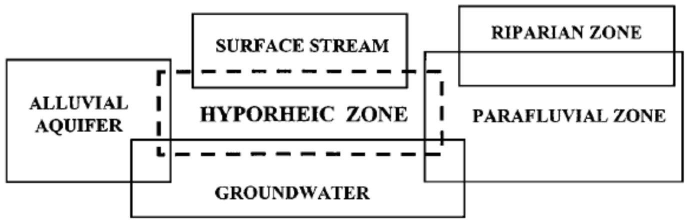


Figure 5.1. Simplified schematic diagram of the hydrological compartments that can interact with the hyporheic zone. Alluvial aquifers typify floodplain rivers with coarse alluvium and are often considered synonymous with groundwater. The parafluvial zone lies under the active channel, which lacks surface water, and it can interact with subsurface water of the riparian zone (Boulton *et al*. 1998).

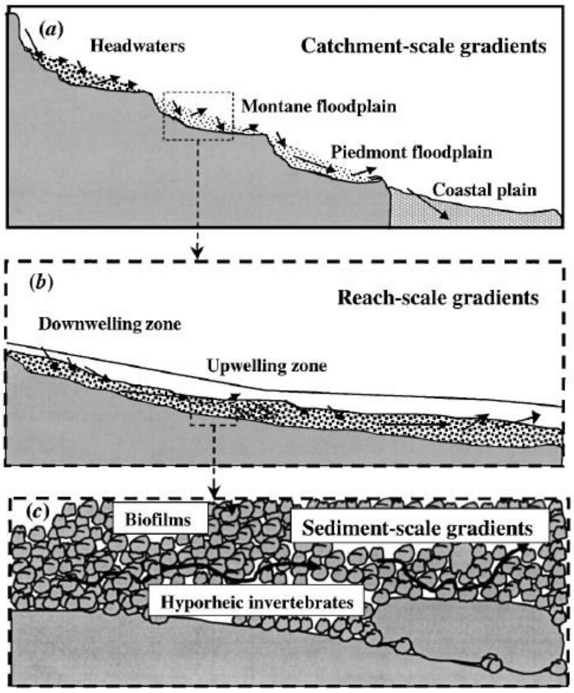


Figure 5.2. Lateral diagrammatic view of the hyporheic zone (HZ) at three spatial scales. At the catchment scale (*a*), the hyporheic corridor concept predicts gradients in relative size of the HZ, hydrologic retention, and sediment size (126). At the reach scale (*b*), upwelling and downwelling zones alternate, generating gradients in nutrients, dissolved gases, and subsurface fauna. At the sediment scale (*c*), microbial and chemical processes occur on particle surfaces, creating microscale gradients. *Arrows* indicate water flow paths (Boulton *et al*. 1998).

Clogged river beds usually have the characteristics of a dense and compact texture with low porosity, high resistance against increasing discharges and reduced hydraulic conductivity (Schälchli 1992). Fine sediment infiltration of particle sizes <4 mm can contribute to the four main processes that can occur in isolation or in combination:

- Reducing interstitial water velocity, increasing the residence time of the hyporheic water and reducing dissolved oxygen delivery;
- Infiltrated material can have its own oxygen demand, reducing dissolved oxygen delivery;
- A physical covering of the spawning gravels by sediment, can prevent natural escapement of larval stages;
- Direct smothering of embryos.

The aim of this study was to compare the hyporheic and gravel bed conditions at four sites during the embryonic and larval period of barbel on spawning gravels over spatial, temporal and diurnal timescales to provide preliminary information on spawning habitat for coarse fish in the River Great Ouse and to identify bottlenecks to the recruitment of the species related to spawning habitat. This was achieved by collecting diatom and hyporheic water quality samples as well as freeze core samples to determine the fine sediment and organic content within the spawning habitats. The objectives were to: 1) assess and compare hyporheic water quality and periphytic diatom growth before, during and after the embryonic incubation period at four spawning gravel habitats; 2) assess diurnal fluctuations in hyporheic water quality during the incubation period; 3) compare gravel size distributions, fine sediment infiltration and organic matter at four spawning gravels; 4) compare gravel size distributions, fine sediment infiltration and organic matter pre and post spawning gravel habitat rehabilitation.

It was predicted that the habitat quality would be a main pressure for the natural recruitment of barbel and that a high biomass of periphytic diatom would be associated with higher organic compounds and reduced oxygen levels within the spawning gravel habitat. It was also predicted that fine sediment and organic matter would be reduced after gravel rejuvenation, in the form of gravel jetting. This information would provide a basis for spawning gravels for lithophilic coarse fish species, and provide options for improving available habitat.

5.2 Methodology

5.2.1 Study site selection

Hyporheic water quality and diatom sampling were collected weekly at sites where barbel were expected to spawn. These sites were; Aquarium, Odell and Pinchmill. In addition, sites were chosen for daily, and twice daily sampling dependent on where barbel were observed exhibiting spawning behaviour during radio tracking (Chapter 4). These sites were; Aquarium, Harrold Bridge and Odell. Gravel enhancement (cleaning) was conducted on the most compacted gravel at Pinchmill and all gravels were freeze core sampled (Figure 5.3 and Table 5.1).

5.2.2 Hyporheic water sampling procedure and analysis

Water samples were collected on a weekly basis during the pre-spawning period. Once barbel had spawned, sampling was conducted daily at Aquarium and Odell, twice daily at Harrold Bridge and weekly sampling continued at Pinchmill. The differences in sampling frequencies are all based on barbel spawning. It was expected that barbel would spawn at Aquarium, Odell and Pinchmill, and so weekly sampling began at these site before the spawning was expected to commence. The first spawning event was observed at Harrold Bridge, which is when twice daily sampling began at that site. Once spawning had occurred at Aquarium and Odell, daily sampling was started. No barbel were observed spawning at Pinchmill and as a result, the weekly sampling was continued.

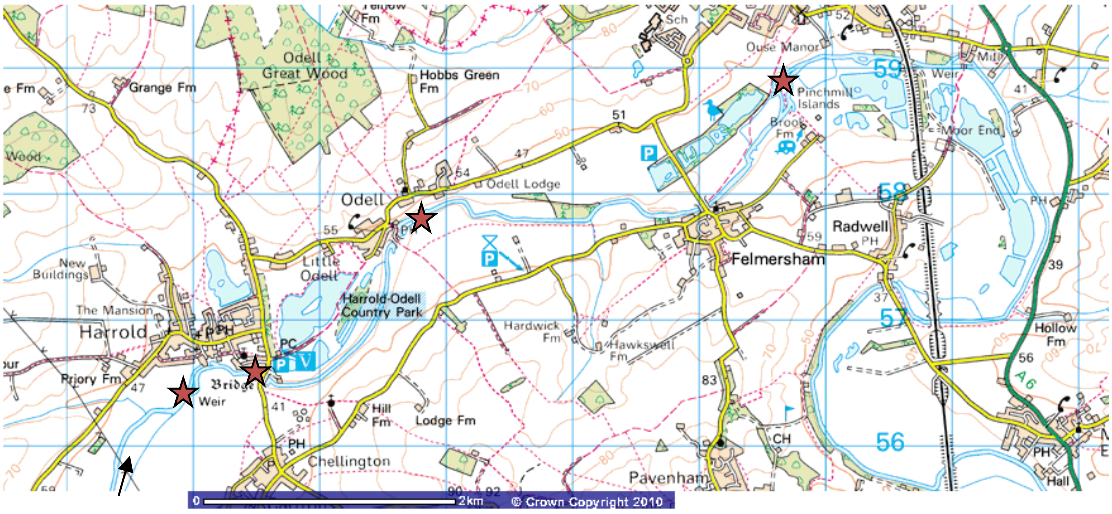


Figure 5.3. ★ Diatom and water quality sample sites. From upstream; Aquarium (SP9501856499), Harrold Bridge (SP 9551856521), Odell (SP 9673357795), Pinchmill (SP9972958706). Arrow indicates direction of flow.

Table 5.1 Sampling conducted at each site on the study river stretch, shaded cells show at which site each study was conducted.

	Weekly diatom	**Weekly water quality**	**Daily water quality**	**Twice daily water quality**	**Gravel jetting**	**Freeze core**
Aquarium	■	■	■			■
Harrold Bridge				■		■
Odell	■	■	■			■
Pinchmill	■	■			■	■

Water samples were taken from within the gravels at depths of 2, 5 and 10 cm below the gravel surface. Three replicate water samples were collected at these depths from the left, centre and right of the spawning gravel, not the river channel. A single surface water sample was collected from the centre of the spawning gravel, mid water column.

The probe (Figure 5.4), consisting of a 1 m length of tubing bound to six metal rods to add strength and support, was inserted into the gravel to the required depth. A small amount of nylon mesh was attached to the end of the tubing to decrease the chances of a blockage. A 60 mL syringe was connected to the tubing and water was drawn from within the gravels at a rate of approximately 10 mL^{-1} to avoid air bubbles forming and altering the sample. Care was taken to avoid holding the barrel of the syringe in case the temperature of the sample was affected by body heat. All water was cleared from the tubing between different depth measurements and channel positions. Samples from each section of the channel, over the course of the study were taken from within a 1 m^2 area. As water samples were collected from spawning gravels, care was taken to avoid trampling eggs and larvae; the same path was taken over the gravels on each occasion.

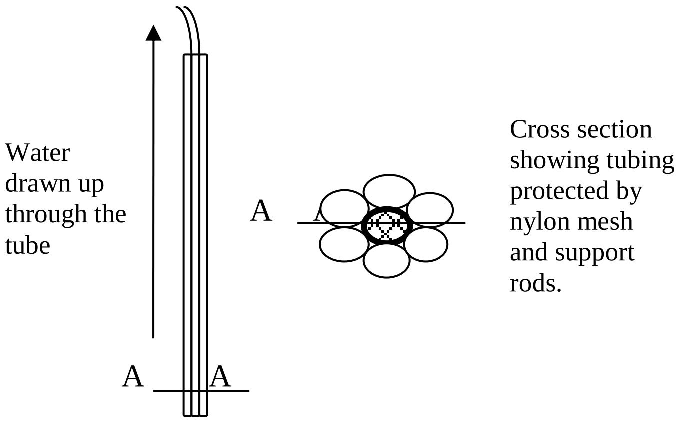


Figure 5.4 Tube and support arrangement of the hyporheic water sampling probe.

Once the syringe was full, it was disconnected from the tubing and the contents emptied into a container at a slow rate. The nozzle of the syringe was held under the surface of the contents of the jug, to avoid disturbance to the surface of the water which could affect water quality readings taken on the bank. Once 250 mL of hyporheic water had been collected, it was analysed in the field for: dissolved oxygen (SAT %), temperature (°C), pH, conductivity (ms) and turbidity (ppm). Samples were then kept in an icebox until they could be refrigerated and analysed at the National Laboratory Service for; Alkalinity, Ammonia, Nitrogen, nitrite, orthophosphate, silicate and phosphorus. A Sonde was buried beneath the gravel surface at Odell to measure dissolved oxygen continuously between 18 May 2010 and 19 June 2010.

Due to the timing and collection of hyporheic water quality samples, the results were split into 3 groups:

- Weekly sampling, enabling pre and post spawning hyproheic water quality.
- Daily, enabling comparisons of water quality at Aquarium, Harrold Bridge and Odell over the incubation period.

Regression analysis was performed in Excel on daily samples for each water quality parameter to identify changes over the period that the samples were collected.

- Twice daily, enabling comparisons between morning and evening samples at Harrold Bridge.

5.2.3 Diatom sampling procedure and analysis

Samples were collected on a weekly basis throughout the pre-spawning, spawning and post spawning period. The diatom sampling methodology followed the Environment Agency Operational Instruction (27_07) as described below.

On each occasion, 5 *in situ* permanently submerged cobbles or large gravel were, taken from separate locations on the spawning gravel, within a 5 m stretch of river were used to collect diatom samples. The cobbles were shaken in the river flow to dislodge surface contamination such as organic matter or sediment.

The cobbles were then placed in a tray with approximately 50 mL of river water. A 2 cm by 2 cm stencil was placed over each cobble, and 5 strokes of a toothbrush over the 4 cm^2 area to remove the diatom film from a known area. Between each rub, the toothbrush was rinsed in the tray to transfer the diatoms. The water and diatom samples were then transferred from the tray into a 125 mL sample pot and river water was used to increase the volume of water to 100 mL. Cobbles were returned to the river channel and the toothbrush was cleaned between the collections of each sample to avoid cross contamination between sites. Samples were fixed with non-acidified *lugols* iodine.l and refrigerated until analysis in the laboratory.

In the laboratory samples were stirred to suspend all cells in the 100 mL sample, a 0.1 mL sub sample was taken and observed in a counting chamber using a Zeiss Axiviet 10 microscope. Diatoms were identified to genus and numbers were multiplied to give a number per mL.

5.2.4 Freeze core sampling procedure and analysis

Representative samples of gravels were taken from the centre of the spawning gravels. Individual samples were obtained by freezing saturated substratum to a hollow steel core tube sunk using a cast iron post-driver. A square steel baffle placed over core tube was used to create still water environment to reduce disturbance to the sample, while ~15 L of liquid nitrogen was poured into the tube to freeze the adjacent intragravel water, gravel and fine sediments to the standpipe. The sample was lifted from the river bed using an A-frame winch.

The average dimensions of the cores collected were 40-45 cm long, 20-30 cm in diameter ranging from 6.1 to 11.9 kg (total dry weight). The defrosting process was helped in the field using a blow torch to heat the steel tubing. The samples were defrosted into a segmented box, separating the core into 0-5, 5-10, 10-20, 20-30 and 30-40cm depths.

Particle Size Analysis (PSA) of fine sediment

Each depth section was stirred to mix all particles. Laser diffraction of a representative subsample using a 1 mm screen was completed with a Malvern Mastersizer 2000 with Hydero 2000 mv accessory unit. Ultrasound was used to assist the dispersion of sediments prior to laser diffraction analysis. Each PSA produced 3 outputs from which an average was taken.

Organic matter

Each depth section was stirred to mix all particles before a random sub sample was taken and placed into an empty pre-weighed ceramic vile. The samples were then baked in the oven for 48 hours, weighed, moved to a furnace for ~4 hours and heated at 475°C before being weighed again.

Secondary sieving

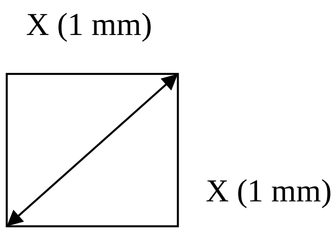
The remaining sediment was wet split at 1 mm. The fine sediment was left to settle in an empty and pre weighed container while the large sediment was prepared for secondary sieving. An empty beaker was weighed and filled with sediment > 1 mm and placed in the oven at 100°C for 48 hours until the sample was dried. This was tested by weighing the sample over a 2 hour period to establish any changes in weight. The total dry weight of the full beaker was then recorded and the contents put through a series of Endcotts sieves, ranging from 64 mm to 1 mm at 0.5ϕ intervals. Each size range was weighed separately and recorded. Once the fine sediment had settled, clear surface water was removed to decrease drying time in the oven at 100°C. The final dried weight was measured and recorded.

Data analysis

Cobbles (>64 mm) were only found in the freeze core sample at Pinchmill and were therefore removed from analysis to enable a better comparison between sites. Freeze core samples <10 kg are too small to accurately represent accurately gravels that include particles of 64 mm and greater (Church *et al.* 1987).

Despite many contradictions to the term ‘fine sediment’, in this study, fine sediment refers to sediment <1 mm. Particles larger than 1 x 1 mm may have passed through the 1 mm sieve due to the diagonal length of the 1 mm square mesh (Figure 5.6); this is also true for all other mesh sizes used. For the purpose of this study, the particles that passed through each sieve will be referred to as smaller than that particular sieve size.

Data on the distribution of sediment sizes in the <1 mm determined by PSA and total dry weight of <1 mm were merged using a Macro enabled spread sheet designed by Hull Univerisity’s Department of Institute of Estuarine and Coastal Studies. Gradistat V7 software, downloaded from Kenpie Associates was used for the analysis of the merged data. Descriptions of each sediment type is based on the scale adopted by GRADISTAT (Figure 5.2).



$$\sqrt{X^2 + X^2} = 1.4 \text{ mm}$$

Figure 5.5. Reason for size discrepancy in secondary sieving results.

5.2.5 Gravel jetting procedure

Water from the river was pressurised and pumped through a hose that decreased in diameter at the nozzle. As water was pumped, the hose was pushed into the gravel by hand to depths between 20 and 50 cm, so the high pressure water displaced the fine sediment so that it entered the water column and was moved downstream.

Table 5.2. Size scale adopted in the GRADISTAT programme, modified from Udden (1914) and Wentworth (1922).

Grain size: Phi	Grain size: mm	Descriptive term	
		Very large	Boulder
-10	1024		
		Large	Boulder
-9	512		
		Medium	Boulder
-8	256		
		Small	Boulder
-7	128		
		Very small	Boulder
-6	64		
		Very coarse	Gravel
-5	32		
		Coarse	Gravel
-4	16		
		Medium	Gravel
-3	8		
		Fine	Gravel
-2	4		
		Very fine	Gravel
-1	2		
	microns	Very coarse	Sand
0	1		
		Coarse	Sand
1	500		
		Medium	Sand
2	250		
		Fine	Sand
3	125		
		Very fine	Sand
4	63		
		Very coarse	Silt
5	31		
		Coarse	Silt
6	16		
		Medium	Silt
7	8		
		Fine	Silt
8	4		
		Very fine	Silt
9	2		
		Clay	

5.3 Results

Barbel were observed spawning at Harrold Bridge between the 18 and 20 May, Spawning at Aquarium and Odell was observed at the later dates of 22 and 23 May, the barbel had moved away from all spawning gravels by 26 May.

5.3.1 Hyporheic water quality

Dissolved oxygen in the hyporheic zone is one of the most important chemical factors during the incubation and hatching period. Dissolved oxygen saturation ranged from 2.8 to 136.6 %, averaging 86.9% (Figure 5.6). Continuous monitoring at showed that DO levels at Odell rose and fell on a weekly basis. On the first day of recording (19 May), the highest level of DO over the month period was logged at 138.3 %SAT, levels generally decreased over the next week to 4.8% SAT (25 May) rising to 125.8 %SAT (30 May) before falling to the lowest value of 2.8 %SAT (6 June) and increasing again to 130.7 %SAT (14 June). Poor DO %SAT levels according to the Water Framework Directive (WFD) (Table 5.3), were recorded at Odell during the incubation and hatching period (Figure 5.6). There was no significant relationship between temperature and dissolved oxygen (Figure 5.7). Overall, surface water at Aquarium had higher average DO concentrations than at the other depths measured at Harrold Bridge or Aquarium, possibly due to the site position, downstream of 2 weir structures. At all 3 sites, DO saturation decreased with gravel depth (Table 5.4).

Within the spawning gravel, temperature at Odell ranged from 9.74 to 30.69°C, averaging 19.5°C (Figure 5.6). Mean surface water temperatures were similar at Aquarium and Odell (16.76 and 16.23 % respectively) but lower at Harrold Bridge (15.77 %). There was no clear change in temperature within the gravels at the different depths. Aquarium and Odell remained on average, warmer than Harrold Bridge (Table 5.4).

On average, nitrogen levels were lower at Odell, 10 cm. Ammonia levels were higher at Harrold Bridge surface water, 2, 5 cm and Aquarium 5 and 10 cm. These levels are classed as high for the WFD and lower than the levels that Policar *et al*. (2010) oversaw in their experiment (Table 5.3). Over the incubation and hatching period, ammonia levels at Harrold Bridge peaked during the days when larval drift occurred, but remained low during the incubation and hatch period (Figure 5.9). Mean orthophosphate levels were similar at all sites and all depths (~0.03 mg L^{-1}), which is between good and high for the WFD, but levels also increased at Harrold Bridge a day before the onset of drift (Figure 5.14). Phosphorus was higher at all sites for the 5 and 10 cm samples (Table 5.2).

Table 5.3. Water quality parameters for the WFD.

	High	Good	Moderate	Poor
DO (% sat)	70	60	54	45
BOD (90 percentile)	4	5	6.5	9
Ammonia (mg L^{-1})	0.3	0.6	1.1	2.5
pH	>6 and <9		4.7	4.2
Phosphate (mg L^{-1})	0.05	0.120	0.250	1

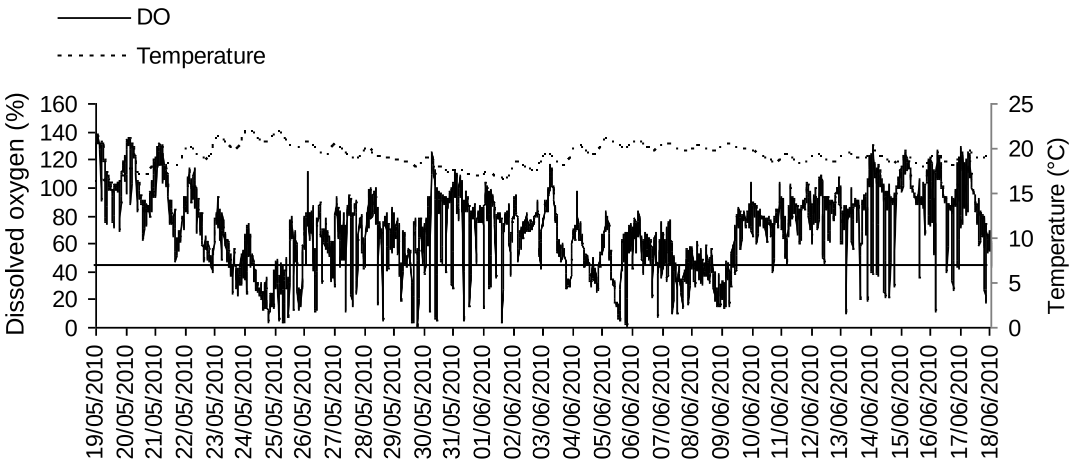


Figure 5.6. Dissolved oxygen (DO) and temperature measured at 15 minute intervals by a Sonde under the surface of the spawning gravel, Odell 2010. The solid line represents the poor DO category for the WFD.

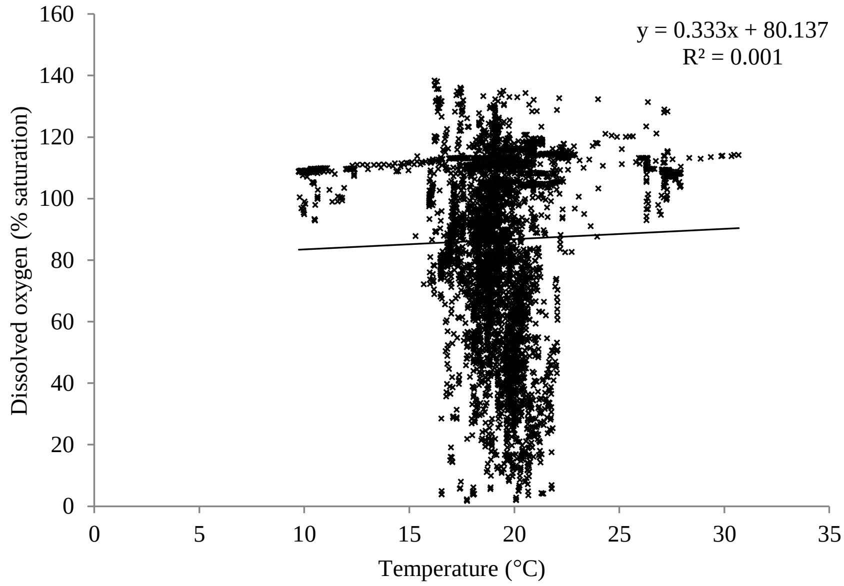


Figure 5.7. Scatter plot and regression analysis of temperature (°C) and dissolved oxygen (% saturation), Odell 2010.

Table 5.4 . Water quality levels (mean±SD(range)) at Aquarium, Harrold Bridge and Odell, for surface water , 2, 5 and 10 cm depths.

Depth	Site	Dissolved oxygen (%SAT)	Temperature (°C)	Silicate ($mg\ L^{-1}$)	Nitrogen ($mg\ L^{-1}$)	Ammonia ($mg\ L^{-1}$)	Ortho-Phosphate ($mg\ L^{-1}$)	Phosphorus ($mg\ L^{-1}$)	Nitrite ($mg\ L^{-1}$)
Surface water	Aquarium	115±11.97 (103-138)	16.76±1.17 (14.5-17.7)	3.23±0.71 (2.17-4.23)	4.37±0.41 (3.78-4.97)	0.06±0.03 (0.03-0.10)	0.33±0.05 (0.26-0.4)	0.46±0.09 (0.34-0.63)	0.07±0.02 (0.04-0.09)
	Harrold Bridge	102±11.64 (89-110)	15.77±1.21 (14.30-17.7)	3.36±0.76 (2.11-4.19)	4.48±0.33 (4.04-4.99)	0.37±0.05 (0.29-0.46)	0.35±0.07 (0.26-0.46)	0.45±0.08 (0.34-0.57)	0.07±0.02 (0.05-0.09)
	Odell	109±15.50 (103-128)	16.23±1.23 (14.40-18.10)	3.18±0.83 (1.79-4.18)	4.41±0.24 (4.11-4.73)	0.05±0.04 (0.03-0.13)	0.35±0.07 (0.25-0.45)	0.46±0.08 (0.34-0.54)	0.07±0.02 (0.05-0.09)
2 cm	Aquarium	110.57±7.57 (73-127)	16.95±1.34 (14.20-19.40)	3.38±0.67 (2.13-4.53)	4.34±0.34 (3.79-4.89)	0.07±0.04 (0.03-0.10)	0.33±0.05 (0.25-0.41)	0.68±0.24 (0.39-1.18)	0.06±0.02 (0.02-0.10)
	Harrold Bridge	100.29±4.08 (95-108)	15.27±1.10 (13.80-17.40)	3.48±0.67 (2.15-4.34)	4.44±0.33 (3.91-5.09)	0.37±0.05 (0.29-0.46)	0.35±0.06 (0.25-0.44)	0.72±0.24 (0.48-1.42)	0.06±0.02 0.03-0.09)
	Odell	105±5.84 (97-121)	16.17±1.11 (14.10-18.10)	3.25±0.74 (1.82-4.05)	4.41±0.3 (410-5.21)	0.05±0.04 (0.03-0.13)	0.35±0.06 (0.24-0.44)	0.77±0.45 (0.36-2.38)	0.06±0.02 (0.04-0.09)
5 cm	Aquarium	108±8.62 (92-124)	16.86±1.24 (14.2-18.5)	3.73±0.82 (2.17-5.66)	4.30±0.37 (3.65-4.92)	0.1±0.07 (0.03-0.28)	0.34±0.05 (0.26-0.43)	1.16±0.49 (0.47-2.56)	0.05±0.02 (0.01-0.09)
	Harrold Bridge	92.95±10.17 (66-106)	15.22±1.02 (14-17.10)	3.5±0.73 (2.22-4.48)	4.46±0.40 (3.95-5.11)	0.07±0.05 (0.03-0.23)	0.35±0.05 (0.29-0.48)	1.29±0.68 (0.42-3.41)	0.05±0.03 (0.02-0.11)
	Odell	99.95±8.79 (82-118)	16.27±1.14 (14-17.9)	3.42±0.82 (1.81-4.5)	4.36±0.26 (3.93-4.78)	0.06±0.05 (0.03-0.21)	0.34±0.06 (0.24-0.46)	1.13±0.51 (0.39-2.49)	0.06±0.02 (0.03-0.09)
10 cm	Aquarium	100.05±15.5 (70-127)	16.91±1.35 (14.20-18.90)	5.42±2.69 (3.05-11.50)	3.92±0.63 (2.59-4.79)	0.11±0.08 (0.03-0.32)	0.32±0.05 (0.18-0.41)	1.78±0.81 (0.77-3.71)	0.04±0.02 (0-01-0.08)
	Harrold Bridge	83.52±16.23 (41-104)	14.92±1.09 (13.20-17)	3.75±0.65 (2.41-4.85)	4.28±0.39 (3.36-5.01)	0.09±0.09 (0.03-0.38)	0.34±0.05 (0.25-0.46)	1.51±0.65 (0.50-2.79)	0.05±0.03 (0.01-0.1)
	Odell	90.19±13.70 (54-109)	16±1.64 (10.80-17.9)	3.63±0.98 (1.97-5.96)	4.28±0.39 (3.13-4.8)	0.06±0.04 (0.03-0.16)	0.34±0.06 (0.25-0.43)	1.66±0.9 (0.39-4.32)	0.05±0.02 (0.03-0.11)

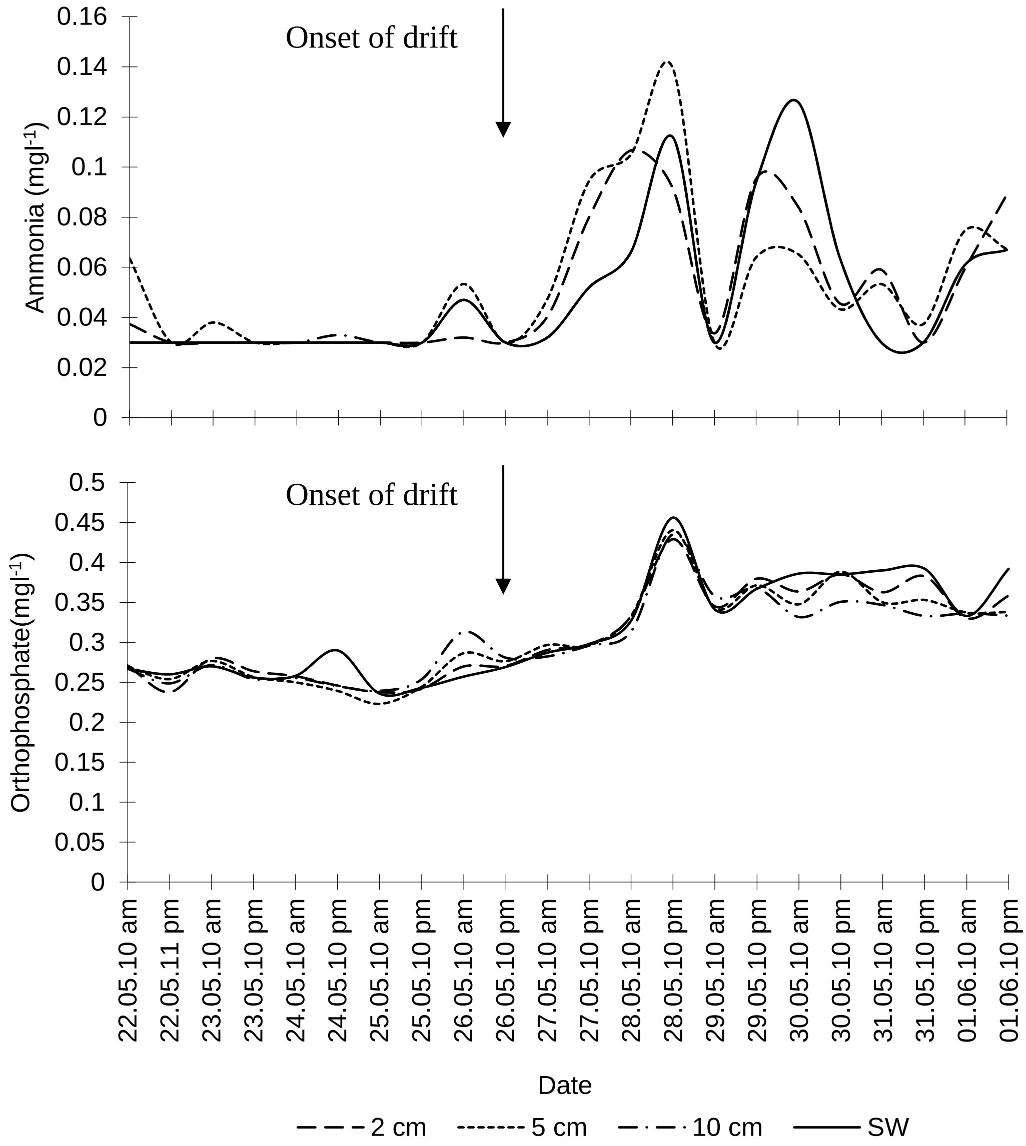


Figure 5.8. Ammonia and orthophosphate levels from the twice daily sampling, Harrold Bridge.

Trends in nutrient levels on each of the spawning gravels show how each reacts differently over the incubation period (Table 5.5). The spawning gravel at Harrold Bridge experienced a significant decrease in alkalinity over time in the surface water (R^2 = 0.56, P<0.05) and 2 cm (R^2 = 0.57, P<0.05) sample points, surface water nitrogen (R^2 = 0.7, P<0.02) at Aquarium. There was an increase in orthophosphate and silicate at all depths and surface water (orthophosphate: 2 cm, R^2 = 0.59, P<0.05; 5 cm, R^2 = 0.55, P <0.05; 10 cm R^2 = 0.57, P<0.05; SW R^2 = 0.58, P<0.05; Silicate: 2 cm, R^2 = 0.77, P<0.01; 5 cm, R^2 = 0.71, P <0.02; SW R^2 = 0.74, P<0.01).

The spawning gravel at Harrold Bridge was the only site to have a significant change in water temperature over the incubation period at each depth (2 cm, R^2 = 0.87, P<0.00; 5

cm, $R^2 = 0.91$, P <0.00; 10 cm $R^2 = 0.66$, P<0.03; SW $R^2 = 0.97$, P<0.00). There was a reduction in alkalinity and nitrogen at all depths over the sampling period (alkalinity: 2 cm, $R^2 = 0.56$, P<0.05; 5 cm, $R^2 = 0.65$, P <0.03; 10 cm $R^2 = 0.66$, P<0.03; SW $R^2 = 0.69$, P<0.02; nitrogen: 2 cm, $R^2 = 0.64$, P<0.03; 5 cm, $R^2 = 0.85$, P <0.00; 10 cm $R^2 = 0.96$, P<0.00; SW $R^2 = 0.87$, P<0.00). There was a significant increase in nitrite and silicate at all depths over the sampling period (nitrite: 2 cm, $R^2 = 0.77$, P<0.01; 5 cm, $R^2 = 0.72$, P <0.02; SW $R^2 = 0.76$, P<0.01; silicate: 2 cm, $R^2 = 0.85$, P<0.00; 5 cm, $R^2 = 0.73$, P <0.01; 10 cm $R^2 = 0.76$, P<0.01; SW $R^2 = 0.80$, P<0.01). Orthophosphate increased over the incubation period at 2 cm and in the surface water (2 cm, $R^2 = 0.67$, P<0.02; 5 cm, $R^2 = 0.60$, P <0.04).

The spawning habitat at Odell experienced a significant decrease in alkalinity and nitrogen at all depths over the incubation period (Alkalinity: 2 cm, $R^2 = 0.72$, P<0.02; 5 cm, $R^2 = 0.67$, P <0.02; 10 cm $R^2 = 0.83$, P<0.00; SW $R^2 = 0.63$, P<0.03; nitrogen: 2 cm, $R^2 = 0.86$, P<0.00; 5 cm, $R^2 = 0.89$, P <0.00; 10 cm $R^2 = 0.64$, P<0.03; SW $R^2 = 0.69$, P<0.02). Whereas nitrite, orthophosphate and silicate increased at all depths over the incubation period (nitrite: 2 cm, $R^2 = 0.86$, P<0.00; 5 cm, $R^2 = 0.89$, P <0.020; 10 cm $R^2 = 0.64$, P<0.03; SW $R^2 = 0.69$, P<0.02; orthophosphate: 2 cm, $R^2 = 0.63$, P<0.03; 5 cm, $R^2 = 0.58$, P <0.05; 10 cm $R^2 = 0.87$, P<0.00; SW $R^2 = 0.70$, P<0.02; silicate: 2 cm, $R^2 = 0.81$, P<0.01; 5 cm, $R^2 = 0.71$, P <0.01; 10 cm $R^2 = 0.80$, P<0.01; SW $R^2 = 0.85$, P<0.00). There was also an increase in surface water phosphorus levels (p<0.05) was also found ($R^2 = 0.65$, P<0.03).

5.3.2 Periphytic diatom growth

Diatom biomass (cells mL^{-1}) fluctuated over the 5 week sampling period were different at each of the sites (Figures 5.9 to 5.13), There was no significant change over time, but biomass for each site peaked on either the 11 or 18 May, coinciding with the most active barbel behaviour. The biomass of diatoms at Aquarium rose and fell weekly over the same period, there was a general increase in ammonia and silicate levels decreased when biomass increased (Figure 5.9 and 5.10). The diatom biomass at Odell peaked on the 11 May and decreased week on week as did the nitrogen and ammonia levels, with the exception of ammonia at 10 cm (Figures 5.11 and 5.12). Pinchmill had the highest diatom biomass of all 3 study sites, even though the silicate and inorganic nutrient levels were similar or lower to the other sites (Figures 5.13 and 5.14).

Table 5.5. Regression analysis of water quality over time at Aquarium, Harrold Bridge and Odell, for surface water, 2, 5 and 10 cm depths, showing *significant relationships.

		Aquarium				Harrold Bridge				Odell			
		2 cm	5 cm	10 cm	SW	2 cm	5 cm	10 cm	SW	2 cm	5 cm	10 cm	SW
Dissolved Oxygen	R^2	0.16	0.00	0.23	0.07	0.30	0.26	0.13	0.11	0.25	0.15	0.88	0.18
	Sig F	0.38	0.89	0.27	0.56	0.20	0.24	0.43	0.46	0.25	0.39	0.00*	0.35
Temperature	R^2	0.29	0.22	0.10	0.26	0.87	0.91	0.66	0.97	0.47	0.44	0.22	0.54
	Sig F	0.21	0.29	0.50	0.25	0.00*	0.00*	0.03*	0.00*	0.09	0.10	0.29	0.06
pH	R^2	0.01	0.26	0.01	0.21	0.67	0.54	0.30	0.40	0.12	0.08	0.05	0.16
	Sig F	0.84	0.25	0.84	0.31	0.02*	0.06	0.20	0.12	0.44	0.55	0.63	0.38
Alkalinity	R^2	0.56	0.55	0.30	0.57	0.56	0.65	0.66	0.69	0.72	0.67	0.83	0.63
	Sig F	0.05*	0.06	0.20	0.05*	0.05*	0.03*	0.03*	0.02*	0.02*	0.02*	0.00*	0.03*
Ammonia	R^2	0.08	0.00	0.30	0.03	0.00	0.02	0.03	0.03	0.05	0.02	0.01	0.03
	Sig F	0.55	0.92	0.21	0.70	0.99	0.74	0.70	0.70	0.64	0.74	0.80	0.70
Nitrite	R^2	0.21	0.08	0.00	0.10	0.77	0.72	0.06	0.76	0.82	0.72	0.91	0.77
	Sig F	0.31	0.53	0.88	0.50	0.01*	0.02*	0.60	0.01*	0.01*	0.02*	0.00*	0.01*
Nitrogen	R^2	0.14	0.54	0.35	0.70	0.64	0.85	0.96	0.87	0.86	0.89	0.64	0.69
	Sig F	0.40	0.06	0.16	0.02*	0.03*	0.00*	0.00*	0.00*	0.00*	0.00*	0.03*	0.02*
Orthophosphate	R^2	0.59	0.55	0.57	0.58	0.67	0.44	0.22	0.60	0.63	0.58	0.87	0.70
	Sig F	0.04*	0.05*	0.05*	0.05*	0.02*	0.10	0.29	0.04*	0.03*	0.05*	0.00*	0.02*
Silicate	R^2	0.77	0.71	0.04	0.74	0.85	0.73	0.76	0.80	0.81	0.74	0.80	0.85
	Sig F	0.01*	0.02*	0.66	0.01*	0.00*	0.01*	0.01*	0.01*	0.01*	0.01*	0.01*	0.00*
Phosphate	R^2	0.03	0.04	0.17	0.20	0.08	0.22	0.29	0.63	0.44	0.10	0.23	0.64
	Sig F	0.72	0.67	0.35	0.32	0.53	0.29	0.22	0.03*	0.10	0.49	0.28	0.03*

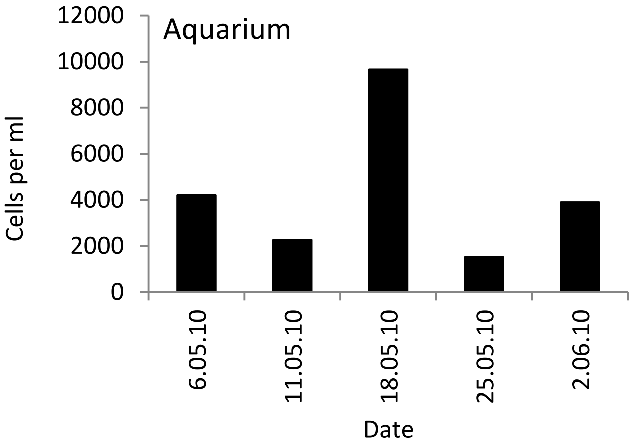


Figure 5.9. Weekly total number of cells mL^{-1} at Aquarium.

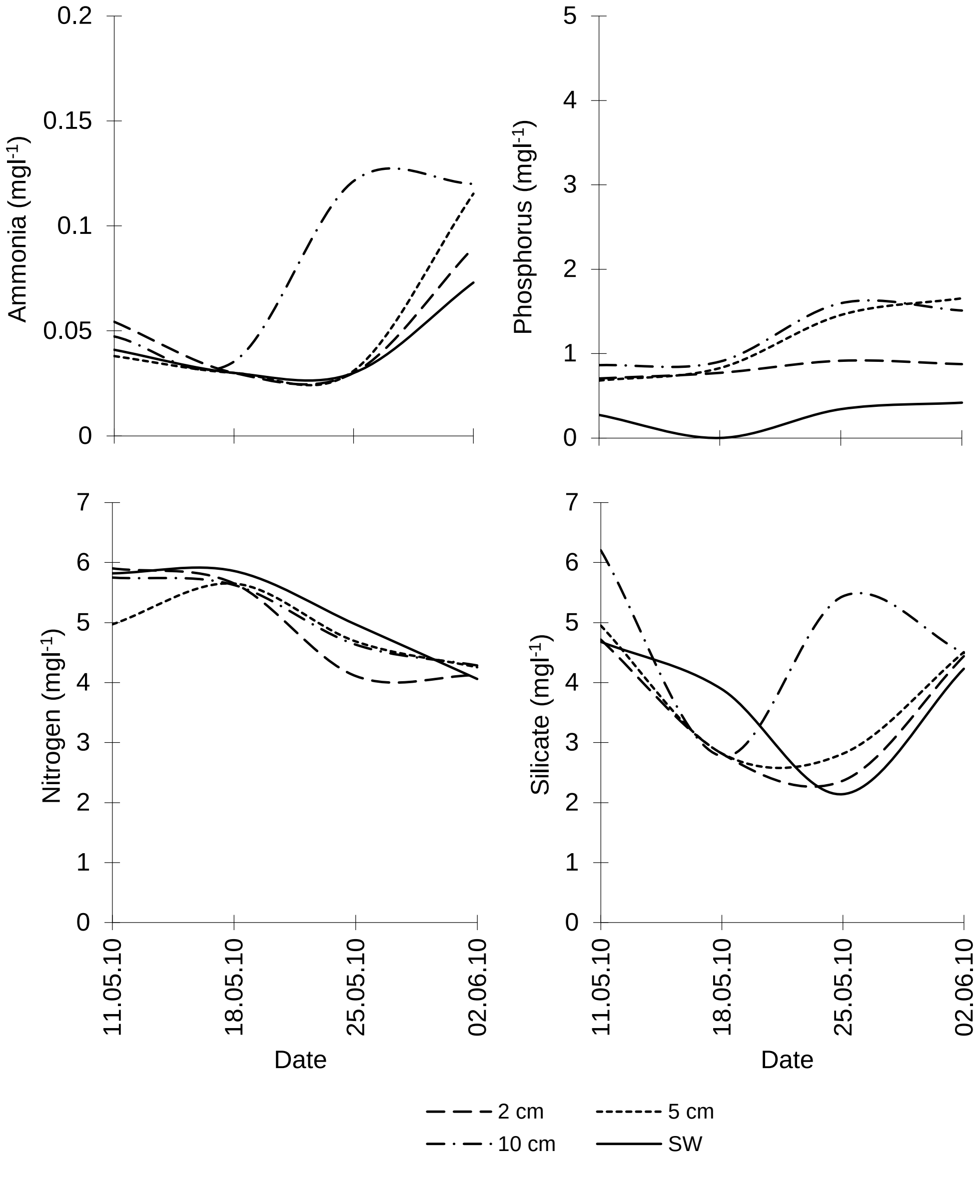


Figure 5.10. Weekly levels of ammonia, nitrogen, phosphorus and silicate, Aquarium.

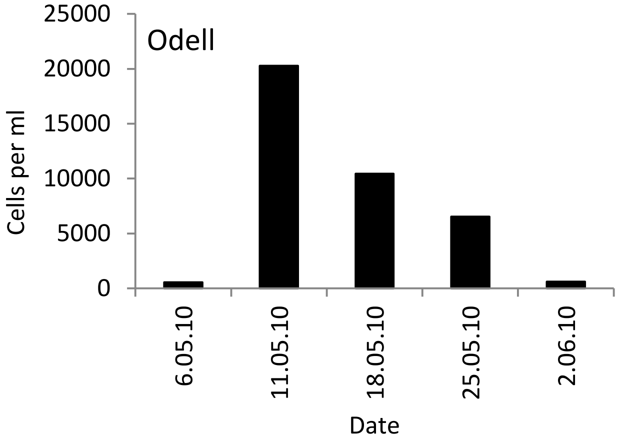


Figure 5.11. Weekly total number of cells per mL^{-1}, Odell.

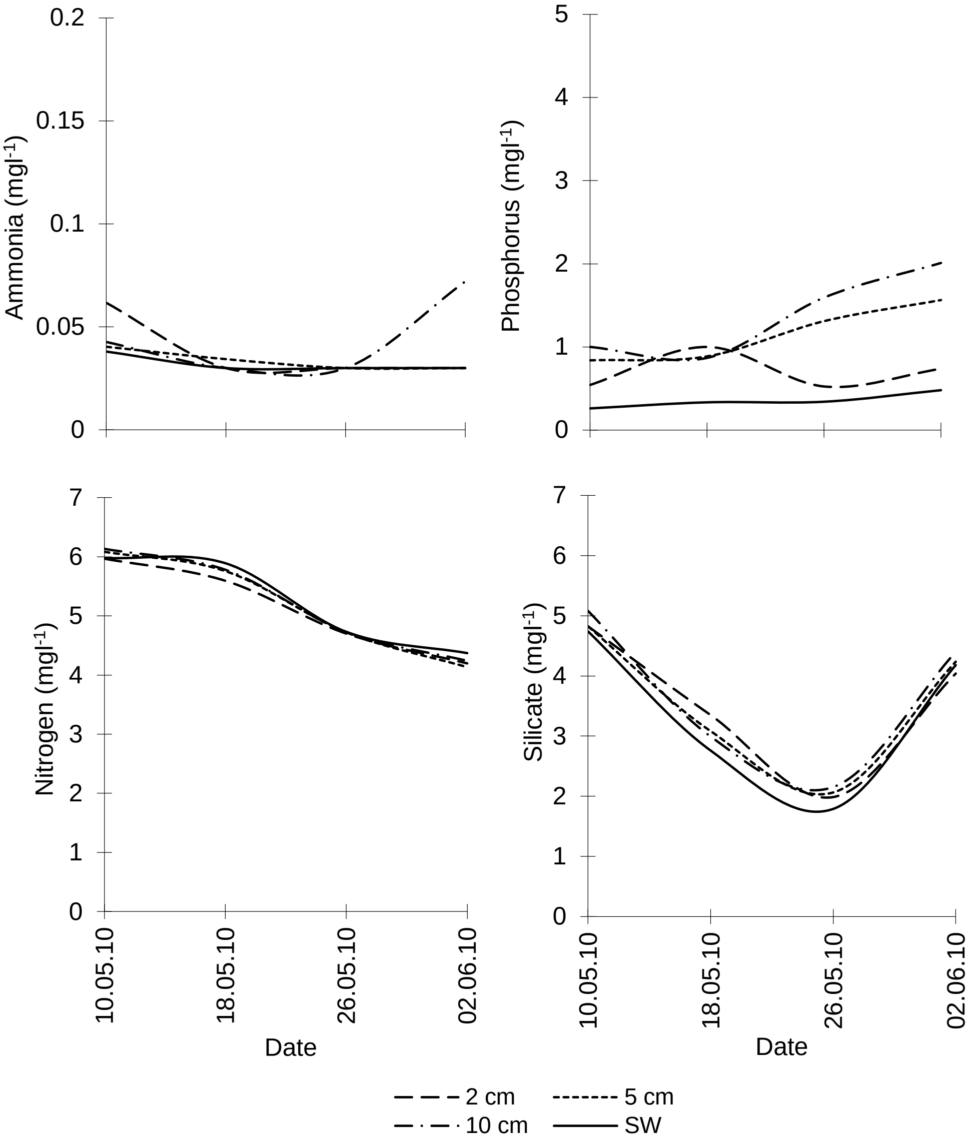


Figure 5.12. Weekly levels of ammonia, nitrogen, phosphorus and silicate, Odell.

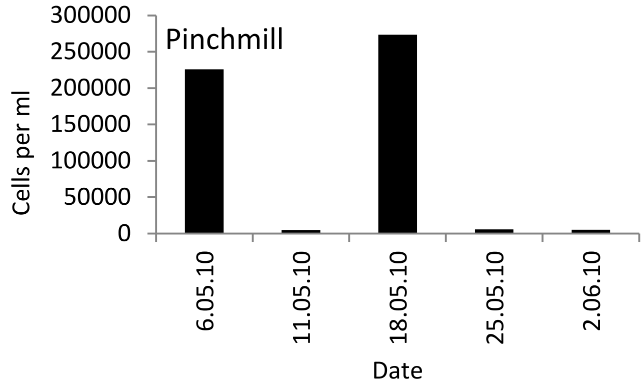


Figure 5.13. Weekly total number of cells per mL^{-1}, Pinchmill,

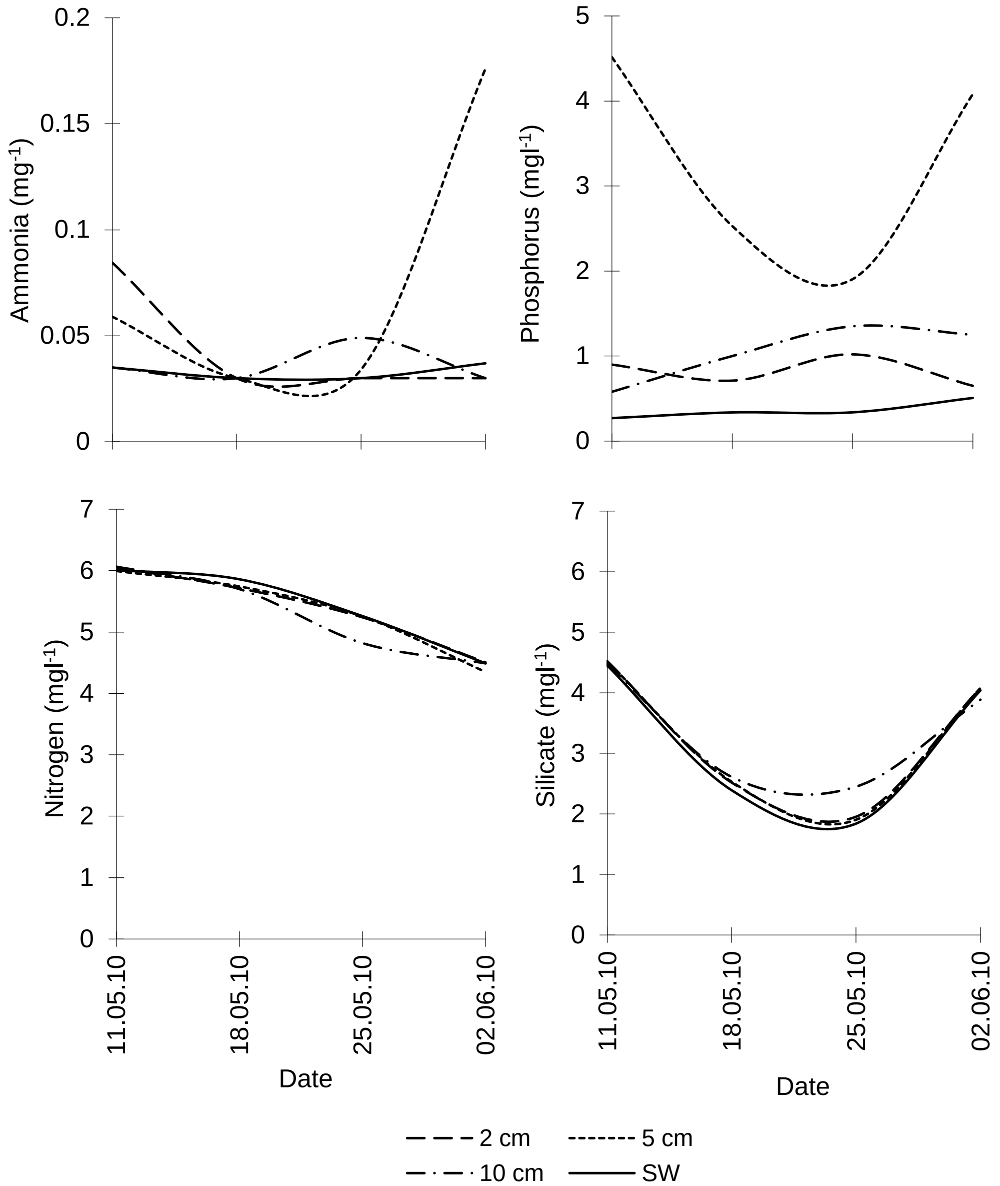


Figure 5.14. Weekly levels of ammonia, nitrogen, phosphorus and silicate, Pinchmill.

There were positive correlations between nitrogen and silicate concentrations with diatom biomass at all sites (Figure 5.15). This correlation was only significant at Odell, at most depths (2 cm, r^2=0.89, $P<0.05$; 5 cm, r^2=0.87, $P<0.05$; 10 cm, r^2=0.87, $P<0.05$; surface water, r^2=0.78, $P>0.05$). There were negative correlations between ammonia and phosphorus with diatom biomass, but these relationships were not significant.

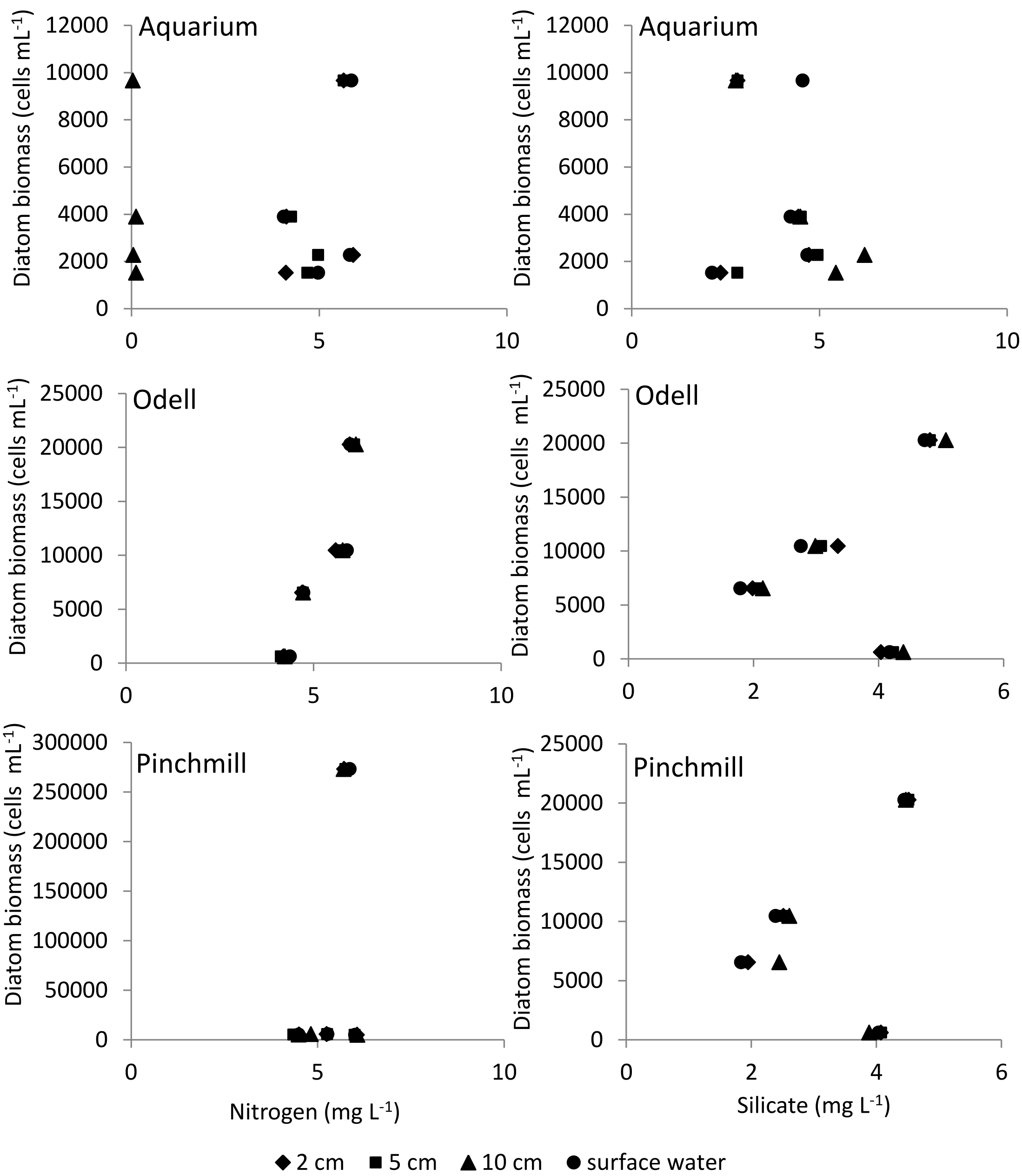


Figure 5.15. Regression analysis of the effect of nutrients on the diatom biomass at three sites on the River Great Ouse.

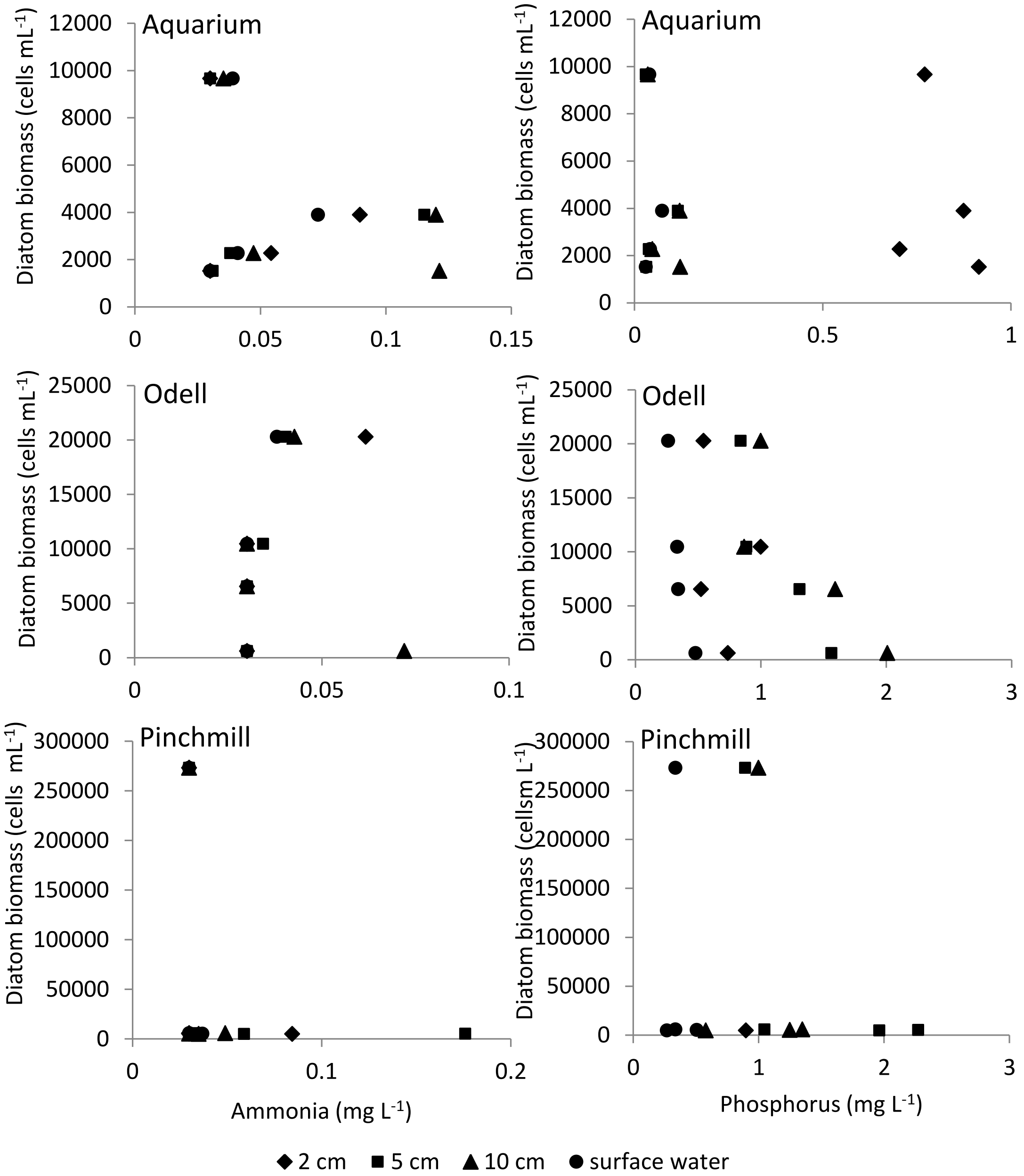


Figure 5.15 (continued). Regression analysis of the effect of nutrients on the diatom biomass at three sites on the River Great Ouse.

Diatom sampling was not conducted at Harrold Bridge, but the morning and evening samples indicated that there was a decrease in DO levels overnight, but no obvious signs of diel fluctuations in pH levels were found (Figure 5. 16).

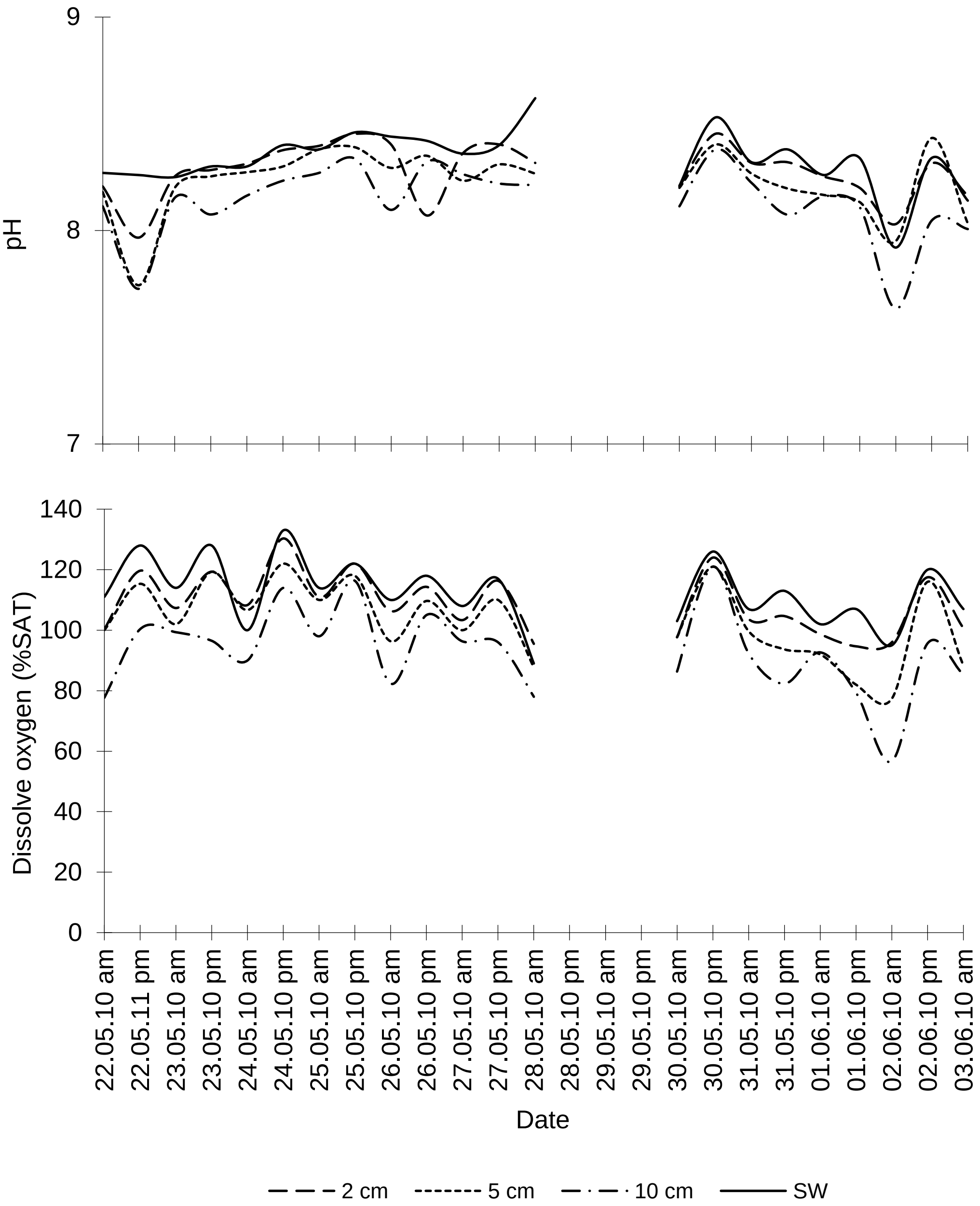


Figure 5.16. Differences in am and pm recordings of pH and DO considering diatom growth, Harrold Bridge.

Diatoms belonging to 27 genera were identified at Aquarium, Odell and Pinchmill. Twenty of these were common among all 3 spawning gravels, 3 were specific to Aquarium and 4 were specific to Pinchmill (Figure 5.17). Using the Trophic Diatom Index 3 (TDI3) at the genus level is not as precise as it was designed to be for the species level. *Gyrosigma*, *Luticola* and Stephanodis found only at Aquarium score high and favour higher nutrient conditions, whereas those found only at Pinchmill; *Ctenophora*, *Meridion*, *Reimeria* and *Tabellaria* score low and favour lower nutrient conditions.

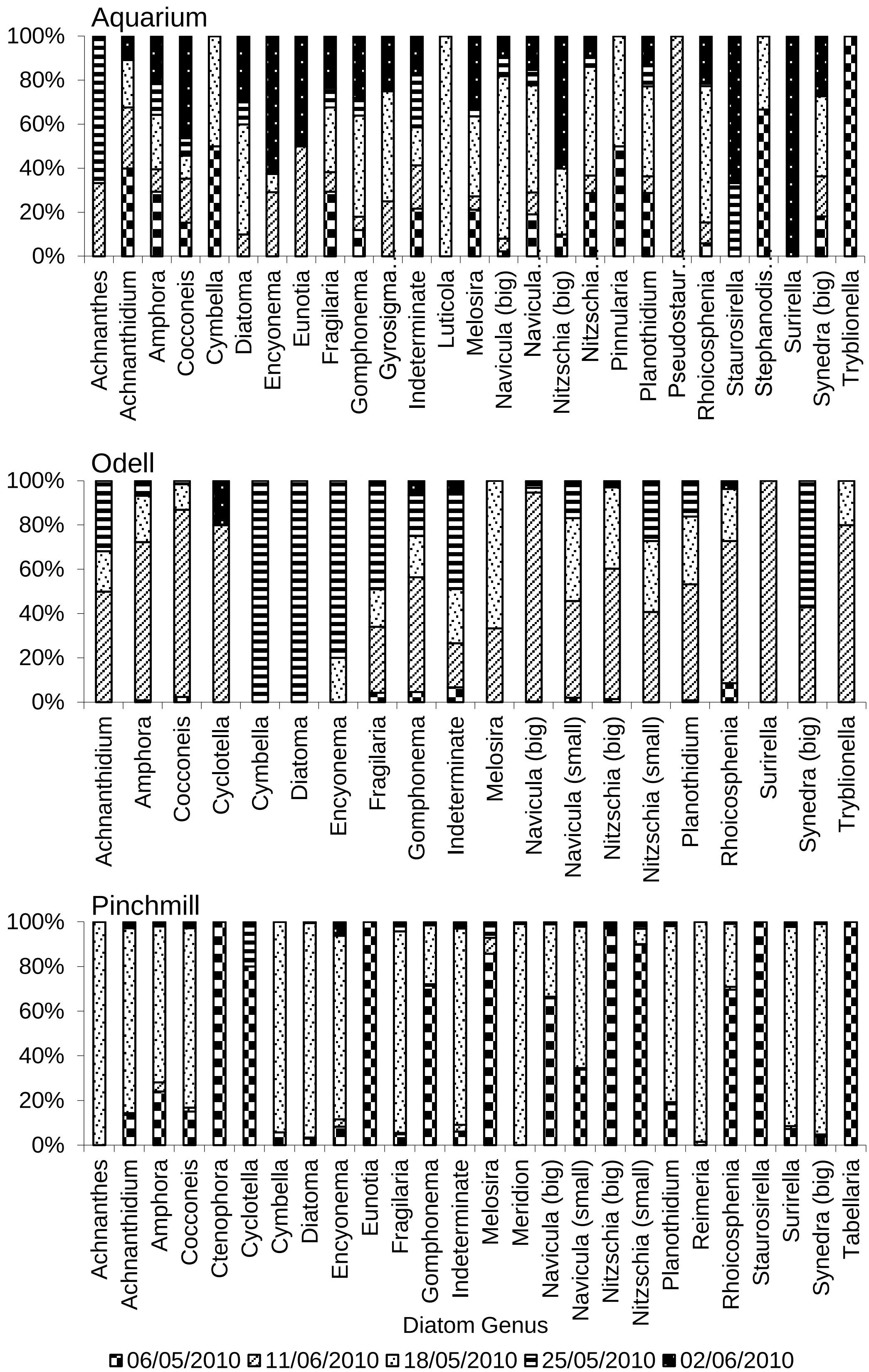


Figure 5.17. Compositions of diatom communities on each of the spawning gravels over 5 weeks. Analysed by the Environment Agency, Brampton.

5.3.3 Gravel size distribution, fine sediment and organic matter infiltration

Visual examination of the freeze core sample from Aquarium revealed root mass and vegetation incorporated in the first 10 cm. Organic matter was present at the 30-40 cm fraction (Figure 5.18). Analysis of the freeze core sample showed that particle size ranged from 31500 to 0.977 µm (Figure 5.19) and the gravel sample type at Aquarium was bimodal and very poorly sorted muddy sandy gravel. Mean surface gravel size (0-5 cm) at Aquarium was 1256.8 µm, belonging to the textural group gravelly sand. At 5-30 cm, the sediment was gravel muddy sand, changing to sandy gravel at 30-40 cm. Fine sediment analysis showed that Aquarium had the highest percentage of fine sediment at each of the core fractions, particularly in the first 10 cm of the gravels (Table 5.6) presumed to be most important for barbel egg and larval development. At each of the fractions, similar amounts of each sediment size were present until the 70th percentile (Figure 5.18).

Visual examination of the freeze core sample from Harrold Bridge revealed that larger gravel was present throughout each fraction (Figure 5.20). Analysis of the freeze core sample showed that particle size ranged from 45000 to 0.977 µm and that the gravel sample type at Harrold Bridge was bimodal very poorly sorted sandy gravel (Figure 5.21). Mean surface gravel size at Harrold Bridge was 3626.6 µm, Sediment from 0-40 cm belonged to the textural group sandy gravel. Fine sediment analysis showed that Harrold Bridge had the second highest percentage of fine sediment in the first 10 cm of the gravels and third highest in the 10 to 30 cm fractions (Table 5.6). This site has the most similar cumulative percentage of sediments at all depths than at all other sites. At the 90th percentile, sediment size for all depths was between 250 and 88.39 µm (Figure 5.21).

Visual examination of the freeze core sample from Odell revealed that large gravel was distributed throughout the sample (Figure 5.22). Analysis of the freeze core sample showed that particle size ranged from 45000 to 1.381 µm and that the sediment sample type at Odell was bimodal, very poorly sorted sandy gravel (Figure 5.23). Mean surface gravel size at Odell was 11133 µm, between 0-10 cm and 20-40 cm the sediment belonged to the textural group sandy gravel. In the 10-20 cm fraction, the sediment was muddy sandy gravel. Fine sediment analysis showed that Odell had the second lowest fine sediment infiltration between 0 and 20 cm (Table 5.6). The fractions 0 to 5 and 5 to

10 cm had very similar cumulative percentage of fine sediment. At the 90 percentile, all sediment was larger than 353.6 μm (Figure 5.23).

Visual examination of the freeze core sample from Pinchmill revealed the sample contained large gravel and cobbles which were more evenly distributed than in the gravel jetted sample (Figure 5.24). Analysis of the freeze core sample showed that the particle sizes ranged from 45000 to 0.977 μm and that the sample type consisted of bimodal very poorly sorted muddy sandy gravel (Figure 5.25). Mean surface gravel size at Pinchmill was 5440.4 μm. Fine sediment analysis showed that Pinchmill had the median percentage of fine sediment infiltration at 0 to 5 cm and the lowest between 5 to 30 cm (Table 5.6). At the 90 percentile, smaller sediment sizes were present at the lower depths (Figure 5.25).

Visual examination of the freeze core sample from the gravel jetted section at Pinchmill revealed the sample contained large gravel and cobbles (Figure 5.26). On close inspection, there were obvious intragravel spaces in the gravel jetted core sample, caused but the disruption to the gravel stratification during the gravel jetting process. Analysis of the freeze core sample showed that the particle sizes ranged from 45000 to 0.977 μm and that the sample type consisted of muddy sandy gravel (Figure 5.27). Mean surface gravel size on the gravel jetted section was 11818.5 μm. Fine sediment analysis showed that the gravel jetted section of Pinchmill had the lowest fine sediment infiltration in the 0 to 5 and 30 to 40 cm fraction. However, in the 5 to 20 cm depths, there were relatively high percentages of fine sediments (Table 5.6). At the 90 percentile, smaller sediment sizes were present at the lower depths (Figure 5.27).

Table 5.6. Percentage of fine sediments (<1 mm) in each core fraction at each site, showing ^ Highest and * lowest percentage for each fraction.

	0_5	**5_10**	**10_20**	**20_30**	**30_40**
Aquarium	^72.4	^78.9	56.9	^58.6	^42.8
Harrold Bridge	42.8	54.07	37.21	40.7	31.47
Odell	25.2	42.7	36.6	43.9	39.9
Pinchmill	31.9	*40.3	*31.5	*26.08	35.3
Pinchmill (gj)	*18.2	50.1	^58.1	34.5	*25.5

Figure 5.18. Freeze core sample over segmentation box, Aquarium.

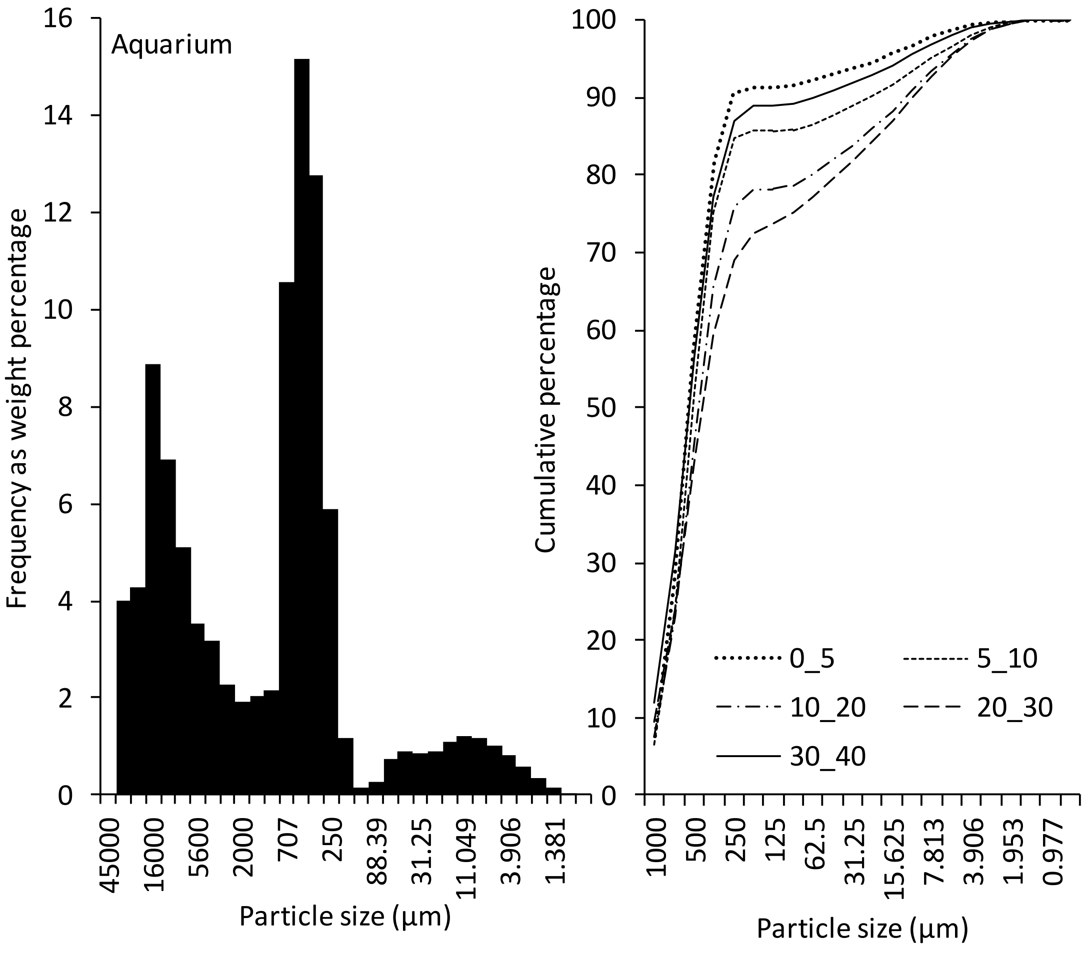


Figure 5.19. (Left) Weight frequency histogram of particle sizes ranging from 45000 to 0.691 µm (Right) and cumulative weight percentage frequency of fine sediments (<1mm), Aquarium.

Figure 5.20. Freeze core sample over segmentation box, Harrold Bridge.

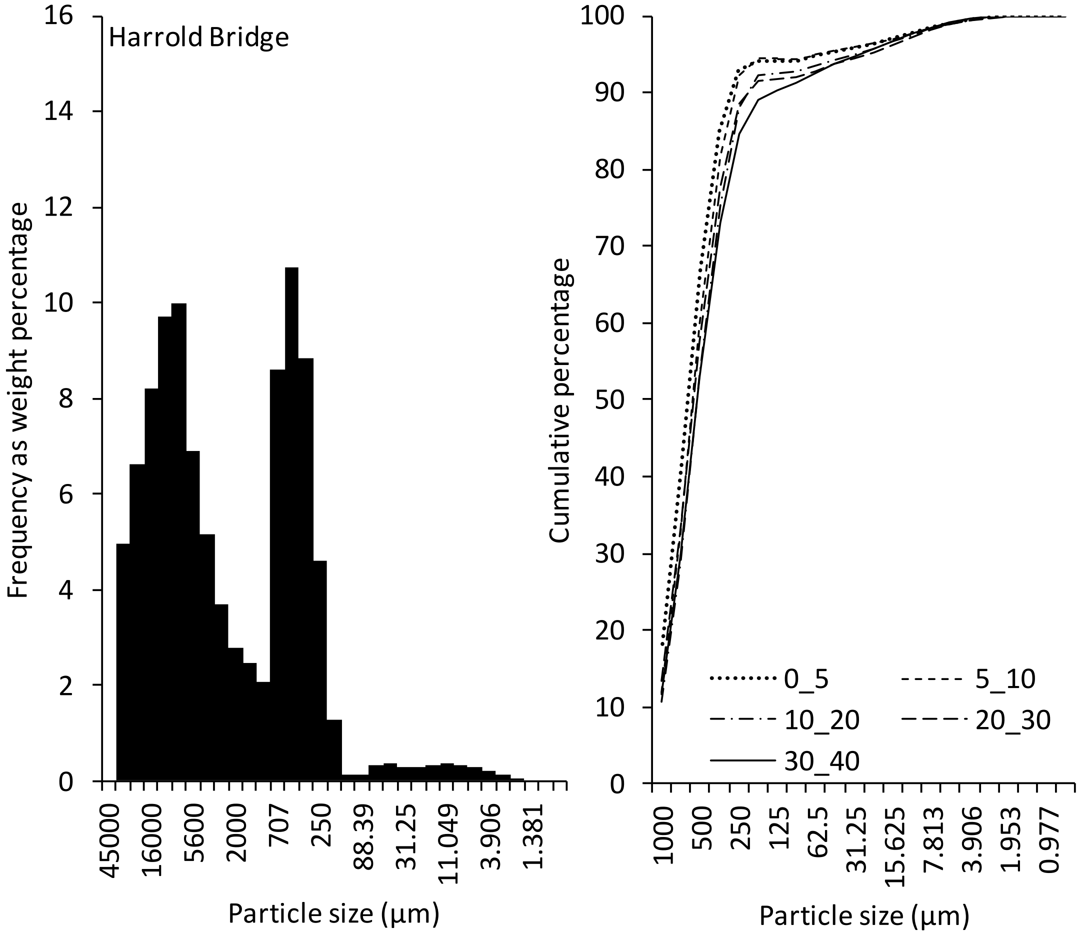


Figure 5.21. (Left) Weight frequency histogram of particle sizes ranging from 45000 to 0.691 µm (Right) and cumulative weight percentage frequency of fine sediments (<1mm), Harrold Bridge.

Figure 5.22. Freeze core sample over segmentation box, Odell.

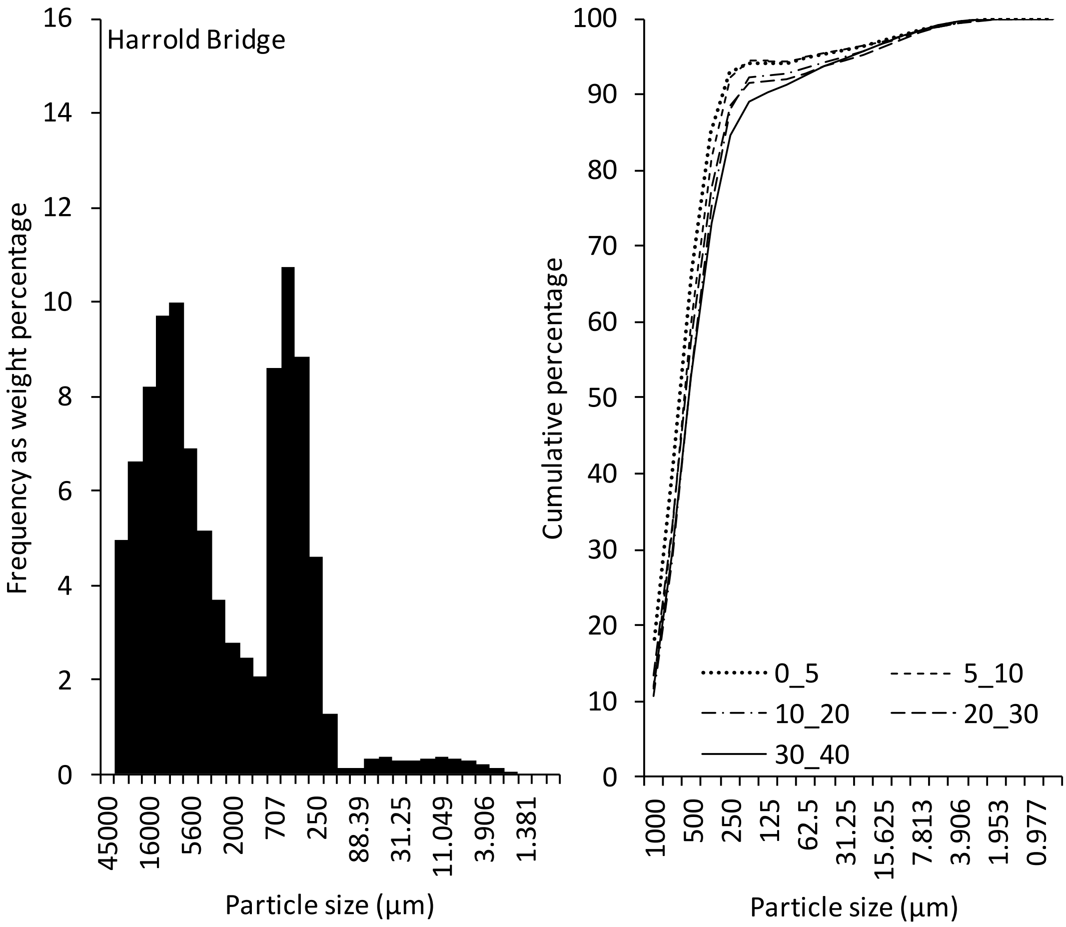


Figure 5.23. (Left) Weight frequency histogram of particle sizes ranging from 45000 to 0.691 µm (Right) and cumulative weight percentage frequency of fine sediments (<1mm), Odell.

Figure 5.24. Freeze core sample over segmentation box, Pinchmill.

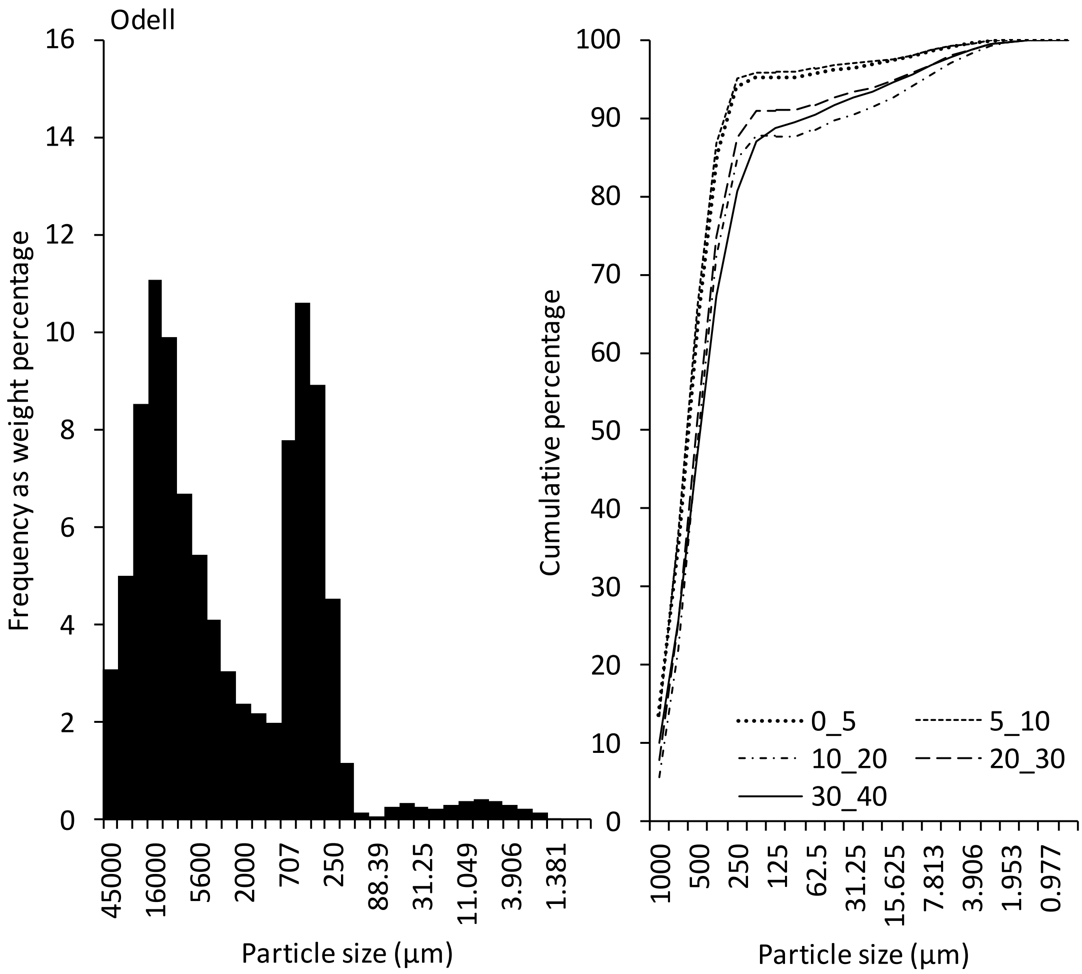


Figure 5.25. (Left) Weight frequency histogram of particle sizes ranging from 45000 to 0.691 µm (Right) and cumulative weight percentage frequency of fine sediments (<1mm), Pinchmill.

Figure 5.26. Freeze core sample (gravel jetted) over segmentation box, Pinchmill.

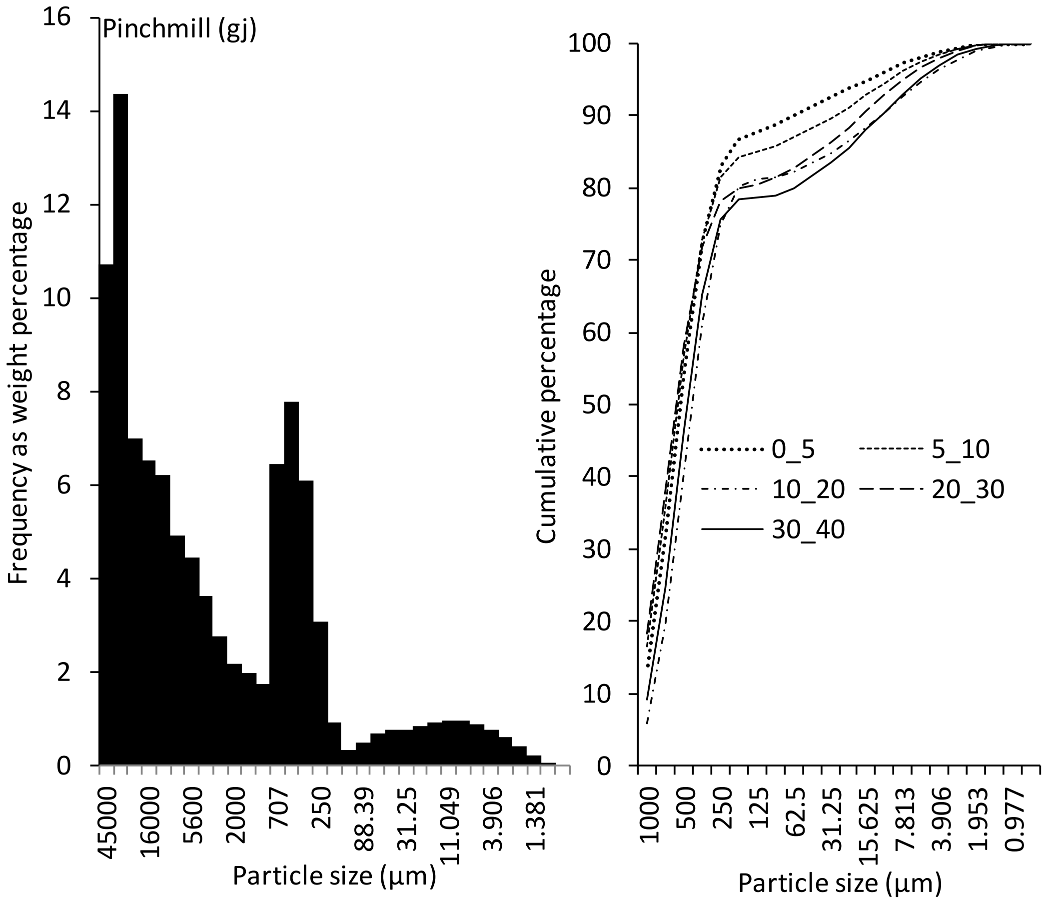


Figure 5.27. (Left) Weight frequency histogram of particle sizes ranging from 45000 to 0.691 μm (Right) and cumulative weight percentage frequency of fine sediments (<1mm), Pinchmill gravel jetted.

Organic matter percentage was higher for all fractions at Pinchmill, except 5 to 10 cm, which was higher at Odell and Pinchmill (gj). Harrold Bridge had low organic content at all depths, whereas percentages fluctuated with depth at other sites. At Aquarium, organic content increased with depth, which is similar to Pinchmill (gj). Organic matter percentage peaked in the 5 to 10 cm fraction at Odell and in the 5 to 10 and 30 to 40 cm fractions at Pinchmill (Figure 5.28).

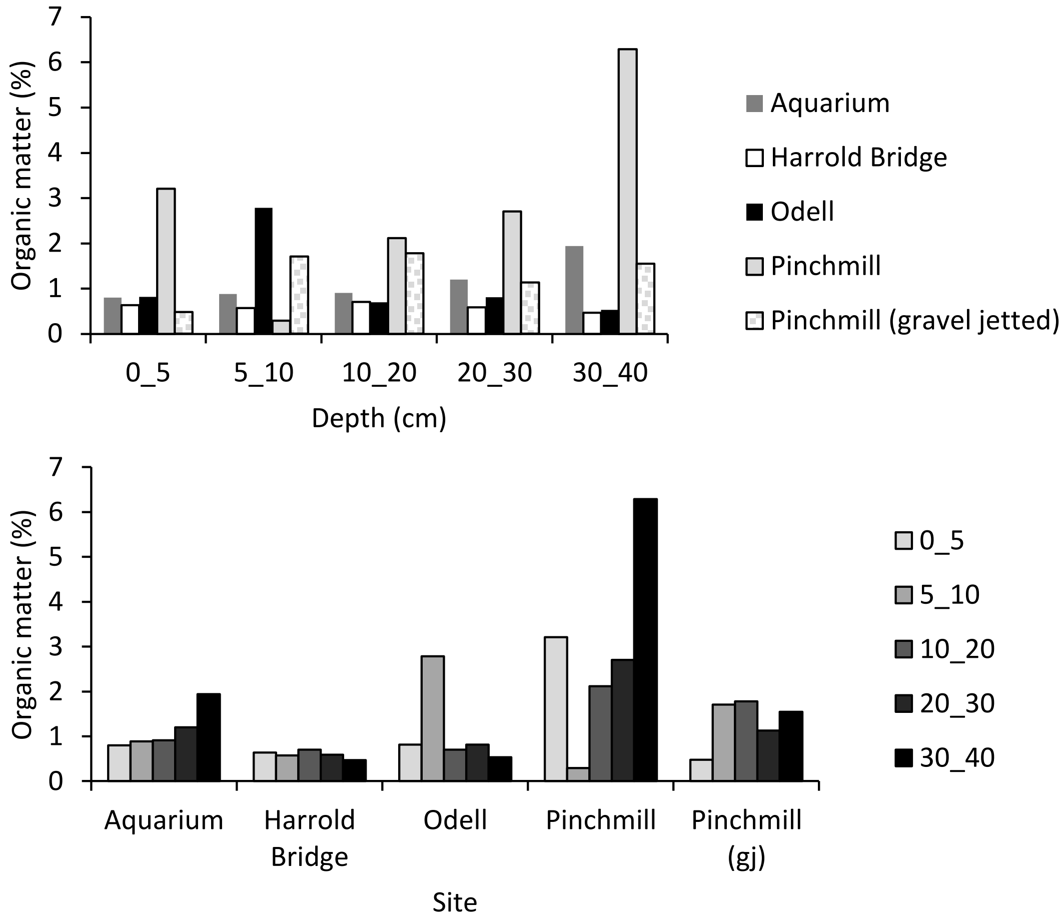


Figure 5.28. Organic matter percentage at each site and at each depth.

5.4 Discussion

Successful spawning and emergence is critical for recruitment success but weak year classes from one or more consecutive years can have massive impacts on the species population. For example: in 2010, barbel were observed spawning within the study section; in 2011, barbel were not observed spawning within the study section; in 2012, barbel were observed spawning within the study section, but this event was followed by heavy rainfall that resulted in increased river level and flow and the possible loss of embryos. It is therefore important that when successful spawning does occur, habitats are in a condition suitable to support the incubation and emergence processes.

Hyporeic water quality

No WQ sampling took place on the 29th May because it coincided with a bank holiday, and the National Laboratory was closed and water samples could not be stored until analysis without affecting the results. Hyporheic water quality is an important control on many in-channel ecological and biogeochemical processes (Boulton *et al*. 1998; Storey *et al.* 2004). The early developmental stages of lithophilic fish such as barbel suffer from a change of the physio-chemical intragravel conditions such as low dissolved oxygen, inorganic nutrient concentrations or reduced intragravel flow (Becker & Neitzel 1985; Chapman 1988; Rubin & Glimsäter 1996; Ingendahl 2001).

Dissolved oxygen saturation

The concentration of oxygen in gravels is the most critical factor for developing eggs and larvae as they require a continuous supply of clean, cool, well oxygenated water for respiration and to flush away waste metabolites (Rubin & Glimsater 1996). For 80% of the continuous monitoring of DO and temperature at Odell, DO was considered as good (>60% SAT) under guidance set by the WFD. For 12% of the continuous monitoring DO was considered as poor (<45% SAT) according to the levels of the WFD. On occasions, DO was reduced to extreme conditions of 2.8% SAT during the incubation period. DO Sat was never measured this low during the daily measurements, the lowest recordings for each depth are as follows: 2 cm, 73% SAT at Aquarium; 5 cm, 66 % SAT at Harrold Bridge; 10 cm, 54% SAT at Odell. The higher levels recorded in the daily samples are most likely related to the time of sampling, as most of the low levels recorded by continuous monitoring were during periods of darkness when BOD is highest. In future it would be beneficial to monitor DO pre and post gravel jetting, to assess the effectiveness of the procedure at removing fine sediment, increasing interstitial flow and therefore DO levels.

Alderdice *et al.* (1958) observed premature hatching and emergence when embryos were exposed to low dissolved oxygen near to their hatch time and fish developing in these conditions tend to be smaller and lighter influencing long term survival after emergence from the gravel into the channel (Youngsen *et al*. 2005). Suggesting that hatched barbel originating from this Odell and other sites if levels reduced to these levels at night, would have a reduced fitness and survival rate, resulting in poor recruitment.

Temperature

Temperature of water in contact with the spawning gravel measured daily ranged from 10.8 to 22.3°C, which were similar to those recorded by Calta (1997) and Policar *et al*. (2010) rearing barbel in controlled conditions and close to that which Lugowska (2009) reported to be the optimal temperature for embryonic development of barbel, 18°C. Continual monitoring of temperature revealed that river temperature was above this threshold for >83% of the recorded time, impacting on the successful embryonic development and emergence. These temperatures would also affect the dissolved oxygen levels available in the water.

Inorganic nutrients

Land use in the Great Ouse catchment is predominantly agricultural and therefore diffuse pollution and entry of inorganic nutrients such as nitrogen and phosphorus into the channel is high.

High inorganic nutrient levels at all depths are carried up to the gravel surface through upwelling. High concentrations of ammonia, nitrates and phosphates contribute to a high BOD and therefore directly affect the functioning of organisms within the river ecosystem, influencing the growth of diatoms. None of the inorganic nutrients measured during the assessment of hyporheic quality are considered to be less than good according to the guidance set by the WFD. However, data suggested that increases in these nutrient levels did have had an impact on diatom growth, particularly during the spawning events and early on in the incubation period.

It is expected that the nutrient levels would be higher in 2011 compared to 2010, due to the reduced flow and river level experienced (Chapter 4), resulting in a reduced dilution effect. This will not only have affected the hyporheic water quality, but also the surface water quality which also contained high nutrient and low DO levels during sampling.

Reduced intra-gravel flow

Particle size composition of all spawning habitats sampled were either comprised of sandy gravel, or muddy sandy gravel with organic content unevenly distributed throughout. This reduces upwelling, downwelling and interstitial flows and consequently the supply of clean, cool, well oxygenated water for respiration and to removal of waste metabolites (Rubin & Glimsater 1996). The high occurrence of these small clogging sediments contributed to high nutrient levels and low dissolved oxygen levels.

Diatoms

High flows have the ability to wash away diatoms connected loosely to substrata. Diatom sampling began on 6 May 2010, 4 days after river level and flow increased. This may have caused enough disturbances to the river bed to result in a reduced number of some diatom genera in the sample. Pinchmill still had a high number of cells mL^{-1}, whereas Odell had significantly lower numbers of cells mL^{-1} in the 6 May sample. There were no high flows after that point to affect the results.

Diatoms are usually the dominant phytoplankton group in rivers (Genkal 1997); they are light-limited and therefore restricted to the surface layers of gravel (O'Connor 2002). Welch *et al.* (1988), Miheeva (1992), Hamm (1993) and Steinhörster *et al.* (1996) indicated that there was an increase in diatom biomass as nutrient concentrations increased, usually in the spring and therefore during the spawning period of barbel. Analysis of data collected in this chapter did not find such a relationship between nutrients and diatom biomass, this may be due to the sampling procedure and the need for continuous monitoring of nutrient concentrations before the diatom sample was taken as fluctuations in nutrient levels leading up to the sample date will affect diatom abundance.

Diatom biomass peaked at the time that barbel were most active, and increasing photosynthesis and respiration of algae caused high diurnal changes to the physicochemical conditions within the hyporheic zone. The increase in diatom biomass affected the water chemistry resulting in low dissolved oxygen at night time, similar to the findings of Ibisch & Borchardt (2002). There was no increase in pH levels as Halstead & Tash (1982) had found. As well as the influences on the physiochemical status of the gravels, the biomass of benthic diatoms is likely to have created a biofilm that hindered gaseous exchange, metabolic waste removal and physically hinders emergence of fish larvae resulting in increased fry mortality.

Fine sediment and organic matter

According to Kondolf (2000), the value of 0.83 mm to describe fine sediment size in the McNeil & Ahnell (1964) study, was due to the set of Tyler sieves used and not a physically significant threshold, and that it is preferable to round 0.83 or 0.85 mm to 1 mm. Interstitial sediments <1mm reduce permeability of gravel (Kondolf 2000). The choice of freeze core sampling over other methods such as the pebble count method (Wolman 1954), bulk core sampling (Kondolf 2000) and grab sampling (Thoms 1992) was down to the success of retaining the fine sediment in the sample.

Representative sampling of vertical sequences of coarse and fine sediment requires 200 kg to get truly representative samples (Church *et al.* 1987). Other studies have also used larger sample sizes: 100 samples (Carling & Reader 1981); 30 samples (Hughes *et al.* 1995); 166 samples (Milan *et al.* 1999); 24 samples (Hendrick *et al.* 2005). The spawning gravels identified during this study were not big enough for that quantity to be removed, without disrupting the natural stratification and distribution of fine sediments (Lisle & Eads 1991). It would have been beneficial however, to collect freeze core samples from multiple non-spawning gravels to act as a comparison to those used by barbel. This would have enabled differences to be identified and a greater understanding into the selectivity of spawning habitat by barbel.

Fine sediment within the freeze core samples and are most likely derived from the surrounding agricultural land resulting from catchment scale geological processes, surface run off and cattle poaching. Fine sediments determine most physical and chemical processes in the hyporeic zone (Boulton *et al*. 1998), contributing to the reduced interstitial flow as previously mentioned and the associated affects. Gravel jetting at Pinchmill proved successful at removing fine sediment and organic content. Although there were low levels of spawning activity at Pinchmill in 2010, barbel were not observed spawning at any of the spawning gravels within the study section in 2011. Therefore, the lack of barbel spawning at Pinchmill has not been attributed to the gravel jetting creating unfavourable conditions, particularly as ~35 chub were observed exhibiting spawning behaviours on this specific spawning gravel.

Spawning substrate size

The largest gravel size at all sites after the removal of cobbles was 45 mm. Pinchmill gravel jetted had the highest frequency of this size sediment, followed by untreated Pinchmill. Aquarium, Harrold Bridge and Odell each lacked this size. At Aquarium, Harrold Bridge and Pinchmill, mean surface gravel (0-5 cm depth) size was smaller than the gravel sizes ranging between 10-40 mm preferred by barbel (Environment Agency 2012), with 1.3, 3.6 and 5.4 mm respectively. Odell and Pinchmill gravel jetted mean surface gravel sizes were 11.1 and 11.8 mm respectively, just within the preferred size range. Aquarium and Odell spawning grounds have since been replenished with 6 tonnes of new gravel ranging from 10 to 60 mm in an attempt to provide more suitable spawning habitat.

Bottlenecks to barbel recruitment related to spawning habitat

There was a lack of literature on spawning gravel and hyporheic water quality needs for barbel and other lithophilic coarse fish species; information available was all centred on salmonid species (Crisp 1996; Shackle *et al.* 1999; Kondolf 2000; Milan *et* al. 2000; Hendry 2003; Kondolf *et al.* 2008; Meyer *et al.* 2008) and as a result, specific critical thresholds for DO, inorganic nutrients and pH are unknown.

This Chapter aimed to compare the spawning gravel habitat quality at four sites during the embryonic and larval period of barbel on spawning gravels over spatial, temporal and diurnal timescales. Hyporheic water quality, periphytic diatom growth, spawning substrate size, fine sediment and organic content were measured; meeting the objectives of the research. This information will provide options for improving spawning habitats for lithophilic coarse fish species.

Five bottlenecks to barbel recruitment relating to spawning habitat have been identified. These are:

- Low dissolved oxygen caused by: periphytic diatoms reducing dissolved oxygen levels at night due to increased BOD and infiltration of fine sediment and organic matter blocking the interstitial spaces within the gravel, reducing the flow of oxygenated water through the gravels and entrapping poor water quality within the hyporheic zone;

- biofilms caused by periphytic diatoms and organic matter directly smothering eggs and larvae;
- water temperatures exceed those deemed optimal for barbel embryonic development.

- surface gravel size of available spawning habitats are smaller in diameter than what is preferred by barbel.

Mitigation

- The introduction of riparian tree overhang will shade the gravels which will: 1) reduce temperatures on the spawning gravel; 2) reduce light available for algal growth. As a consequence, dissolved oxygen levels may also be improved. Tree shading has also been found favoured by spawning barbel (Melcher & Schmutz 2010).
- Fencing to reduce cattle poaching and the resulting introduction of fine sediment and organic matter into the river system.
- Findings from this study in this Chapter have prompted a new gravel redressing programme on the Upper Ouse at sites similar to these spawning habitats, comprised of surface gravels with small diameters has already been started (Figure 5.29). The work will use locally sourced gravel ranging in size from 10 to 40 mm, complimenting the surface size of existing gravel. The new gravel will be placed on top of recently gravel jetted existing material, aiding all processes that occurs in the hyporheic zone.
- It is recommended, where possible, to incorporate measures into the gravel rehabilitation work that will continually reduce fine sediment infiltration. The creation of higher velocities by the placement of flow deflectors, rocks, large woody debris would require less maintenance than a yearly gravel jetting programme. Increased flows also reduce the ability of some diatoms to adhere to the spawning gravels, which would lessen the risk of egg smothering during the incubation period.

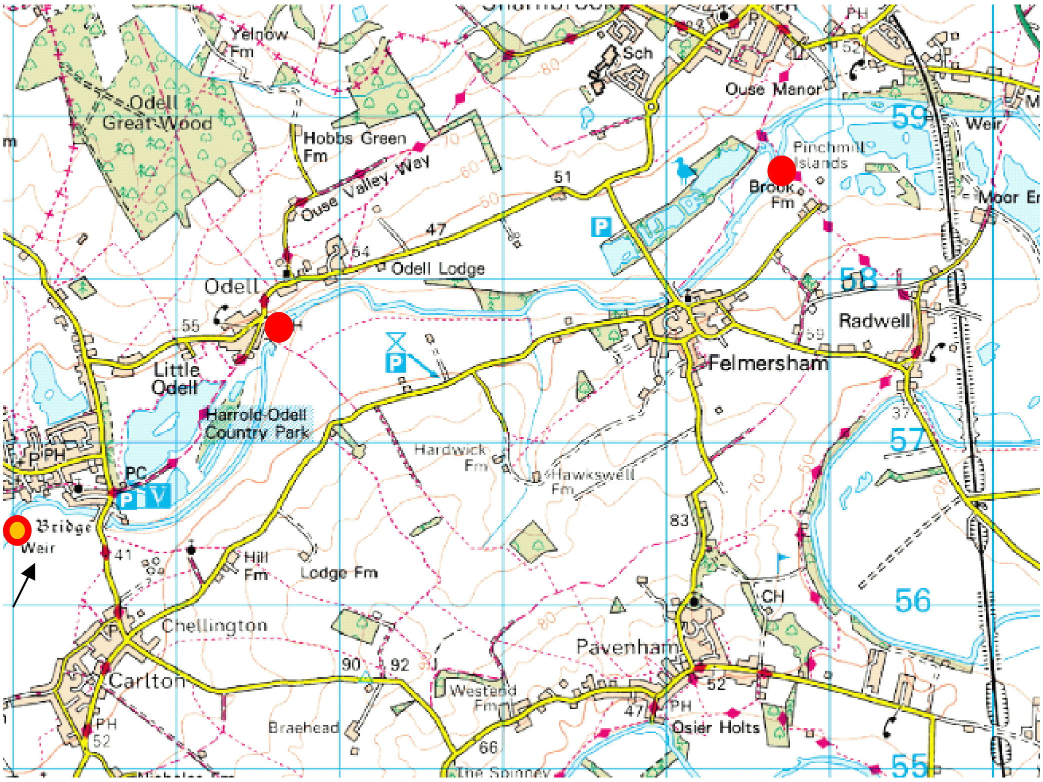


Figure 5.29. Map of study section highlighting ● Gravel jetted spawning habitat, ● gravel jetted and redressed spawning gravels. Arrow indicates the direction of flow.

6 YOUNG BARBEL IN THE RIVER GREAT OUSE

6.1 Introduction

Abundance of young of year (0+) fish species has been recognised as a good indicator of reproductive success and recruitment during individual years (Nunn *et al.* 2003; Nunn 2005; Valova *et al*. 2006). In temperate regions, most evidence suggests that other than spawning success, the main cause for recruitment bottlenecks in non salmonid fish populations is survival or growth of newly hatched larvae (Mills & Mann 1985). Barbel is a long lived species that matures later in its life history, small barbel are not routinely encountered during routine surveys and as a result, changes in their population structure can take many years to become apparent. The availability of micro-habitats along the ontogenetic niche profiles is decisive for recruitment success (Scheimer *et al.* 2003) and previous studies have reported on small barbel population characteristics, based on data collected as part of a community assemblage and habitat investigations (Pilcher *et al.* 1997; Watkins *et al.* 1997; Gozlan *et al*. 1998; Jurajda 1999; Valova *et al.* 2006). Few have looked into growth and production of a single species, specifically barbel, despite the species providing major interest to anglers and concerns over numbers and distribution. Any measurement of population structure needs to consider natural recruitment versus the impact of previous stocking events.

The aim of this study was to identify presence of naturally recruited barbel in the River Great Ouse, assess the population characteristics and to identify bottlenecks to the recruitment of the species related to young barbel. This was achieved by sampling specifically for 0+ to 3+ barbel. The objectives were to: 1) Identify natural recruitment; 2) Evaluate the first two years growth and relate to degree days >13.5°C; 3) associate barbel presence on a micro-habitat and meso-habitat scale.

It was predicted that habitat preferences would alter as barbel became older. It was also predicted that growth rates of barbel in the first 2 years would be different between naturally recruited and captive-reared barbel. This information would verify that natural recruitment is occurring in the Great Ouse catchment and improve the understanding of the young barbel population in the River Great Ouse. As well as highlight habitats to target for rehabilitation.

6.2 Methodology

6.2.1 Study site selection

All sites were selected based on availability of preferred habitats of 0+ to 3+ barbel, based on the literature reviewed in Chapter 2. Larval drift was conducted at 3 locations identified in Chapter 4 (Figure 6.1), the methodology is described in Section 6.2.2. Micromesh seine netting was conducted at locations where local angling clubs had informed the Environment Agency that they had witnessed barbel spawning. There were nine sites on the River Great Ouse (Figure 6.2), one site on the Ouzel and two sites on the Ivel, the latter two both tributaries of the River Great Ouse (Table 6.1), the methodology is described in Section 6.3.3. In 2009, semi-quantitative electric fishing was conducted at four sites (Figure 6.3), three of these had previously been used for seine netting (Aquarium, Pinchmill and Tempsford) (Table 6.1). The fourth site was Wode Farm, Newport Pagnell (SP881440). In 2010, hoop nets were set at randomly chosen locations between Harrold weirs and Sharnbrook, the methodology is described in 6.2.5. In 2010 and 2011, semi-quantitative and point abundance sampling by electric fishing (PASE) were performed at several sites between Harrold weirs and Sharnbrook weir (Figure 6.4), including Aquarium and Pinchmill from the previous surveys, the electric fishing methodologies are described in 6.2.4.

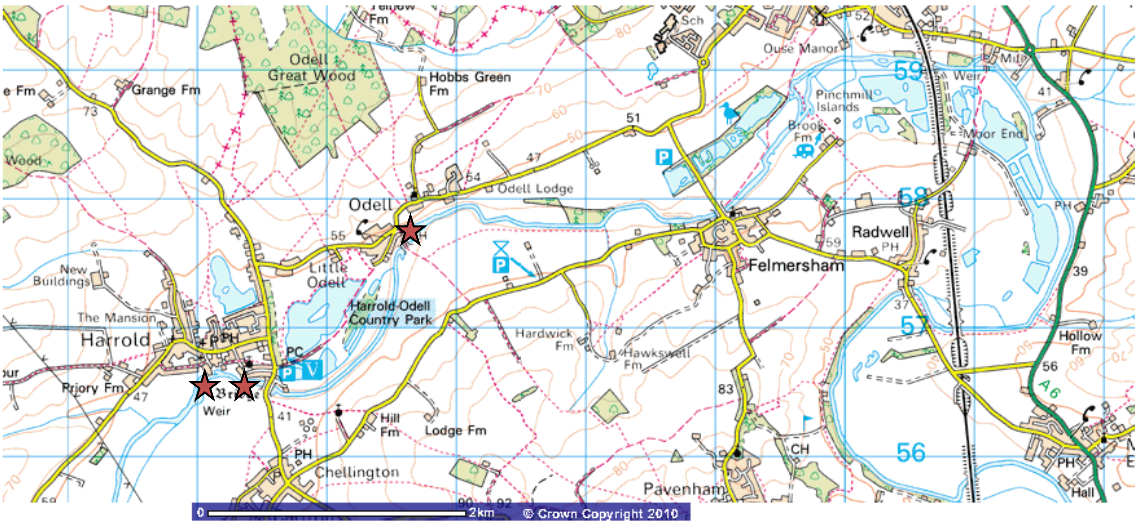


Figure 6.1. Larval drift sampling sites (★) between Harrold weirs and Sharnbrook in 2010. Arrow indicates direction of river flow.

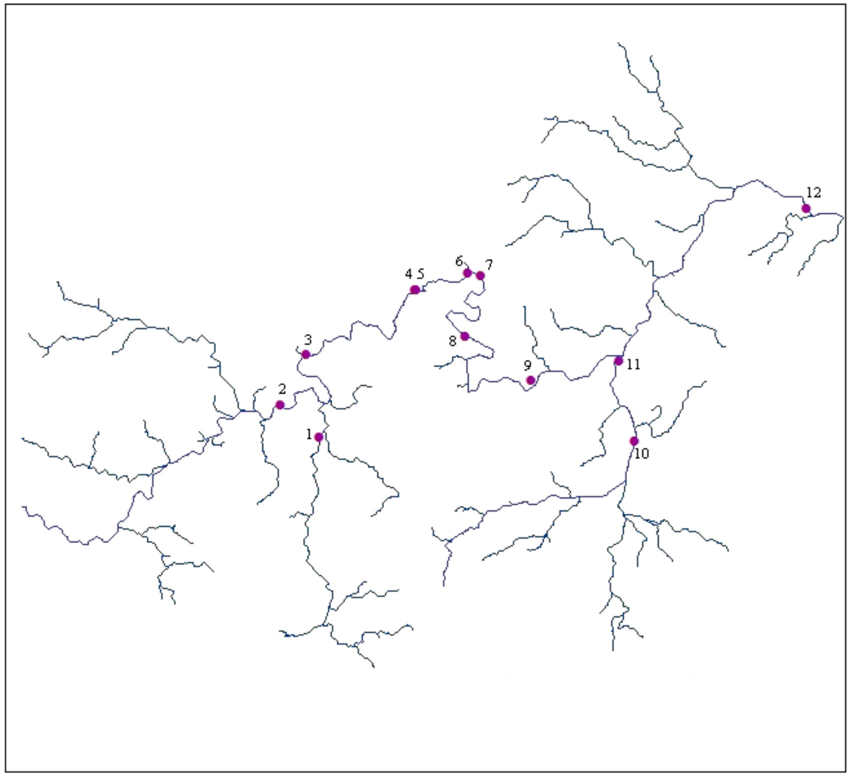


Figure 6.2. Locations of seine netting locations between Willen sluice and St Ives on the River Great Ouse.

Table 6.1. Study sites of micromesh seine netting studies on the River Great Ouse

Site		**River**	**NGR**
1	d/s Willen sluice	Ouzel	SP8817940910
2	Haversham weir	Great Ouse	SP8399443353
3	Ravenstone Mill	Great Ouse	SP8556048620
4	The Aquarium	Great Ouse	SP9520056500
5	d/s Harrold weir	Great Ouse	SP9499656549
6	Pinchmill Island	Great Ouse	SP9983859007
7	Sharnbrook weir	Great Ouse	TL0115558986
8	Oakley	Great Ouse	TL0065152905
9	New Cut	Great Ouse	TL0769949669
10	St Ives sluice	Great Ouse	TL3139970566
11	Biggleswade Common	Ivel	TL1859545539
12	d/s Tempsford saw Mill	Ivel	TL15801 53014

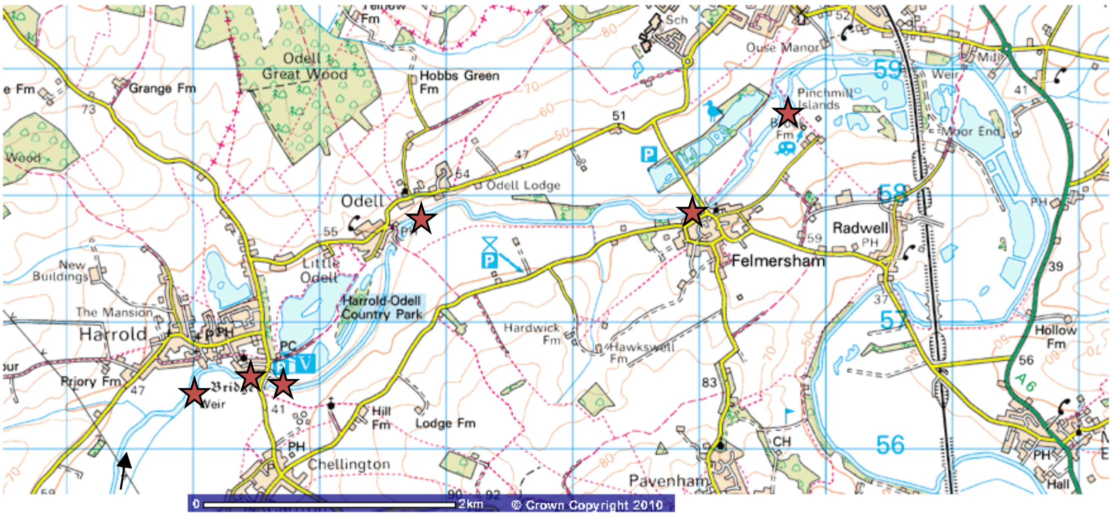


Figure 6.3. Electric fishing sites in 2009, 2010 and 2011 (★)From upstream; Aquarium (SP9501856499), Harrold Bridge (SP 9551856521), d/s Harrold Bridge, Odell (SP 9673357795), Felmersham Bridge and Pinchmill (SP9972958706). Arrow indicates direction of river flow.

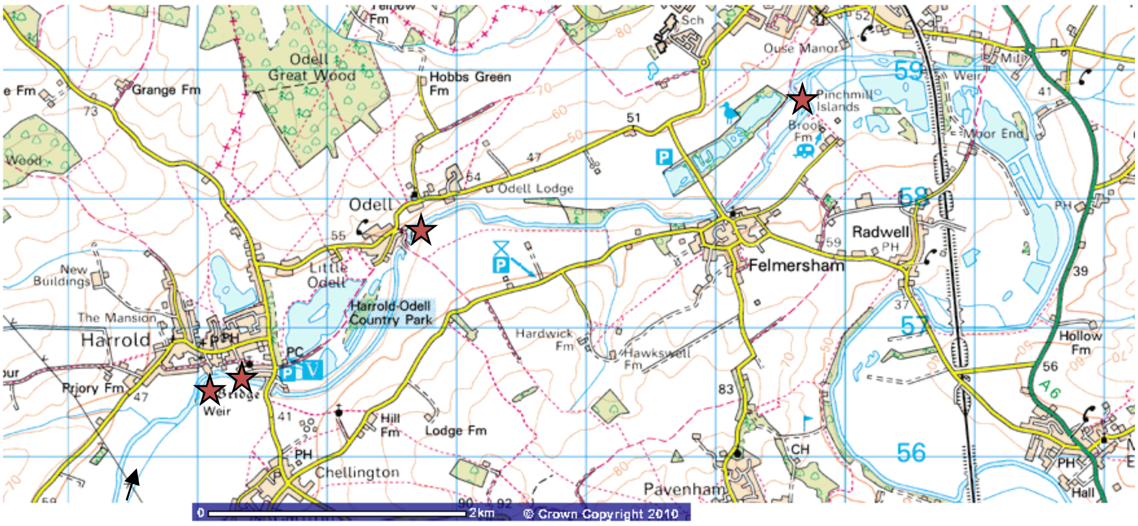


Figure 6.4. PASE sites in 2010 (★) From upstream; Aquarium (SP9501856499), Harrold Bridge (SP 9551856521), Odell (SP 9673357795) and Pinchmill (SP9972958706). Arrow indicates direction of river flow.

6.2.2 Larval drift

Larval drift was investigated at three sites for a period of 18 days between 23 May 2010 and 9 June 2010, on this date, no fish had been caught for a period of seven days. The traps were emptied in the daylight hours (Bischoff & Freyhof 1999). The nets used were square to conical in shape (Penaz *et al*. 1992; Copp *et al.* 2002; Reichard & Jurajda 2007), with an opening of 0.25 x 0.4 m, length of 0.65 m and 0.5 mm mesh size, which has been proven efficient at capturing fish >5 mm (Riechard 2002; Reichard & Jurajda

2007). They were anchored to the river bed using stakes to avoid displacement due to river flow.

Many authors have commented that the bank where water velocities were highest caught more fish (Copp *et al*. 2002; Zitek *et al.* 2004; Upper Thames), and nearly all methodology encountered positioned multiple drift nets at different places in the channel. For this reason, three drift nets were set at each site, positioned left, centre and right of the channel in locations where the majority of flow left the spawning gravel.

When the nets were removed this was carried out without letting more river water enter the net. The river flow was used to work all debris to the end of the net so that all content could be emptied. The nets were then placed back in their original positions.

Samples were sorted in the field, immediately after collection, in a white plastic tray and this task was restricted to a 20 minute time limit to provide a common unit of inspection per sample (Reichard *et al*. 2004). Larger fish caught in the nets were identified, measured and returned to the river, unidentifiable fish and eggs were preserved immediately (Humphries *et al*. 2003) in 10% Formalin to be identified and counted in the laboratory. Taxonomic identification and length measurements (fork length to the nearest 0.1 mm) were made under an Olympus SZ61 microscope. Species were assigned to a developmental stage according to Pinder (2001). Damaged larvae that could not be determined to species level were assigned as unidentified (Zitek *et al.* 2004).

6.2.3 Micromesh seine netting

Sites were sampled on a fortnightly basis over 2 days from 02.06.09 to 14.08.09, between the hours of 0930 and 1900. Sampling was restricted to the margins and shallow lentic fringe areas in water <1.5-m deep, where the water velocity was slow and 0+ group fishes, particularly barbel tend to be aggregated (Copp & Garner 1995; Pilcher & Copp 1997; Nunn *et al.* 2002). The micromesh seine net used was 25 m long and 3 m deep with a 6 mm hexagonal mesh size, with added weight to hold the net in the flow. The net was set out from the banks in a rectangular shape and then, fished to the bank in the usual manner for a beach seine and captured fish were transferred to large water-filled containers prior to analysis (Nunn *et al.* 2002).

Where possible, all fish were identified to species level and measured (fork length, nearest millimetre) in the field (Nunn *et al.* 2002). When identification was not immediately possible, fish were preserved in 10% formalin and returned to the laboratory for analysis (Pinder 2001). On occasions when excessively large numbers of fish were caught, a random subsample of known percentage of the total catch was either measured in the field or retained for analysis in the laboratory.

6.2.4 Electric fishing

Two different electric fishing methodologies were used during surveys conducted in 2009, 2010 and 2011; these were single pass electric fishing and Point Abundance Sampling by Electro-fishing.

Single pass electric fishing

Each reach was fished semi-quantitatively, with a single pass and no stop nets (Weber *et al.* 2009) over gravels in shallow water depths <1 m. All stunned barbel were caught and measured (fork length) to the nearest mm and returned to the water. Scales were taken from barbel >50 mm for age analysis in the laboratory. All fish were released after recovery.

Percent abundance of habitat features for the sampled areas were recorded at each site. These included:

- channel substrate; % silt (< 0.06 cm), % sand (0.06–0.2 cm), % gravel (0.2–6.3 cm) and % cobbles (6.4–25 cm). Sediment size was either judged by eye (larger sediment) or by touch (fine sediment) (Copp 1993);
- tree roots along the river bank;
- riparian vegetation;
- instream macrophytes;
- woody debris and overhang from trees.

Point Abundance Sampling with Electric fishing (PASE)

Fish were collected from 20 sample points at each site (Bischoff & Freyhof 1999), sample points were chosen by a person bank side deciding on two numbers, the person controlling the anode then converted these numbers into steps and moved in a direction of their choice, without looking at the river channel, sampling downstream to upstream avoiding disturbance to areas not yet sampled (Copp & Garner 1995).

Each sampling point was approached discretely to avoid disturbance (Bischoff & Freyhof 1999). Prior to sampling, the activated anode was swiftly immersed into the water, approximately 1cm off the river bed. The switch was held for 5 seconds (Copp 1993). The dip net was immersed at the same time as the anode, but 50 cm downstream to collect fish affected by the electric field (Copp & Garner 1995). The PASE methodology followed Garner's suggestion that fish missed in the upward sweep of the net were ignored, therefore providing a quantitative, reproducible sample (Copp & Garner 1995). The net was raised as slowly as possible to avoid the backwash of specimens (Copp & Garner 1995).

Once the electric fishing sample was taken, a reference marker was put in place so that semi-quantitative and quantitative environmental variables were measured from within the field of the anode. These were:

- distance from the bank (m);
- water depth (m);
- channel width (m);
- slope of bank (depth divided by the distance from the bank);
- channel substrate; % silt (< 0.06 cm), % sand (0.06–0.2 cm), % gravel (0.2–6.3 cm) and % cobbles (6.4–25 cm). Sediment size was either judged by eye (larger sediment) or by touch (fine sediment) (Copp 1993);
- riparian vegetation (present/absent);
- In stream vegetation rooted in area (%);
- Overhang from in stream vegetation, not rooted in area (%);
- Oxygen concentration;
- Water velocity.

All stunned barbel were caught and measured (fork length to the nearest mm) and returned to the water. Scales were taken from barbel >50 mm for age analysis in the laboratory. All fish were released after recovery.

6.2.5 Hoop netting

Ten hoop nets (Figure 6.5) measuring 1 m in length and 30 cm in diameter were set weekly between 7 July and 1 September at randomly chosen locations for a 24 hour period, secured to the bank and weighted flush to the river bed. Upon removal, all fish were measured (fork length to the nearest mm) and recorded. At the exact position of the net and each half of the river along a transect, the following variables were measured using the DAFOR scale (Dominant = >75%, Abundant = 75-51%, Frequent = 50-26%, Occasional = 25-11% and Rare = 10-1%):

- Channel substrate; clay (< 0.05 μm), % silt (< 0.06 cm), % sand (0.06–0.2 cm), % gravel (0.2–6.3 cm) and % cobbles (6.4–25 cm). Sediment size was either judged by eye (larger sediment) or by touch (fine sediment) (Copp 1993);
- Roots;
- Riparian vegetation;
- Riparian overhang;
- Emergent and overhanging instream macrophytes.

The following information was also recorded:

- turbidity (ppm);
- temperature (°C);
- depth (cm);
- velocity (m sec^{-1});
- land use.

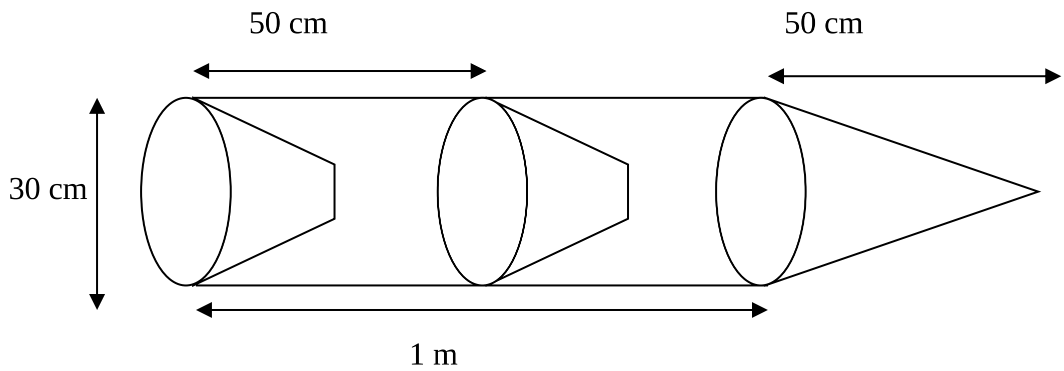


Figure 6.5. Hoop net design and measurements.

6.2.6 Habitat analysis

Brodgar (v 2.7.2) was used to perform Canonical Correlation Analysis (CCA), a multivariate method to describe potential relationships between 0+ to 3+ barbel assemblages and their physical environment on a meso-habitat scale.

6.2.7 Scale aging and Year Class Strength

Samples were collected from barbel >50 mm that were caught during surveys and a sub sample of 100 of 3000 barbel reared at Calverton fish farm, before being stocked into the upper Ouse (January 2012). Scales were removed from each fish from between the dorsal fin and lateral line, using forceps that were cleaned between each fish to avoid cross contamination. A minimum of three scales was taken to safeguard against the collection of regenerated scales. The best scale from each fish was examined using a microfiche projector.

Year Class Strength (YCS) was calculated using the Cowx and Frear (2004) method as it enables data from single surveys over a discrete time period to be used. These data are typically encountered as a result of Environment Agency surveys. YCS is calculated by:

$N_o = N_t/(\exp(-Z_t))$

Where: N_o = Number of fish at time $_t$; N_t = number of fish caught at age $_t$; Z = mortality rate; $_t$ = age of fish in years.

National scale aging data, analysed by the Environment Agency National Fish Laboratory, Brampton, which were used to determine the growth rates illustrated in Chapter 2, along with scales collected from this study were used to compare the growth rate of barbel during the first two years of life. This was done by back calculation of the average length at age, a technique that uses a set of measurements made on a fish at one time to infer it's length at an early time or times (Francis 1990). The method used was Dahl Lee where: $L_n = (S_N\, S_T^{-1})\, L_F$.

6.2.8 Diet analysis

Fish from electric fishing surveys in 2009 and the larval drift study in this chapter, were used for diet analysis. Samples were fixed in 10% formalin and taxonomic identification and length measurements (fork length to the nearest 0.1 mm) were made under an Olympus SZ61 microscope. Species were assigned to a developmental stage according to Pinder (2001). The dissection and diet analysis followed Nunn (2005), where the contents of the entire gastrointestinal tract were removed. Food items were identified to the highest practicable taxonomic level using various keys (e.g. Scourfield & Harding, 1966; Fitter & Manuel, 1986).

Community diversity descriptives including: Shannon-Weiner Diversity index (H'), Peilou's Evenness Index (J'), species richness (S) and total number (N) were used to analysis of gut content of young barbel sampled at each site. Mann Whitney U was then performed on H' to compare differences in feeding selectivity of young barbel between sites.

6.2.9 River temperature

Regression analysis was performed on 275 daily mean in river temperature recordings from a data logger positioned at Odell and air temperature recorded at the nearest station in Cambridge (Figure 6.6). The resulting equation (y = 0.9967 x -1.2425), was used to transform historical air temperature data into river temperature data.

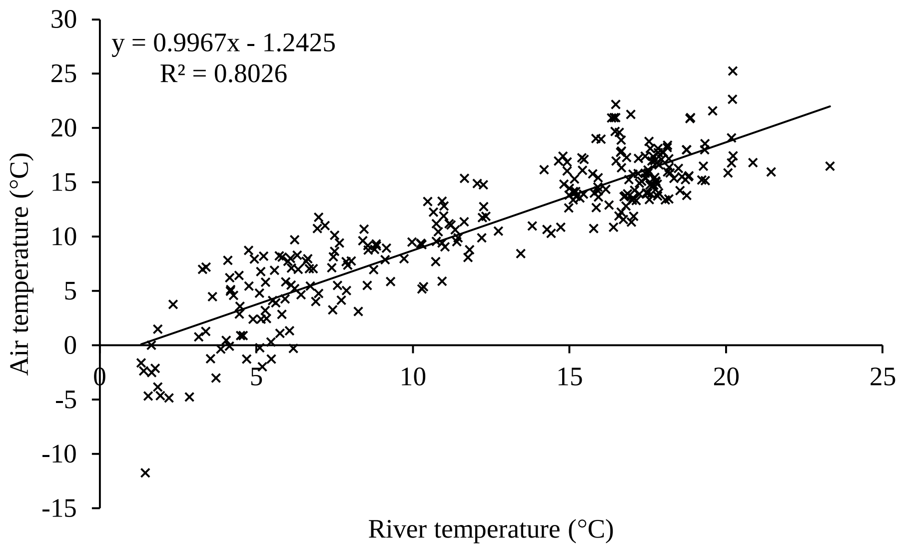


Figure 6.6. Scatter plot and regression analysis of air temperature (°C) and river temperature.

6.2.10 Community diversity

A Bray-Curtis similarity matrix was calculated in the PRIMER (Plymouth Routines In Multivariate Ecological Research) statistical package, using the total number of each fish species caught in the seine netting surveys in 2009. The Bray-Curtis similarity index (C_z) was used to determine similarity patterns between samples and is calculated as:

$$C_z = 2W/(a + b)$$

where W is the sum of the lesser percent abundance value of each taxon common to two samples (including tied values), and a and b are the sums of the percent abundances of taxa in samples a and b, respectively. The index ranges from 0 (no taxa in common) to 1 (identical composition). In addition, variations in the diversity and evenness of fish caught in these surveys were calculated by applying the Shannon-Wiener Diversity Index (*H'*) together with Pielou's Measure of Evenness (J') calculated as:

$$H' = -\Sigma P_i \ln P_i$$

$$J = H'/H'_{max}$$

6.2.11 Flow on spawning gravels

An M9 unit Acoustic Doppler Current Profiler manufactured by Sontek, using differential GPS was pulled along transects of the river channel. This was conducted upstream and downstream of the spawning gravels, as the spawning gravels were too shallow for the equipment to work. The unit had two sets of four transducers of differing frequencies to measure velocity and a single beam to measure depth. The data was then extracted into MatLab which provided the utm co-ordinates and the depth of the bed below the water surface.

6.3 Results

6.3.1 Larval drift

Over the incubation period, temperatures ranged from 16 to 21°C and barbel hatched after 4 days. The number of drifting larvae increased with higher flow (Figure 6.7). Larval and juvenile stages of barbel (n=52), bullhead (*Cottis gobio*) (n=13), chub (*Leuciscus cephalus*) (n=7), spine loach (*Cobitis taenia*) (n=1), bleak (*Alburnus alburnus*) (n=1) minnow (*Phoxinus phoxinus*) (n=1), perch (*Perca fluviatilis*) (n=1) and 4 unidentifiable individuals were caught during the larval drift study. More larvae drifted in the centre of the channel at Aquarium and Harrold Bridge, than at the left or right side of the spawning gravel (Figure 6.8). Flows in this location of the river channel, were between 0.15 and 0.4 m s^{-1} and there was a larger range of flows at either side (Figures 6.9 and 6.10). The drift net at Odell caught the least number of larvae in the centre net and the highest number of individuals in the left net (Figure 6.8). These two positions had the highest flow (0.4 to 0.8 m s^{-1}) whereas the right side of the channel had lower flow (0.0 to 0.4 m s^{-1}) (Figure 6.11).

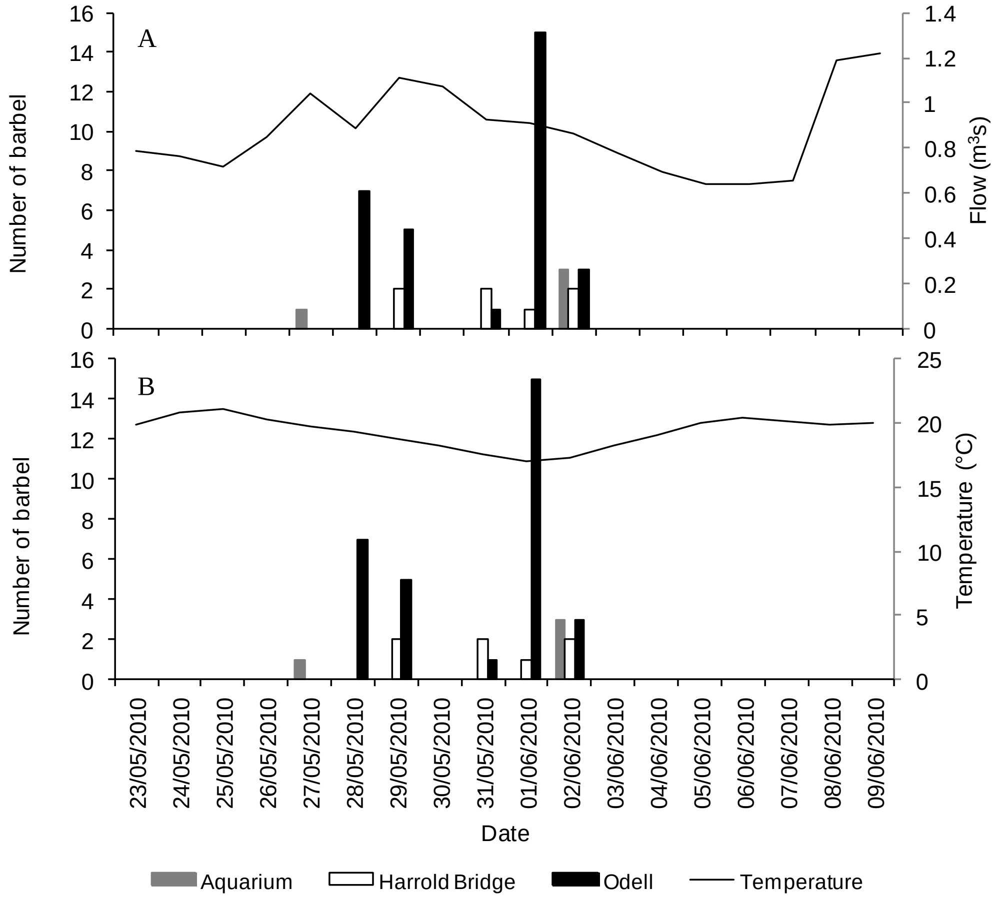


Figure 6.7. Flow (A) and temperature (B) values during the incubation and drift period.

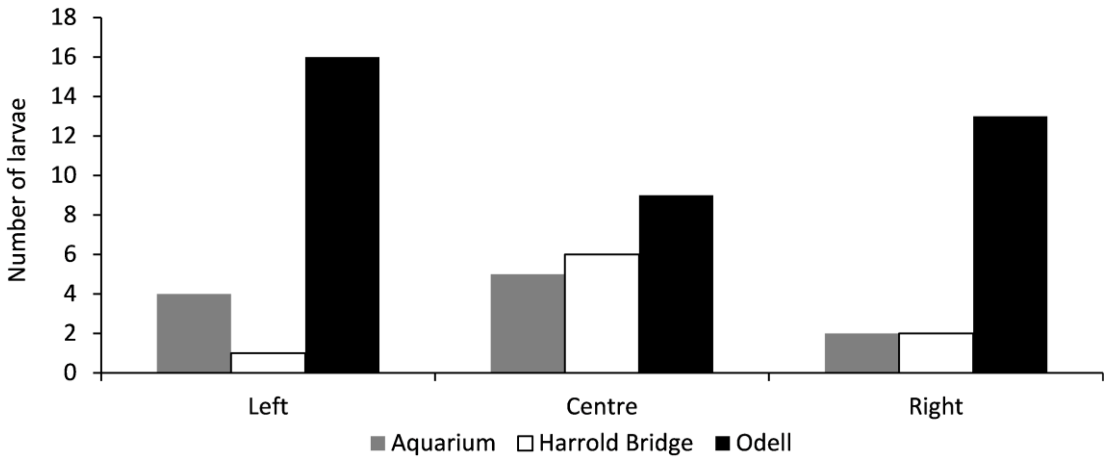


Figure 6.8. Number of barbel larvae caught in each net position at Aquarium, Harrold Bridge and Odell.

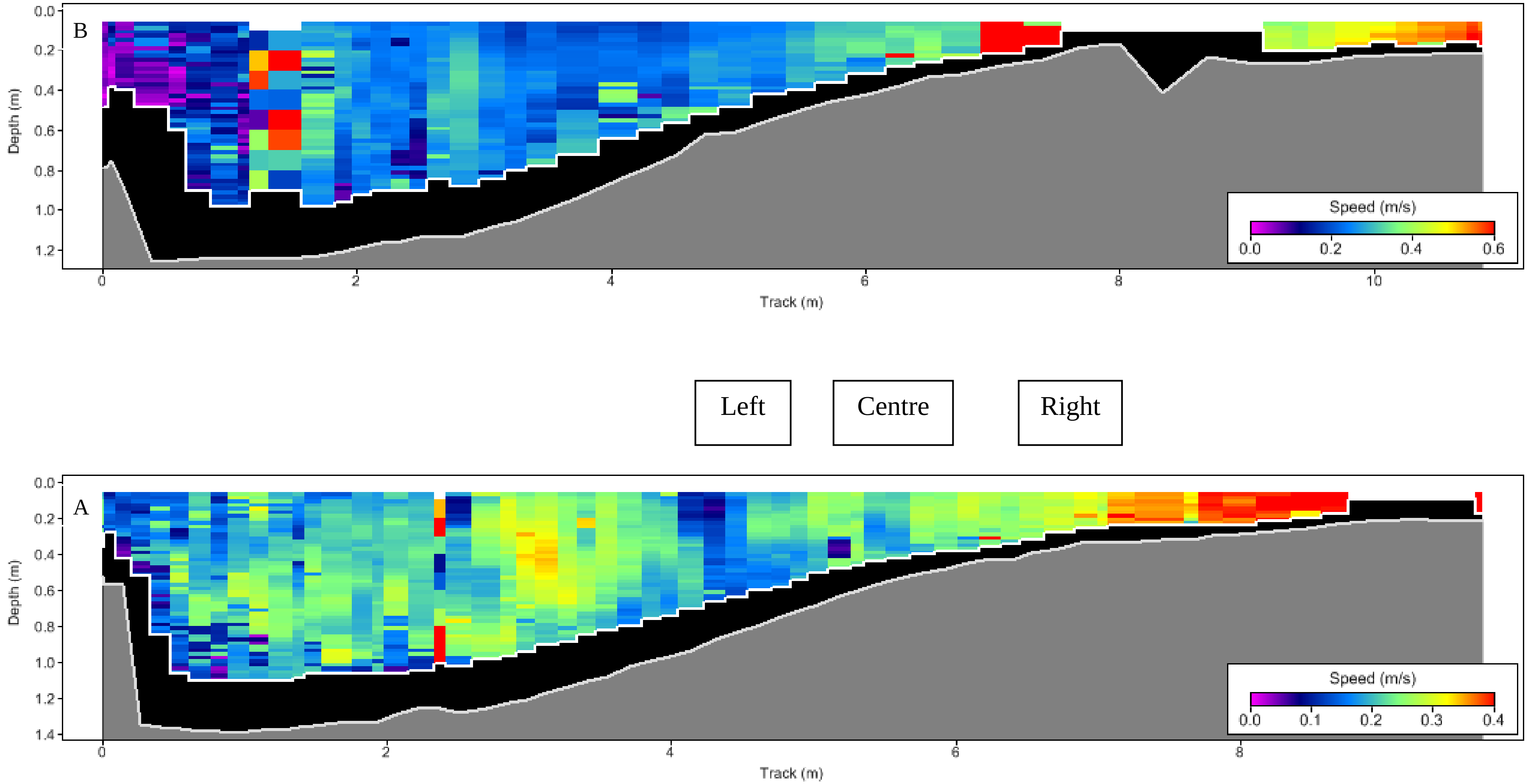


Figure 6.9. Flow rate and depth cross sections directly upstream (A) and downstream (B) of the spawning gravel at Aquarium. Left, centre and right represent the positioning of each larval drift net.

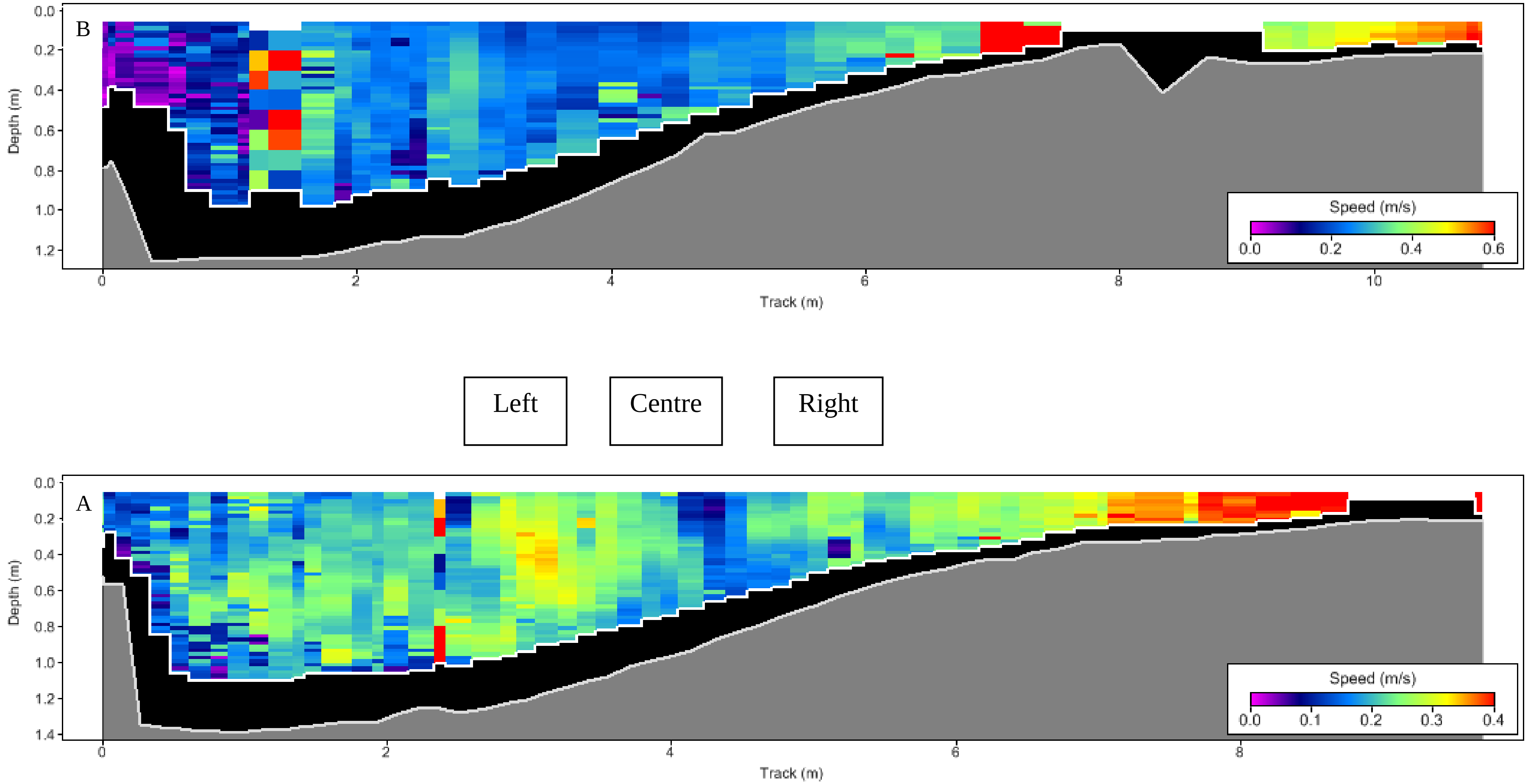


Figure 6.10. Flow rate and depth cross sections directly upstream (A) and downstream (B) of the spawning gravel at Harrold Bridge. Left, centre and right represent the positioning of each larval drift net.

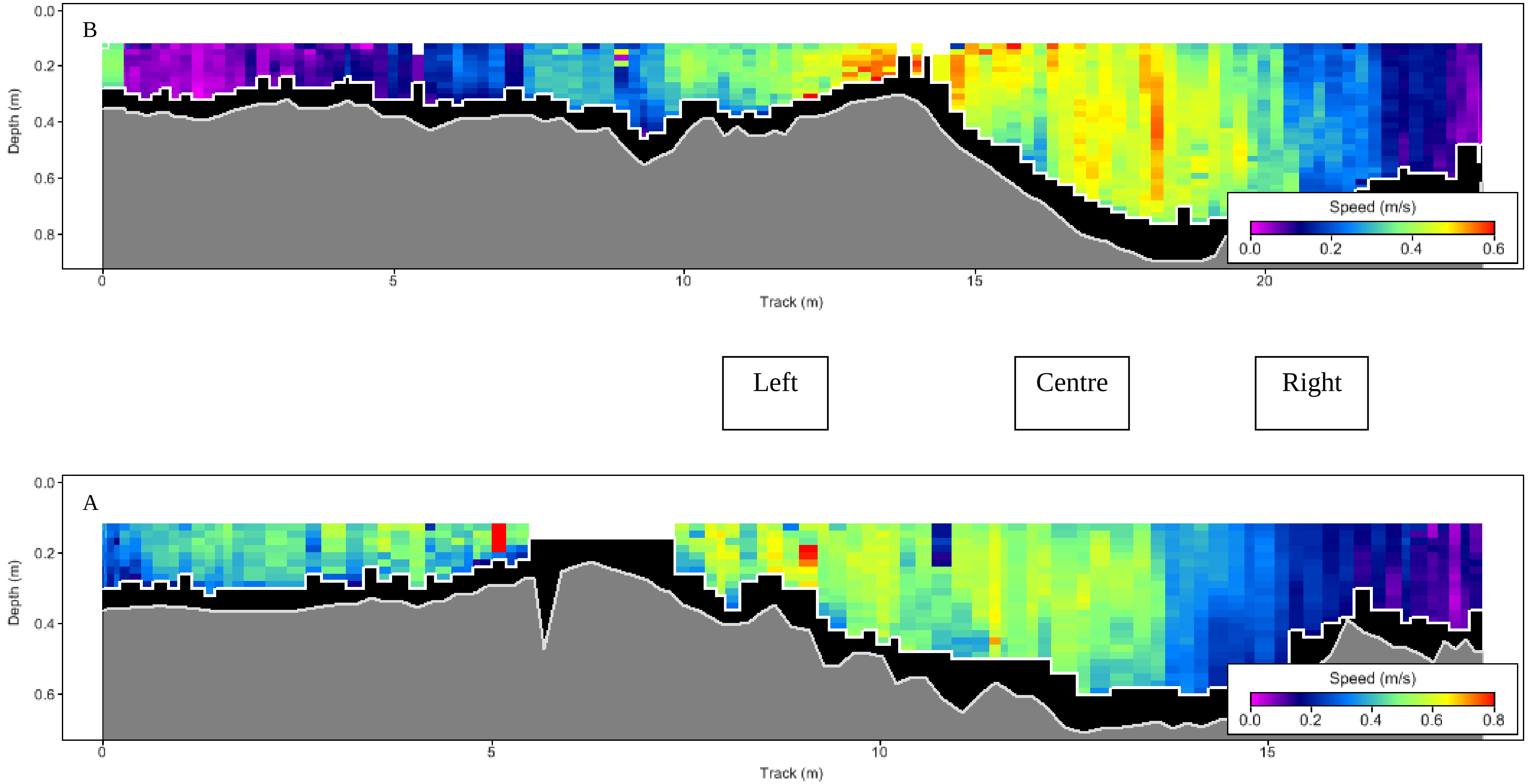


Figure 6.11. Flow rate and depth **c**ross sections directly upstream (A) and downstream (B) of the spawning gravel at Odell. Left, centre and right represent the positioning of each larval drift net.

Of the three sites sampled for larval drift, the most barbel were caught at Odell, followed by Harrold Bridge whilst the least were caught at Aquarium (Figure 6.12). Barbel lengths and larval stages ranged from 10.4 to 14 mm (Figure 6.13) and L2 and L4 (Figure 6.14), with the majority of barbel at L3. No barbel drifted at L1. Most drift occurred at night (~90%) thus is unlikely to be the result of active migration, which Pavlov *et al*. (2008) found to occur in daylight hours. Unidentifiable eggs were found in the drift nets between 24 May and 4 June.

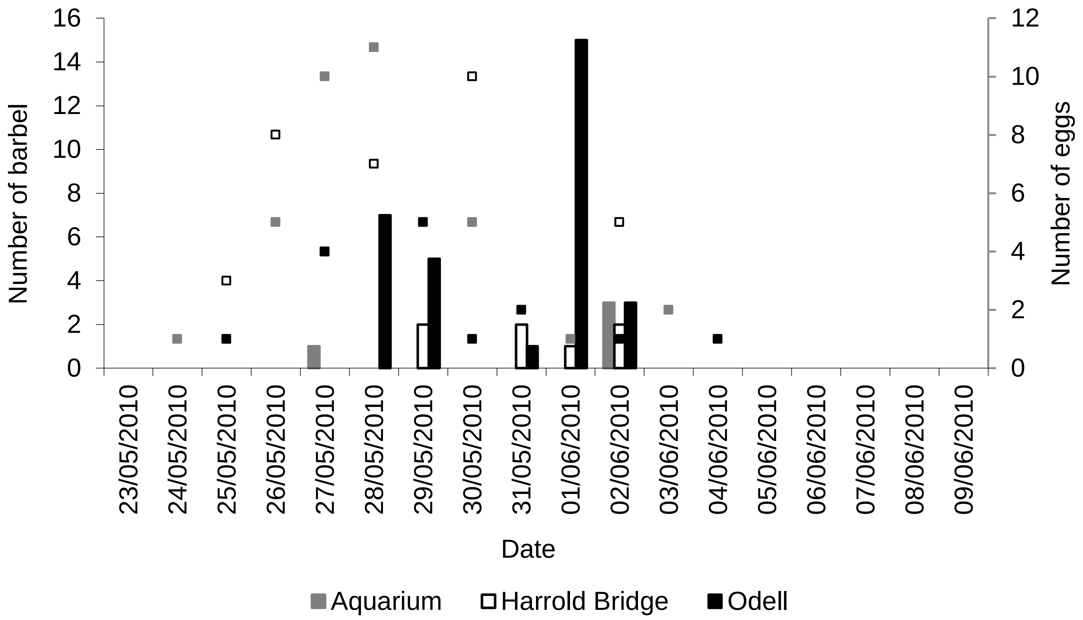


Figure 6.12. Numbers of larval barbel (bars) and eggs (squares) caught at each drift site.

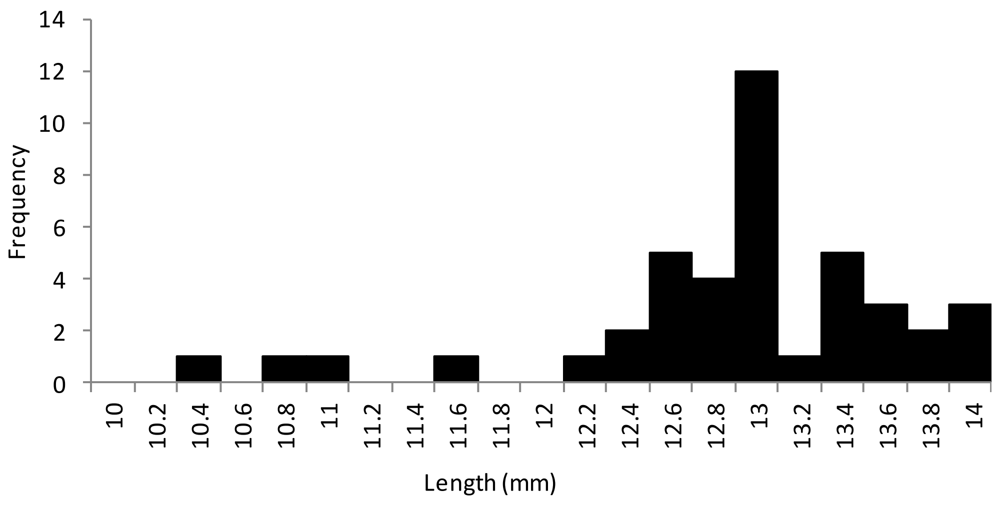


Figure 6.13. Length frequency histogram of larval barbel caught at all three sampling sites.

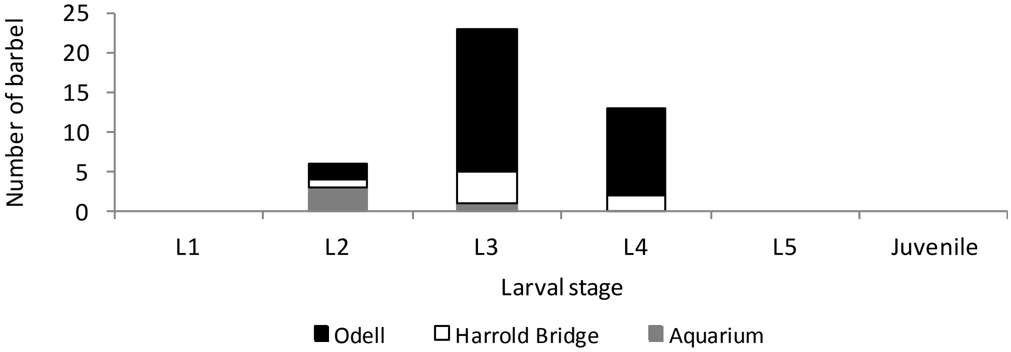


Figure 6.14. Number of barbel in each larval stage as defined by Pinder (2001).

6.3.2 Sampling strategies

In 2009 a total of 13,791 fish were caught by micromesh seine netting (Table 6.2). The most caught species were minnow (n = 4683), roach (*Rutilus rutilius*) (n = 3534) and chub (n = 2600). A total of 7 barbel was caught, 5 from Tempsford and 2 from Biggleswade Common.

Table 6.2. Total number of each species caught throughout the seine netting study, and the range in length for each species.

Species	Total	Length range (mm)
minnow	4683	8 - 58
roach	3534	15 - 189
chub	2600	10 - 79
bleak	969	16 - 199
dace (*Leusiscus leusiscus* (L.))	855	21 - 175
perch	253	21 - 234
common bream	236	19 -374
gudgeon (*Gobio gobio*(L.))	227	19 - 124
bull head	141	8 - 51
3 spine stickleback (*Gasterosteus aculeatus* (L.))	131	16 - 42
spined loach	106	8 - 78
stone loach (*Barbatula barbatula* (L.))	20	18 - 76
barbel	7	27 - 49

Total number of species (S) and total number of individuals (N) caught at each site ranged from 9 to 11 and 369 to 4437 respectively. Aquarium (H'=1.78, J'0.81) and Sharnbrook (H'=1.9, J'=0.78) had the highest species diversity and evenness, Oakley (H'=0.82, J'=0.36) and Willen sluice had the lowest (H'1.22, J'0.51) (Table 6.3). Fish community structure at Willen Sluice was least similar to any of the other sites, whereas the others can all be grouped for similarity. For example: Oakley, Pinchmill and

Haversham weir; Ravenstone Mill and Biggleswade; Aquarium, Harrold Bridge, Sharnbrook, New Cut, Tempsford and St Ives were all similar (Figure 6.15).

Juvenile populations of other lithophilic species such as dace and chub were caught throughout the upper and middle Great Ouse. Within the study stretch, length frequencies of chub ranged from 14 to 44 at Aquarium and 18 to 42 mm at Pinchmill (Figure 6.16). No chub were caught at Aquarium, but those caught at Pinchmill ranged from 22 to 70 mm (Figure 6.17).

Table 6.3. Community diversity descriptives for fish caught by seine netting, 2009.

Sample	**s**	**n**	**d**	**J'**	**H'(loge)**	**1-Lambda'**
Willen sluice	11	4437	1.191	0.5102	1.223	0.6082
Haversham weir	11	1445	1.374	0.6469	1.551	0.7155
Ravenstone Mill	11	1226	1.406	0.619	1.484	0.7261
Aquarium	9	219	1.484	0.8092	1.778	0.7885
Harrold Bridge	10	223	1.664	0.6785	1.562	0.7187
Pinchmill	9	1078	1.146	0.6178	1.358	0.6602
Sharnbrook	11	680	1.533	0.7739	1.856	0.8268
Oakley	10	1856	1.196	0.3568	0.8216	0.3507
New Cut	9	369	1.353	0.6507	1.43	0.716
Biggleswade	11	1223	1.407	0.6568	1.575	0.712
Tempsford	11	485	1.617	0.6331	1.518	0.7328
St Ives	9	601	1.25	0.6887	1.513	0.7392

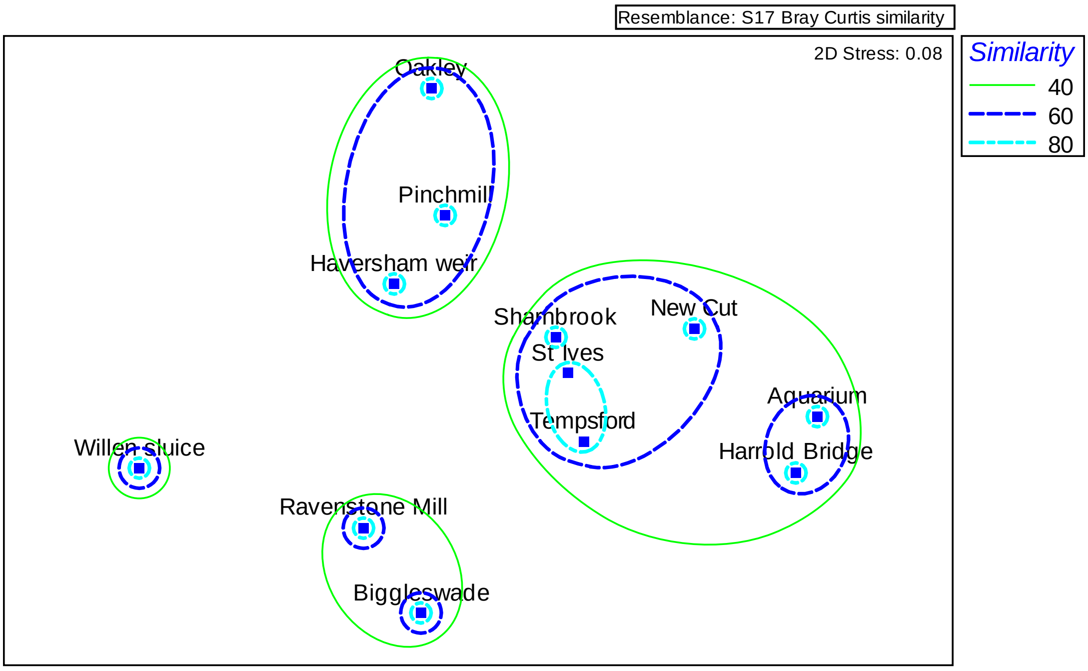


Figure 6.15. MDS showing the similarity of seine netting fish catches between sites, 2009.

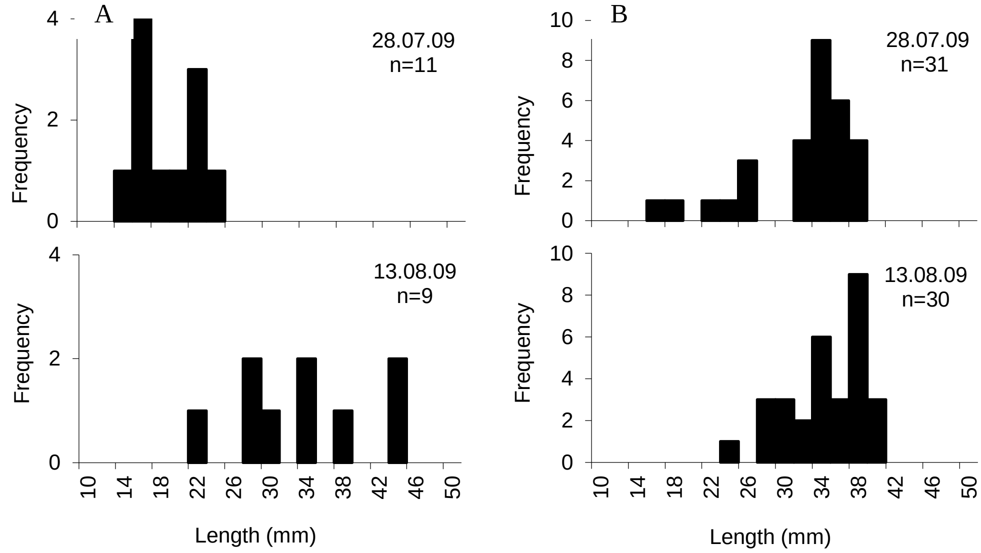


Figure 6.16. Length frequency distribution of chub caught by seine netting, Aquarium (A) and Pinchmill (B) 2009.

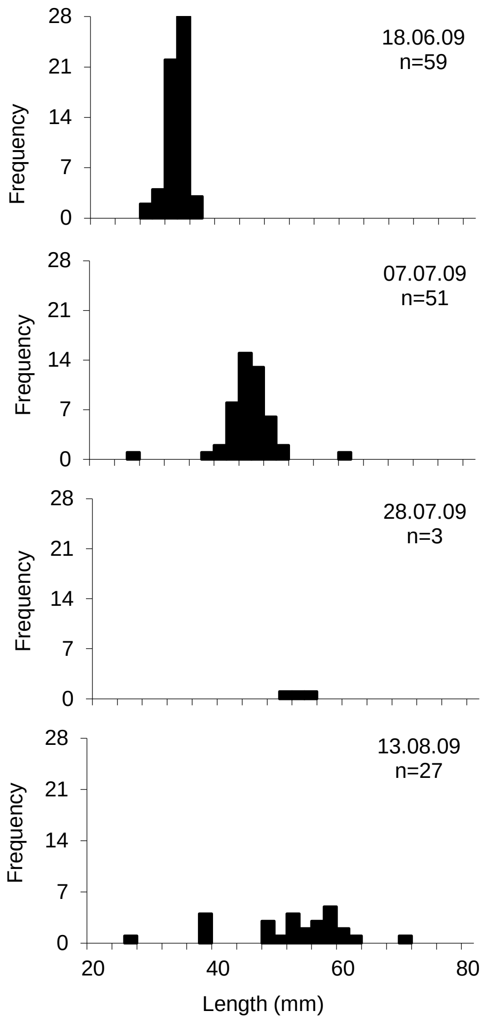


Figure 6.17. Length frequency distribution of chub caught by seine netting, Pinchmill 2009.

Single pass electric fishing in 2009, 2010 and 2011 once at two to five sites (Figure 6.18) between Harrold weirs and Sharnbrook weir, caught at total of 58, 62 and 20 barbel respectively, whereas PASE and hoop netting were not successful in capturing any barbel, but other species were caught, including crayfish (Figure 6.19). Of the fish species caught, minnow were the most abundant, benthic species including spine loach, stone loach, gudgeon and bullhead were also caught. Higher numbers of crayfish were caught compared to fish, even though the traps were unbaited (Figure 6.19).

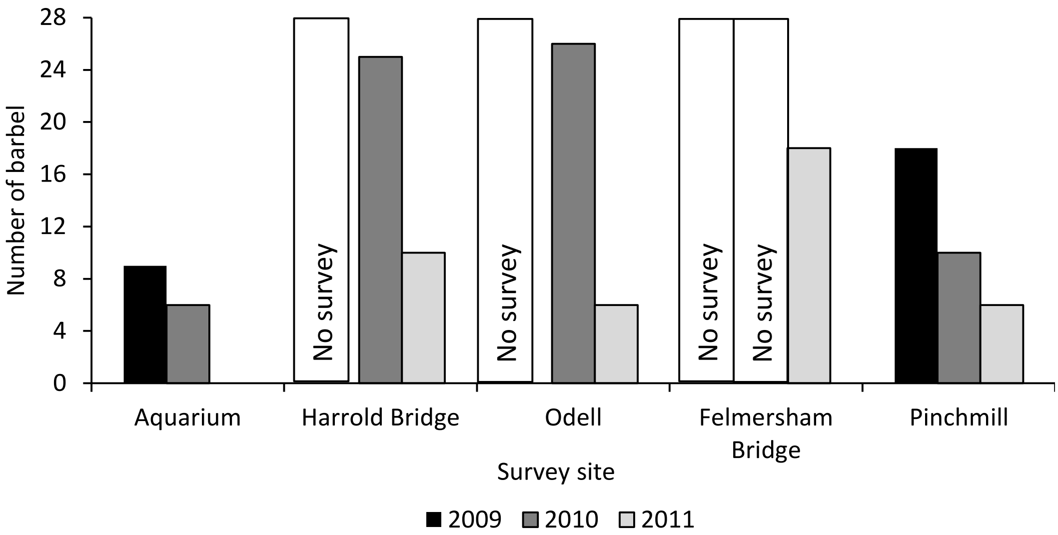


Figure 6.18. Electric fishing catch of young barbel at each site between Aquarium and Sharnbrook weir.

In each site, in each year, samples were heavily dominated by minnow. At Aquarium, diversity and Evenness were highest in 2009 (H'=1.68, J'=0.25) when most fish were caught (n=90) at which time bullhead barbel and pike had a high percentage abundance. In 2010 with the lower diversity (H'=1.06, J'=0.64), fewer fish were caught and stone loach and bullhead had highest percentage abundance (Figure 6.20 to 6.22). At Harrold Bridge diversity and evenness increased between 2010 and 2011 (H'=1.33, J'=0.62 and H'=1.47, J'=0.37). The number of species had remained the same (s=9) but the number of fish caught had increased (2010 n=35; 2011 n=117), with a high abundance of dace, barbel and bullhead (Figures 6.21 and Figure 6.22). At Odell, in 2011, diversity and evenness had increased compared with the previous year (2010: H'=1.0, J'=0.45; 2011: H'1.57, J'0.34), species diversity and evenness also increased between years (s=7 to s=9) but total number of fish caught was lower (n=218 to n=180). More roach and dace were caught in 2011 than in 2010 (Figures 6.21 and Figure 6.22).

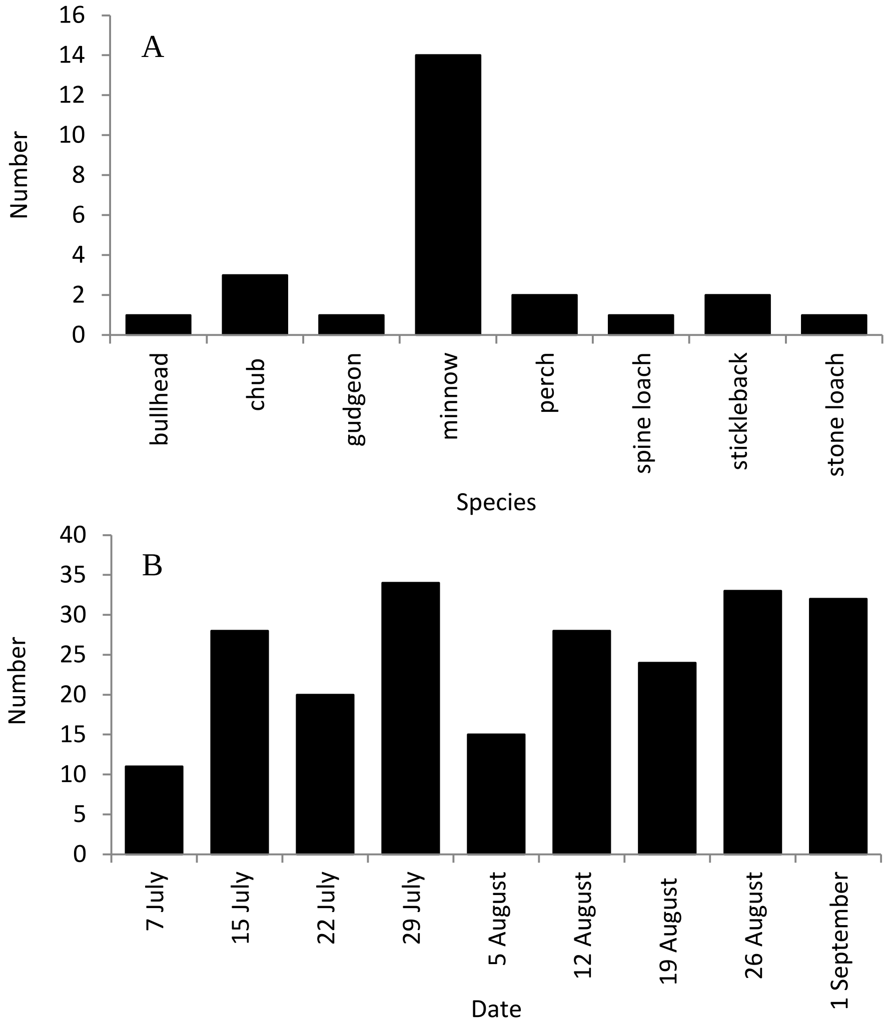


Figure 6.19. A) Number of each fish species caught and B) number of crayfish caught each week, using the hoop netting methodology.

At Pinchmill diversity and evenness increased between 2009 and 2010, but were reduced in 2011 (2009: H'=1.44, J'=0.34; 2010: H'=1.56, J'=0.21; 2011: H'=1.06, J'=1.42). Species diversity followed a similar pattern (2009: s=9; 2010 s=10; 2011: s=8), but total numbers were higher in 2009 and 2011 than in 2010 (2009: n=214; 2010 n=79; 2011: n=84) bullhead, stoneloach and dace had high percentage abundance in each year (Figure 6.20 to 6.22). There were no significant difference in species diversity between sites (Aquarium and Harrold Bridge, t=-0.09, df=1, P>0.05; Aquarium and Odell, t=0.20, df=2, P>0.05; Aquarium and Pinchmill, t=0.04, df=1, P>0.05; Harrold Bridge and Odell, t=0.39, df=1, P>0.05; Harrold Bridge and Pinchmill t=0.28, df=3, P>0.0; Odell and Pinchmill, t=-0.21, df=2, P>0.05).

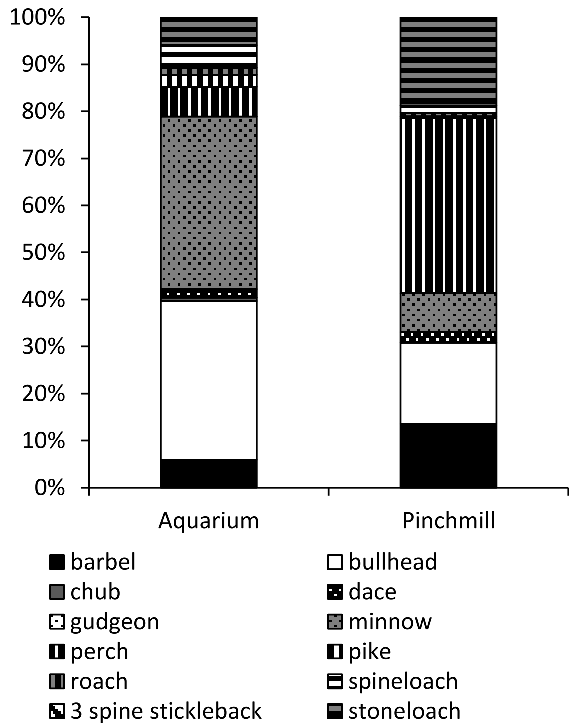


Figure 6.20. Percentage abundance of species caught using the single pass electric fishing technique in 2009.

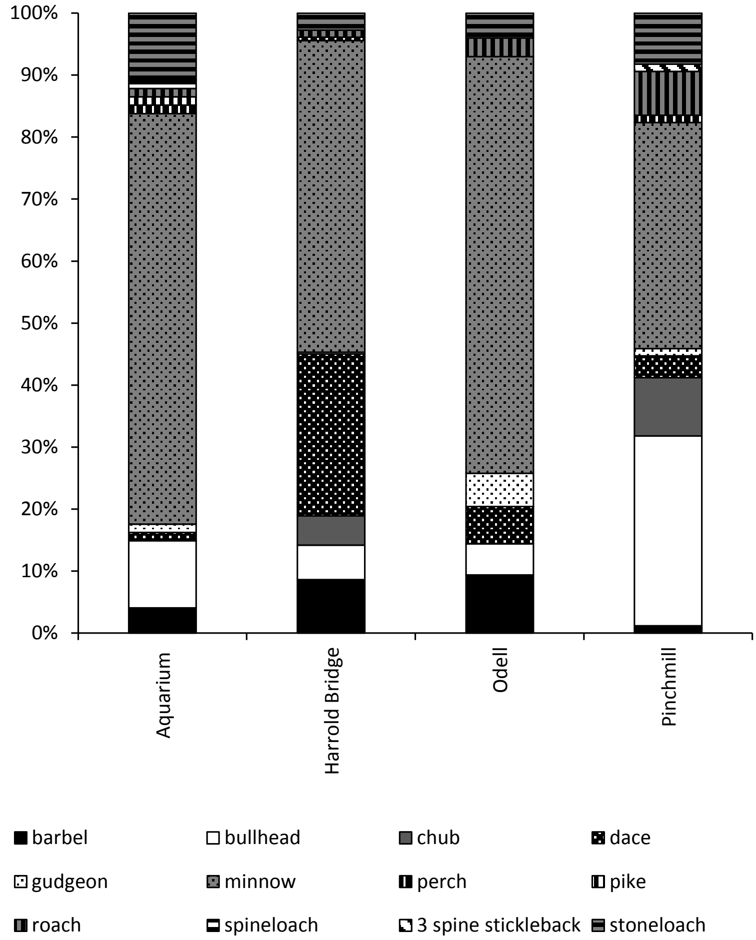


Figure 6.21. Percentage abundance of species caught by single pass electric fishing technique in 2010.

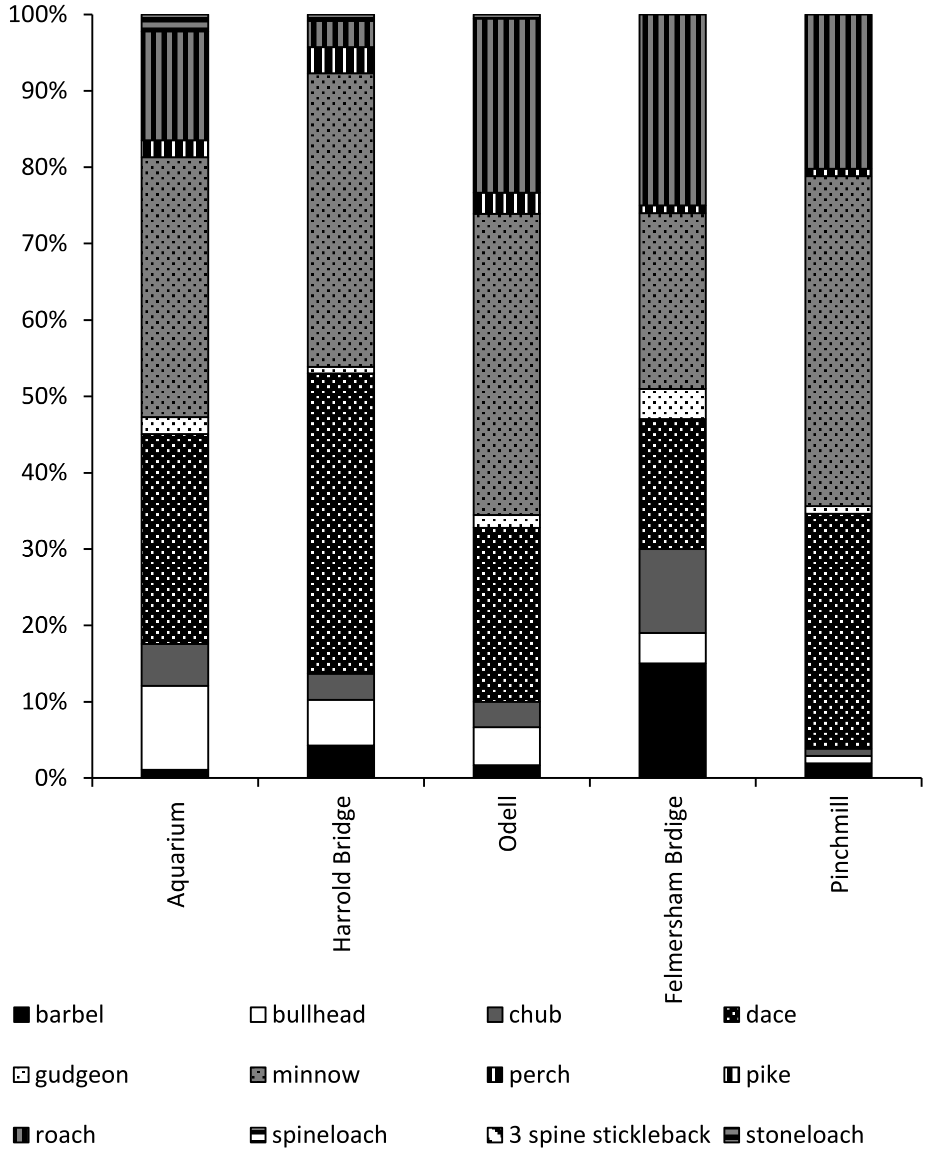


Figure 6.22. Percentage abundance of species caught using the single pass electric fishing technique in 2011.

6.3.3 Population structure and Year Class Strength

Pooled length frequency data of all barbel caught using electric fishing between 2009 and 2010 ranged from 52 to 263 mm, representative of 0+, 1+ and 2+ barbel (Figure 6.23). Progression of year classes can be seen between 2009, 2010 and 2011. The length frequency distributions were similar between Harrold Bridge, Odell and Felmersham. Aquarium had the fewest barbel and Pinchmill had the smallest size range (Figure 6.24). YCS information based on data collected in 2011 suggest that there is no year class from 2009, but this year class was present in 2010 (Figure 6.25).

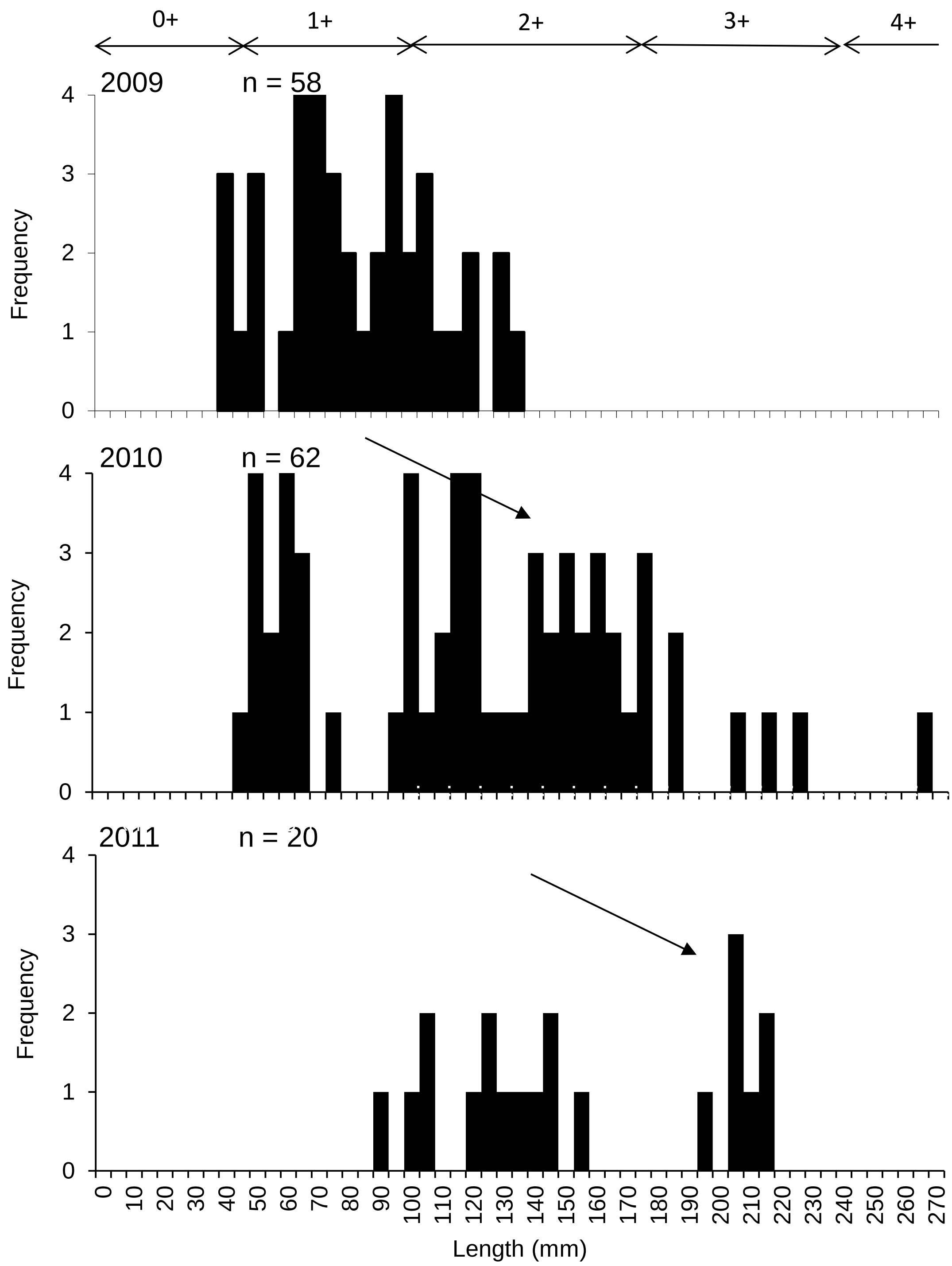


Figure 6.23. Length frequency histograms of barbel caught in 2009, 2010 and 2011 using the single pass electric fishing technique. Length at age arrows resulting from scale data obtained from these surveys. Arrows indicate average length at age.

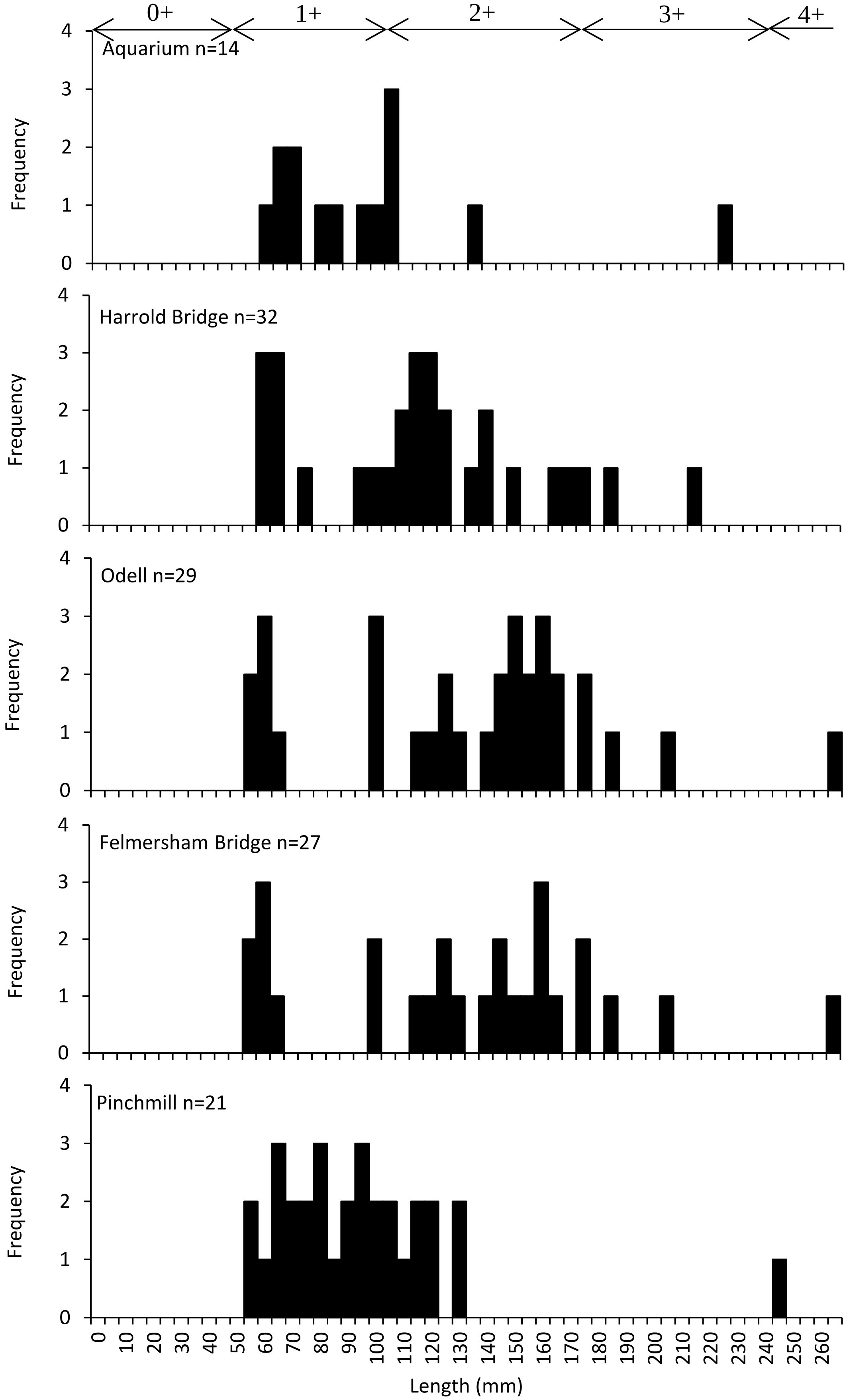


Figure 6.24. Length frequency distribution of young barbel caught using the single pass electric fishing technique at each site between Aquarium and Sharnbrook from 2009 to 2011. Arrows indicate average length at age.

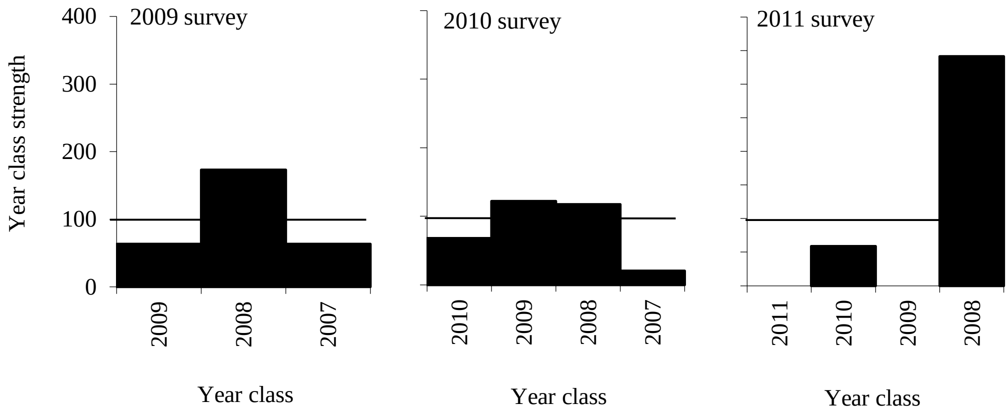


Figure 6.25. YCS based on surveys targeting young barbel between 2009 and 2011.

6.3.4 Habitat use

Pooled data from all years electric fishing sampling revealed that 0+ barbel have a high affinity to tree cover and 3+ barbel were found in areas with a greater abundance of in stream macrophytes (Figure 6.26).

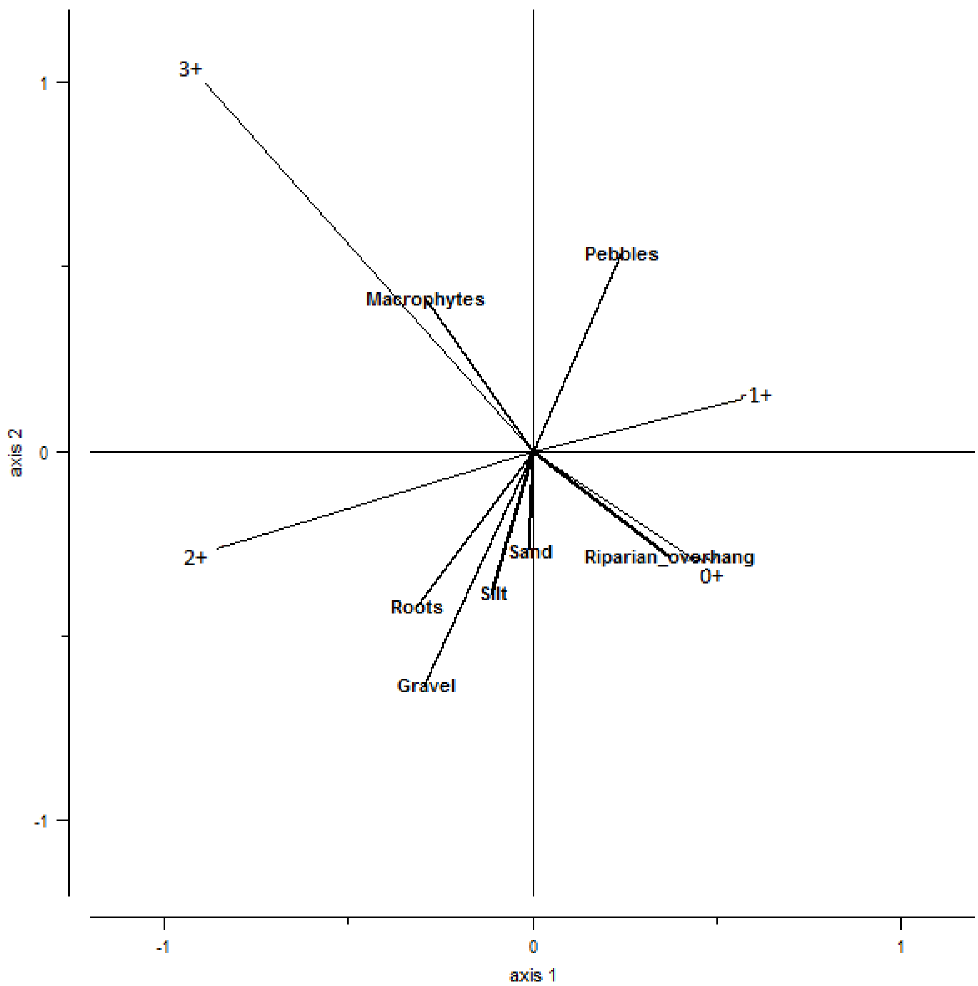


Figure 6.26. Canonical Correspondence Analysis for meso-habitat use for young barbel of different ages.

6.3.5 Diet analysis

There was no prey found in the gut of all L2 barbel sampled. Mean percentage abundance of prey altered at each barbel developmental stage. Individuals at L3, L4 and juvenile stages showed a progression of preference from *Closterium* and daphniidae at L3, to include cyclopidae at L4 (Figure 6.27). Prey of juvenile barbel were simuliidae larvae, and Chydoridae (Alona).

There were differences in feeding selectivity between barbel caught in the morning and those caught in the evening (Figure 6.28). Afternoon samples, which were collected during daylight hours, only consumed *Closterium*. Barbel caught in the morning samples, which had presumably been feeding at night, consumed *Closterium*, *Daphniidae*, chironomid larvae and unidentified eggs.

The highest species richness of prey was recorded in barbel from Tempsford (S=5), Aquaium, Pinchmill and Odell (S=4) (Table 6.4). Prey species diversity was highest at Odell (H'=1.213, J' 0.875) and Biggleswade (H'=0.709, J' 0.645) whilst lowest at Harrold Bridge (H'=0) and Newport Pagenell (H'=0.055, J' 0.079). Different mean percentage abundance of prey items consumed, were found at each site (Figure 6.29). Barbel from Harrold and Odell on the River Great Ouse had high mean percent abundance of *Closterium*, Daphniidae and Cyclopidae, owing to the higher numbers of L3 and L4 barbel caught at this site (Figure 6.7). Whereas barbel from Aquarium and Pinchmill on the Great Ouse, Biggleswade and Tempsford on the Ivel had higher percentage abundances of Simuliidae larvae and Chydoridae, due to the higher numbers of juvenile barbel sampled from these sites. These differences were not significant (Table 6.4).

There was no obvious progression of feeding preference over a seven day sampling period (Figure 6.30), but further confirmation that the increase in the variety of prey consumed as the species develops during the larval stages was obtained. Larval barbel caught in the evening also had a more diverse diet than those caught in the morning.

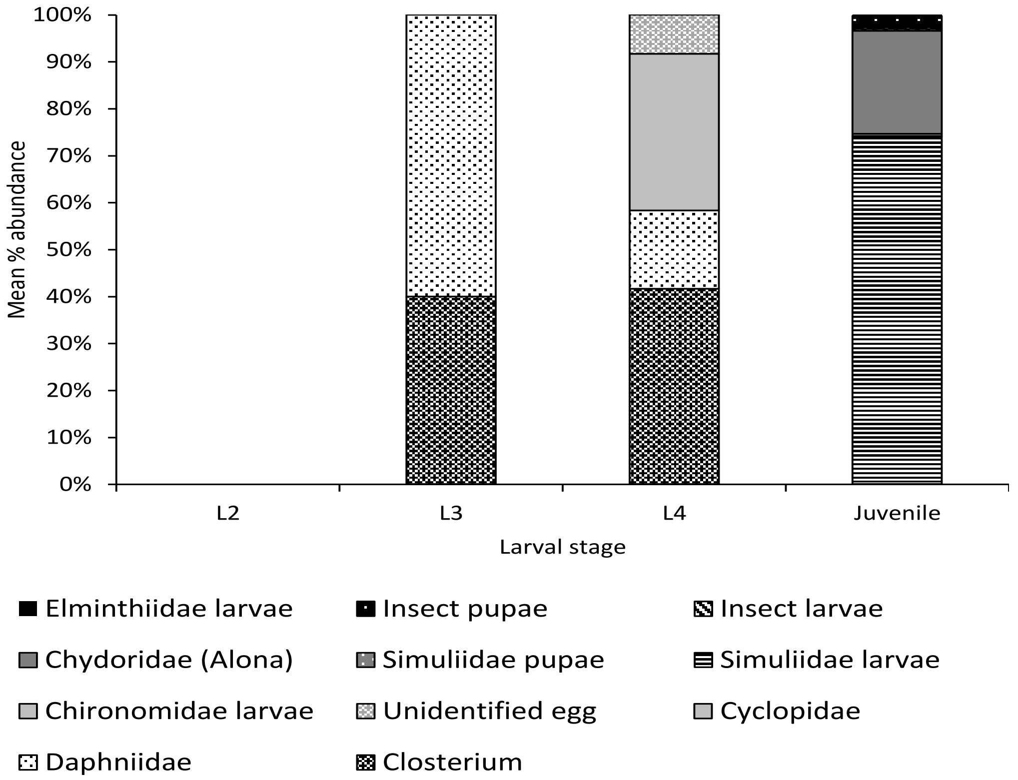


Figure 6.27. Mean percent abundance of each prey item by each larval stage.

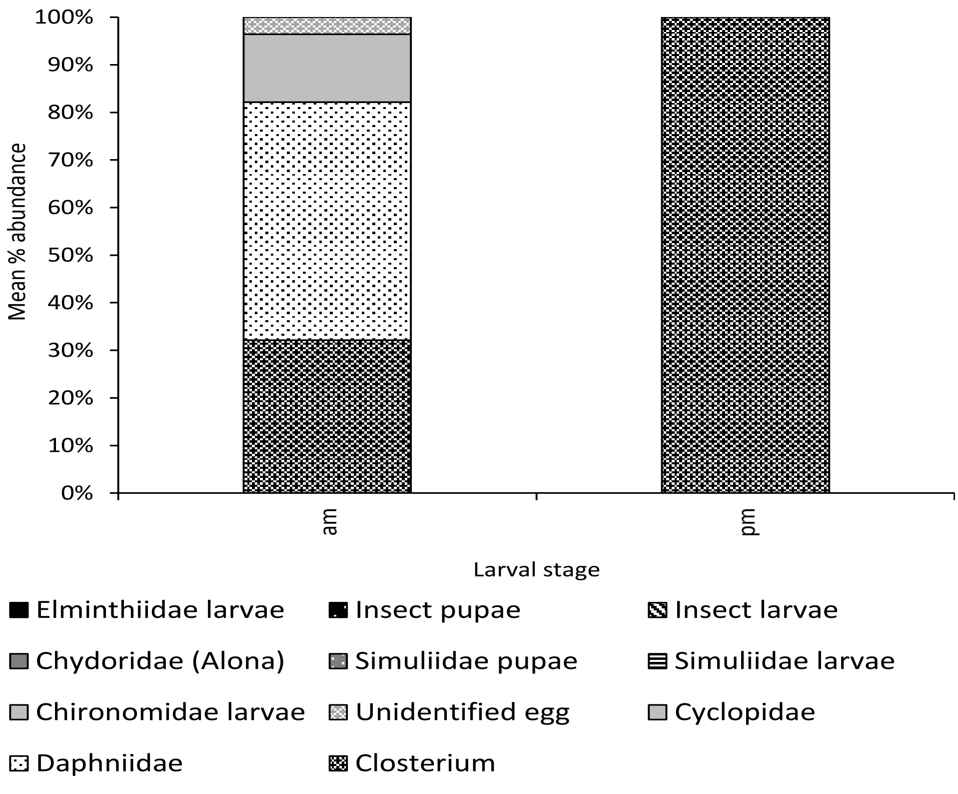


Figure 6.28. Mean percent abundance of each prey item in the am and pm samples.

Table 6.4. Shannon-Weiner Diversity index (H'), Pielou's Evenness index (J'), Species richness (S) and total number (N) analysis of gut content of young barbel sampled at each site.

Site	N	S	H'	J'
Harrold Bridge	6	1	0	
Newport Pagnell	102	2	0.055	0.079
Aquarium	102	4	0.165	0.119
Tempsford	133	5	0.244	0.152
Pinchmill	279	4	0.262	0.189
Biggleswade	36	3	0.709	0.645
Odell	8	4	1.213	0.875

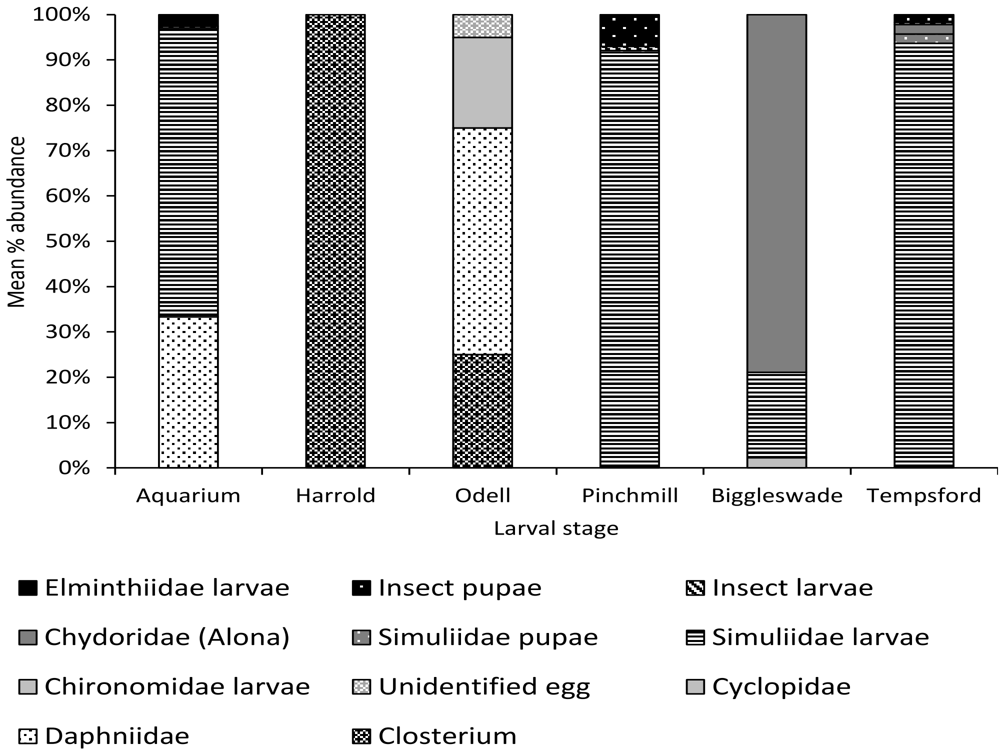


Figure 6.29. Mean percent abundance of each prey item by larval and juvenile barbel at each site.

Table 6.5. Mann Whitney U Test results comparing differences in feeding selectivity of young barbel between sites.

	Aquarium	Biggleswade	Harrold Bridge	Newport Pagnell	Odell	Pinchmill	Tempsford
Aquarium		Z=0.23 U=56.5 P>0.05	Z=0.985 U=45 P>0.05	Z=0.6 U=51 P>0.05	Z=-0.03 U=59.5 P>0.05	Z=-0.3 U=55.5 P>0.05	Z=0.37 U=59.5 P>0.05
Biggleswade			Z=0.72 U=49 P>0.05	Z=0.29 U=55.5 P>0.05	Z=-0.13 U=58 P>0.05	Z=-0.4 U=54 P>0.05	Z=-0.59 U=51 P>0.05
Harrold Bridge				Z=-0.33 U=55 P>0.05	Z=-0.91 U=46 P>0.05	Z=-1.05 U=44 P>0.05	Z=1.31 U=40 P>0.05
Newport Pagnell					Z=-0.62 U=50.5 P>0.05	Z=-0.76 U=48.5 P>0.05	Z=-1.05 U=44 P>0.05
Odell						Z=-0.3 U=55.5 P>0.05	Z=-0.4 U=54 P>0.05
Pinchmill							Z=0 U=60 P>0.05

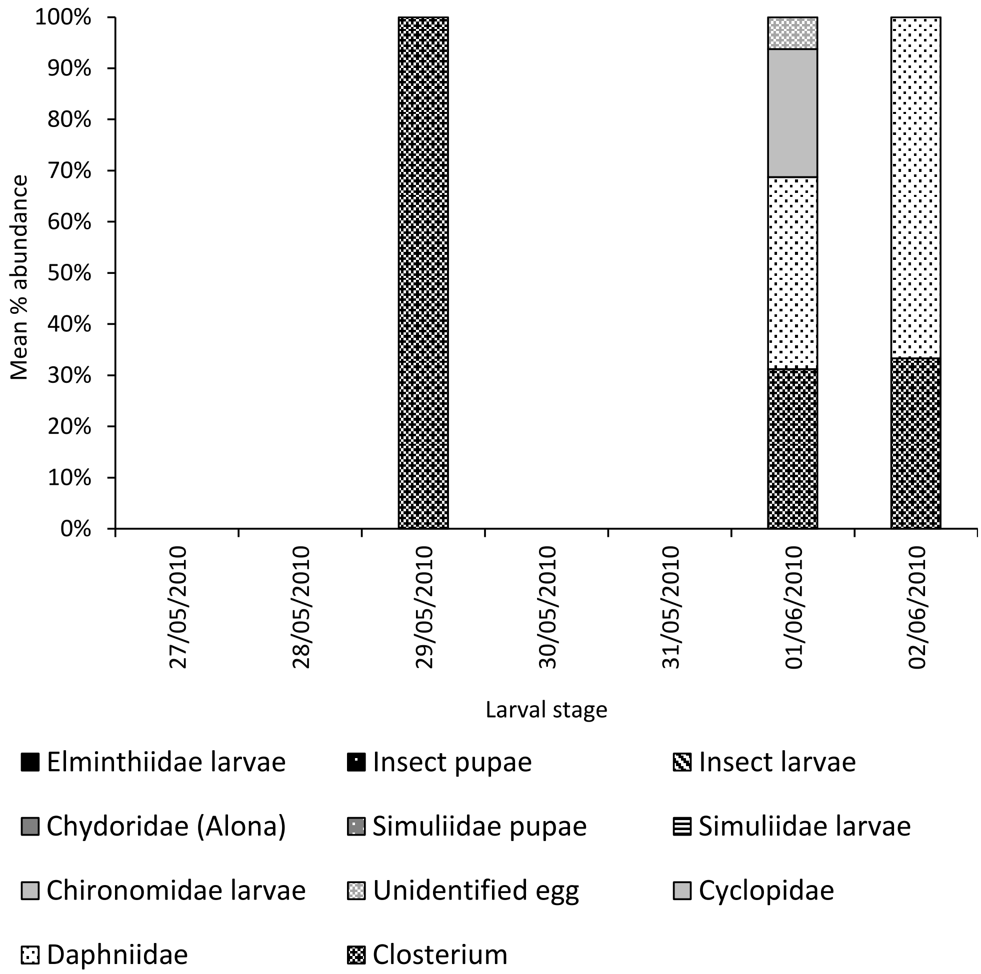


Figure 6.30. Mean percent abundance of each prey item over seven consecutive days.

6.3.6 Growth of young barbel

Based on the first two years growth from all scale readings available, on average, barbel from Calverton had slower growth than national, Anglian, River Great Ouse and barbel from the study stretch. The River Great Ouse had a similar growth rate to the combined Anglian region growth rate, whereas the growth of barbel in the study stretch was between that of the Great Ouse and Calverton Fish Farm (Figure 6.31). This could indicate the presence of stocked and naturally recruited barbel.

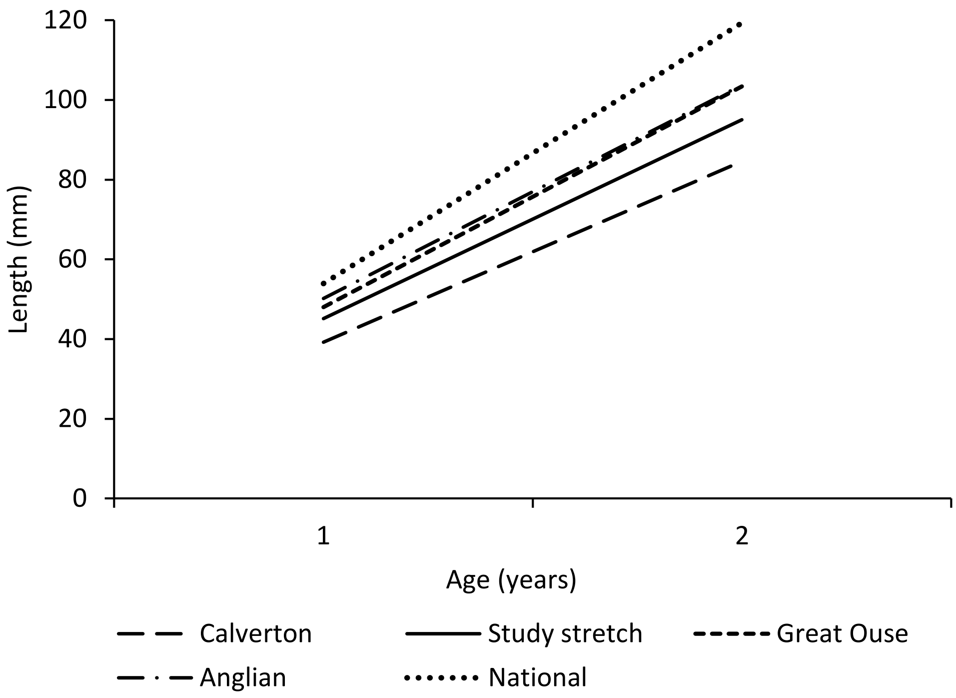


Figure 6.31. Comparison of the first two years of growth in barbel from Calverton fish farm, the study reach, River Great Ouse, Anglian Region and nationally.

Barbel from Aquarium and Pinchmill have similar length at age 1, whilst those from Odell and Calverton had similar length at age 1 (Figure 6.32). Barbel from Pinchmill and Calverton, Felmersham and Harrold Country Park, Aquarium and Odell have a similar Laength at age. Annual differences in length at age during at year one and year two have been identified (Figure 6.33). Length at age decreased from 1993 to 1995, from 1996 to 1998 and increased from 2007 to 2009. Several authors (Mills & Mann 1985; Mann 1995; Cowx 2001; Nunn *et al* 2003; 2007) have indicated that growth at the end of the first year is critical for overwinter survival and is driven by temperature. According to Philippart and Vranken (1983) barbel has an affinity for high-temperature with optimal growing temperatures between 14–23 ˚C. Below 13.5˚C, 0+ barbel stop growing (Baras & Philippart 1999). In the Great Ouse, this is usually between March and September. Cumulative discharge days >13.5˚C (Figure 6.34 and Figure 6.35) had a significant effect on the growth of barbel in the first year ($t=-16.9$, $df=12$, $P<0.01$) and second year ($t=-8.0$, $df=28$, $P<0.01$).

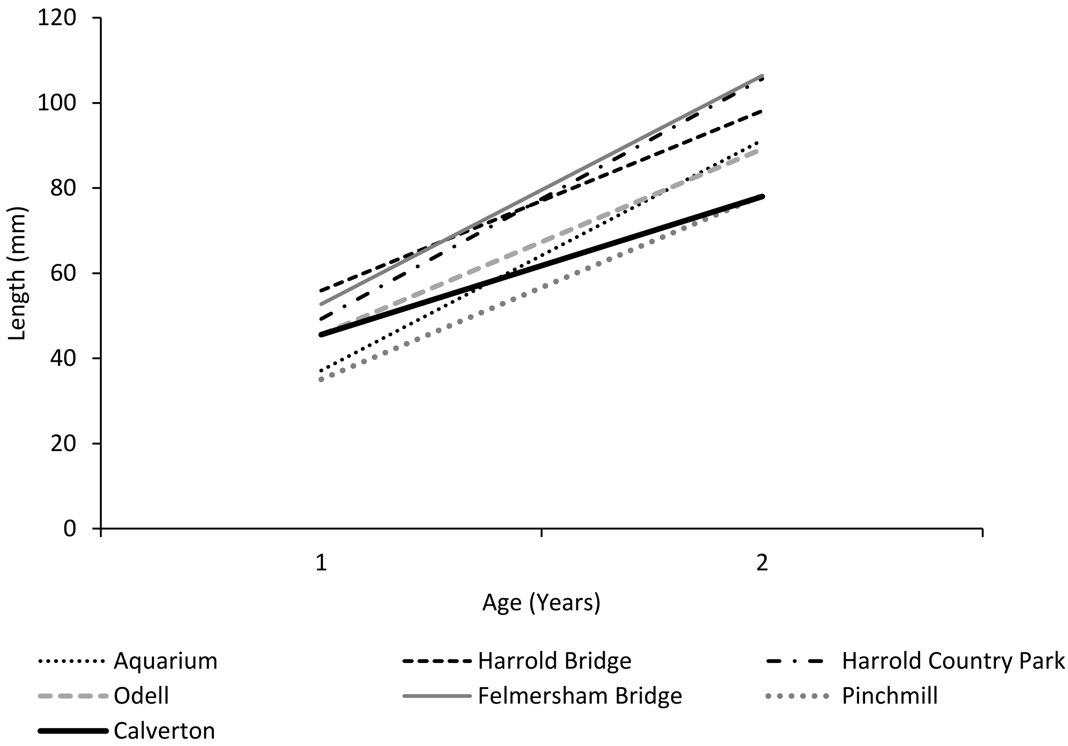


Figure 6.32. Comparison of the first two years of growth in barbel from each study site between Aquarium and Sharnbrook and known stocked fish from Calverton.

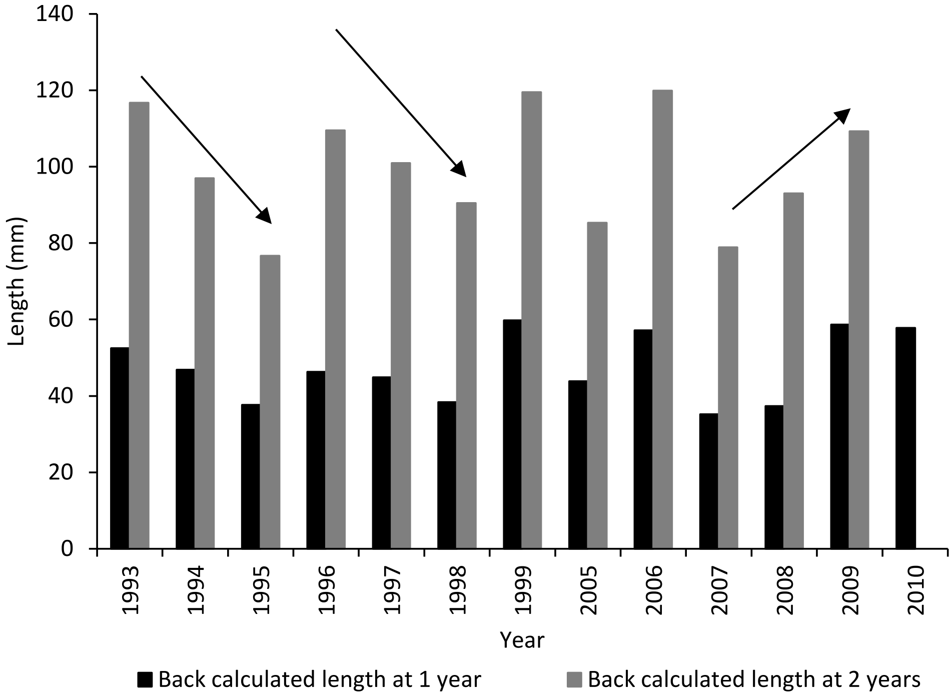


Figure 6.33. Annual changes in first and second year growth rates of barbel caught between Aquarium and Sharnbrook. Arrows indicate decrease and increase in growth in the first and second year.

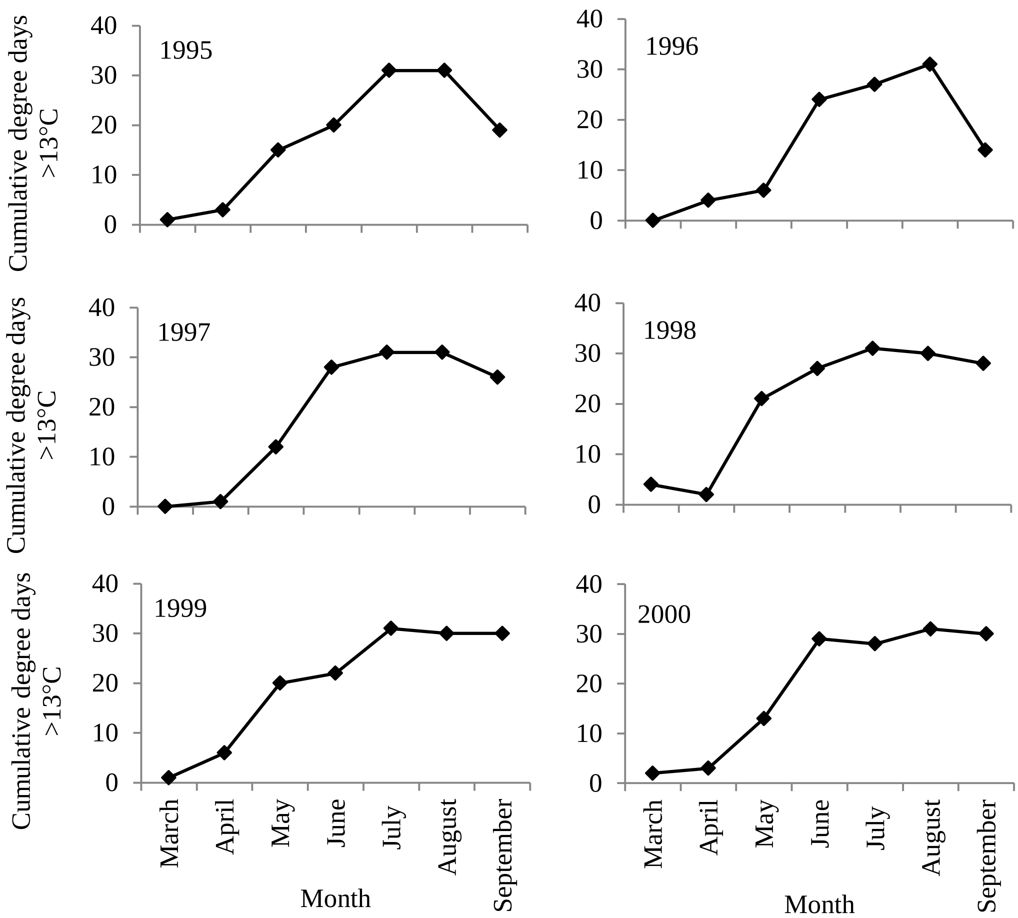


Figure 6.34. Cumulative degree days above 13.5°C in the Great Ouse between 1995 and 2000.

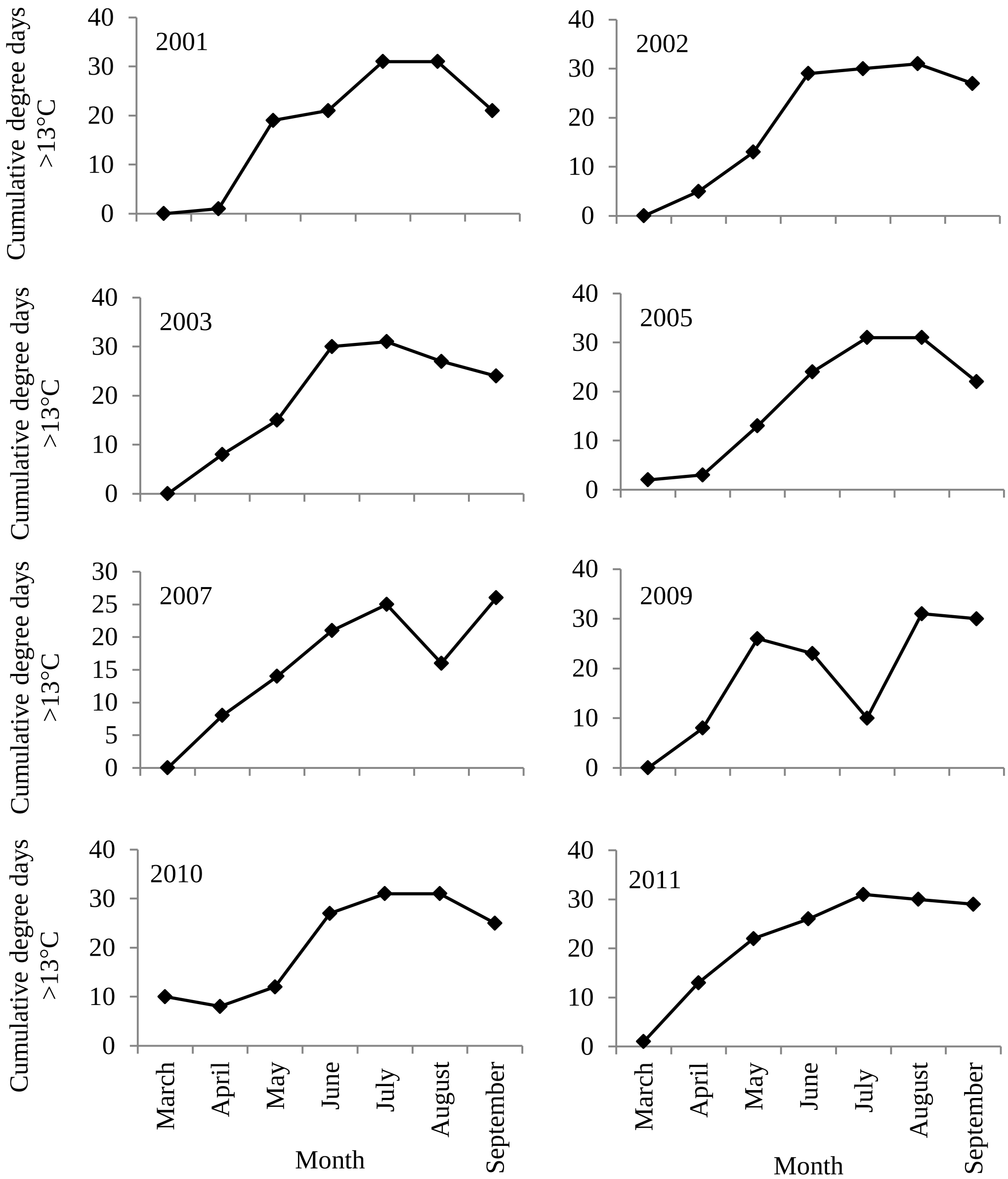


Figure 6.35. Cumulative degree days above 13.5°C in the River Great Ouse between 2001 and 2011. Data for 2004, 2006 and 2008 were unavailable.

6.4 Discussion

Larval drift

The presence of barbel larvae indicated the species spawn and produce viable embryos in the study section. It also confirmed that the origins of larval or juvenile fish are from the Great Ouse (Humphries & Lake 2000). The downstream movement of aquatic species has been the focus of research for many decades (Carter *et al.* 1986; Churchill & Finucane 1991; Scheidegger & Bain 1995; Humphries & Lake 2000; Humphries *et al.* 2002; Reichard *et al.* 2004; Peterka *et al.* 2004; Reichard *et al.* 2007; Pavlov *et al.* 2008), the unidirectional movement facilitated by water current that plays an important role in the dynamics of many species populations (Reichard & Jurajda 2007). Drift in fishes typically occurs during the early developmental stages; free embryos, larvae and juveniles (Brown & Armstrong 1985; Pavlov 1994). The process of larval drift is important in the early ontonogy of many riverine fish species (Penaz *et al*. 1992) as this mechanism is linked to growth, survivorship and recruitment success (Copp *et al*. 2002). As barbel is a lithophilus and rheophilous species, the role of drifting to more suitable nursery habitats is important.

Over the incubation period, temperatures ranged from 16 to 21°C and barbel hatched after 4 days, supporting the findings of Mann (1996). Reichard *et al*. (2004) reported a typical seasonal peak of drift abundance in the first week after hatching This study found that drifting only occurred for seven days after the onset, peaking on the sixth. No larvae were caught for the first 5 days and the last 7 of sampling, which suggests that the nets were placed at the correct time.

Cyprinid species have different tendencies to drift (Reichar *et al*. 2002a), and the assignment of captured larvae to developmental stages allowed the identification of ontologically preferred drift stages of barbel (Zitek *et al.* 2004; Reichard & Jurajda 2007). Zitek *et al*. (2004) noted that a high proportion of cyprinid larvae drift at larval stage L1, pointing strongly to the ecological importance of drift to the distribution of fish to alternate habitats. This study found that no barbel drifted at L1 and that most of the barbel caught were at larval stages L3, with a relatively large body size similar to the findings of (Penaz 1973).

Of the three recognised forms of downstream migration, passive, active-passive and active (Figure 6.36), the first two are normally the method of drift for free embryos and fish larvae (Copp *et al*. 2002). The majority of drift measured was the result of passive migration, typical of early life stages, is usually observed at twilight or at night time (Jurajda 1998; Copp *et al*. 2002; Reichard & Jurajda 2007; Pavlov *et al*. 2008). Some studies have interpreted drifting at night to be related to visual disorientation (Brown & Armstrong 1985) whereas Pavlov *et al*. (2008) suggested that it is due to the fish’s inability to withstand the flow.

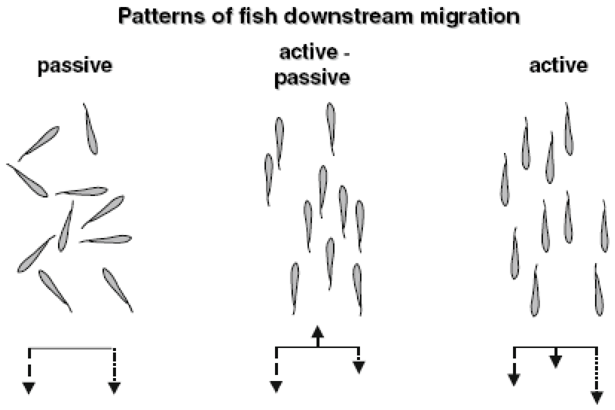


Figure 6.36. Variations of the downstream movement of larval and juvenile life stages of fish species. In passively migrating fish, speed of migration (dotted arrow) is equal to the flow velocity (dashed arrow); actively migrating fish move faster than the water flow because their own swimming velocity (solid arrow) is added to the flow velocity counter current swimming of ''actively-passively'' migrating fish makes the speed of downstream migration less than the flow velocity (from Pavlov, 1979)

Low numbers of other fish species were caught during drift, despite chub being seen spawning on the gravels at Harrold Bridge and the assumption that; gudgeon, roach, dace and bullhead should still have been spawning. The larval drift study was not repeated in 2011, because no barbel spawning was observed. This may have been due to differences in environmental influences during the spawning period of 2011 compared with 2010. In 2010, the River Great Ouse at Newport Pagnell had higher mean daily flow (2010 = 1.03 m^3 day^{-1}, 2011 = 0.54 m^3 day^{-1}: Mann Whitney *U*-test: z = -6.691, n=200, P<0.001) and mean daily river level (2010 = 53.92 metres Above Ordinance Datum (mAOD) day^{-1}, 2011 = 52.71 mAOD day^{-1}: Mann Whitney *U*-test: z=-5.845, n=200, P<0.001) than in 2011. There was no significant difference in temperature or rainfall between 2010 and 2011 (Temperature 2010=15.66°C, 2011=15.30°C, Mann Whitney *U*-test: z=-374, n=200, P>708. Rainfall 2010= 0.80 mm, 2011= 1.1 mm, Mann Whitney *U*-test: z=.-1.373, n=200, P>170).

Sampling methodologies

Methodologies for capturing 0+ and young (1+ to 3+) barbel include; larval drift traps (Copp *et al*. 2002; Sonny *et al.* 2006), Point Abundance Sampling with electric fishing (PASE) (Jurajda 1995; Watkins *et al.* 1997; Bischoff & Freyhoff 1999; Copp *et al.* 2005), micromesh seine netting (Nunn *et al.* 2007) and semi quantitative electric fishing (Vilizzi *et al.* 2006; Webber *et al.* 2009). Environment Agency investigations targeting lampreys, found that hoop nets were successful in capturing young barbel (Joel Rawlinson, (*pers. comm.*).

Of all the techniques used to capture young barbel, only larval drift and continuous electric fishing were successful. The same sites sampled by PASE were the same that were sampled by continuous electric fishing; therefore there was a known presence of young barbel at each site where PASE was used. Scarfe *et al*. (2009), noted that "A single method to capture a species, is not sufficient for drawing a complete picture of the population size structure" and the advantages and disadvantages of sampling for YoY fish have been well documented (Chessel 1978; Copp and Penaz 1988; Persat & Copp 1990; Scholten 2003). Chessel (1978) stated that multiple small samples are more representative and statistically reliable than one or a few large samples, but despite a number of investigations being successful in capturing YoY barbel by PASE, findings from this investigation were to the contrary. This may be due to the lack of shallow slack water, increased mobility and inaccessibility to densely vegetated areas (Copp & Penaz 1988; Sarafy *et al.* 1988). Seine netting has been effective in capturing small barbel in other rivers such as the Trent and the Yorkshire Ouse (Hull International Fisheries Institute), it is likely that the areas sampled in the Great Ouse had too higher flows for the seine net to be effective, even with additional lead on the bottom with the aim of keeping the net in contact with the river bed.

Habitat relationships and feeding preferences

Species habitat relationships are an important aspect of community ecology and fish life history, particularly in early ontogeny (Copp 1992). The preferred habitats of 0+ fish are different for each species (Mann 1996). This is because fish during their first year of life, go through a series of anatomical and corresponding physiological changes resulting in a shift in resource uses. Therefore each species has the potential to go through several meso-habitat shifts during their first summer (Bischoff & Freyhof 1999; Balon 1984). Barbel left the gravel at a relatively large body size and therefore it was expected that 0+ barbel alter habitat use at an early age (Bischoff & Freyhof 1999).

Previous research has identified barbel <20 mm are associated exclusively with the marginal zones and shallow bays with low flow, submerged and overhanging vegetation and no water current (Watkins *et al.* 1997; Bischoff & Freyhoff 1999) as these habitats offer refuge from high flows and predation (Power 1987; Copp 1992a; Copp & Jurajda

1993). Habitat types as close to these references were sampled with the micromesh seine netting methodology and resulted in very few (0.05%) barbel being captured, the smallest of which was 27 mm. Shallows bays with low velocities were not present in the study section and there are few accessible in the upper Great Ouse. Copp (1992) observed that microhabitat overlap between different larval stages increased at lower velocities, concluding that water velocity was not a key determinant of larval distribution unless it was sufficiently high to displace larvae. Other authors (Murphy & Eaton 1981, 1983; APEM 2009) suggested that vegetation cover, specifically water crowfoot, offer refuge to small barbel and increase survival. Watkins *et al.* (1997) revealed that bank slope, submerged vegetation and width were prominent variables influencing microhabitat use and Rincon *et al.* (1992) found that 0+ cyprinids occupied larger areas of the river channel as they developed and swam more efficiently. 0+ and 1+ barbel in the study section shifted from areas in which riparian overhang and pebbles were prominent features, to habitats where macrophytes and woody debris and root systems provided in channel cover. The movement of juvenile barbel from marginal waters to gravel habitats coincides with the completion of the fins which enables the fish to move more swiftly (Bischoff & Freyhoff 1999; Krupkra 1988).

Older barbel (>1+) prefer deeper waters over gravel bottoms further away from the bank without submerged vegetation (Watkins *et al*. 1997). Bischoff and Freyhoff (1999) found that almost all juveniles >59 mm were caught in riffle habitats and thatindividuals between 70-89 mm preferred discharge of up to 120 cumecs. The maximum sustainable swimming speed of barbel is a direct function of length (Bischoff & Freyhof 1999; Webb & Weihs 1986 & Mills 1991).

Diet

Some studies have assessed the diet on captive juvenile barbel under controlled laboratory conditions (Calta 1998; Policar *et al.* 2007; Kaminski *et al*. 2010; Sikorska *et al.* 2012), but few have done so in the field. The movement of juveniles to high velocity areas and profitable feeding positions may be adaptive behaviour for juvenile barbel (Bischoff & Freyhoff 1999). Foraging in riffles is energy efficient for larger YoY barbel because those habitats are highly productive and are used by many bottom dwelling and drifting benthic organisms especially Simuliidae and chironomid larvae that are the most important insect orders in the diet of 0+ barbel, corresponding with the findings of Bischoff & Freyhoff (1999), however in this study, barbel did not feed on

Ephemeroptera as they had found. There were changes in the feeding preferences of young barbel as they developed.

Growth

Reliable and accurate methods of scale ageing are required for accurate assessments of population structures, growth, YCS and mortality rates. Studies comparing the growth of stocked fish and wild fish, have found differences due to standard husbandry practices involved with rearing fish in captivity (Britton *et al.* 2004; Ibáñez *et al.* 2008). Changes to temperature, food availability result in altered growth patterns, and these can be exhibited in the form of false 'checks', resulting in an overestimation in age (Britton *et al.* 2004). Circuli patterns have been used to differentiate between hatchery reared and wild fish prone to the formation of multiple 'checks'. These species include; Atlantic salmon (Stockesbury & Lacroix 1997), roach (Britton *et al.* 2004; Ibanez *et al.* 2008), dace, common bream and barbel (Britton *et al.* 2004).

Readings of scales collected during the 2009 surveys showed 0+ and 1+ barbel of were of similar lengths (Figure 6.37). Although it is not unusual to have overlap in length distributions between age classes, 6000 unmarked juvenile barbel, reared at Calverton Fish Farm, were stocked at multiple locations throughout the study reach previous to 2009. Of the 100 scales taken from barbel reared at Calverton Fish Farm in January 2012, of a known age of 1+, only 2% showed 'false checks', resulting in them being aged at 2+. False checks are known to occur in wild fish due to sharp changes in temperature and alterations in feeding (Skurdal & Anderson 1985; Ibanez *et al*. 2008), it is therefore assumed that barbel caught were naturally recruited.

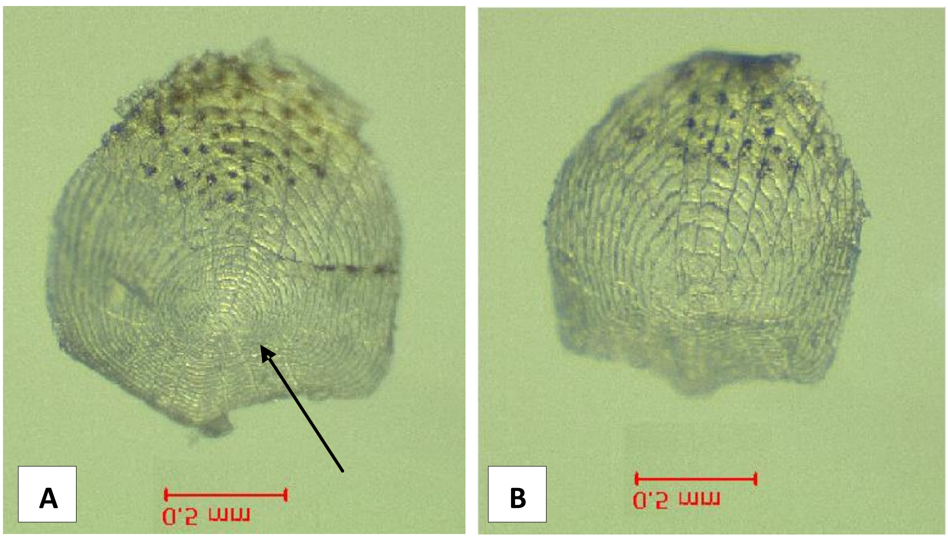


Figure 6.37 A) Scale of 67 mm barbel, with visible check. **B)** Scale of 70 mm barbel, no visible check.

Bottlenecks to barbel recruitment at the larval and juvenile life history stages

This Chapter aimed to identify a presence of naturally recruited barbel and assess the population characteristics of the species. Different sampling methodologies were applied to specifically target young barbel, and collect data on habitat and feeding preferences, and increased growth was associated with degree days >13.5°C; meeting the objectives of the research.

Two bottlenecks to the recruitment related to larval and juvenile barbel have been identified. These are:

- no lentic habitats available for drifting larvae and young fish, increasing the risk of year classes getting washed down stream in main river flows;
- the presence of signal crayfish.

Mitigation

- create much needed slack water areas at locations downstream of spawning gravels so that larvae can successfully drift into them and avoid the main flows of the river channel;
- implement an intensive and continuous signal crayfish trapping program to manage the population, particularly in river stretches close to spawning habitat and during the spawning and incubation period. It would also be beneficial to target known refuge areas of small fish with low swimming and there for escapement capabilities.

7 DISCUSSION AND PRACTICAL MANAGEMENT PLANS

7.1 Introduction

The project aimed to address the concerns over distribution and perceived lack of natural recruitment of barbel in the River Great Ouse with a series of studies targeting different life history stages of barbel (Figure 7.1), from which, recommendations could be applied to the Great Ouse and other rivers or catchments. Fragmentation, river regulation and water quality, and how these alter available habitats, particularly with increases in drought years and summer flooding were all identified as threats to barbel populations (Chapters 3, 4 and 5). Options to mitigate these pressures are gradually being addressed by the Water Framework Directive through River Basin and Catchment Management Plans, findings in this Chapter, provide the Environment Agency with management options they can build into their framework to improve rivers on a larger scale and other stakeholders with a number of options to improve their fisheries with 'stand-alone' enhancement projects.

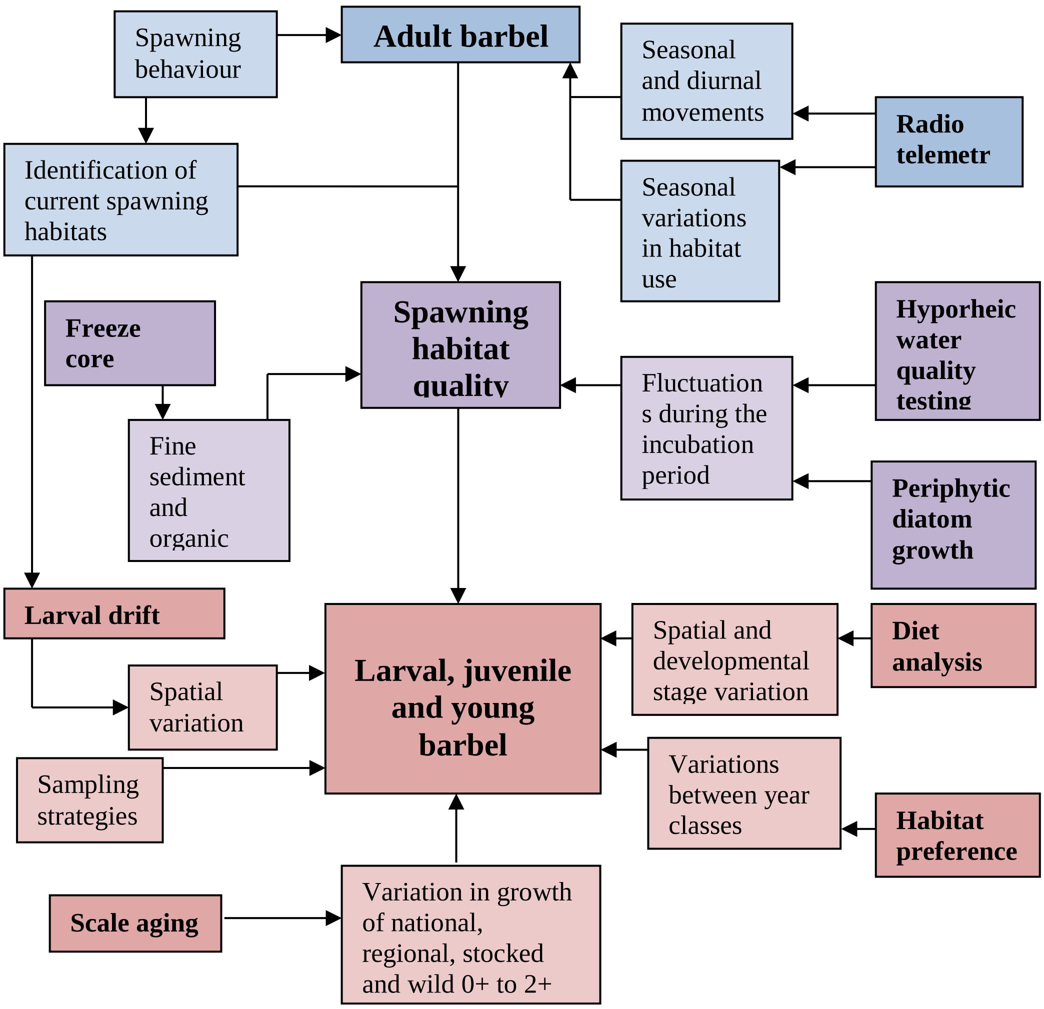


Figure 7.1. Summary diagram of topics covered within thesis (blue = Chapter 4, purple = Chapter 5, red = Chapter 6). The main themes for each Chapter are in **bold**.

7.2 Key conclusions of research

It was deemed essential to review previous research and available historical barbel population information to provide a thorough understanding of the species and identify potential areas for research. The literature review on the European barbel (*Barbus* barbus) (Chapter 2) provided a summary of the species and its natural distribution in England after the last Ice Age. Information on habitat requirements, reproduction, physiology, growth and food preferences were used during the planning of investigations (Chapters 4, 5 and 6). There was a lack of literature on spawning gravel and hyporheic water quality needs for barbel and other lithophilic coarse fish species; information available was all centred on salmonid species (Crisp 1996; Shackle *et al.* 1999; Kondolf 2000; Milan *et* al. 2000; Hendry 2003; Kondolf *et al.* 2008; Meyer *et al.* 2008).

There are advantages and disadvantages to using Environment Agency data to assess national barbel populations. On the one hand, they should be used with caution when examining catch population trends due to selectivity, variability in effort and the availability of temporal and spatial data sets representing any particular year. On the other hand, it is the largest standardised data set relating to barbel lengths and numbers available for use. In the Anglian Region, the main rivers influencing this are the Great Ouse and Stour. Average density at each site, over time and average number of barbel caught per day fished (calculated from Environment Agency survey data), showed fluctuations in barbel numbers rather than a definite decline over the last 25 years (Chapter 2). It is still unknown how much of an effect stocking has had on all of these populations.

In terms of the WFD, the Great Ouse is ‘Good’ for biological and chemical quality (Chapter 3), but water quality in the hyporheic zone is of great concern considering the temperatures reached and the low dissolved oxygen levels recorded (Chapter 5). There are also a high number of abstraction points that impact on flow and influence barbel behaviour (Chapter 4) and barriers that affect longitudinal connectivity (Chapter 4). General habitat scores for the River Habitat Survey have identified much of the upper Great Ouse as being good, but much needed lentic habitats were missing for larval fish (Chapter 6). Other issues for barbel numbers highlighted in Chapter 3 such as endocrine disruption, parasites and predators could not be addressed in this research project due to the time constraints generated by the other studies.

Features of this investigation, such as the use of radio telemetry, larval drift and habitat use had already been conducted in the interest of barbel ecology in other European rivers (Hunt & Jones 1974; Baras & Cherry 1990; Baras 1997; Vilizzi *et al.* 2006; Ovidio *et al.* 2007; Copp *et al*. 2002). The use of these methods in this research was critical. Radio telemetry provided information on behaviours, movements, habitat use and effects of environmental influence specific to the Great Ouse to gain the evidence necessary to improve the status of the barbel population and aided in the identification of several spawning gravel which were used in subsequent research Chapters (Chapters 5 and 6).

This research has identified some similarities and differences with other investigations into the movement patterns of barbel (Chapter 4), highlighting mobile and sedentary individuals as well as the ability of some barbel to pass a small weir in normal flow conditions. The effects of temperature and flow on movements will need to be considered if years of low rainfall and low flow are followed by years with summer flooding, similar to what was seen between 2009 and 2012 on the River Great Ouse. The river stretch ~8.5 km in length, provided a range of suitable seasonal habitats for adult barbel and the selection of spawning gravels provided the opportunity to obtain an insight into spawning gravel habitat use by barbel. The study also found that some spawning habitats were bypassed by some barbel, but were being used by others.

The investigation into comparing the hyporheic water quality, periphytic diatom growth and fine sediment infiltration (Chapter 5), provided the first insight into spawning habitat for rheophilic species in the River Great Ouse. The size of naturally available substrate was much smaller in diameter than preferred sizes according to Environment Agency advice, which are typically 10 to 40 mm in diameter. Spawning habitat quality varied between the locations within the study stretch. Dissolved oxygen levels within the hyporheic zone fell much lower than expected, and periphytic diatom growth peaked during the incubation period. Despite the small freeze core sampling quantity, there was a reduction in fine sediment and organic matter within the spawning habitat post gravel enhancement work. Odell and Harrold Bridge had the lowest percentage of fine sediment and organic content, with the highest number of larvae drifting from the gravels. It would have been beneficial to continuously monitor DO before and after gravel jetting to determine and improvement.

Low species diversity was found during the larval drift study, barbel accounted for 74% of the total abundance. Although agreeing with Scarfe *et al.* (2009) in that a single method is not suitable for samping Young of Year fish, contrary to other research that has focused on catching 0+ community fish, this research found that for a more reliable estimation on populations of YoY barbel, continuous electric fishing is the preferred methodology (Chapter 6). In future, this could be conducted by dividing the channel into functional habitats such as 'gravel substrate' or 'vegetated' to link the presence of juvenile barbel to specific habitat types. The habitat use of young barbel in this study was different to other studies, possibly because those habitats were not available in the study stretch.

From these key findings, it has been identified that bottlenecks to barbel recruitment in the Great Ouse include:

- home ranges and therefore longitudinal movements were limited by the presence of weirs acting as barriers to migration. Adult barbel were therefore not able to colonise other habitats outside of the study section for feeding, refuge or spawning (Chapter 4);
- low flows and high temperatures significantly affected behaviour of barbel, specifically the movements made in 2010 but it is also likely that the reduction in flow was responsible for the lack of spawning in 2011 (Chapter 4). Water temperatures exceed those deemed optimal for barbel embryonic development (Chapter 5);
- spawning gravel quality, specifically increased periphytic diatom biomass, reducing dissolved oxygen levels at night; infiltration of fine sediment and a combination of fine sediment and diatoms causing biofilms directly smothering eggs and larvae (Chapter 5);
- surface gravel size of available spawning habitats are smaller in diameter than what is preferred by barbel (Chapter 5);
- no lentic habitats available for drifting larvae and young fish, increasing the risk of year classes getting washed down stream in main river flows (Chapter 6);
- the presence of signal crayfish (Chapter 6).

General mitigation measures were provided at the end of each Chapter, these can be applied to other rivers and catchments that are exhibiting similar declines in fish species. These mitigation measures are suitable or other fish species.

7.3 Practical management plans

Based on the evidence obtained from these studies, a series of options have been considered for management plans based on using European legislation such at the Water Framework Directive and Eel Regulations (2009) or Salmon and Freshwater Fisheries Act (1975) as drivers. Decisions should be made on the best available science and experience, the findings discussed here and options in the Practical Management Plan, can be integrated into future strategies. Post rehabilitation monitoring is most important to provide evidence of success and so that those not effective can be developed before future use.

7.3.1 Improve longitudinal connectivity

Restriction to longitudinal connectivity was identified as a bottleneck to recruitment (Chapter 4). Catchment Management Plans provide the perfect opportunity to undertake feasibility studies on removing unused structures throughout the catchment. Anglian Central Barriers project has already been implemented in the Region by the Environment Agency and priority for assessment was given to the lower reaches of the Great Ouse which are important to migratory species such as eels (*Anguilla* Anguilla) and sea trout (*Salmo trutta*). These require access from the sea to spawning and nursery grounds. Radio telemetry studies have identified that barbel in this reach are unlikely or unable to travel upstream or downstream of the major barriers. Of the 20 barbel tracked, none were located upstream of Harrold weirs (u/s min 0.11 m, max 0.38 m, d/s min 004 m, max 0.57 m) or downstream of Sharnbrook weir (min 1.06 m, max 2.1 m) that acted as the boundaries for the study reach.

Fish passes, bypass channels, and barrier lowering or removal where possible would enable increased fish movement and allow access to additional feeding, resting, refuge and spawning habitats. Solomon (2011) reviewed gauging structures in the Anglian Region, including the upper Ouse and found that 92 gauging stations are no longer in use, including those at Harrold and Sharnbrook. The elimination of these barriers by any of the previously mentioned methods would open up a further 11 km of river to the fish, giving free access to 20 km of river.

Harrold weirs (Figure 7.2A) are no longer used for gauging and therefore the removal, lowering or bypass of this barrier would provide access to another 5 km of river. There is more scope for this action on the upstream weir, but removal may impact on known spawning gravels for barbel, chub and dace because river level and velocity would be considerable altered. It would also be necessary to maintain the head difference due to private dwellings that would be at risk from changes in river levels. Therefore, other fish pass options and instream structures to help retain the spawning gravels should be considered.

Harrold Bridge (Figures 7.2B and 7.3) is passable by some barbel, but it is unlikely smaller fish would be successful. The creation of a bypass channel or removal of the weirs is not a viable options in this location. The most likely path that the barbel take over the weir is the second arch on the left, where it would be possible to create a rock ramp. This would also retain the head difference and retain the downstream spawning gravels, but might not be suitable for many of the smaller species.

The removal, lowering or bypass of Sharnbrook weir (Figures 7.2C and 7.4), would provide access to another 15 km of river. There is an existing bypass channel that could be retrofitted to create a definite channel. At present, the channel is clogged with emergent and submerged vegetation and is therefore impassable for large fish such as barbel.

Future research

It is not certain that an installed fish pass will be used by fish. Measuring the efficiency of fish passes and factors affecting efficiency have previously been discussed in literature (Lucas & Baras 2001; Travade & Larinier 2002; Marmulla & Welcomme 2002; Roni 2005; Santo 2005; Ordeix *et al*. 2011). Factors affecting fish passage, principally temperature, level and flow will need to be recorded, to collect evidence of fish use in terms of numbers and species.

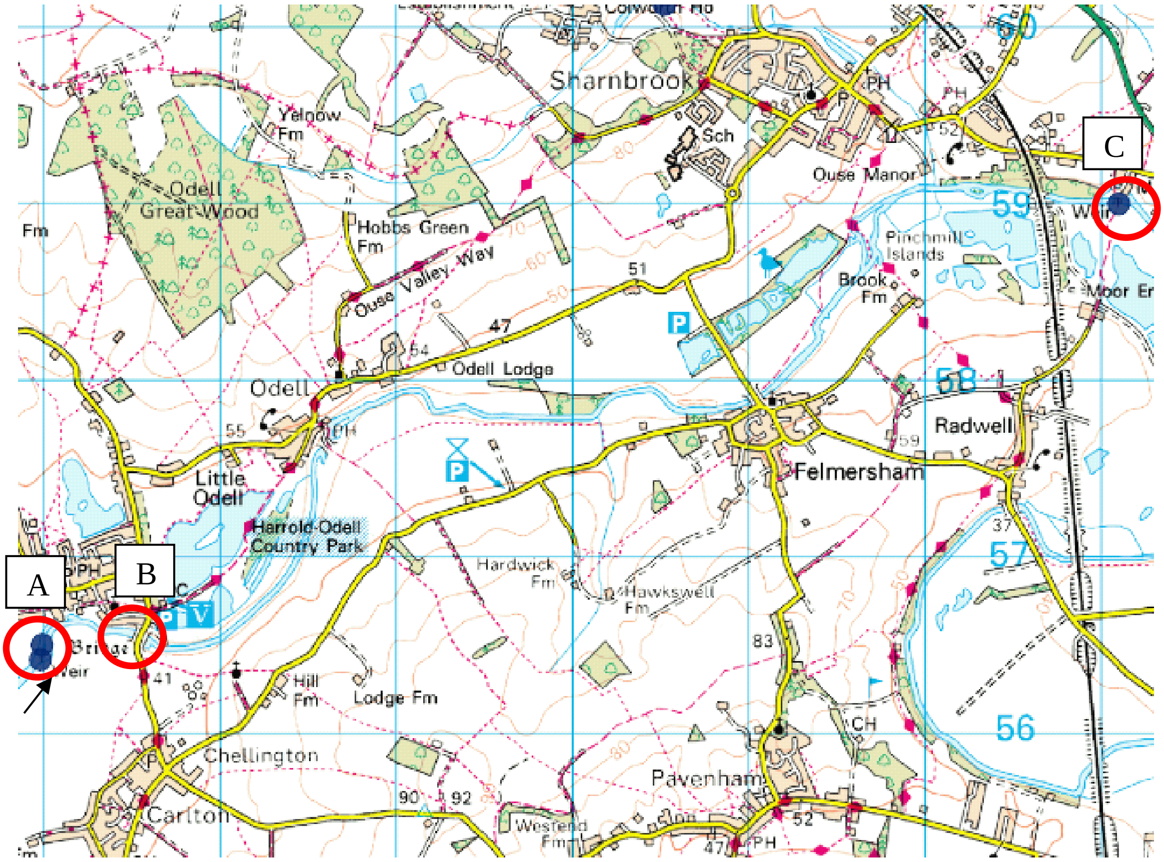


Figure 7.2. Map of study section highlighting the location of weirs: (A) Harrold weirs; (B) Harrold bridge weirs; (C) Sharnbrook weir. Arrow indicates direction of river low.

Figure 7.3. Harrold Bridge weirs, photo taken in an upstream direction.

Figure 7.4. Sharnbrook weir, photo taken in an upstream direction.

The following are most appropriate for these locations:

- PIT tagging, requires a power source for the PIT loops to record fish movement. Data collected will be dependent on the number, species and size of fish tagged. Tagging fish upstream and downstream, with PIT loops either end of a bypass channel, or at stages along the main channel, will monitor upstream and downstream movements. These data can be used to calculate travel times. PIT tags can last for years, therefore the method offers potential for large amounts of data.
- Radio tracking is more costly in terms of money, time and man power particularly if the aim is to collect data with a high level of accuracy. By contrast, it would enable us to see what fish use which habitats after the removal of the barrier, or within a bypass channel. The battery life on the radio tag depends on the size of the tag and ping rate, which dictates the minimum fish size that can be tagged. Tagging fish upstream and downstream will enable the monitoring of fish in both directions.
- Mark and recapture methods, using fish from upstream and downstream will enable monitoring of fish in both directions. This method is more cost effective

and will provide the information that fish have passed what was previously impassable, but information on travel times and habitat use will be undetermined. It also does not provide levels of efficiency as this would require a measure of recapture efficiency and 100% tag retention, which has not been proved (Bolland *et al*. 2009).

7.3.2 Reduce sediment loading

Fine sediment and organic content were identified as bottlenecks to the recruitment of barbel (Chapter 5). Lowland river systems such as the River Great Ouse are particularly vulnerable to sedimentation due to their low energy and limited ability to recover (Brookes 1995). Collins *et al.* (2009a, b) demonstrated that agriculture in England and Wales dominated present day sediment inputs into rivers (76%) compared with eroding channel banks (15%), diffuse urban sources (6%) and point source discharges (3%). Research on fencing to reduce cattle poaching and sedimentation has primarily focused on salmonids (Evans *et* al. 2006; Collins *et al.* 2010), but the processes are the same in lowland rivers.

Within this river stretch, livestock is impacting on the river in two ways. The first is cattle poaching, introducing excessive sediment into the channel system and the second is the entry of natural waste into the channel, increasing organic nutrient levels. Livestock farmed in this area include cattle and sheep, although there are areas where they are kept away from the river bank and channel, there are other sections where cattle have unlimited access to the river channel, specifically Harrold and Odell Country Park (Figure 7.5). There is fencing at the upstream end of the Country Park, but towards the bottom end there are numerous cattle drinks for the cows. At this point the river is wide and slow flowing, there is not enough energy to move the sedimentation downstream resulting in areas of deep silt.

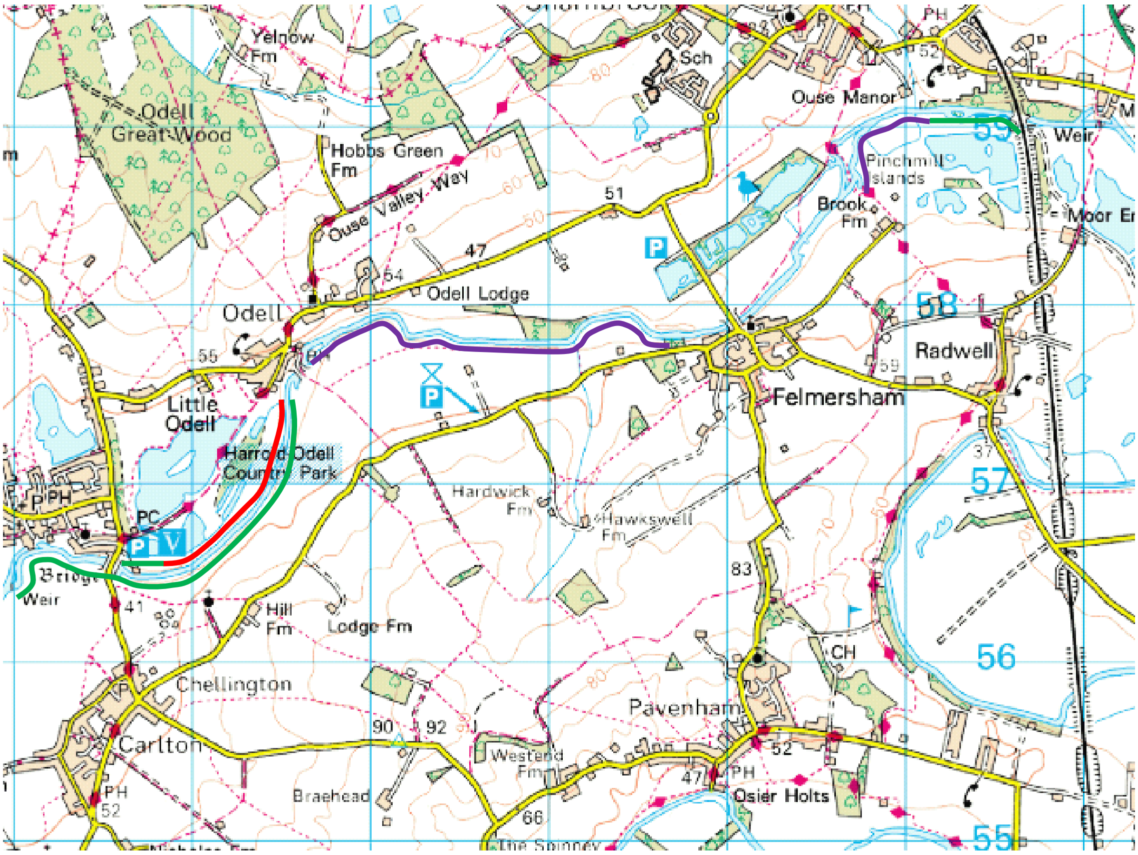


Figure 7.5. Map of the study section showing the banksides where — Cattle are present but have no access to the river bank or channel. — Cattle have unlimited access to the river bank and channel. — Sheep are present but have no access to the river bank or channel.

Suspended solids data collected from Harrold weirs and Sharnbrook weirs before they were decommissioned illustrate that turbidity was usually highest from November to March than other times of the year at Harrold and Sharnbrook (Figures 7.6 and 7.7). It is unknown whether the suspended solids entered the channel during these months or were just re-suspended due to increased flow. These suspended solids settling before or during the spawning period will have major impacts on recruitment success. To try and reduce sediment loading and subsequent consequences, good communication with the Harrold and Odell Country Park will be necessary and options for reducing cattle access to the river bank and channel will need to be addressed. Due to the impounding effect of the two weirs at Harrold, sedimentation in the downstream stretch is most likely to come from within the reach and therefore, issues need to be tackled within this reach.

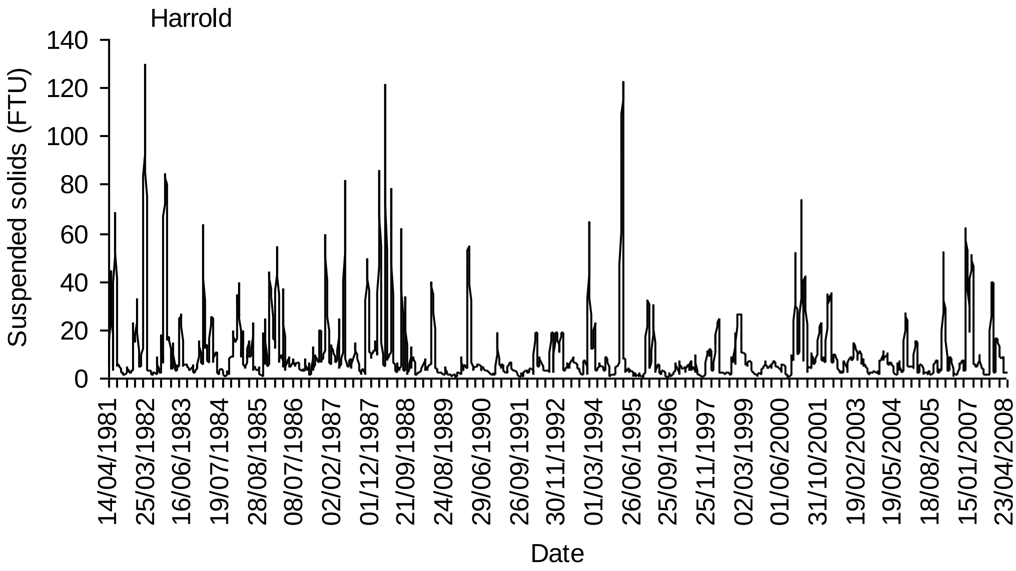


Figure 7.6. Suspended solid levels measured in the River Great Ouse, Harrold weirs 1981 to 2008.

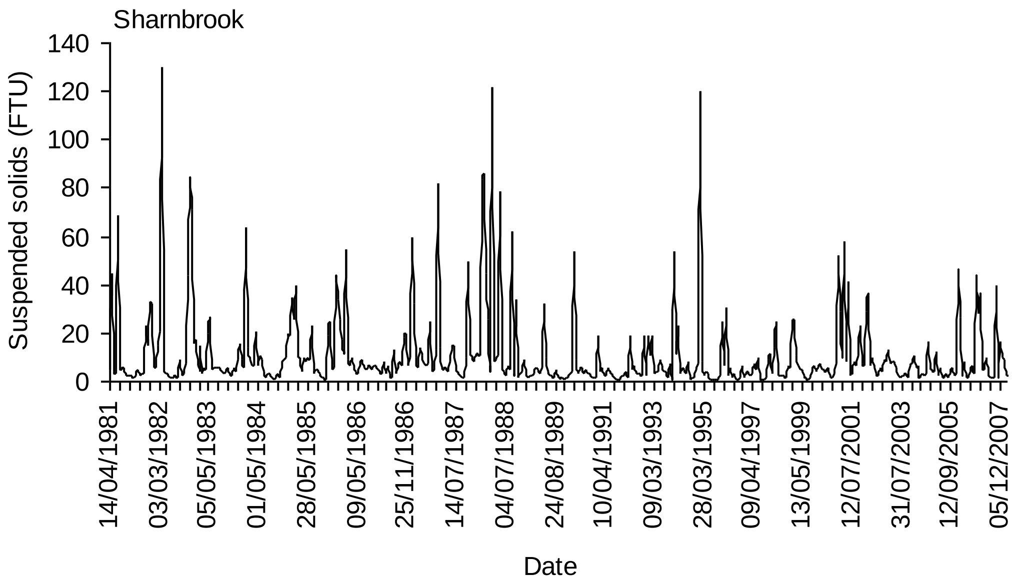


Figure7.7. Suspended solid levels measured in the River Great Ouse, Sharnbrook weir 1981 to 2008.

7.3.3 Improve spawning habitat

Fine sediment and organic matter infiltration, as well as periphytic diatom growth, was identified as a bottleneck to the recruitment of barbel. This area is well known for lithophilic species such as barbel, chub and dace. During this study six spawning gravel habitats were identified for these species (Figure 7.8). For this reason multiple spawning gravel enhancements have already been conducted (Figure 7.9), including gravel jetting and redressing mentioned in Chapter 5.

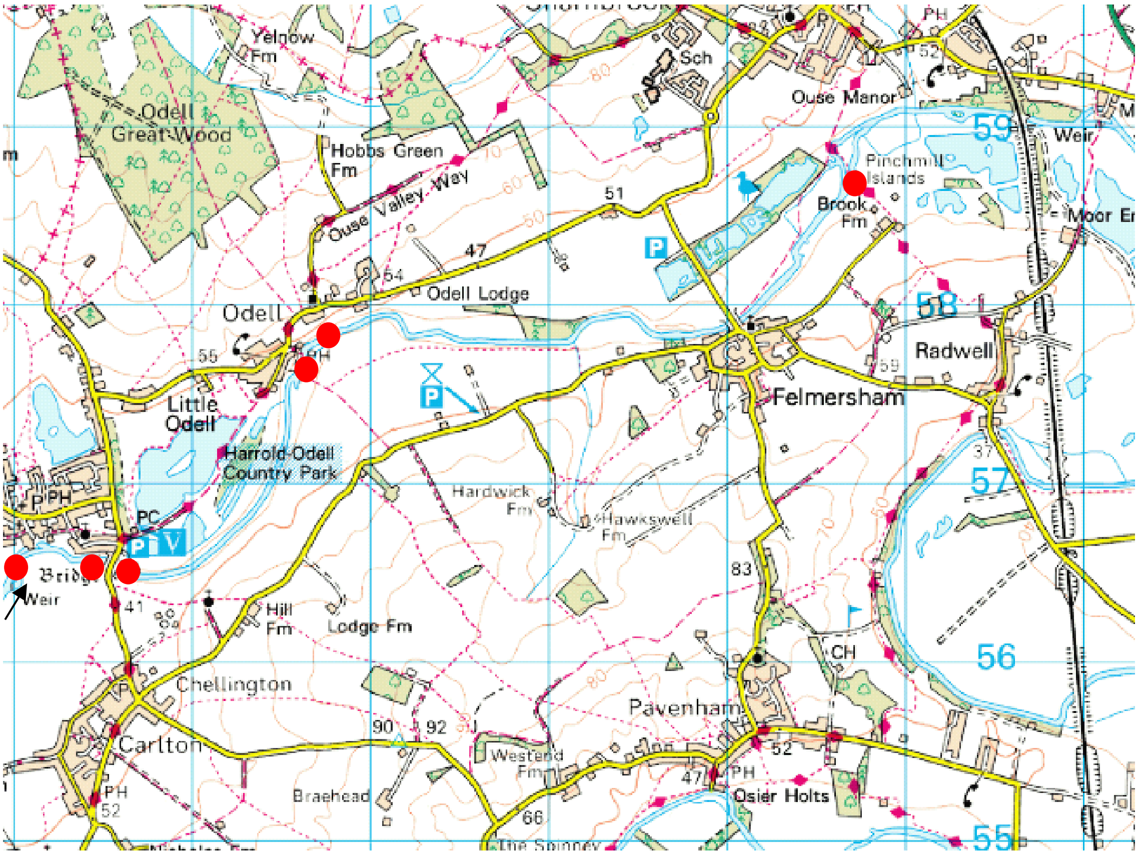


Figure 7.8. Map of study section highlighting identified spawning gravels on the River Great Ouse between Harrold and Sharnbrook. Arrow indicates the direction of river flow.

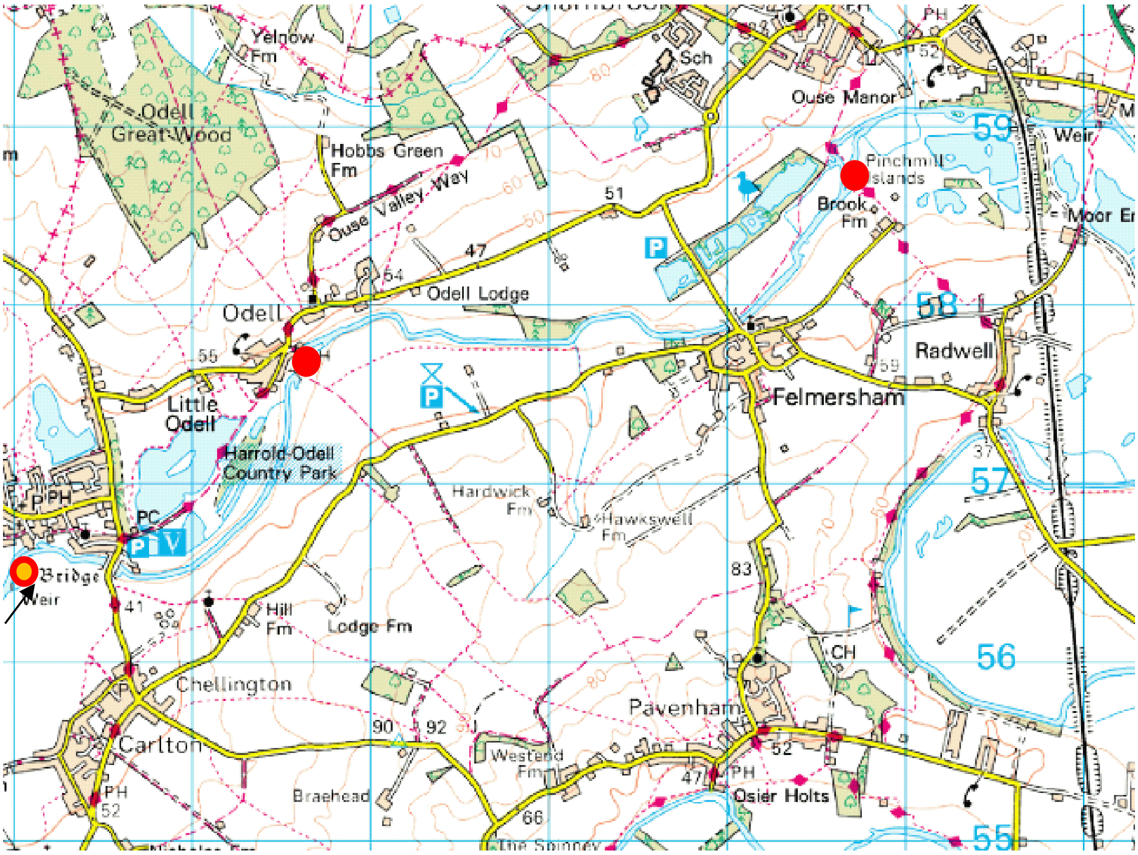


Figure 7.9. Map of study section highlighting Gravel jetted spawning habitat, gravel jetted and redressed spawning gravels. Arrow indicates direction of river flow.

Excessive growth of submerged and emergent vegetation reduces the amount of water that is able to flow, this in turn can reduce responses in river level rises and can cause localised flooding (Cowx & Welcomme 1998). Anglers prefer fishing environments free from dense vegetation to enable more successful capture. Marginal vegetation should remain untouched and there should be no removal of vegetation in the summer months to avoid removal of eggs and important refuge areas. The removal of some emergent vegetation downstream of the first weir at Harrold (Figure 7.10), acted as a pinch point in the channel and increased velocities which had the energy to scour the gravels on the downstream spawning habitat. This would also be possible in river sections at the downstream end of Harrold and Odell Country Park, where emergent vegetation covers the width of the channel on an annual basis.

Large woody debris from upstream was grounded on the gravels and created a scouring effect before it was removed (Figure 7.11). This method could be used on non-navigable river sections such as this to remove fine sediment naturally and reduce the formation of biofilms. Melcher and Schmutz (2010) identified shading and the occurrence of vegetation along river banks important for barbel spawning, demonstrating that efficient river restoration would require riparian vegetation as well as hydromorphological habitat improvements in order to provide adequate spawning habitats.

Figure 7.10. Narrow channel opened by the removal of some emergent vegetation to create higher velocities.

Figure 7.11. Scoured gravels as a result of woody debris obstruction on the spawning gravel.

Extreme high temperatures were identified as a bottleneck to the recruitment of barbel (Chapter 5). Good communication with land owners could provide an opportunity for more riparian tree planting to create more shading on the spawning gravels. This would be most beneficial near to the spawning gravels identified in Chapter 4 (Figure 7.8), Shading over deeper waters would also benefit adult barbel, high temperatures were identified as a bottle neck to barbel recruitment at the adult life history stage (Chapter 4), as it affected their migratory and spawning behaviour.

Future research

It would be useful to measure the rate that fine sediments re-infiltrate the gravels between the gravel jetting and barbel spawning, in addition to further core sampling as comparative findings from this research, particularly to compare gravels spawned on with those not spawned on to identify any differences. Larval drift studies will be needed to assess whether these methods have been successful and increased recruitment. This could be conducted on improved gravels and gravels that have not undergone any rejuvenation

The Barbel Society has been attempting to collate a national data set on barbel spawning gathering information such as date, time, location and number of barbel. This scheme would benefit from further advertising through fishing clubs and consultatives. Spawning gravel enhancement by ‘Local action’ has proven successful in previous studies working to improve spawning gravels and channel heterogeneity targeting salmonid populations (Hendry *et al.* 2003; Merz *et al.* 2004; Wheaton *et al.* 2004). These rehabilitation methods including the introduction of gravel, stone deflectors, washed river rock berms, staggered bar, riffle, or complex channel geometry configurations increased survival rates of hatched fish. These habitat improvements increase the production of benthic invertebrates and provide refuge for invertebrate and algal communities provide food resources for multiple species.

7.3.4 Improve nursery and juvenile habitat

A lack of lentic habitat was identified as a bottleneck to recruitment (Chapter 6). This is not specific to the study section; it is an issue which is mirrored throughout the upper Ouse. These habitats need to be available downstream of spawning habitats for newly hatched larvae and developing YoY fish that have limited swimming capabilities. The creation of shallow bays (Apem 2009) and slack waters downstream of the spawning gravels to act as nursery habitat for the larval, juvenile barbel and many other fish species, creating shelter from the main river channel velocity, much needed in high flow events during wet summers will help survival rates (Rabeni & Jaconson 1993; Copp *et al.* 1994; Watkins *et al.* 1997; Bischoff and Freyhof 1999; Jurajda 1999; Nunn *et al.* 2007).

It has been noted that on this section of the Great Ouse, these vital habitats are missing. Following 2011 when barbel spawning in particular was poor, successful spawning in 2012 was followed by heavy rain which would have washed away any newly hatched larvae, resulting in two bad year classes and massively impacting on the population. These shallow bay habitats can be created to enable shallow littoral plant communities with further increase habitat diversity for aquatic flora and fauna, particularly Simuliidae larva, Chironomidae larvae and *Closterium*, which are important food preferences for larval and juvenile barbel. Issues with these habitats may occur in the summer, when river levels fall and shallow areas become dry. Modelling should prevent this. The majority of the surrounding land of the study section is used for farming and a Country Park, so there is an opportunity to create these habitats (Figure 7.12). For lithophilic species, it is important that where possible, they are created downstream of the spawning gravels to avoid newly hatched larvae and young fish from being washed downstream. It is critical that these habitats do not dry out during low flow events.

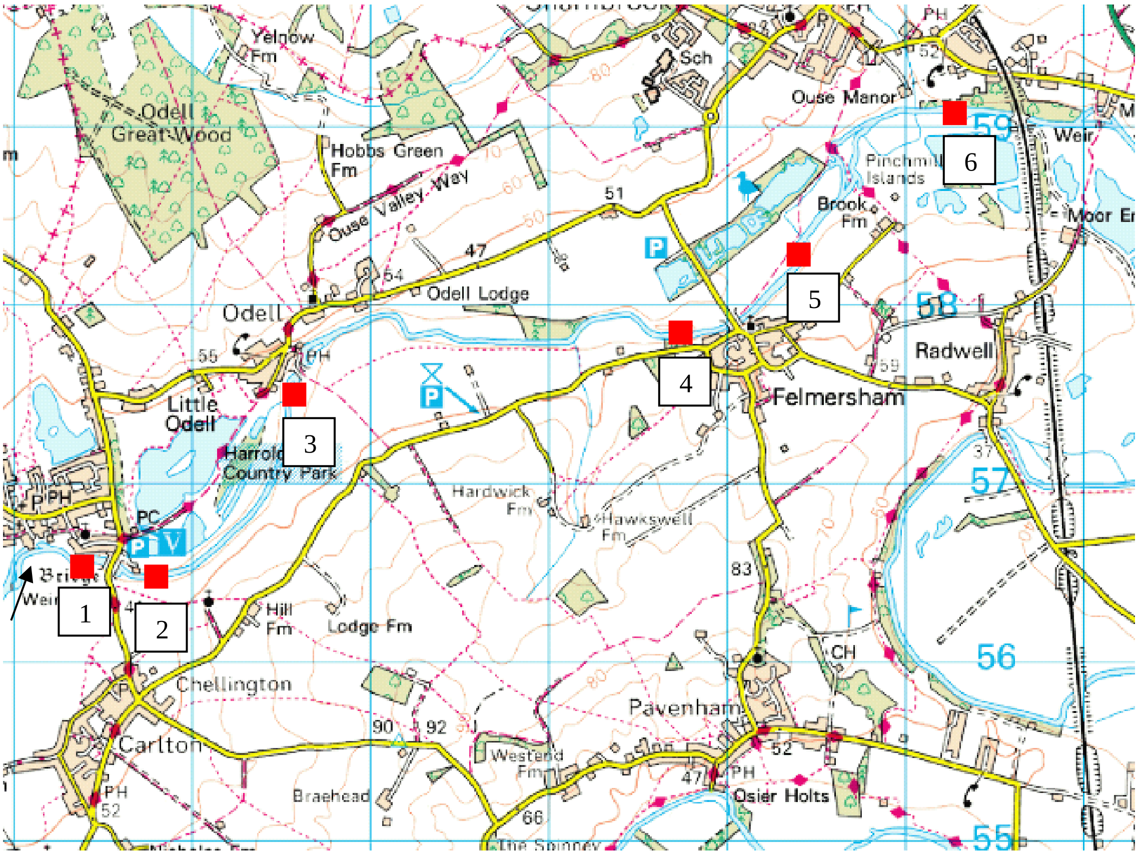


Figure 7.12. Map of the study section highlighting ■ possible locations for the creation of shallow slack waters. Numbers refer to the explanation points below. Arrow indicated direction of flow.

1) Upstream from Harrold Bridge and downstream from two spawning gravels is a ditch that currently only floods when the river is bank full (Figure 7.13). If landscaped into a backwater that is connected to the channel at all times, this could be successful in reducing the number of young and small fish that get carried downstream of the weirs and are unable to return.
2) There is a ditch located on the left hand bank at Harrold Country Park that only fills in time of high river levels (Figure 7.14). It is down stream of an identified gravel bed and is upstream of a wide/straight section of the channel that would facilitate the rapid removal fish with low swimming capabilities in times of high flow.
3) Available maps show a backwater upstream of Odell (Figure 7.15); this back water is only wet after intense rain and is never more than a few centimetres deep.
4) Downstream of Odell (Figure 7.16) there are a series of ditches that remain dry but would be beneficial to fish that hatch at Odell, the landowner has already expressed his wishes to create back waters with these. Upstream of Felmersham Bridge is a ditch that could be excavated to create a slack water (Figure 7.17).

This is upstream of a spawning gravel and wouldn't necessarily benefit drifting barbel larvae, but could benefit other species within the fish community.

5) Downstream of Felmersham Bridge there is a backchannel that has become silted and overgrown with emergent vegetation (Figure 7.18). This could be re-opened into back channels or partially excavated to create slack water areas.
6) Downstream of Pinchmill Islands, is a backchannel that has become silted and overgrown with emergent vegetation (Figure 7.19). This could be re-opened into back channels or partially excavated to create slack water areas.

Figure 7.13. Map showing the possible location for shallow slackwater habitat at Harrold Bridge (SP9551556489).

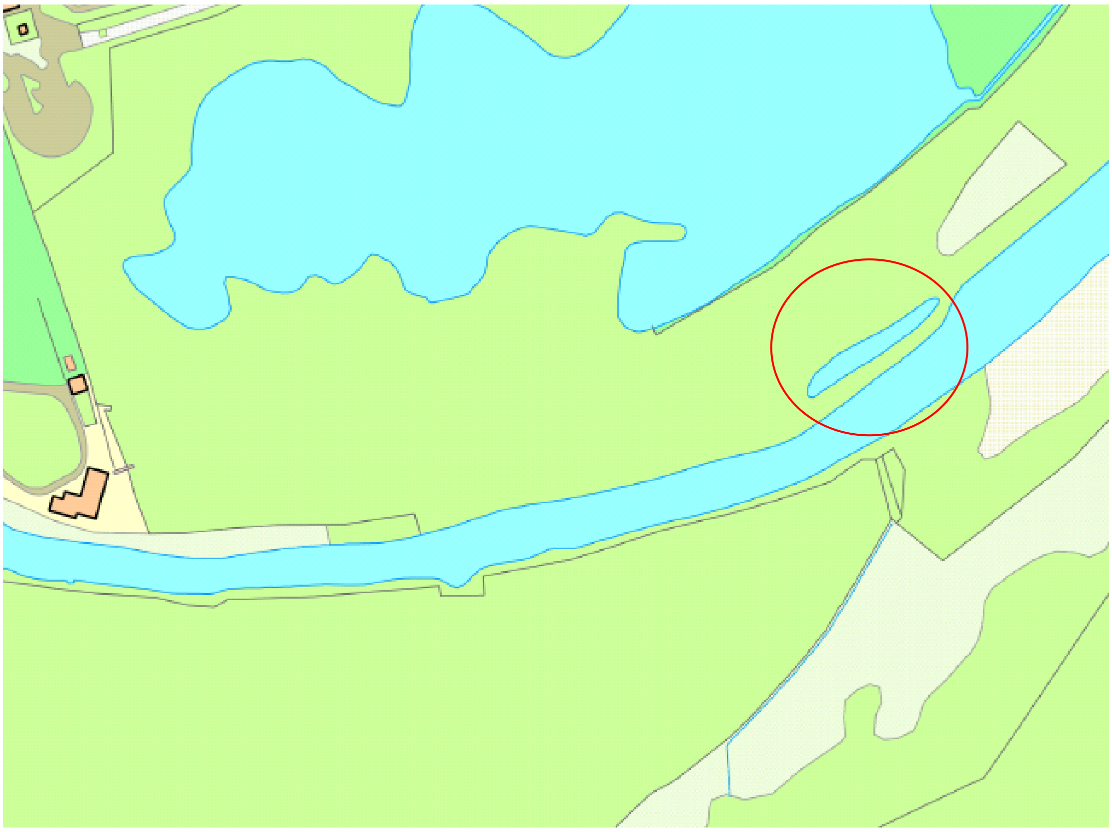


Figure 7.14. Map showing the possible location for shallow slackwater habitat at Harrold Country Park (SP9601856555).

Figure 7.15. Map showing the possible location for shallow slackwater habitat upstream of Odell (SP9658557568).

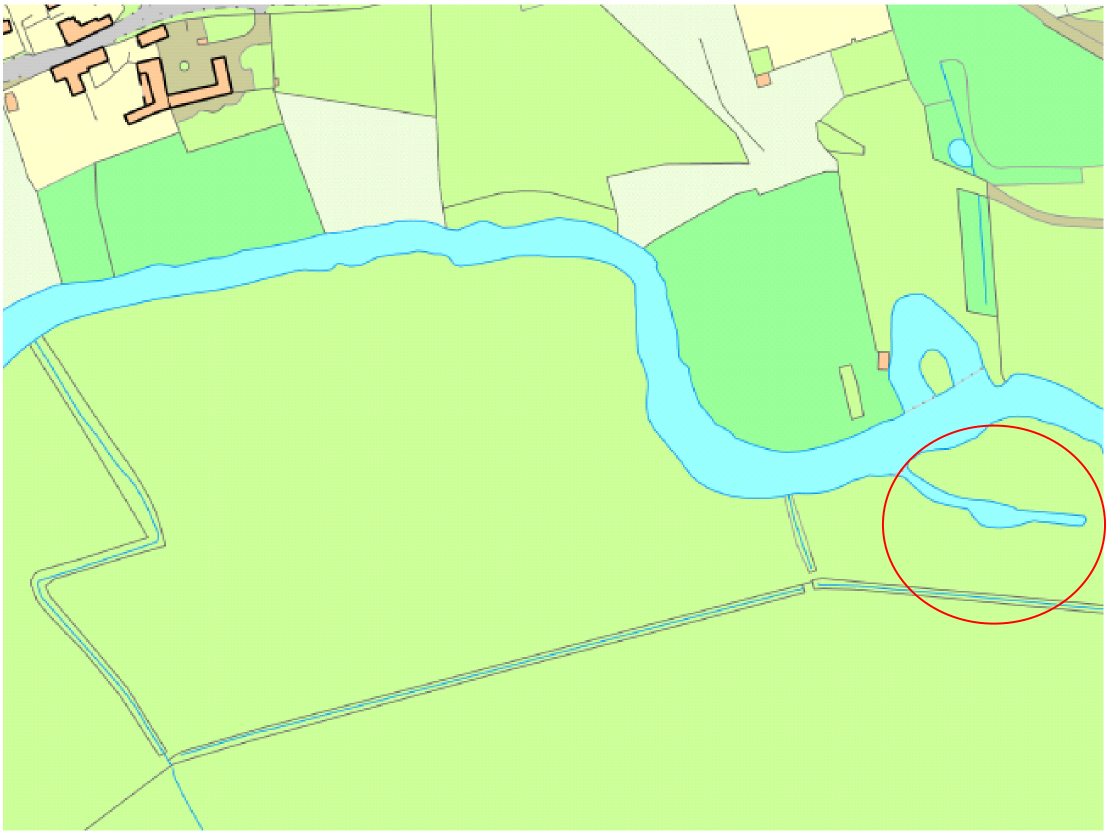


Figure 7.16. Map showing the possible locations for shallow slackwater habitat at downstream of Odell (SP9730957812).

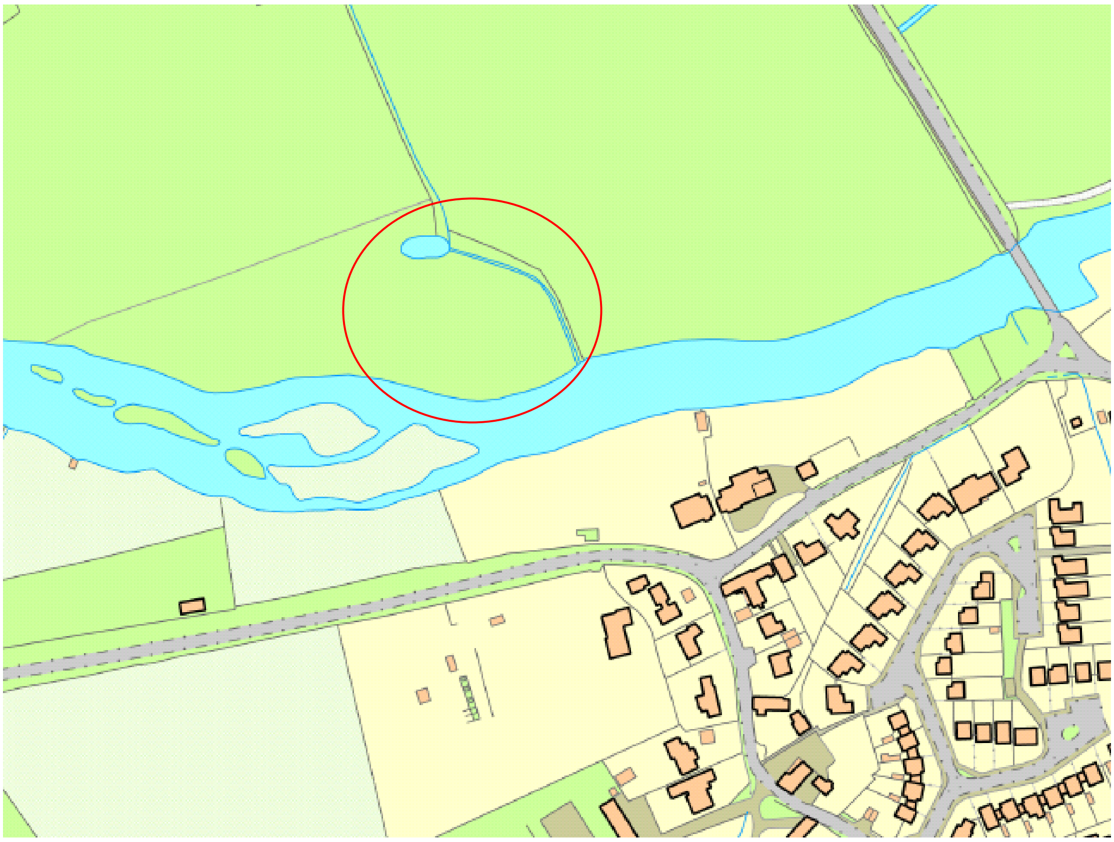


Figure 7.17. Map showing the possible location for shallow slackwater habitat at Felmersham Bridge (SP9883157851).

Figure 7.18. Map showing the possible location for shallow slackwater habitat at downstream of Felmersham Bridge (SP9944558306).

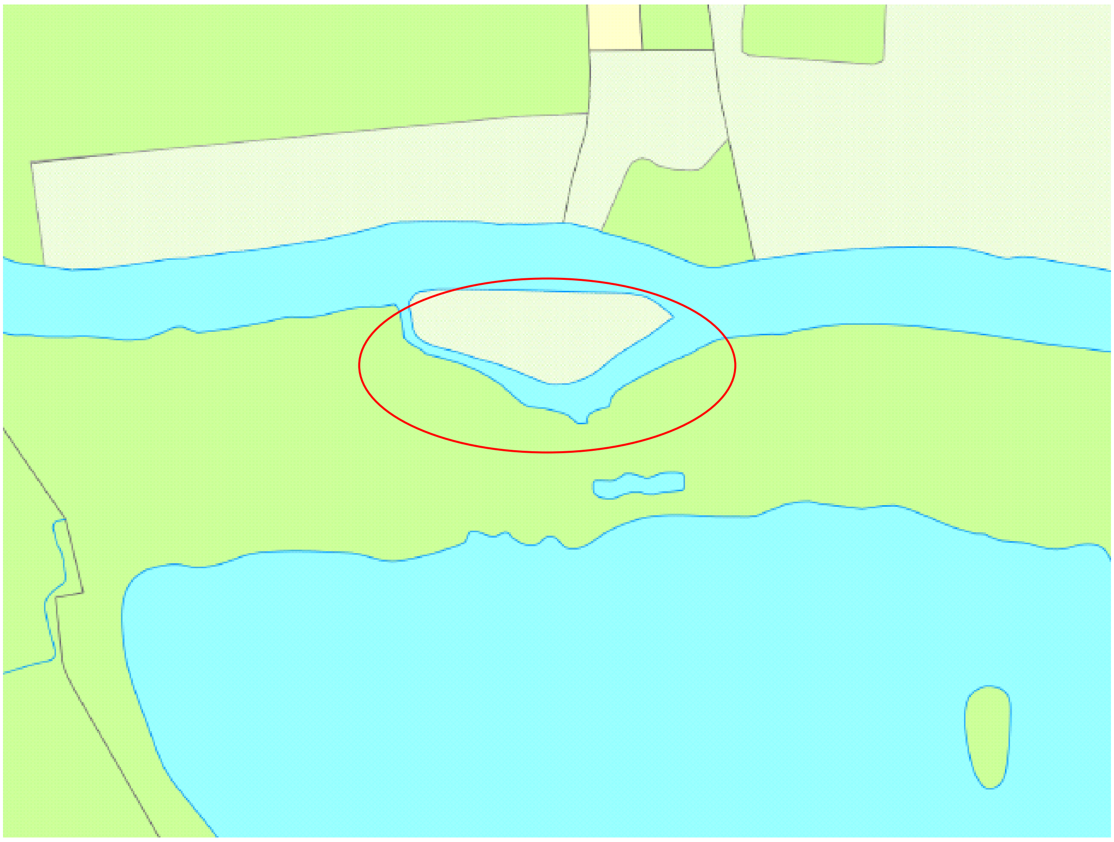


Figure 7.19. Map showing the possible location for shallow slackwater habitat at downstream of Ouse Manor (TL0030159024).

Future research

A sampling strategy should be developed to quantify the use of slackwater habitats by barbel, once they have been created. This could involve netting not immediately after spawning events and electric fishing from September onwards. Radio tracking or PIT tagging young barbel would provide data seasonal and diurnal movements of 1+ to 3+ barbel in and out of the back water that can be related to flow.

7.3.5 Restocking

The restocking of barbel has been a standard approach to boosting populations. In 2011 alone, 6,400 1+ barbel were stocked over several sites along the Upper Great Ouse, contributing to a total of 15,000 in the last decade. The dispersal and survival success of the stocked juvenile barbel is largely unknown. Mark recapture experiments or telemetry studies should be used to identify initial movements of stocked individuals, habitat use and home ranges, as it is believed that stocked and wild individuals differ. Bolland *et al.* (2008) noted a difference in behaviour between stocked and wild juvenile chub. Stocked individuals did not disperse immediately after release, spending more time in open water than did wild fish, which preferred areas of habitat complexity. Stocked fish are not influenced by environmental factors such as temperature and flow in the same way that the wild fish are Bolland *et al.* (2009).

Pegg and Britton (2011b) and Taylor *et al.* (2004) found that suppressed growth was a consequence of increased inter and intra specific competition through stocking juvenile barbel. It is therefore recommended that barbel should only be stocked following several years of poor recruitment, for example after poor spawning in 2011, followed by heavy rain after spawning in 2012 and 2013. To identify the strength of natural recruitment in rivers, it would be necessary to discontinue the stocking of juvenile barbel for a minimum of two consecutive years and begin a monitoring program to target juvenile barbel by using a continuous electric fishing technique found to be most effective at catching young barbel (Chapter 6). This will make it possible to collect data on 0+, 1+ and 2+ fish that are certain to be naturally recruited and YCS estimations will not be influenced as a result of stocking.

Future research

Tracking stocked barbel and wild barbel would highlight the differences or similarities in movement and habitat use.

7.3.6 Reduce predation

High abundance of signal crayfish was identified as a bottleneck to the recruitment of barbel (Chapter 6). The implementation of an intensive and continuous trapping program to reduce the numbers of signal crayfish, particularly around spawning habitats in the months leading up to and during the spawning period would help to reduce predation. With regard to concerns over the impact of otter predation on barbel numbers, as the otter is a native species it is protected by the Habitats Directive (92/43/EEC) there are no options for controlling numbers to reduce predation. The installation of woody debris within the water channel, would provide protective habitats and refuge areas. This would also be effective protection against cormorants, protected under the Wildlife and Countryside Act (1981).

7.3.7 Partnerships and funding

This research had large amounts of support and contribution of monies from local angling clubs, consultative and the Barbel Society. Small opportunistic local initiatives, including the installation of woody debris and gravel jetting are effective and possible to complete on an ad hoc basis. Large scale research and rehabilitation can only occur when funding is available, and rod license funding is due to be lower in 2013 than previous years. While conservation initiatives such as the WFD provide EU funding, other partnerships including those with the Environment Agency, Angling Trust, Rivers Trust, Wildlife Trust, Local Authorities and Natural England, can provide the prospect of further financial support. Volunteer groups offer practical support at no or low costs.

7.4 Conclusion

There are a complex set of factors that have a combined effect on the barbel population in the study section and in other river systems. Barriers to fish movement prevent the colonisation of new and potentially higher quality and more valuable spawning, nursery, feeding and refuge areas that could improve recruitment and survival rates. At present the adult barbel in the study section have access to habitats with heterogeneity in overhang, woody debris, pools, riffles, vegetation and hydromorphology supporting seasonal changes in habitat use. Although mink and otters are known to occupy this area of the Great Ouse, in total, 18 out of the 20 tagged barbel were still accounted for after the 73 week tracking period, with no evidence to suggest that they were predated on.

The barbel between Harrold weirs and Sharnbrook weir had access to six spawning habitats, for the majority of these, mean surface gravel size on the spawning habitats were notably smaller than the recommended diameters, high temperatures were recorded, biofilms developed on the gravel beds and dissolved oxygen fell to unfavourable levels at critical times during the egg incubation and larval development stages. Fine sediment and organic matter infiltration varied between the four sampled habitats, but there are no empirical data on coarse fish spawning habitat to compare with. The use of gravel jetting techniques to clear the gravel of these fine sediments appears to be effective based on this study.

The larvae drifted off the gravels with limited slack-waters available, marginal vegetation provided the possibility of refuge for larval and juvenile barbel. The differences in the habitat use of young barbel in this study compared with others suggests that preferred habitat types are unavailable and refuges less suited to these life stages are being used, possibly lessening their defence against predation from crayfish and cormorants, common to the study section and other fish. This will influence on Year Class Strength, and over many years can have a major impact on the local barbel population.

As fewer generations survive to become mature and the number of barbel able to reproduce in this section decrease, genetic fitness is reduced. As has occurred previously in this river and others, stocking is used to improve stocks after years of poor recruitment. Survival rate of stocked barbel is undetermined, but the biggest threats to farmed fish are avoidance predation and being unaccustomed to flows, these are usually higher in the months when stockings occur. To improve the chances of survival of young barbel from either source, the essential refuge habitats need to be provided.

The impact of predation on eggs, small and adult barbel could not be addressed in this research. Improvements to all habitat types will benefit many fish, plant and invertebrate species and improve the ecology of the river as a whole. The research has provided a basis for understanding the barbel ecology in the River Great Ouse, and information gathered is transferable to other rivers as the influences are still relevant. It is important to highlight that to be successful; a combined rehabilitation approach is needed for the conservation of barbel.

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