Factors affecting the growth and recruitment of cyprinid populations of the River Wensum, Eastern England, with special reference to roach *Rutilus rutilus* (L.)

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Abstract

1. The roach *Rutilus rutilus* population of the River Wensum, Eastern England, has long been the topic of deliberation amongst the angling community due to a perceived decline in their catches since the 1970s. Analysis of fish population survey data collected by the Environment Agency and its predecessor organisations since 1983 revealed that although the roach populations have shown considerable temporal variability around their long-term mean abundances, their estimated abundance in 2009 was not significantly different to that estimated in the 1980s. A significant decline in the abundance of dace *Leusicus leusicus* (L.) was detected, although the abundance of chub *Leuciscus cephalus* (L.) has increased.

2. Annual variation in the recruitment strength of 0 group roach contributed to their temporal variability in population abundance. Recruitment was largely driven by climate, specifically water temperatures in the first year of life of year classes. Point abundance electric fishing sampling conducted in 2007 and 2008 revealed that nursery habitat was limited for the larval and juvenile life stages of the roach population, revealed by only 6 % of all points sampled containing

at least one roach. The probability of roach capture in a sample point only exceeded 0.80 when depths exceeded 1m and macrophyte cover the sampled area exceeded 60 %.

3. The growth rate of adult roach has declined between the 1970s and the present, with this long-term depressed growth only apparent since the initiation of phosphate stripping in the mid to late 1990s. Prior to phosphate stripping, roach growth was largely dependent on water temperature; post-stripping, it was significantly associated with levels of ortho-phosphate. Thus, whilst this reduction in nutrient input into the river was positive for its chemical and biological water quality, it now prevents individual fish growing rapid to a size considered as a 'specimen' by anglers (>1 kg). It is this depressed growth and reduction in the numbers of 'specimen' roach being produced in the river that is contributing to the perceived declines of roach by the angling fraternity.

4. To prevent flooding in the river catchment, a number of flood prevention works have been regularly completed by authorities, including channel straightening and removal of in-stream woody debris. Whilst these tend to have negative consequences for fish production, the cutting of in-stream macrophytes during the summer months to ensure the channel was sufficiently clear to facilitate flood relief flows was measured as having a significant deleterious impact for juvenile roach. Comparison of pre- and post-weed cutting electric fishing point samples revealed presence and abundance of juvenile roach decreased by approximately 50 % following weed cutting.

5. These outputs were used to develop a series of management recommendations to assist the production of roach in the river without compromising other river management perspectives such as flood risk management. A key aspect of this is the creation of in-stream and off-channel refuge and nursery areas for roach that promote their survival and growth across all aspects of their lifecycle.

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Declaration

I confirm that the work presented in this thesis is my own, with the following exceptions:

Chapter 3 is published in collaboration with Dr. Rob Britton as:

Beardsley, H & Britton, JR 2011, ‘Contribution of temperature and nutrient loading to growth rate variation of three cyprinid fishes in a lowland river’. *Journal of Aquatic Ecology*, vol. 46, pp 143-152.

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Helen Beardsley

Chapter 1: Introduction

1.1 The River Wensum

'The River Wensum, the loveliest of Norfolk's rivers' (Wilson, 1997)

The River Wensum is a temperate lowland river in the East of England (source: 52º46’27.59”N, 0º51’42.07”E mouth: 52º37’17.85”N, 01º19’24.29”E, Fig. 1.1) that is of high national and international importance for the purposes of nature conservation. This is reflected by it being selected by English Nature (now Natural England) as a Site of Specific Scientific Interest (SSSI) for 70 km of its length in 1993. Much of this recognition was a consequence of it being a naturally enriched, lowland calcareous river, with over 100 species of aquatic and riparian plants, a rich invertebrate fauna and a diverse fish assemblage (Natural England, 1993). In 2005, the conservation importance of the river was further confirmed by it being designated as a Special Area of Conservation (SAC) under the European Habitats directive (Joint Nature Conservation Committee, 2005). The Annex I primary reason for selection is the River Wensum being an example of a water course of plain to montane levels with water crowfoot vegetation, *Ranunculus fluitantis* and water starwort, Callitricho-Batrachion vegetation. Annex II reason for selection cites the presence white clawed crayfish (*Austropotamobius pallipes*) with populations of bullhead (*Cottus gobio*), brook lamprey (*Lampetra planeris*), and Desmoulins whorl-snail (*Vertigo mouslinsiana*) as qualifying features (Sear *et al*., 2006). Thus, the river is a relatively rare example of a temperate river of calcareous geology (especially in

Eastern England) that has consequently been recognised as having a high degree of conservation designation.

1.2 The fish community of the River Wensum

The diverse macrophyte and invertebrate communities of the river support a relatively diverse fish community (for the UK) that tends to be dominated in the middle and lower reaches by species of the Cyprinidae family, principally roach *Rutilus rutilus* (L.), chub *Leuciscus cephalus* (L.) and dace *Leuciscus leuciscus* (L.). During the 1970s and 1980s, the river attracted a great deal of angling interest at a national level on account of the quality of the fishing available, particularly for *R. rutilus* of specimen proportions (> 1 kg). For example, it was not uncommon for anglers to catch up to 10 kg of these fish with a number of specimens often being of specimen size. Indeed, according to Wilson (1977), the river in the 1970s '………produced fish of an exceptionally high average size and in good numbers too. Its roach are fantastic – growing up to 3 lb and over'.

In the last twenty years, however, the performance of the river's fisheries, especially in regard to *R. rutilus*, has been perceived as having declined substantially 'The glorious specimen roach fishing days on the Wensum are now a distant memory……The roach populations for which the river was nationally famous for have all but disappeared with very few juvenile fish to replace the leviathans as they died off' (Johnson, 2004). Similarly Church (2009) stated 'Anglers recognise the Wensum as being a shadow of its former status from an angling perspective. The commonly held view is that fish populations have been in continual decline……Adding to the frustration is the inaction of any environmental authority to take any action'.

In 2010 John Wilson compiled a report detailing the economic consequences of the deterioration of angling as a leisure activity along the River Wensum valley, over a 30 mile stretch from Norwich to Fakenham. It states 'this has meant a substantial reduction in business to local pubs, shops, post offices, supermarkets, hotels and the once numerous, once prolific coarse fisheries.' Such frustrations attracted a great deal of adverse negative publicity nationally, resulting in local stakeholders (such as controlling angling associations), raising high levels of complaints to the Environment Agency and its predecessors over the situation. In particular, numerous concerns have been raised of the influence on the fish community (and, hence, the fishery) of bird and mammal predation and of river management strategies that are perceived as having had a detrimental effect of processes such as fish recruitment, including channel modification and flow regulation.

1.3 River management of the Wensum

Anthropogenic modifications to the river and its channel have an extremely long history and have resulted in the river channel today having relatively limited lateral and longitudinal connectivity compared to its natural form. In particular, these include large-scale changes to the form of the river channel (Section 1.3.1) and its longitudinal connectivity through the construction of water mills (Section 1.3.2).

1.3.1 Original form of the river channel

Prior to any form of anthropogenic modification, the river would have been a single sinuous channel with adjoining tributaries, surrounded by wet fen and carr woodland that covered the floodplain in its entirety (Sear *et al*., 2006). Clearance of these vast woodland floodplains for settlement and agriculture took place around 4500 years ago, with the river modified such that by medieval times it represented the single thread channel that is present today, (Sear *et al.*, 2006). This represents a loss of lateral connectivity within aspects of the floodplain and subsequent substantial changes in land use (such as urbanisation and intensive agriculture) have impacted its hydrological regime. Nevertheless, the chalk geology of the river still means it is aquifer fed, with ground water an important component of its flow regime (rather than surface run-off).

1.3.2 Water Mills

The river has a long history of water mills being used in the catchment. Mill construction began around 900 years ago for the milling of corn and paper and seed-crushing where the working practice involved impounding the river over a 24 hour period to create a head of water, and then releasing it through the mill stream to power the mill wheel (Atkins, 2010). Pulses of high-energy water would have been discharged at regular intervals, scouring the substrate downstream of the mills (Perrow, 1998). The regulation of water flow in this manner had the effect of creating an impounded section of river immediately upstream of the mill that was relatively deep and slow flowing, whereas immediately downstream were pools and fast flowing riffles. This would have had a profound influence on local flow velocities and the dimensions and structure of the channel. The control of water levels through the mill, sluice and weir operations have played a significant role in the downstream movement of sediment within the Wensum, shaping channel dimensions for hundreds of years (Boar *et al*., 1994).

This shift in the river's flow regime to impounded sections via milling is likely to have had a profound influence on river ecology. The increased diversity in flow and habitat conditions, effectively creating lentic and lotic sections in close proximity, would have enabled the river to support both limnophilic and rheophilic species. For example, limnophilic fish species such as common bream *Abramis brama* (L.), tench *Tinca tinca* (L.) and rudd *Scardinius erythrophthalmus* (L.) would have now been able to tolerate the flow conditions in the impounded areas, with species such as brown trout *Salmo trutta* (L.) continuing to utilise the shallower and faster flowing riffle and pool habitats downstream. Conversely changes in fish community composition have been observed in the upper reaches of the Suffolk Stour following increases in flow as a result of the Ely-Ouse Transfer Scheme. Since the onset of this scheme in the 1980s to supplement the increasing demand for water within the Stour catchment, the fish community structure has shifted from roach, eels *Anguilla anguilla* (L.) and dace to that of predominantly chub, (Clarke, 2009).

Today, fourteen mills and associated water flow control structures exist along the length of the Wensum (Figure 1.2a-b). Indeed, perhaps the greatest change in water usage within the catchment in recent years has been the cessation of water milling (Boar *et al*., 1994), as the majority of mills ceased production by the early 1960s

(Atkins, 2010). Nevertheless, their presence along the river has still resulted in a loss of longitudinal connectivity within the catchment, with the impoundments effectively creating discrete sections of river. Although the effect of these on fish movements (particularly upstream) has not been tested on the Wensum, they are likely to inhibit the movement of fish between sections (Ward & Stanford, 1995; Lucas & Baras, 2001; Trussart *et al.*, 2002).

1.3.3 Management influences on the river in the 20th and 21st Century

There has been a wide range of more recent river management schemes and tools that have further impacted the channel form and its flow regime. These are summarised below:

- Changes in channel form, associated with both the 1953-57 post-war policy of intensive land drainage for agricultural purposes and intensive dredging to increase the carrying capacity of the channel for flood risk management. In particular, removal of large meander loops, alongside straightening and major deviation of the channel, was common at this time. Located within the mid to upper Wensum, a meander loop at Great Ryburgh Common was bypassed in the 1950's when the river was widened, straightened and deepened as part of a land drainage improvement scheme (RCC, 2011). The emphasis was to convey water away as directly and rapidly as possible from the surrounding land, preventing flooding of crops. This resulted in increased habitat homogeneity in the river channel, potentially reducing habitats for fish during crucial parts of their lifecycle, for example, off-channel areas important as nursery areas for larval and juvenile fishes (Welcomme & Cowx, 1998; Garner, 1996; Watkins *et al*., 1997; Copp, 1997).

- Regular channel maintenance, such as dredging, removal of obstructions like woody debris and control of aquatic and riparian vegetation, for the purposes of maintaining the ability of the river to act as a drainage channel for flood relief, occur annually. Similar to the above, such activities all reduce habitat heterogeneity for the fish community (Robertson & Crook, 1999; Mott, 2010; WTT, 2012). Potential consequences include the removal of important spawning substrate such as gravel and tree roots, (Mann, 1973; Mills, 1981; Punchard *et al*., 2008) and reduced availability of refugia from periods of high flow and predators (Mann & Bass, 1997; Pinder, 1997; Allouche *et al*., 2001; Cowx *et al*., 2004).
- Intensive agricultural schemes that reclaimed backwaters and water meadows for crops, resulting in a loss of lateral connectivity between the main river channel and its floodplain. Embankments built-up in many locations along the river for example, from Elsing to Swanton Morley in the middle reaches of the Wensum, removed connectivity by confining the movement of water to within the channel, allowing faster water movement and removing the risk of excess water flowing over into the floodplain. This has the effect of removing areas of reduced flow that would be important for minimising the displacement of juvenile fish in episodes of high flow periods (Copp, 1997; Garner, 1996; Cowx *et al*., 2004).
- Increased abstraction and irrigation through increased water demand in the catchment through substantial residential and industrial development, in conjunction with intensive farming practises in the catchment (Perrow, 1998).

In its lower reaches, the river is now classified as over-abstracted at times of low flow (Environment Agency, 2011). The net effect of this is an overall reduction in river volume and flow that may result in the siltation of important spawning gravels through the reduced capacity of the river to flush out fine sediments (Maitland, 1995; Acreman *et al*., 2000; Cowx et al., 2004).

- Increased sediment loading from agricultural practices and road run-off, smothering gravel substrates and reducing their spawning suitability for rheophilic fishes. For many years Norfolk Anglers Conservation Association (NACA) have been concerned about the increasing sedimentation and compaction of spawning riffles for barbel *Barbus barbus* (L.). The Environment Agency have been working with NACA to gravel jet riffles where spawning activity has been observed, using high power jets of water to clean and loosen gravels.

In combination, these river management practises have resulted in a heavily regulated river that, even in periods of high rains onto saturated land in winter periods, tends to stay within its channel and not flood surrounding lands. In this respect, it has similarities with many UK rivers, especially those in Eastern England such as the Great Ouse that have been primarily regarded in the last fifty years as large flood relief and drainage channels by a number of regulatory authorities (Mann, 1988; Garner, 1997). The channel modifications outlined have resulted in decreased heterogeneity in fish habitats throughout the catchment, with losses of spawning and nursery habitats, including areas of refugia during episodes of high flow (Copp, 1997; Garner, 1996; Cowx *et al*., 2004).

1.4 Factors affecting the fish community and fishery

It was mentioned in Section 1.2 that the River Wensum fishery, especially that component reliant on *R. rutilus*, has been perceived to have declined in recent years. Indeed, articles in the angling press, in conjunction with anecdotal information, have even suggested declines in the populations of indigenous fishes of the river since the 1960s, especially *R. rutilus*. There are no data from this time to be able to support or refute the allegations.

The perceived decline in the *R. rutilus* population was suggested as initially being at least partly attributable to the major incidence of 'Columnaris Disease' that caused the high mortality of considerable numbers of fish in the 1960s (Smith, 1968). Caused by the bacterium *Flexibacter Columnaris* that remains present in all freshwaters, it infects fish through the skin, gills and wounds causing a white fungal-like appearance. All freshwater fish are susceptible to the disease under environmental conditions that are favourable to the bacterium and stressful to the fish, with the majority of outbreaks occurring when the water temperature is between 20 and 30ºC, (Wakabayashi, 1991). For a severe outbreak to occur it would be expected that the fish were already immuno-compromised, as Columnaris is usually a secondary infection in response to an already weakened immune system, for example through a long-term response to a stressor such as poor water quality. Given the lack of data available from the river from this time, any further analysis or interpretation is speculative and without foundation.

The chub is not indigenous to the river and was introduced in the 1950's to enhance the fishery by providing an additional angler-target species (Perrow, 1998). Whilst the species thrived in the habitat conditions present and soon began to dominate angler catches in the mid to lower reaches over the river (John Wilson, personal communication), it is not known whether their populations had any adverse ecological consequences. Nevertheless, aspects of the apparent declines in *R. rutilus* catches in the 1980s to an increase in catches of *L. cephalus* were noticed by the angling community. For example, in 1985, John Wilson (a famous local angler) documented that in the 1970s, the river regularly produced large number of roach of over 2lbs (approximately 1 kg; specimen size) but in the 1980s he stated that the "…..roach stocks are at a painfully low ebb. Yet there are now so many quality chub in the Wensum that it is being referred to as one of the top chub rivers in England, the balance has swung from one species another. Whilst roach are incapable of propagating their kind at present, the chub are having a field day, they are not the reason for the roach decline as many would have it but their presence will certainly hamper roach trying to re-establish themselves because they occupy all the best roach holding areas". More recently, Chris Turnbull, another well known local angler, wrote: "Those of us who have been close to the Wensum over the past 30 years or more will be only too aware of how far the river has declined as a fishery over that time. The glorious specimen roach fishing is now a distant memory, its huge wild trout are now also long gone and even its shoals of dace have become few and far between. Indeed, if it was not for the non-indigenous chub that have flourished throughout many of its reaches, most of the Wensum would have long ago been abandoned as a fishery" (Turnbull, 2007).

The lack of fish stock assessment data from the 1960s and 1970s prevented testing of whether the *R. rutilus* population had actually significantly declined in those time periods, as regular and targeted stock assessment only commenced in 1983 (Chapter 2). Irrespective, in response to the concerns of the local angling community, a period of stock enhancement of *R. rutilus* commenced in the mid-1980s, with approximately 35000 individuals stocked between 1986 and 1996 (Perrow, 1998). It is not known whether these actually had any long-term effect (beneficial or otherwise) on the indigenous *R. rutilus* population of the river.

1.5 Historical fish research in the River Wensum

A report by Perrow (1998) suggested that the cause of the decline of roach was associated with recruitment failure, occurring as an indirect consequence of the changes in the channel form and function arising from the agricultural and flood defence schemes, and the abstraction, that were outlined in Section 1.3. The report highlighted that aspects of river management were adversely impacting the Wensum fishery through sedimentation of spawning gravels, increased concentrations of un-ionised ammonia, increased nutrient levels and through the reduction of suitable habitat required for different life stages of roach, primarily a lack of nursery areas for juvenile fish (Perrow, 1998).

In recognition of the importance of the river for angling and through this increasing concern regarding reduced fish stock abundance (in relation to some fish stock assessment exercises; *cf*. Chapter 2), a Fisheries Action Plan (FAP) was developed for the river by the Environment Agency in 2004. It was developed in partnership with angling club representatives and other stakeholders within the catchment and set out plans to identify and deal with the underlying fish population and fisheries issues associated with the apparent fishery decline, particularly as regards *R. rutilus*. As a response to concerns raised by the FAP, the Environment Agency commissioned an initial study to investigate the past and present fish populations on the River Wensum that documented that eutrophication, sedimentation of gravels and constant low level inputs of ammonia were likely to have been responsible for the apparent declines in fish stocks (Roche, 2007). The factors were identified as causing long-term chronic problems in fish health, ultimately leading to increased mortality through disease (Roche, 2007).

In 2006, Natural England commissioned the Geomorphological Appraisal of the River Wensum Special Area of Conservation. This report provided insight into the physical processes determining sediment transport within the Wensum necessary to develop a tool for river restoration, whilst taking into account the constraints of flood risk management. It stated that the Wensum's gravel bed substrate is left behind as a relic of past geomorphological processes that no longer function in the current flow regime of the river. Through the widespread input of fine sediment and nutrients from road and field run-off, the ecological function of the gravel substrate for spawning activity is greatly reduced. The capacity of the gravel to store fine sediment combined with the lack of gravel flushing is thought to have detrimental effects on the fish populations through the reduction in suitable habitat required by the various life stages of certain lithophylic fish species. Whilst the focus of that particular study was not specific to fish stocks within the Wensum, it does provide an insight into how the channel form and function has changed over time that then had an interaction effect with aspects of the ecology of the fish community.

Whilst the initial investigation into the adult roach community was completed by Roche (2007), this did not consider any aspects of the population dynamics and life history traits of this fish and how these may have changed temporally and in response to environmental change. There were also no data available on the recruitment of the fish, whether from information derived from the adult stock or through targeted surveys on the 0 group fishes. Whilst other studies have surmised that changes in water quality, river management and lack of suitable habitat on fish populations have caused issues, these have been piecemeal and failed to test important relationships between fish population metrics and available environmental data (Ros Wright, personal communication). Consequently, further research was necessary to determine and understand the long-term factors affecting the fish populations (in both adult and juvenile life phases) of the River Wensum, and how these may have resulted in reduced population abundance of some species in the last 30 years that then impacted aspects of fishery performance. This is the focus of this study.

1.6. Thesis objectives

The aim of this thesis is to determine the long-term population status of *R. rutilus, L. leusiscus and L. cephalus* in the River Wensum, and identify the important environmental variables that influence the population processes that determine their abundance. This may quantify temporal shifts in aspects of the adult stock in relation to other species in the fish community.

The management implications of the outputs of these aims will be discussed. The specific objectives are to:

(1) Identify spatial and temporal changes in the fish community composition and population abundance of angler-targeted cyprinid species and identify the potential biotic and abiotic factors that may be influencing them (Chapter 2);

(2) Analyse the age structure and somatic growth rates of angler-targeted cyprinid species between 1970 and 2009, with identification of the role of abiotic and biotic variables in their determination (Chapter 3);

(3) Determine the temporal trend in recruitment of *R.rutilus* in the river and identify the influences of climate, hydrology and growth in their first year of life on the recruitment process (Chapter 4);

(4) Evaluate the key habitat features for the presence and abundance of 0 group roach and other fishes in the community. Ascertain the effect of river management on 0 group fishes, with emphasis on roach through a case-study testing the effects of weed-cutting on 0 group fish abundance, biota and physical characteristics of the river (Chapter 5);

(5) Design a series of management recommendations that aim to maintain the requirements for flood defence operations but without further compromising the roach (Chapter 6).

The rationale and specific hypotheses for each of these objectives will be outlined in the introduction to each relevant chapter.

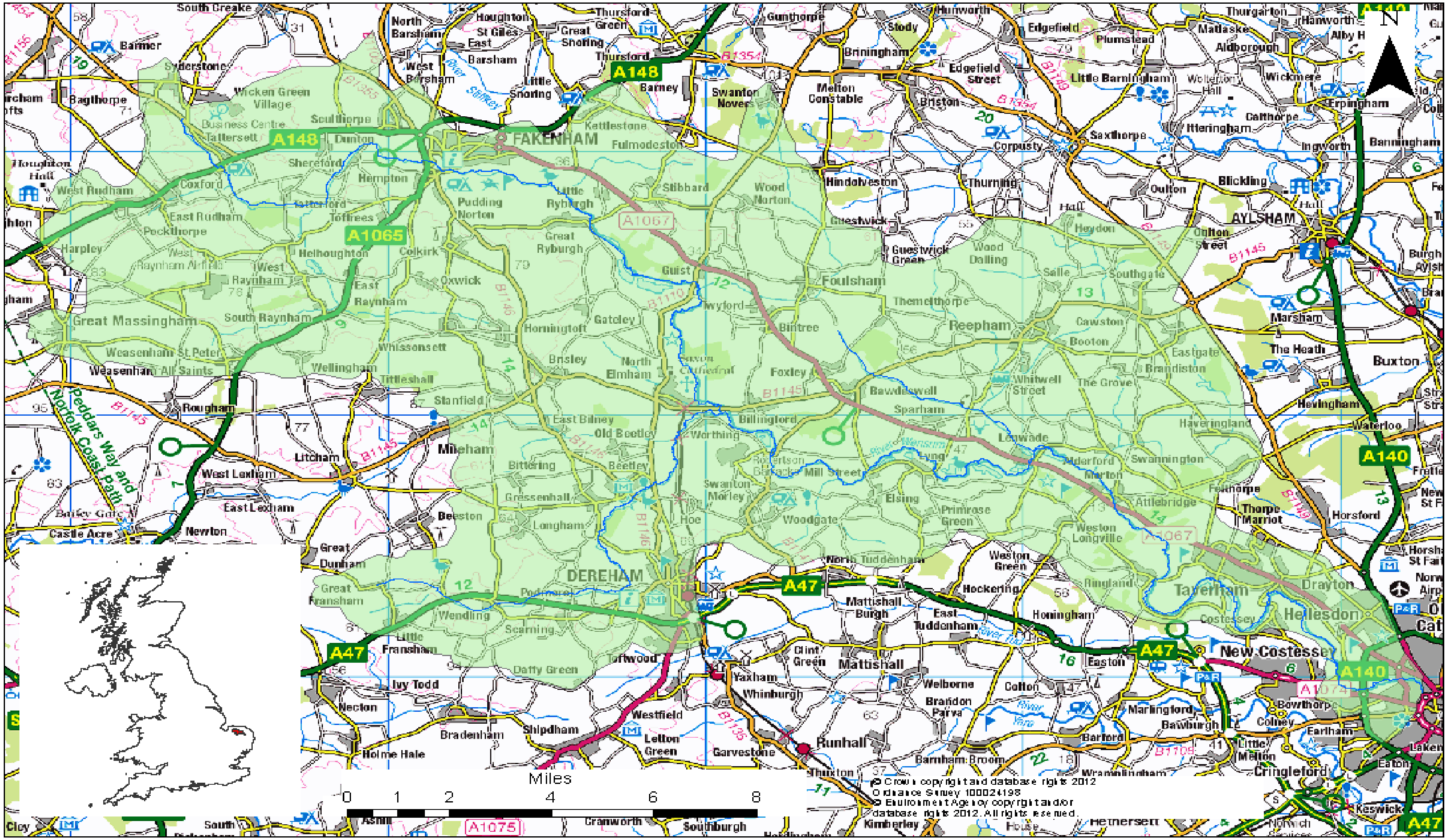

Figure 1.1. The River Wensum catchment; the area shaded in green shows the drainage area.

a)

b)

Figure 1.2. (a) Top: Lenwade Mill by-pass channel and (b) Bintree Mill by-pass channel. (Photos: Atkins, 2010).

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Chapter 2: Spatial and temporal relationships in fish community structure and population abundance

2.1 Introduction

A complex array of interacting physical, chemical and biological factors have been considered as important in influencing the distribution and abundance of fish populations (Symons & Heland, 1978; Bagliniere & Champigneuille, 1982; Cowx, 2001). Biological factors, such as availability of food resources, population density, predation, competition and disease, and chemical factors associated with water quality such as eutrophication, are fundamentally important in regulating riverine fish populations (Bagliniere & Champigneuille, 1982; Grenouillet *et al*., 2001). However, underpinning these factors in temperate rivers is the density-independent, abiotic factor of climate that plays a key regulatory role in the population dynamics of cyprinid fishes (e.g. Mills & Mann, 1985; Grenouillet *et al*., 2001; Nunn *et al*., 2003, 2007; Britton *et al*., 2004; Chapter 3, 4).

The relative importance of different abiotic factors on the abundance, growth and recruitment of riverine cyprinid fish populations varies spatially and temporally, suggesting that significant shifts in these variables may cause significant shifts in abundance, growth and recruitment rates (Nunn *et al*., 2003, 2007). However, no single factor is directly responsible for constraining the development of coarse fish populations but it is their interactions that may be more important (Cowx, 2001; Nunn *et al*., 2003). Additional anthropogenic factors have also been found to impinge on fish populations, including past and present river management. For example, Mann (1988) suggested that the construction of canals and interconnecting waters during the 18th and 19th Centuries facilitated the spread of some fish species between catchments.

Water quality is perhaps one of the main factors determining fish communities with rivers in heavily industrialised areas being prone to chronic and acute pollution events (Nolan & Guthrie, 1998). Other human impacts affecting fish populations include acidification, introduced species, eutrophication and barriers to migration (e.g. Byers, 2002; Pont *et al*., 2006). Resident fish communities will thus respond to the consequent shifts in their environmental conditions, for example showing changes in their reproductive and recruitment rates that will subsequently affect their abundance (Maitland, 2004). In many lowland rivers, including the River Wensum (Section 1.3.3), intensive agricultural practices have had long-term impacts on riverine ecosystems via accelerated drainage processes through wetland removal and changes in floodplain land use that, in combination, inhibit productivity of the natural resources through changes in habitats and water quality (Bayley, 1995). Habitats become less heterogeneous and connected (Britton & Pegg, 2011), diffuse pollution increases and the water chemistry becomes more eutrophic (Kronvang *et al*., 1995; Sliva & Williams, 2001). For fish, this may be reflected by shifts in the species composition of their community to more generalist and pollution tolerant species (Noble *et al*., 2007), and declines in pollution sensitive species' distribution and abundance, such as barbel (Britton & Pegg, 2011). Water-borne diseases in the River Wensum by the late 19th Century, were rife and the beauty of the river destroyed" (Countryside Agency, 2006), although the catchment was not subject to heavy industrial discharges, inputs of phosphates and nitrates from agricultural and sewage waste were commonplace throughout the catchment, thus an understanding of the physical, chemical and biological factors and their interactions within the River Wensum is vital.

In the last 50 years, many European rivers have undergone significant improvements in their biological and chemical water quality following long periods of decline that were initiated by pollutants discharged via new industrial processes in the Industrial Revolution (Amisah, 2000a,b). For example, in England, rivers running through heavily industrialised areas, such as the Rivers Trent, Mersey and Don, had fish populations that were severely impacted (to the point of their complete absence) by a range of pollutants including ammonia and heavy metals, yet in recent years all are considered as ‘recovering’, being recognised as major fisheries based on cyprinid fishes, with Atlantic salmon *Salmo salar* also known to be increasingly present, especially in the Mersey and Trent (APEM, 2007; Cowx & Broughton, 1986; Amisah, 2000a,b; Lyons *et al*., 2007).

In the last decade, many rivers including the River Wensum have been further improved through decreasing the extent of their eutrophication by reducing their nutrient loading (Wade *et al*., 2002). For example, reduced phosphate loadings of sewage effluents have been achieved through phosphate stripping, resulting in reduced concentrations in the rivers concerned (House *et al*., 1995; Neal *et al*., 2002). This may be important given that eutrophication can have profound effects on fish communities and populations, with cyprinid fishes such as roach dominating communities in highly eutrophicated systems (Willemsen, 1980; Winfield, 1992).

Given these long-term declines and then subsequent improvements in many of the physical and chemical characteristics of lowland rivers then it is important that the temporal and spatial relationships in their fish communities are understood in order to provide underlying knowledge of how fish interact with their environment (Mann, 1988). Understanding the processes and factors that influence the community structure are thus fundamental to the management of fisheries and aquatic ecosystems in general. For example, comprehension of the complex relationship between underlying geology, nutrient input, respiration and photosynthesis of aquatic plants governing the River Kennet has been vital for its management (Neal *et al.*, 2000). Once the influences of these factors have been identified then appropriate remediation and/ or mitigation measures may be implemented if they are deemed necessary. In lowland rivers, measures may include schemes that rehabilitate the river habitat for fish (such as for spawning and nursery areas etc), re-establishing the lateral and longitudinal connectivity of the river to facilitate fish migration and enhancing fish populations through restocking programmes (Britton & Pegg, 2011).

For any of these management measures to be successfully implemented requires some understanding of the current constraints on the fish stock that would be typically gained through stock assessment exercises using appropriate methodologies (Cowx, 1991). In England and Wales, under Section 6.6 of the 1995 Environment Act, the Environment Agency (EA) has a statutory duty to maintain, improve and develop fisheries with an associated policy that aims to maximise the social, recreational and economic benefits arising from the sustainable exploitation of the fish stocks that underpin fisheries. It is obliged to ensure the conservation and maintenance of the diversity of freshwater fish, salmon, sea trout and eels and to conserve their aquatic environment (Environment Agency, 2003). Part of this is reliant on the long-term monitoring of river fisheries and their fish stocks across England and Wales, including the River Wensum, where stock assessment exercises have been carried out by the Environment Agency and its predecessor organisations since 1983, providing information about the long-term status of its fish populations for over 25 years. The rationale for completing these surveys has been strengthened through the internal requirements of the EA’s National Fisheries Monitoring Programme (NFMP) that was implemented in 2001, and especially the Water Framework Directive (WFD) that requires fish to be monitored as a metric of ecological status (Noble *et al.*, 2007). Fish are recognised as strong indicators of ecological status as they occupy a wide range of ecological niches and operate over a wide range of ecological scales (Simon, 1999).

This long-term monitoring of the fish stocks enables the temporal and spatial relationships in aspects of their populations to be determined and so allows temporal trends and changes in fish stocks and fishery performance to be identified. In the River Wensum, these surveys have been completed, on average, every three years when assessments of the fish populations present at 18 sites are completed. The aim of this chapter is to thus provide an overview of the outputs from these fish stock surveys between 1986 and 2009 in order to provide a temporal perspective of changes in the fish populations and how these may relate to angler perceptions of fishery decline. Note that data on the age, growth and recruitment of the fishes are the subject of Chapters 3 and 4. Allied to these outputs is the identification of the long-term trends in metrics of water quality of the river (where data were available). Thus, the objectives of this Chapter were to: (i) describe the long-term trends in aspects of the chemical water quality of the River Wensum, particularly regarding nutrient enrichment; and (ii) identify the long-term patterns in the fish species composition and abundance in the river.

2.2 Materials and Methods

2.2.1 Water chemistry

Aspects of the water chemistry of the River Wensum have been monitored by the EA and its predecessor organisations since at least 1981. Monitoring has been through data collected by a combination of automated recording stations and water samples collected by officers from across the catchment that were subsequently sent to EA laboratories for analysis. Consequently, the first step of this exercise was to access the EA water quality archive for the River Wensum and source all of the water quality data available between 1981 and the present. During this exercise, it was found that in 1996, general improvement works were made at two of the largest Sewage Treatment Works (STW) serving the catchment at Fakenham and East Dereham (Table 2.1), followed by the implementation of phosphate stripping technology shortly afterwards. It may thus be anticipated that declines in phosphate concentrations may be apparent from 1997.

This data mining exercise provided chemical water quality data for phosphate (as biologically available orthophosphate), biochemical oxygen demand (BOD), total oxidized nitrogen (TON) and ammonia (all units in mg l^{-1}) for the river between 1981 and 2010. As these data were collected regularly throughout each year but not daily, mean annual values were determined with their standard deviation. Subsequent analyses aimed to determine whether their mean annual values changed temporally and if so, whether these were statistically significant (linear regression with ANOVA tests). For linear regression, the independent variable from taken as the number of years from the first data recording, rather than the actual year; the dependent variable was the mean annual value of the chemical parameter concerned. Central England Temperature (CET) data was also collected between 1981 to 2010.

2.2.2 Temporal and spatial relationships of the River Wensum fish populations

Fish stock assessment surveys of the River Wensum were completed at 18 sites on average every 3 years by the EA (Table 2.1; Fig 2.1). Sites range in width from 7 to 23 m in width, 0.5 to 3 m in depth (Table 2.1), with habitat comprising of riffle and pool reaches, with some lengths of deeper glides. Note there were no surveys completed on the river between 1997 and 2002 due to changes in the survey programme, and some data were available from surveys collected in 1989 and 1991 (Chapter 3). Thus, data were available from 1986, 1990, 1994, 2003, 2006 and 2009 (with supplementary data from 1983, 1989 and 1991 in the form of scale packets obtained from the National Fish Laboratory archives).

Table 2.1 Locations of the River Wensum stock assessment sites, 1986 to 2009. The site number refers to those on Figure 2.1. Please note site dimensions were specific to surveys undertaken in 2006.

		Length (m)	Width (m)	Area (m^2)	Upstream NGR
1	Fakenham Common	210	9.5	1995	TF9250629236
2	Pensthorpe Hall	180	7.5	1350	TF9444928804
3	U/S Gt Ryburgh	170	6.0	1020	TF9638827484
4	D/S Gt Ryburgh	170	7.5	1275	TF9659426837
5	D/S Guist Mill	180	13.0	2340	TF9976124933
6	U/S Bintree Mill	240	15.0	3600	TF9968824479
7	County School	180	7.0	1260	TF9922622732
8	D/S Billingford Bridge	200	11.0	2200	TG0075119866
9	Swanton Morley	200	11.0	2200	TG0180179361
10	D/S Elsing Mill	200	18.0	3600	TG0510217838
11	Lyng Pits	200	13.1	2620	TG0616218693
12	U/S Lenwade Mill	205	23.0	4715	TG1009517902
13	Attlebridge Hall Farm	180	13.0	2340	TG1387515572
14	D/S Ringland Bridge	200	14.6	2920	TG1393113259
15	Alders Spinney	170	9.0	1530	TG1667612847
16	Blakes Meadow	180	10.6	1908	TG1770113206
17	U/S Drayton Green Lane	210	10.0	2100	TG1854512884
18	Hellesdon Rd (Albert's)	150	15.3	2295	TG1991409798

When each site was surveyed, the fish populations were isolated by stop-nets positioned across the width of the channel at the up- and downstream boundaries, with these marked out according to the length of the site. If site dimensions differed due to conditions present on the survey day, lengths and widths were updated for the specific site and survey year on the National Fisheries Populations Database (NFPD) in order that the actual area surveyed each year was used in subsequent density/biomass calculations (Table 2.1). Sampling was completed using electric fishing and occurred in August and September of each survey year, when the fish populations were considered well dispersed (Jordan & Wortley, 1985). Until the 1990 surveys, the electric fishing was completed using 50Hz Alternating Current (AC). After that time, 50 Hz Pulsed Direct Current (PDC) was used on account of it being less harmful to fish (Allen-Gil, 2000). The electric fishing was completed using two 0.6 m diameter hand-held anodes powered by a 2.5KVA generator that produced between 3-8 amps. The effect of the electricity in the water was to temporarily immobilise the fish within the electric field, enabling their removal by hand nets. The fish were then held in water-filled holding bins whilst the rest of the survey was completed. The physical conditions at each site (width, depth etc.) dictated whether the electric fishing took place from a boat or a combination of boat and wading.

In each survey, the fishing consisted of three consecutive hauls (‘runs’) of equal fishing effort. At their conclusion, the captured fish were counted, identified to species level, measured (fork length, nearest mm) and a sample of between three and five scales removed for the purposes of the ageing the fish (Chapter 3) with data for each survey recorded on NFPD. Individual weights were not recorded but were reconstructed later using standard EA length-weight equations (Froese, 2006). After their processing, the fish were then returned alive to the river. Quantitative population estimation using the Carle & Strub population model (Carle & Strub, 1978) enabled the calculation of mean biomass and density estimates with 95 % confidence limits for each fish species that were > 99 mm present during the surveys, where biomass was determined from the predicted weights. The maximum weighted likelihood equation of Carle & Strub provides robust population estimates from data derived from sequential catches, even under circumstances with no or very poor catch depletion (Carl & Strub, 1978). Density and biomass estimates for only individuals > 99 mm in fork length are reported. Fish below this length were not considered in the estimates as although electric fishing is one of the most efficient and least selective methods of fish capture, it is biased against catching small fish (Zalewski & Cowx, 1990). Examination of data of surveys from 1986 to 1997 revealed that Carle & Strub density and biomass estimates for fish < 99mm were invalid, for this reason outputs for fish > 99mm were utilised.

The electric fishing surveys enabled the relationships in the spatial and temporal patterns in mean density and biomass of species and surveys, along with their 95 % confidence limits, to be identified and examined. Long term means for both density and biomass (using spatial survey data) were calculated and plotted to ascertain with 95 % confidence whether a particular year's density/biomass estimate differed significantly from the long term mean. Species specific trends in total mean density and biomass were tested against their long-term means for the angler-target species of roach, chub, dace in order to identify any temporal shifts in their population abundances.

2.3 Results

2.3.1 Temporal relationships of water chemistry parameters

The major change in the water chemistry of the river relates to the change in its nutrient enrichment that occurred in the late 1990s after the implementation of the phosphate stripping on the catchment's major sewage works (Section 2.2.1). From 1981 to 1997, the mean annual orthophosphate concentrations were relatively high, albeit with high variability within and between years, but with the highest mean recorded in 1996 at 0.72 ± 0.46 mg l^{-1} versus the long-term mean concentration of 0.32 mg l^{-1} (Fig. 2.1). Since 1997, the general pattern of orthophosphate concentration in the river has been of progressive decline (Fig. 2.2), with the temporal trend being significant (R^2 = 0.45, $F_{1,28}$ = 23.2, p < 0.01). By 2000, the mean annual concentration had reduced to 0.13 ± 0.02 mg 1^{-1}, a reduction of 59 % from the long-term mean. By 2005, the mean was 0.07 ± 0.02 mg 1^{-1} (78 % below the long-term mean value). From 2005 to 2010 annual mean orthophosphate concentrations have remained consistently stable, approximately 0.07 mg 1^{-1} (Fig. 2.2). Grouping the data into the period before phosphate stripping (1981 to 1996) and after (1997 onwards) enabled use of ANOVA to compare the mean concentrations of orthophosphate between the periods. Pre-stripping, the mean concentration was 0.47 ±0.15 mg 1^{-1} (range 0.13 to 0.72 mg 1^{-1}) compared to 0.19 ± 0.14 mg 1^{-1} post stripping, with this difference being significant ($F_{1,24}$ = 21.05, p < 0.01).

Concentrations of ammoniacal nitrogen (as N) and biological oxygen demand (BOD) followed a similar pattern to that described for orthophosphate (Fig. 2.2).

Prior to stripping and improvement works to the main STW serving the catchment, both parameters displayed much variability in their annual mean concentrations from 1981 to 1996. After 1996, levels for both reduced consistently below their associated long-term means, with this overall temporal decline being significant (ammonia: $R^2 = 0.60$, $F_{1,24} = 25.81$, $p < 0.01$; BOD: $R^2 = 0.60$, $F_{1,24-} = 29.87$, $p < 0.01$). The annual mean for ammoniacal nitrogen in the period 1981 to 1996 was 0.10 mg ± 0.03 mg 1^{-1} ranging from 0.06 to 0.15 mg 1^{-1}, compared to the period from 1997 to 2005 where the annual mean concentration reduced to 0.05 ± 0.01 mg^{-1} with a range of 0.03 to 0.07 mg 1^{-1}, (Fig. 2.2b). The annual means pre- and post-stripping were significantly different ($F_{1,24} = 25.81$, $p < 0.01$). Annual mean BOD during the period 1981 to 1996 was 1.80 ± 0.21 mg 1^{-1} (range 1.43 to 2.23 mg 1^{-1}; (Fig. 2.2c). As with orthophosphate and ammonia, annual mean BOD in the period 1981 to 1996 was significantly lower than 1997 to 2005 ($F_{1,24} = 29.87$, $p < 0.01$).

The mean annual concentration of total oxidized nitrogen (TON) during 1981 to 1996 (7.03 ± 0.69 mg 1^{-1}) was not significantly different to the period from 1997 (7.18 ± 0.44 mg 1^{-1}) ($F_{1,24} = 0.31$, $p > 0.05$); Fig. 2.3), with the overall temporal trend also being non-significant ($R^2 = 0.03$, $F_{1,24} = 0.31$, $p > 0.05$). Thus, the source of TON into the river does not appear to relate to the discharges of treated sewage effluents and so are more likely to be from diffuse sources associated with agriculture. Between 2005 and 2010, mean annual TON concentrations were significantly below the long-term mean value of 6.98 mg 1^{-1} ($F_{1,28} = 6.24$, $p < 0.05$) suggesting that a reduction in TON entering the river from diffuse sources was taking place (Fig. 2.3a). Mean annual air temperature throughout the period has varied considerably around the long-term mean of 10.1ºC (Fig. 2.3b).

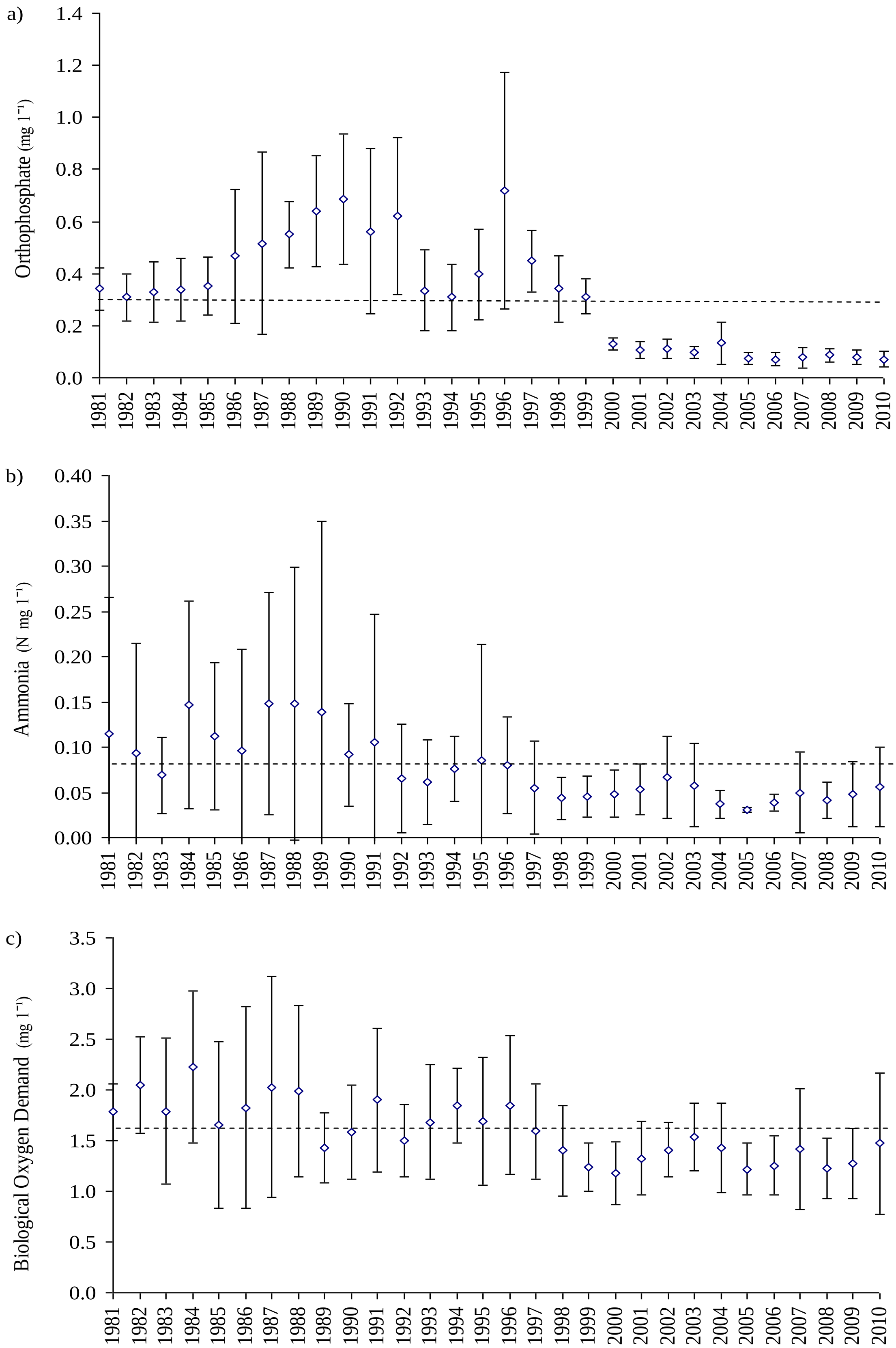

Figure 2.2 Annual mean (± SD) values of (a) orthophosphate, (b) ammoniacal nitrogen and (c) Biological Oxygen Demand in the River Wensum from 1981 to 2010. Long-term mean values represented by dashed line.

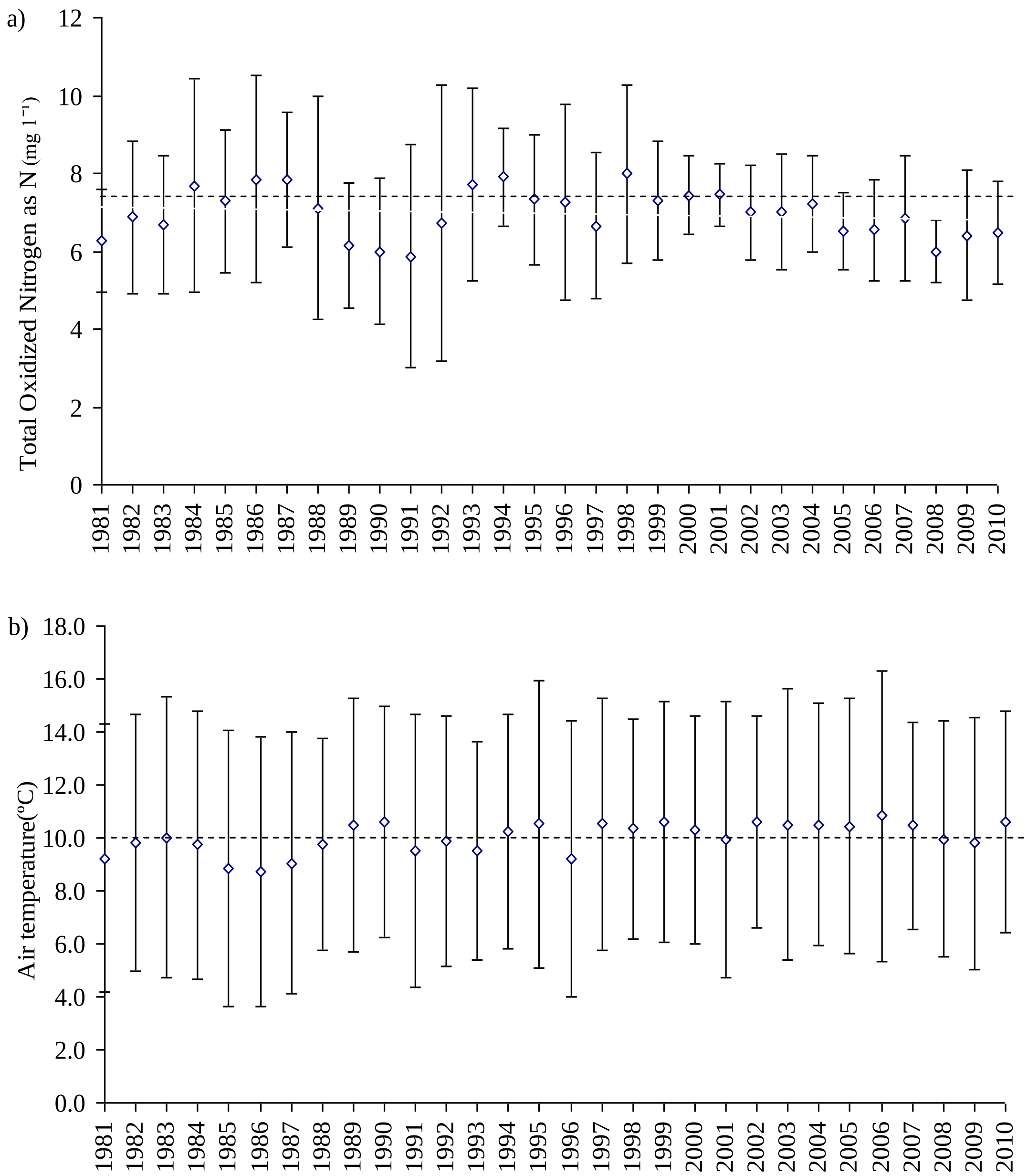

Figure 2.3 Annual mean (± SD) values of (a) Total Oxidized Nitrogen in the River Wensum from 1981 to 2010 and (b) air temperature using Central England Temperature (CET) records. Long-term mean values represented by dashed line.

2.3.2 Temporal and spatial relationships in fish species composition and abundance

Overview of section

Due to the amount of survey information collated during the EA surveys, this section provides only an overview of the data relevant to the thesis, focusing on data from roach, dace and chub, with mention of other species perch *Perca fluviatilis* (L.), pike *Esox lucius* (L.) and eels only where appropriate. In Figure 2.5 and Appendix 1, 'others' constitute gudgeon *Gobio gobio* (L.), stoneloach *Barbatula barbatula* (L.), brown trout, brook lamprey, bullhead, 3-spined stickleback *Gasterosteus aculeatus* (L.), 10-spined stickleback *Pungitius pungitius* (L.) and minnow *Phoxinus phoxinus* (L.) The focus of this chapter is primarily on temporal changes although differences between specific sites over time are discussed. Data on site differences by survey year are provided in Appendix 1.

Fish species composition

The fish community of the River Wensum is relatively diverse for a temperate lowland river, with 20 fish species encountered in surveys over the entire period. Although European eel *Anguilla anguilla* (L.) was a dominant species in surveys between 1986 and 1997, particularly of the mid to upper sites, their proportion in recent surveys throughout, has declined significantly (density: $R^2 = 0.61$, $F_{1,5} = 7.79$, $p < 0.05$; biomass $R^2 = 0.55$, $F_{1,5} = 6.05$, $p < 0.01$), (Fig. 2.5a-b; Fig. 2.6f; App. 1a-b).

Of the angler target species, the percentage contributions to survey catches of roach, dace and chub within the surveys have varied temporally. Nevertheless, roach maintained a minimum contribution of 20 % to the total density during all survey years, with the exception of 1986 (8 %) and 1997 (2 %). Dace and chub have both upheld 10 % minimum contributions to all surveys, with chub remaining at consistent values throughout the period. (Fig 2.5a-b).

Estimates of fish abundance and biomass

The long-term mean density of fish (all species > 99 mm) across the 18 sites and surveys (Table 2.1) was 3.8 $100m^{-2}$. Overall, from 1986 (5.34 fish.$100m^{-2}$) to 2009 (3.63 fish.$100m^{-2}$) there has been a significant temporal decline in total fish density ($R^2 = 0.55$, $F_{1,5} = 6.06$, $p < 0.05$; (Fig. 2.4a). Peak density of fish was recorded in 1986 at 5.34 $100m^{-2}$ (41 % above the long-term mean), with eel (2.0 fish.$100m^{-2}$), dace (1.8 fish.$100m^{-2}$) and roach (0.5 fish.$100m^{-2}$) dominating the catch (Fig. 2.5a; Fig. 2.6).

The long-term mean biomass of fish (>99mm) was 1045.0 g.$100m^{-2}$, with an overall decline of 13 % from 1986 levels to those of 2009 (Fig. 2.4b). Peak biomass was recorded in 1986, although it was dominated by eel (415.4 g.$100m^{-2}$), chub (347.2 fish.$100m^{-2}$) and pike (165.3 fish.$100m^{-2}$) rather than roach (Fig 2.5.b). This overall pattern of fish biomass decline was not significant ($R^2 = 0.45$, $F_{1,5} = 4.03$, $p > 0.05$).

Roach

Roach were a major component of the fish community of the river across the surveys with a long-term mean density of 0.68 fish.100m² and mean biomass of 77.1 $g.100m^{-2}$ (Fig. 2.6a). Estimates of density and biomass of roach were highest in 1990 (1.39 $fish.100m^{-2}$ and 136.4 $g.100m^{-2}$ respectively). The survey of 1997 recorded the lowest density (0.08 $fish.100m^{-2}$) and biomass (8.2 $g.100m^{-2}$) estimates (Fig. 2.6a). Overall, there was no significant difference in roach density or biomass over the entire study period ($F_{1,125} = 1.23$, $p > 0.05$; $F_{1,125} = 0.25$, $p > 0.05$ respectively). Post-hoc Tukey's HSD tests also showed no significant differences between surveys. Furthermore, analysis of surveys before and after phosphate stripping installations revealed also that there is no consequent and significant change to roach density (ANOVA $F_{1,125} = 0.99$, $p > 0.05$) or biomass (ANOVA $F_{1,125} = 0.45$, $p > 0.05$).

Dace

Dace populations have exhibited considerable change over the study period with recent surveys recording relatively low population estimates. The species was a major component of the uppermost survey sites between 1986 to 1990. Most recent surveys of the same sites in 2006 and 2009 reveal significantly lower densities of dace, now being dominated by pike and 'other' species, namely bullhead, stoneloach and brook lamprey (App. 1a-b). The long-term mean density was 0.7 $fish.100m^{-2}$ and biomass at 50.4 $g.100m^{-2}$ (Fig. 2.6b). In 2006 and 2009, mean densities reduced to 0.4 $fish.100m^{-2}$ and 0.3 $fish.100m^{-2}$ respectively compared with 1.8 $fish.100m^{-2}$ in 1986. The biomass in 1986 was 146.8 $g.100m^{-2}$ compared to 13.5 $g.100m^{-2}$ in 2009.

Whilst the overall pattern of total mean density of dace is significant according to linear regression ($R^2 = 0.63$, $F_{1,5} = 8.64$, $p < 0.05$), when analysed using survey year as the grouping variable then across the 18 survey sites there was sufficient intra-year variability between sites that significant differences could not be detected between surveys (ANOVA $F_{1,125} = 1.78$, $p > 0.05$). For biomass, however, both their overall trend was one of significant temporal decline ($R^2 = 0.69$, $F_{1,5} = 11.34$, $p < 0.05$), with significant differences observed between the survey groupings (ANOVA $F_{1,125} = 2.61$, $p < 0.05$). Post-hoc Tukey's HSD tests revealed the biomass of dace in 2009 was significantly lower than 1986.

Chub

The chub population estimates remained relatively stable throughout the duration of the study period, with mean density and biomass exhibiting little deviation around the long-term mean value (density $R^2 = 0.6$, $F_{1,5} = 0.02$, $p>0.05$; biomass $R^2 = 0.19$, $F_{1,5} = 1.25$, $p > 0.05$). The long-term mean density for chub was 0.4 $100m^{-2}$ and biomass at 275.6 g $100m^{-2}$ (Fig. 2.6c). Peak density was observed in 1990 at 0.47 fish.$100m^{-2}$. Chub have expanded in range from the early surveys where from 1986 to 1997 they were not captured above Billingford Bridge, in 2009 they were captured at Pensthorpe Hall (App. 1a-b). As with roach, the chub population estimates suggested their abundance was cyclic and so likely to be associated with long-term recruitment patterns, although this is purely speculative. There were no significant changes in chub density and biomass over the study period or between surveys ($p > 0.05$).

Perch and pike

Both perch and pike significantly increased in density and biomass during the survey period (perch density: $R^2 = 0.54$, $F_{1,5} = 5.90$, $p < 0.05$ and biomass $R^2 = 0.59$, $F_{1,5} = 7.11$, $p < 0.05$; pike density: $R^2 = 0.77$, $F_{1,5} = 17.11$, $p < 0.05$ and biomass $R^2 = 0.80$, $F_{1,5} = 20.61$, $p < 0.05$) (Fig. 2.6d-e). Post-hoc Tukey's HSD tests in ANOVA revealed the mean density and biomass of perch observed in 2009 was significantly higher than that recorded in all other survey years ($p < 0.05$). For pike, the mean density and biomass recorded in 2003, 2006 and 2009 was significantly higher than in other surveys ($p < 0.05$). Surveys from 1986 to 1997 pike were captured in surveys primarily in the lowermost reaches of the Wensum. 2003 to 2009 surveys reveal their increased distribution throughout the survey sites particularly the uppermost sites (App. 1a-b). It was apparent that increased density and biomass of both species were captured in the post phosphate stripping survey period (perch density: ANOVA $F_{1,125} = 10.24$, $p < 0.01$ and biomass ANOVA $F_{1,125} = 13.23$, $p < 0.01$; pike density: ANOVA $F_{1,125} = 32.37$, $p < 0.01$ and biomass ANOVA $F_{1,125} = 19.34$, $p < 0.01$.

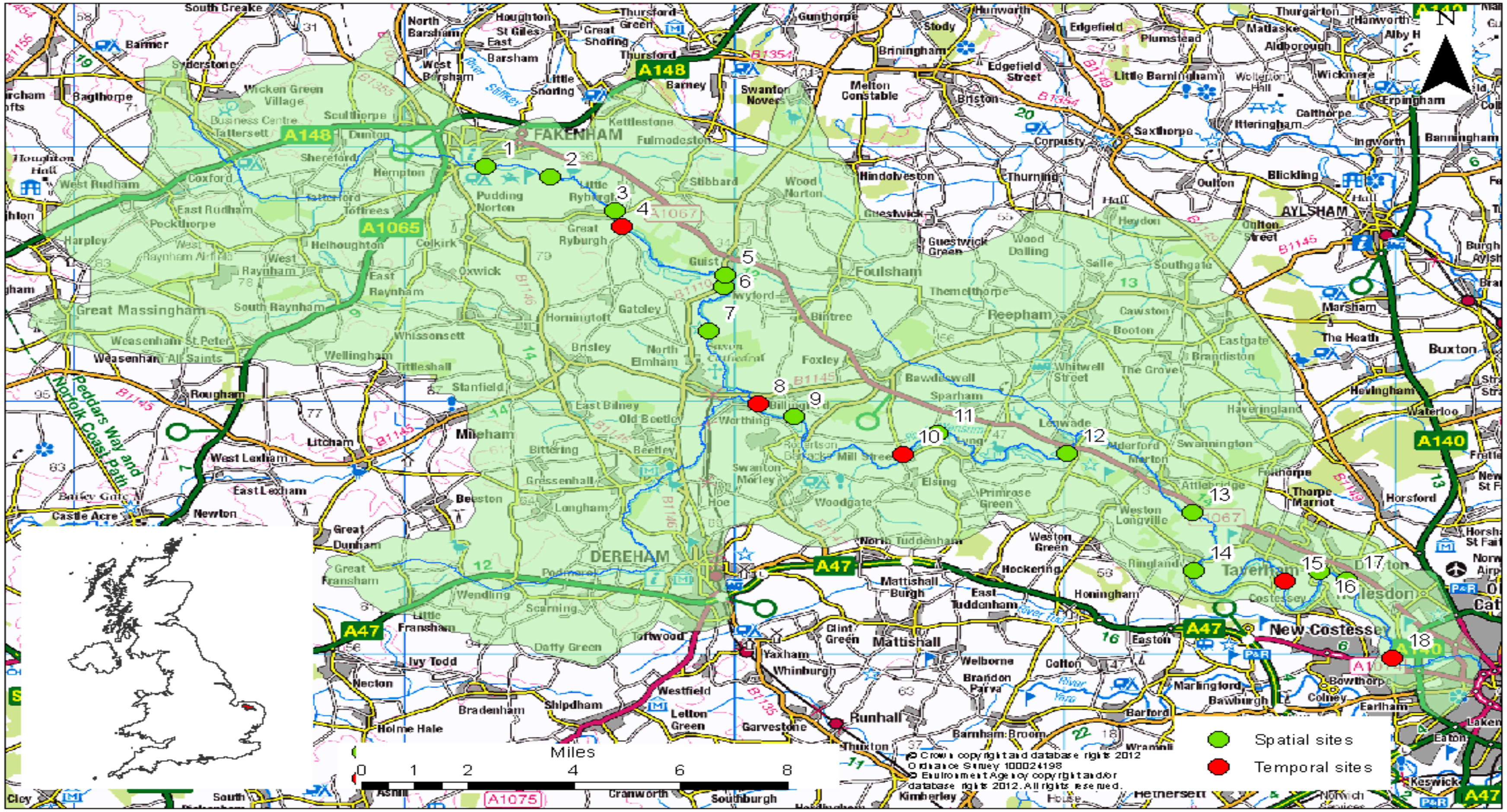

Fig 2.1. Site locations of the fish stock assessment exercises of the River Wensum, the area highlighted in green shows the drainage area. Numbers relate to Table 2.1. Red shows temporal survey sites, green sites show spatial survey sites.

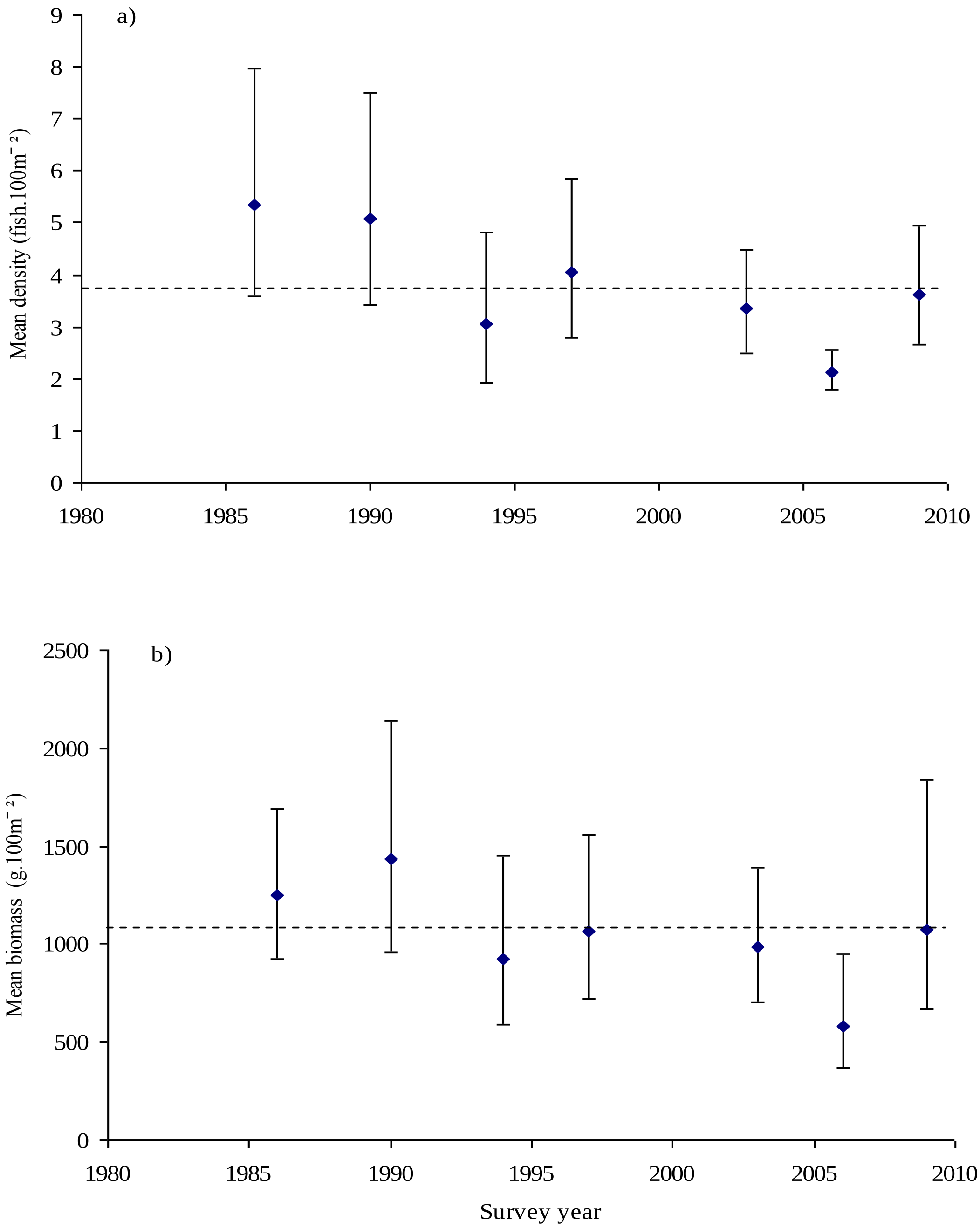

Figure 2.4 Estimated (mean ± 95% CI) density (a) and biomass (b), of total fish sampled (>99mm) in the River Wensum between 1986 to 2009, in comparison to the long-term means, (represented by dotted line).

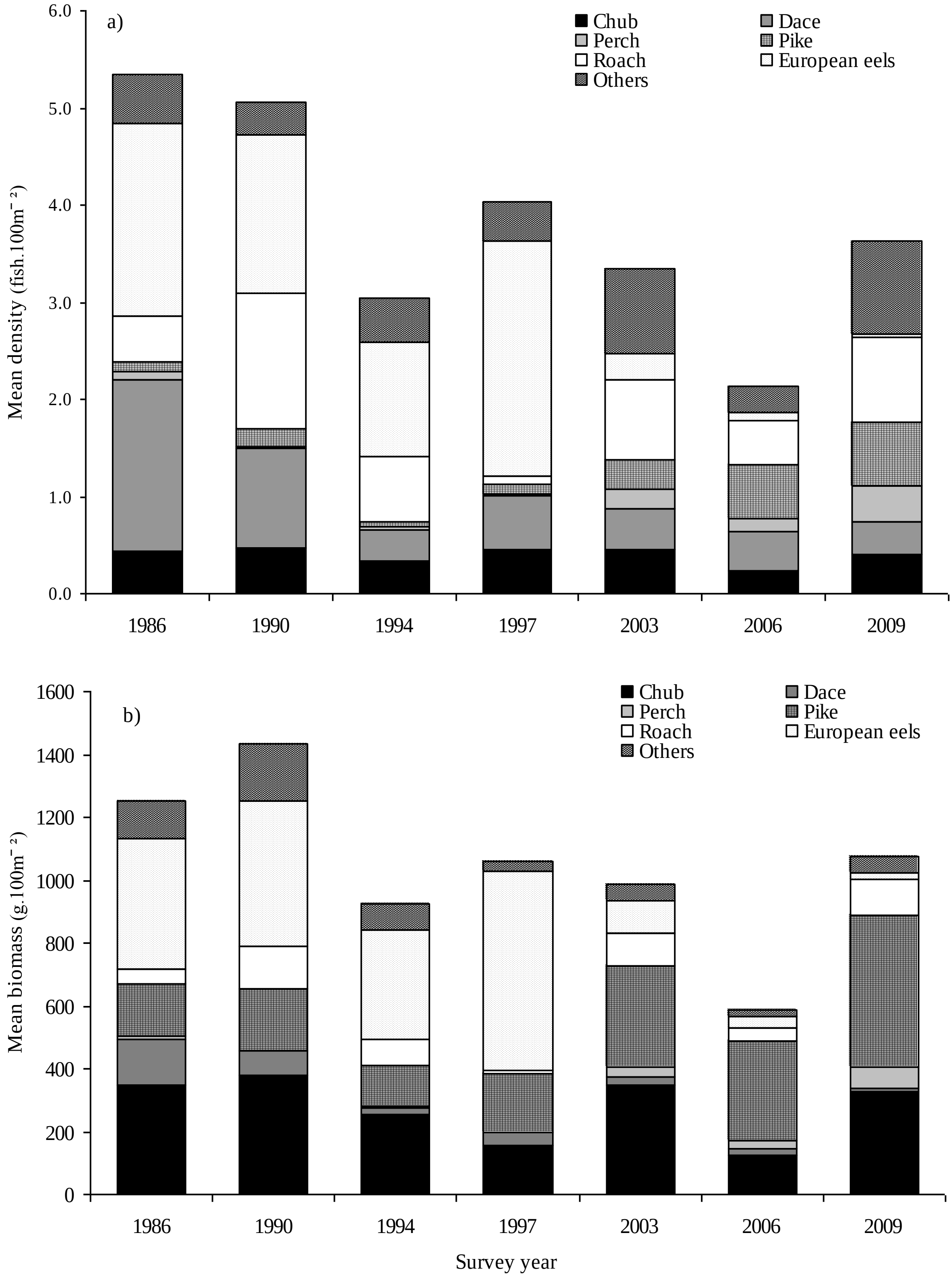

Figure 2.5 Estimated mean density (a) and biomass (b), of fish species sampled (>99mm) in the River Wensum between 1986 to 2009.

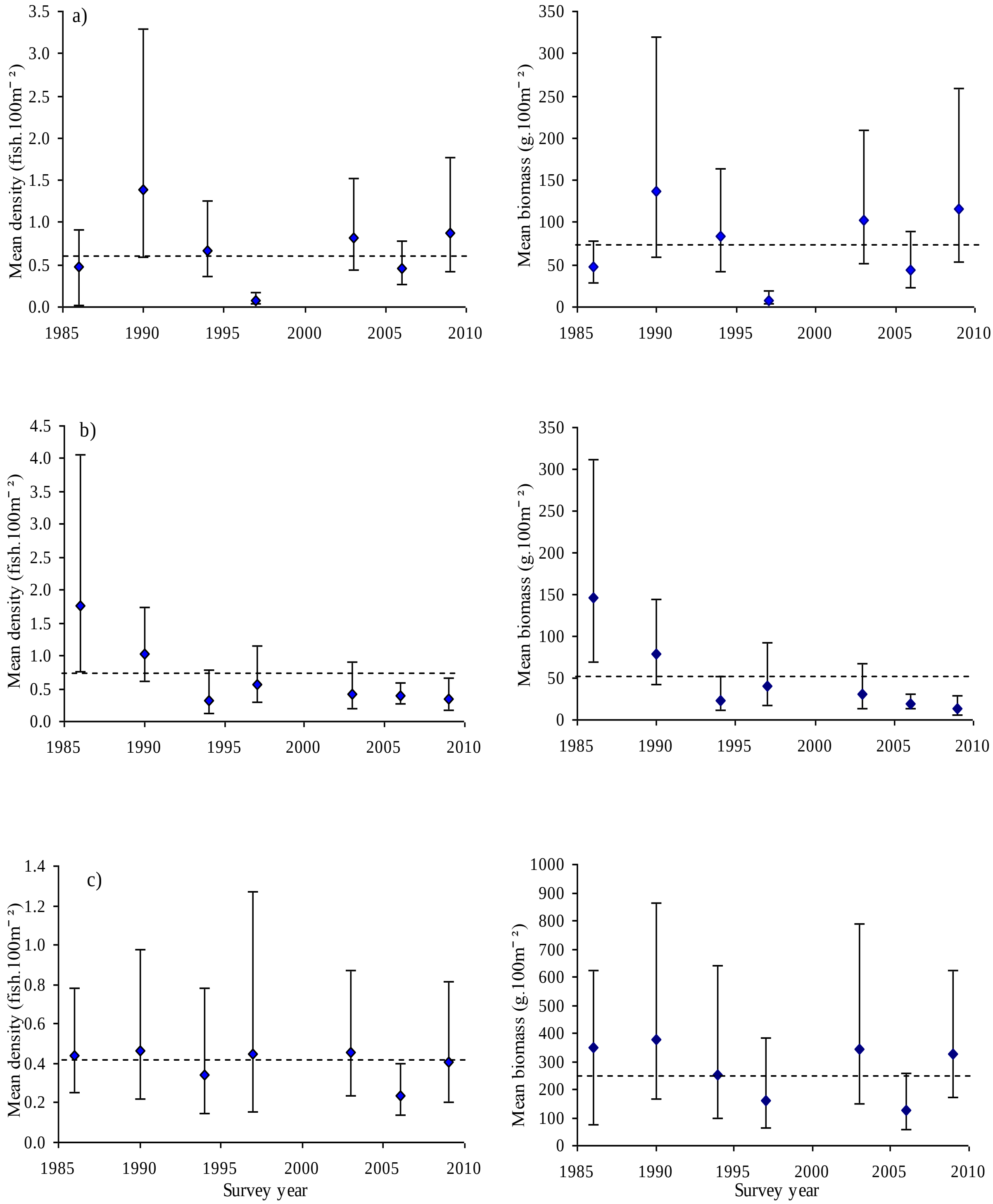

Figure 2.6. a-c. Estimated (mean ± 95% CI) density and biomass of (a) roach, (b) dace and (c) chub (>99mm) sampled in the River Wensum between 1986 to 2009, in comparison to the long-term means, (represented by dotted line).

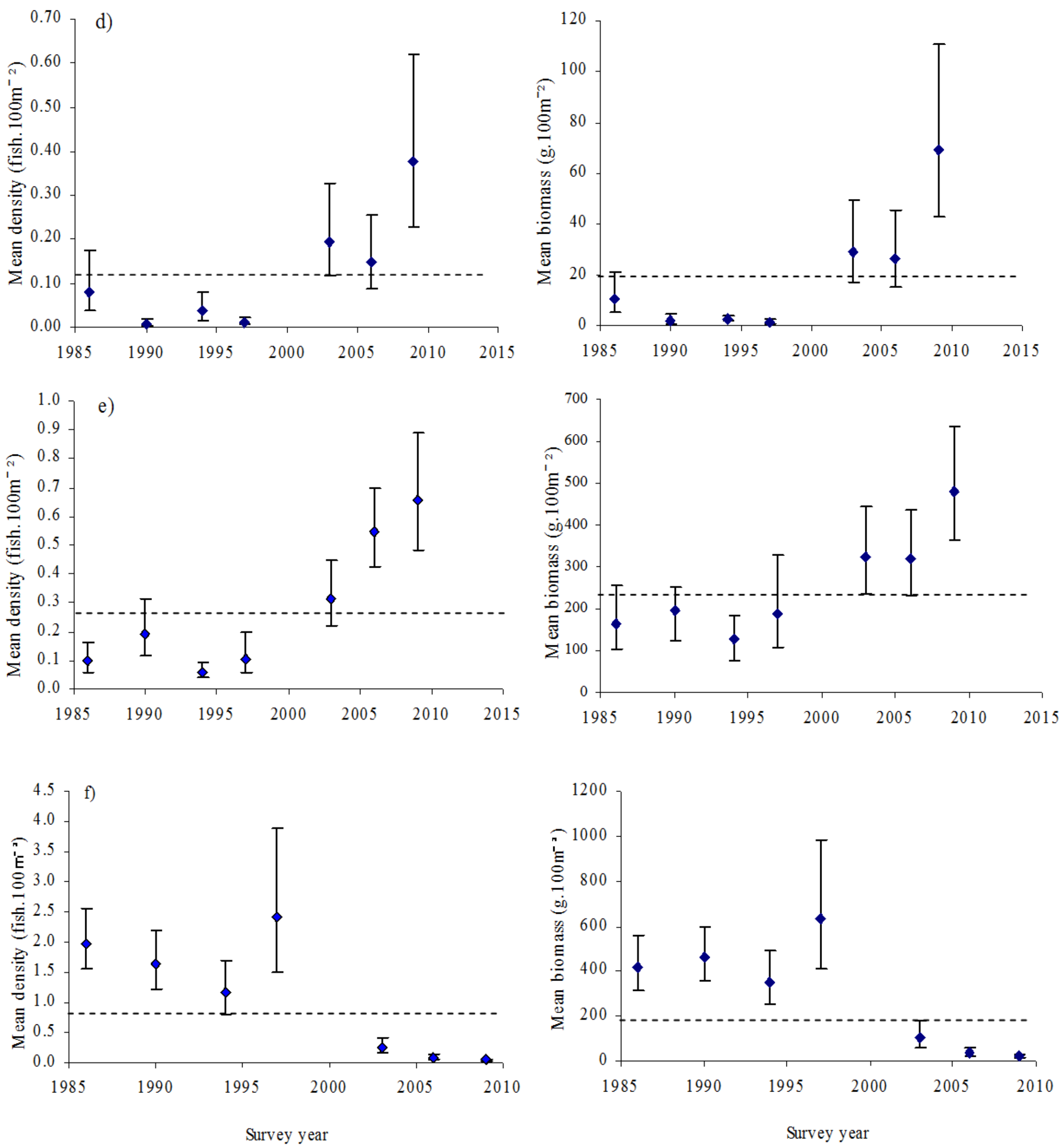

Figure 2.6. d-f. Estimated (mean ± 95% CI) density and biomass of (d) perch, (e) pike and (f) eel (>99mm) sampled in the River Wensum between 1986 to 2009, in comparison to the long-term means, (represented by dotted line).

2.4 Discussion

2.4.1 Temporal patterns in the water chemistry parameters of the River Wensum

The general improvements made to two of the largest sewage treatment works serving the Wensum catchment at Fakenham and East Dereham (Fig. 2.1) and the implementation of phosphate stripping technologies resulted in significant changes in the nutrient loading of the river from 1997. Significant reductions in orthophosphate, ammonia and BOD were detected, suggesting a reduction in the anthropogenic eutrophication of the river. That total oxidized nitrogen did not reduce after STW improvements suggests that their source is mainly from diffuse sources associated with agricultural activity. Recent improvements may relate to local government schemes put in place to reduce point and diffuse agricultural run-off from agricultural operations, such as Nitrate Vulnerable Zones (NVZs) initially designated in 1996 and the England Catchment Sensitive Farming Delivery Initiative (ECSFDI) implemented in 2006. Evaluation into the effectiveness of (ECSFDI) using water quality data from 2007 to 2010 has been a success in priority catchments across the country, with evidence of reducing nitrate and total oxidized nitrogen concentrations the River Wensum (Environment Agency, 2011).

This reduction in nutrient loading and so the level of anthropogenic eutrophication was likely to have been beneficial in enabling the River Wensum to support more diverse aquatic communities comprising of a range of pollution tolerant and sensitive species (Wade et al., 2002). Moreover, in the River Wensum species such as bullhead, brook lamprey and brown trout were observed to be increasingly contributing to the composition of the upper reaches after 2003 (App. 1a-b), following significant improvements to water quality. A study of Swedish rivers and streams found anthropogenic eutrophication responsible for the increasingly homogenised biota encountered during fish surveys from the 1960s to the 1990s, with significant reductions in salmonid species (Eklov *et al*., 1998). Following the improvement in waste-water treatment from STW and industrial effluent, re-colonization by species such as brown trout *Salmo trutta* was observed. Winfield *et al*., (2007) documented the decline of Arctic Charr *Salvelinus alpinus* (L.) from Lake Windermere in north-west England over a 30 year period and related this to increased eutrophication within the catchment. This has also been coincident with an increase in roach populations that are apparently thriving on the increased productivity of the lake (Winfield *et al*., 2007).

Nevertheless, the reduced phosphate loading may have limited productivity, as studies suggest that within aquatic ecosystems with reduced nutrient input, the carrying capacity of the fish biomass declines that is associated with reduced food supply (Winfield & Townsend, 1988; Perrow *et al*., 1997; Phillips & Moss, 1994; Meijer, 1994). Moreover, in rivers that are either clean or mildly polluted then an increase in organic matter or nutrient enrichment can actually improve the fishery by increasing fish growth rates without causing community changes. In reality this delicate balance is rarely achieved, with such additions more often causing detriment to the fishery (Moss *et al*., 1979). These aspects are explored further in Chapter 3.

In lowland rivers, the impact of organic enrichment on fish populations can conversely cause a reduction in diversity of the aquatic fauna (with communities dominated by more tolerant species such as roach) alongside an increase in total biomass (Mason, 1981). Shifts in community composition therefore occur following the improvement of water quality, with the fish assemblage shifting from one previously dominated by more tolerant species to one dominated by a greater number of sensitive species such barbel. Such change was observed on the River Trent following improvements to water quality (Cowx & Broughton, 1986). This shift was documented in the Independent: “the removal of sewage and other suspended solids has made the water clearer and less rich in organic matter, thus making small fish more vulnerable to predators whilst having less to feed on. The result has been the disappearance of much aquatic life, especially the spectacular shoals of roach,” (McCarthy, 1999b). Despite these apparent declines in roach stocks since the 1970s and 1980s, ultimately the water quality of many lowland rivers, including the River Wensum, is considerably higher today than at any time since the onset of the Industrial Revolution. “Fish are now thriving in once polluted rivers. The Tyne has seen record numbers of migrating salmon, while the Thames recorded its highest number of sea trout since many species were wiped out in parts of the river by pollution in the 1830s” (Sample, 2010). The increase in predator species in the River Wensum may be related to water quality improvements, in particular the improved clarity of water following phosphate stripping may have facilitated the ease of capture of prey species, enabling perch and pike populations to thrive. It is therefore possible that the current levels of roach and dace populations (Section 2.4.2) and are thus more representative of those prior to anthropogenic influences on lowland rivers that result in organic enrichment. The exception here is chub given their introduction into the Wensum in the 1950’s (Section 1.4).

2.4.2 Temporal and spatial relationships in fish species composition and abundance

It was apparent in the survey data that considerable shifts have occurred within the fish community of the river, with reductions in mean total density and biomass (32 and 13 % respectively). Allied to this have been considerable temporal changes in the fish species composition. During the initial surveys from 1986 to 1994, the fish community was numerically dominated by eel, dace and roach, whereas biomass was dominated by eel and chub (a reflection of their larger body size). In more recent surveys, the density is largely comprised of roach and smaller species (including bullhead and brook lamprey) and pike, with biomass now dominated by pike and chub. Minimal numbers of dace and eel have been caught in recent surveys. Thus, the reduction in the overall total fish density and biomass observed in the river in recent years is actually associated more with significant declines in eel and dace populations, and not roach.

The total mean density and biomass of roach throughout the study period has displayed considerable variation around the long-term mean for the species, reflecting the many biotic and abiotic factors determining their temporal patterns in somatic growth and recruitment (Chapter 3, 4) that may help explain the cyclical patterns of population peaks and troughs within the data. For example, in 2009 the mean density and biomass of roach was above that of the long-term mean for the species, following on from levels below the long-term mean in 2006. Thus, the combination of changes in water chemistry and roach population dynamics (Chapter

3) have not necessarily resulted in the long-term decline in roach populations as postulated by the angling community.

In addition to these temporal shifts within the community, some spatial changes are also evident. Species such as dace and eel that once dominated the mid to upper reaches of the river are now largely absent from these areas (Appendix 1). Chub have become increasingly prevalent in more recent surveys, expanding their distribution within the river by colonising areas further upstream of the mid reaches. It has been hypothesised by many anglers that the 'decline' of roach is directly related to the introduction of chub into the Wensum in 1956. Indeed, they are a known predator of coarse fish eggs and juveniles, being described as opportunistic omnivores (Mann, 1976). This claim may be also substantiated through personal observation of large aggregations of spawning roach within the Wensum, that are watched closely by large numbers of chub taking advantage of the food source after spawning has taken place. Nevertheless, there was no evidence to suggest that the roach population has declined overall, despite the apparent predation pressure (albeit unmeasured) being exerted by the chub.

Eel was once widespread throughout the catchment, contributing particularly heavily to the overall fish abundance in the lower reaches of the river, but are now largely absent throughout, being caught infrequently in recent surveys. This significant decline is a reflection of their Europe-wide decline, as they have undergone a sharp decline in recruitment, yield and stock, and is likely to continue for years to come (ICES, 2006; Freyhof & Kottelat, 2010). Although the exact cause of the decline is not known, the species has many threats including; unsustainable harvesting, the parasitic nematode of the swim bladder *Anguillicoloides crassus* that may compromise their ability to migrate to their spawning grounds in the South Atlantic (Kirk, 2003), high mortality of downstream migrating eels into hydropower turbines and pumping stations, barriers to migration routes, predation, pollution, loss of habitat and climate change (Starkie, 2003; Laffaille *et al* 2005; Feunteun, 2002). In 2008, the International Union for Conservation of Nature (IUCN) classified European eels within the 'Red List of Threatened Species' as 'Critically Endangered' (Freyhof & Kottelat, 2008). Similarly advice from the International Council for the Exploration of the Sea (ICES) in 2006 indicated that the stock of European eel was outside of the safe biological limits across European waters.

2.4 Conclusions

To conclude, this chapter revealed a series of changes and shifts in the spatial and temporal relationships of the fish community and their abundance as the fish responded to changes in their environment. In the most recent fish surveys, the major changes detected were in the populations of eel and dace, with more chub present. When viewed across 23 years (1986 to 2009) then the population abundance of roach has not actually changed *per se*, with abundances in 2009 being favourable to those of the 1980s and early 1990s.

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Chapter 3. Temporal variation in the growth rate of roach, dace and chub in the River Wensum

Aspects of this chapter are published in the following paper:

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3.1 Introduction

Estimating fish growth in order to understand the processes and factors that influence them remain integral and fundamental components of fisheries biology (Bagenal & Tesch, 1978; Francis, 1990; Coggins & Pine, 2010). These data remain crucial in addressing the questions on basic ecological management of fisheries specifically and aquatic ecosystems more generally. Consequently, understanding temporal and spatial patterns of fish growth rates is important in developing knowledge on how fish interact with their environment, applying this knowledge to environmental problems and issues, and to models capable of predicting responses of fish growth to environmental change (Ricker, 1975; Campana, 2001; Coggins & Pine, 2010).

In temperate river systems, the growth of cyprinid fishes, and their population dynamics generally, tend to be density-independent and determined largely by abiotic factors (e.g. Mills & Mann, 1985; Nunn *et al*., 2003, 2007; Britton *et al*., 2004). For example, climatic effects are increasingly recognised as being important in causing inter-annual variability in the production and abundance of fish in lowland rivers, with broad-scale climatic effects having strong underlying effects on the growth and recruitment of juvenile fishes (Grenouillet *et al*., 2001; Nunn *et al*., 2003). Moreover, the relative importance of different abiotic factors on the growth and recruitment of riverine cyprinid fish populations varies spatially and temporally, suggesting that significant shifts in these variables will cause significant shifts in growth and recruitment rates (Nunn *et al*., 2003, 2007). The importance of understanding the role of temperature in determining fish growth rates is also reflected in the number of growth meta-analyses that use latitude as a surrogate of temperature in order to understand variability in species' growth rates over their distribution ranges. For this, studies have been completed on both native (e.g. Lappalainen *et al*., 2008) and introduced fishes (Cucherousset *et al.*, 2009; Benejam *et al*., 2009; Britton *et al.*, 2010a). In general, faster growth rates and earlier maturity tend to be coincident with habitats located at more southerly latitudes due to increased water temperatures that result in longer and warmer growth seasons (New *et al*., 1999; Lappalainen *et al*., 2008).

Temperature is, however, only one factor affecting the growth of riverine cyprinid fishes, with water chemistry also a key determinant for some species (Persson, 1991; Schindler *et al*., 2000). The chemistry of a waterbody (including nutrient concentrations, dissolved oxygen levels, ammonia concentrations and pH) can play an important role in determining the productivity of the water and so regulate productivity in the fish populations. For example, even relatively pristine riverine habitats that suffer from periodic failures in dissolved oxygen levels, the biota would reflect this pressure through depressed populations of salmonid fishes and other species requiring highly oxygenated waters. Fish communities would comprise of more tolerant and generalist species such as roach. The mid to upper reaches of the River Tas in Norfolk possess reduced populations of brown trout *Salmo trutta* despite suitable physical habitat, with abundant cyprinid species primarily due to such periodic failures in dissolved oxygen (Environment Agency, 2011).

Following World War II, the requirement for the UK to become self-sufficient and increase food production led to the intensification of agricultural practises, including addition of fertilizers to support the production of higher yields. In lowland areas, such as East Anglia, impacts from such practises resulted in the deterioration of water quality through diffuse run-off containing elevated levels of nutrients including nitrates and phosphates (Croll & Hayes, 1988; Mainstone & Parr, 2002; Ulén *et al*., 2007). Allied with effluent discharges from sewage treatment works, the nutrient loadings of rivers increased sufficiently for the riverine fish communities to be dominated by pollution tolerant species such as roach and gudgeon (Cowx & Broughton, 1986).

In recent years, legislative measures to reduce the input of organic and industrial effluents into watercourses has been introduced by many countries in Western Europe and has entailed that many rivers have undergone significant improvements in their biological and chemical water quality following long periods of decline (e.g. Firth, 1996; Amisah & Cowx, 2000a,b). Moreover, many rivers have been further improved through decreasing the extent of their eutrophication by reducing nutrient loading in sewage effluents (Wade *et al*, 2002). For example, reductions of phosphates in sewage effluents can be achieved through phosphate stripping, resulting in reduced concentrations being discharged (House *et al*., 1995; Neal *et al*., 2002). This may be important given that eutrophication can have profound effects on fish communities and populations, with cyprinid fishes such as roach dominating communities in highly eutrophicated systems (Willemsen, 1980; Winfield, 1992). Thus, in considering the growth rates of cyprinid fish in lowland rivers, the respective roles of temperature and water chemistry (as nutrient loading) should be examined.

The aim of this chapter is to identify the temporal growth patterns of the roach, chub and dace populations of the river between 1975 and 2006. Growth patterns were obtained using scale data collected from the 1986 to 2006 surveys. These will be tested against the shifts already outlined in the nutrient loading of the river since the implementation of the phosphate stripping on the two major sewage treatment works in the catchment (Section 2.3.1). In addition, growth patterns will be tested against annual flow rates and water temperature, enabling their respective effects to be also measured on growth and in relation to the changes in organic loading. It is predicted that growth of fishes will be dependant on temperature and discharge (and, hence, growth is climatically driven), with years of higher temperatures and lower flow rates resulting in increased growth increments in the fishes. Objectives were to (i) identify any temporal shifts in the growth rates of each of the species between 1975 and 2006; (ii) identify the effects of the implementation of phosphate stripping in 1997 on the phosphate loading of the river in the pre and post stripping periods (*cf*. Section 2.3.1); and (iii) test the influence of phosphate loadings, temperature and river discharge on the temporal growth rate patterns of the fish between these two periods.

3.2 Materials and methods

3.2.1 Study area

As in Chapter 2 which detailed spatial and temporal perspectives on the EA fish population surveys, this chapter concentrates on growth analysis of fish captured during all surveys on the River Wensum from 1986 to 2006 (sites 1 to 18, Table 2.1, Figure 2.1), where channel dimensions ranged from 7 to 23 m in width, 0.5 to 3 m in depth (Table 2.1), with habitat comprising of riffle and pool reaches, with some lengths of deeper glides. Scale data obtained from the National Fish Laboratory archives was also used, providing additional information regarding growth rates of roach, dace and chub captured from the Wensum in 1983, 1989 and 1991.

3.2.2 Scale collection, ageing and initial analysis

Scales were available for analysis from data obtained during 1986, 1990, 1994, 1997, 2003 and 2006 using electric fishing from boats (Section 2.2.2). Supplementary ageing data available from 1983, 1989 and 1991 where appropriate has been added to the dataset providing further information into the growth rates of Wensum roach, dace and chub. For example, roach captured in 1983 were aged up to 13 years old, thus corresponding to the year class of 1970. During sampling of each population, fish were captured, identified, measured (fork length, mm) and scale samples taken for ageing. At least three scales were removed from each fish from body area as described by Steinmetz & Müller (1991). In general, scales were taken from all individuals sampled. When large numbers of fish were sampled, however, scales were only collected from a sub-sample of 10 fish per 5-mm length increment per species. These were then stored in a cool and dry scale archive room. For the purposes of this study, the scales were retrieved from their archive in 2009 and then aged using a projecting microscope. The scales were aged by the author in conjunction with Gareth Davies of the Environment Agency. An example of an aged scale is shown in Figure 3.1. Following ageing of scales, they were measured to allow lengths at age to be derived by back-calculation using the scale proportional method (Equation 3.1) with the underlying assumption that growth of the scales is in direct proportion to the growth of the fish (Francis, 1990):

$$n = (Cr/Tr) \times L \quad \text{(Equation 3.1)}$$

where n = Length of fish at age

Cr = Radius of the scale to annual check (n),

Tr = Total radius

L = Length of the fish.

To analyse the temporal growth rates of the fish by species, the initial step was to plot the back-calculated length at the last annulus of each fish (due to their sampling in their growth season) against its age on a scatter plot to identify the extent of the variability in the lengths at age across the study period. The relationship between these back-calculated lengths and ages were then determined using a quadratic model, as length increments decreased with age. To enable the growth rates of the fish to be compared between surveys and over the 25 year period, the standardized residuals of these lengths at age were stored. For each species, these residuals were compared between surveys using ANOVA with Tukeys post-hoc tests, and their means and 95 % confidence limits were determined and plotted.

3.2.3 Influence of phosphate reductions, temperature and river flow on fish growth

Data on the phosphate loading (as orthophosphate, mg l^{-1}) were used as annual means from 1981. There was significant co-correlation between orthophosphate, total oxidised nitrate and biochemical oxygen demand (Section 2.3.1), hence the latter two parameters were not included in analyses. Differences in the orthophosphate concentration of the study reach before and after implementation of phosphate stripping was determined using ANOVA. Water temperature data (W_T) were available for only 756 days in the entire study period, rather than daily. Consequently, the relationship between air temperature (A_T;Central England Temperature dataset; Meteorological Office 2009) and the water temperature was determined according to linear regression (R^2 = 0.87; $F_{1,754}$ = 879.2, P < 0.001) and the used to convert daily air temperature data into water temperature data via the regression equation ($W_T = A_T \times 0.90 + 1.95$; R^2 = 0.87; $F_{1,754}$ = 879.2, P < 0.001). These water temperature data were then used to determine the annual number of degree-days >12°C (Nunn *et al*. 2003), as this temperature is generally required for growth of temperate cyprinid fishes (Britton, 2007). Data on daily river flows were available from a monitoring station (established in 1969) within the study section and used to determine the annual numbers of flow days above the mean flow rate (Nunn et al. 2003). The hydrological values of Q10 (flow exceeded 10 % of the time) and Q90 (flow exceeded 90 % of the time) were also determined. Both air temperature and flow data were also tested for differences between the pre- and post-stripping periods using ANOVA.

These abiotic data from the pre- and post-phosphate stripping periods were then tested against data on the temporal growth patterns of the fish. To avoid statistical complications (e.g. auto-correlation, pseudo-replication) from using repeated measurements from individual fish in the same test (i.e. all growth increments gained from back-calculated lengths), the analysis used one growth increment per fish. The increment used was that produced between age 1 and 2 years, the rationale being that: (i) using length at age 1 as the increment may be impacted by the timing of adult spawning and multiple spawning events in chub (Bolland *et al*., 2007), causing variability in the duration of the growth season for 0 group fish between years that could not be accounted for by degree-days; and (ii) between age 1 and 2, roach tend to be sexually immature at this latitude (Lappalainen *et al*., 2008) and so energy resources for growth are used primarily for somatic growth, rather than gonad growth (in contrast to fish of age > 2 years). Thus, the temporal growth pattern was determined by taking the back-calculated lengths at age 1 and 2 of each fish and determining the annual increment. The year in which this increment was produced (the 'growth year') was also determined. For each species, the mean increments and standard deviation was calculated and the standardized residuals stored. Differences in the standardized residuals were determined between the pre- and post-stripping periods using ANOVA. The annual means per incremental age for the pre- and post-phosphate stripping periods were then tested against the temperature and flow data using multiple regression. The dependent variable was the mean standardized residuals of the annual growth increments; the independent variables were degree-days > 12 ^{o}C, flow days above the mean and mean annual orthophosphate concentration. The effects of the independent variables on the growth of the species were compared using their standardized beta coefficients (β) and their significance; those variables with the largest β values made the strongest singular contribution to explaining the dependent variable when all the other model variables were controlled.

Statistical tests were completed in SPSS v16.0 and 17.0, testing for normality was completed prior to using parametric tests, ANOVA tests were used only when Levene's test indicated equal variances between the groups (indicated by $P > 0.05$), and error bars represent 95 % confidence limits unless stated otherwise.

3.3 Results

3.3.1 Initial growth analyses

In the scale ageing data analysed from 1983 and 2006, roach were aged up to age 13 (n = 592), dace to age 10 (n = 502) and chub to age 18 years (n = 1095). Back-calculated length at age plots revealed temporal changes in fish growth over the study period for roach, dace and chub, with a decline in length at age for roach caught during the most recent surveys in 2003 and 2006 (Figure 3.2). These age-length relationships according to the quadratic model were significant (roach: $R^2 = 0.89$, $F_{2,558} = 2162.1$, $P < 0.01$; dace: $R^2 = 0.94$, $F_{2,472} = 3901.4$, $P < 0.01$; chub: $R^2 = 0.95$, $F_{2,1090} = 7797.7$, $P < 0.01$).

Comparison between the surveys of the mean standardized residuals of back-calculated length at the last annulus revealed some significant differences between surveys. In this analysis, due to generally low numbers of roach above 8, dace above age 5, and chub above age 14 years, and their reducing annual growth increments by age (almost negligible in some cases), then data from fish of these ages have been omitted from the quadratic model, which was run subsequently with the standardized residuals stored. In total, they comprised < 10 % of the sample sizes. Comparison between the surveys of the mean standardized residuals of back-calculated length at the last annulus revealed some significant differences between surveys. For roach, length at age was significantly depressed in surveys completed in 2003 and 2006 compared with those completed between 1983 and 1994 (Figure 3.3a). For dace and chub, whilst some significant differences in lengths at age were apparent between surveys, mean values in 2003 and 2006 were similar to those from the 1983 survey (Figure 3.3b,c and Figure 3.4 a-c).

3.3.2 Influence of phosphate loading, temperature and river flow on fish growth

In the period before phosphate stripping (1981 to 1996), the mean annual phosphate concentration in the study reach was 0.47 ± 0.15 mg l^{-1} (range 0.31 to 0.72 mg 1^{-1}) and after stripping had been implemented the period 1997 to 2008 it reduced to 0.19 ± 0.14 mg 1^{-1} (range of 0.07 to 0.45 mg 1^{-1}). This difference between the two periods was found to be highly significant ($F_{1,26}$ = 40.40, $P < 0.01$). Between the same periods, differences were not significant for degree days > 12°C ($F_{1,26}$ = 2.18, $P >$ 0.055) and flow days above mean rate ($F_{1,26}$ = 2.53, $P > 0.05$). There was also no relationship between orthophosphate and degree-days (R^2 = 0.07, $F_{1,26}$ = 0.87, $P >$

0.05) and orthophosphate and flow days (R^2 = 0.04, $F_{1,26}$ = 0.48, P > 0.05) in the period 1981 to 2008.

The mean daily flow of the study reach across this period was 2.77 ± 2.10 $m^{-3}s^{-1}$, Q90 was 1.09 $m^{-3}s^{-1}$ and Q10 was 5.11 $m^{-3}s^{-1}$. In the months between June and October (i.e. the approximate fish growth season), the mean flow was only 1.24 ± 0.27 $m^{-3}s^{-1}$, with only 18 days where Q10 was exceeded between 1981 and 2008. As the majority of high flow events occurred in the months of November to March, i.e. outside of the fish growth season, with little flow variability within the fish growth season between 1981 and 2008 (ANOVA, $F_{1,26}$ = 0.78, P > 0.05), then the influence of flow on fish growth rates was not considered further.

The temporal pattern of growth increment production between age 1 and 2 were then tested for all species versus the abiotic data (except flow). For roach, growth increments were significantly larger in the pre-stripping period than post stripping ($F_{1,490}$ = 77.61, P < 0.01; Fig 3.5a). In the pre-stripping period, degree-days >12°C had a significant influence on the roach growth increments, with warmer years producing higher increments (β = 0.75, P < 0.05), but with no relationship of increment production with phosphate in this period (β = -0.13, P > 0.05). However, in the post stripping period the relationship between temperature and growth was lost (β = 0.33, P > 0.23), with the phosphate loading now being significantly related to increment production (β = 0.78, P < 0.05). For dace, there was no difference in their growth increments between the pre and post stripping periods (Figure 3.5b). The growth increments of chub were significantly faster in the pre-stripping phase compared with post stripping ($F_{1,665} = 44.01$, $P < 0.01$; Figure 3.5c), although this pattern was not significantly associated with either phosphate or temperature.

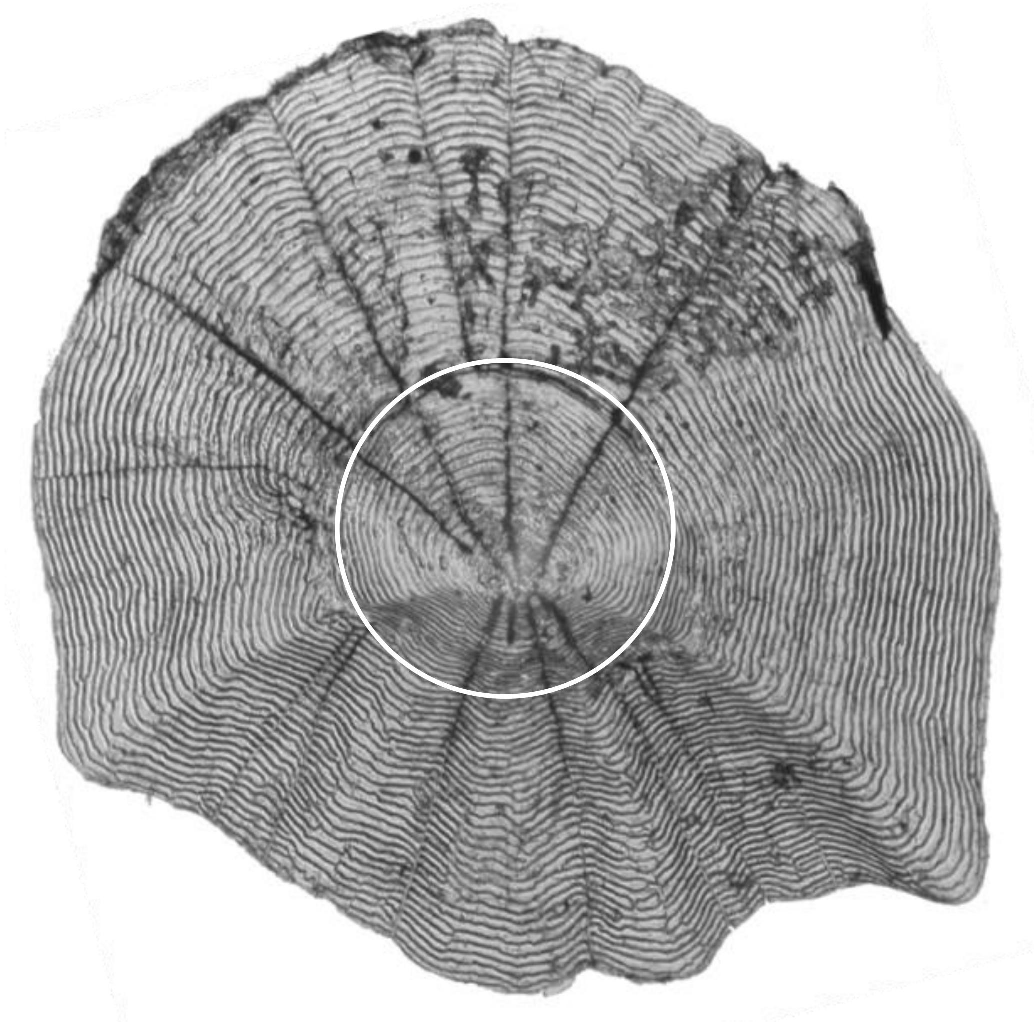

Figure 3.1 Scale image of a 101 mm River Wensum roach, age 1+ years, where the white circle denotes the 1st annulus.

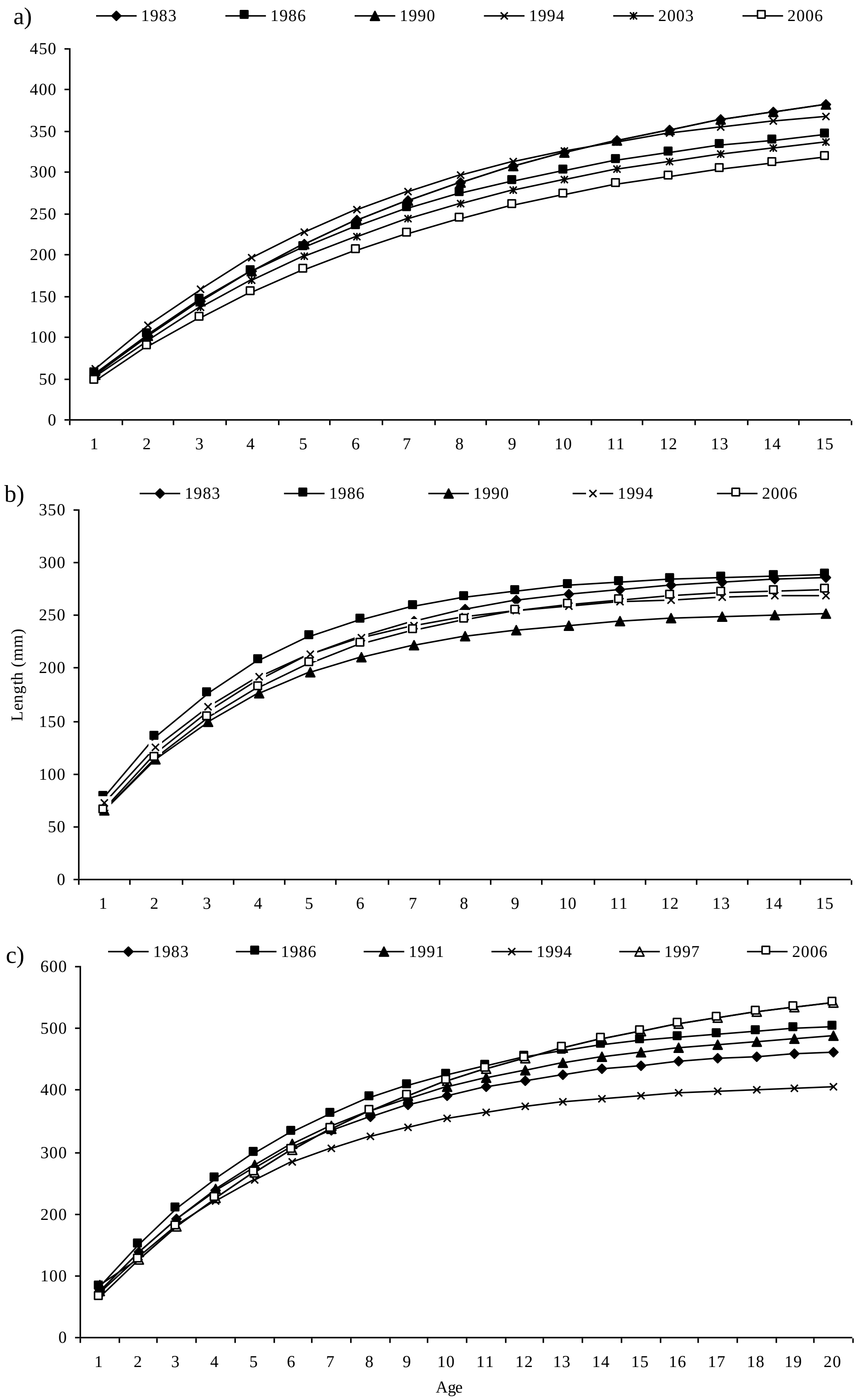

Figure 3.2. Von-Bertalanffy growth curves of (a) Roach, (b) Dace and (c) Chub from the River Wensum, sampled between 1983 and 2006.

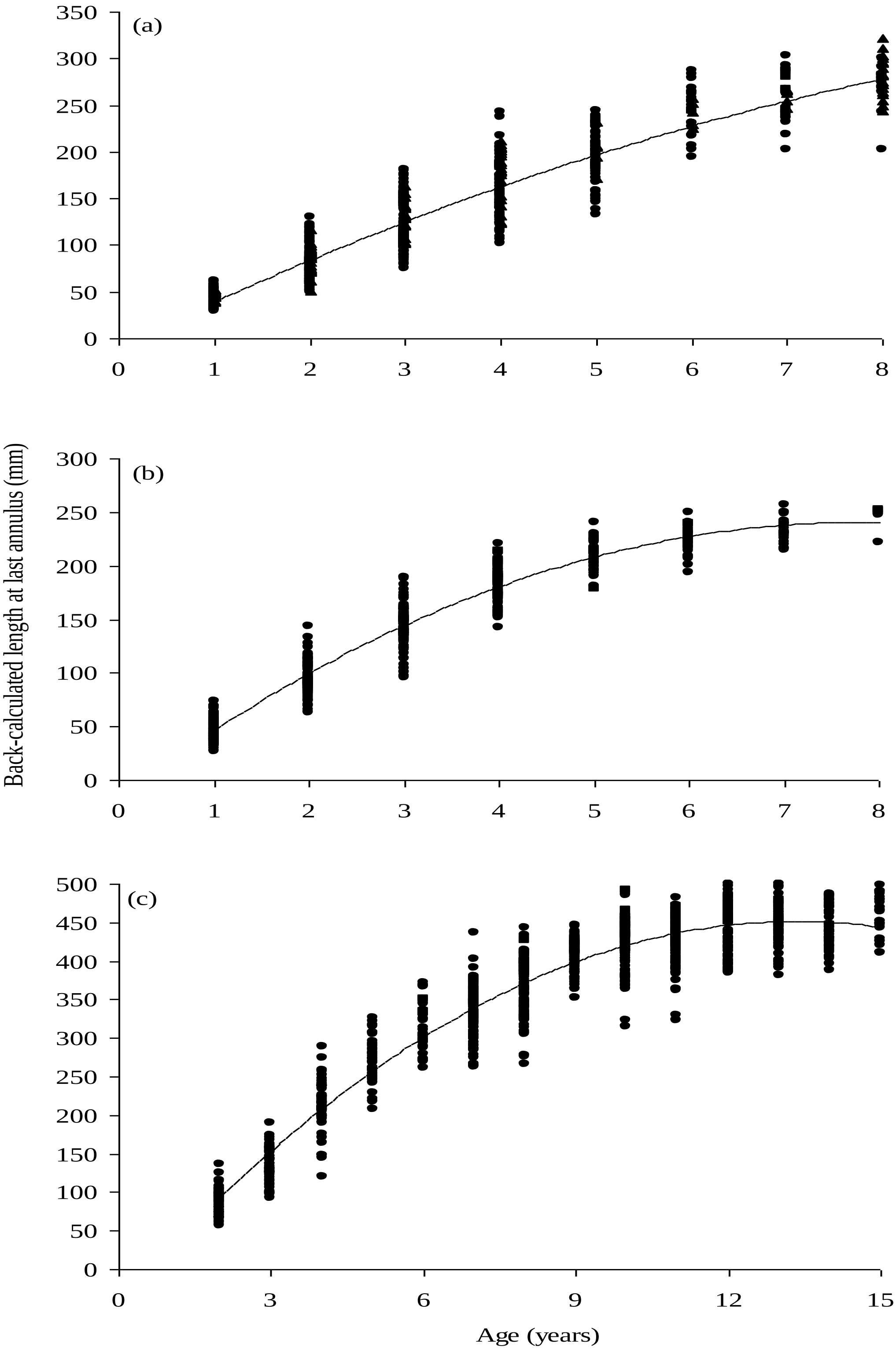

Figure 3.3. Fork length at age (back-calculated to last annulus) of (a) Roach, (b) Dace and (c) Chub from the River Wensum, sampled between 1983 and 2006. Note: Extended x axis in (c) to reflect older ages reached by chub.

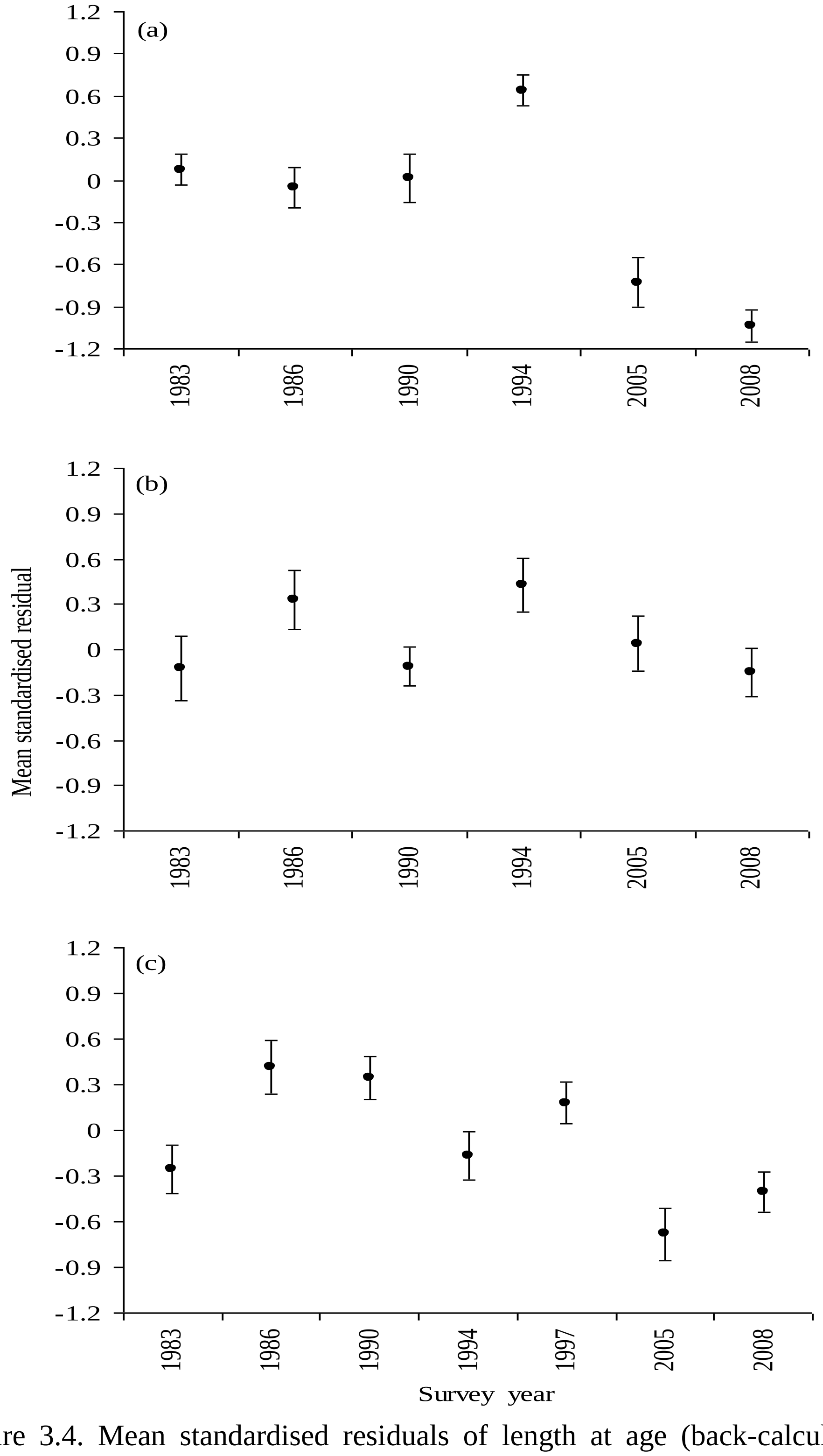

Figure 3.4. Mean standardised residuals of length at age (back-calculated to last annulus) for (a) Roach, (b) Dace and (c) Chub from the River Wensum in surveys completed between 1983 and 2006. Note that in the 1997 survey, data were available for chub only. Error bars denote 95 % confidence limits.

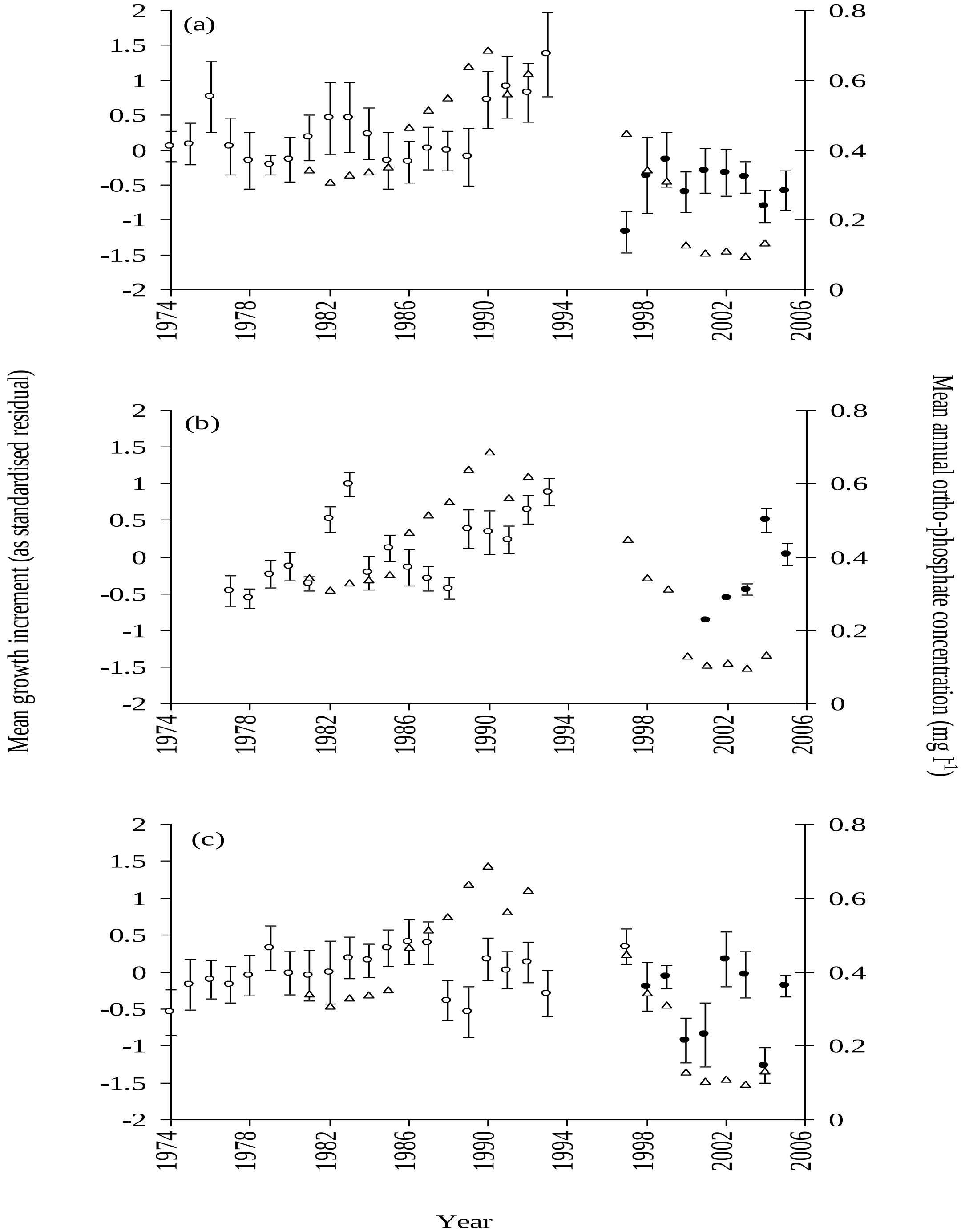

Figure 3.5. Mean standardised residuals of annual length increments between age 1 and 2 years in the pre (○) and post (●) phosphate stripping periods for (a) Roach, (b) Dace and (c) Chub. Error bars = 95% confidence limits, and where Δ = mean annual phosphate concentration, for which 95 % confidence have been omitted for clarity.

3.4 Discussion

There have been numerous studies in both lacustrine and lotic systems on the growth rates of roach (e.g. Hellawell, 1972; Mann, 1973; Horppila, 1994; Volta & Jepsen, 2008), dace (e.g. Mann, 1974; Weatherley, 1987) and chub (e.g. Cragg-Hine & Jones, 1969; Mann, 1976; Koç *et al*., 2007). However, only a few of these studies provide analysis on their long-term growth patterns in a single location, despite temporal studies into other aspects of their life history, such as timing of reproduction, providing key insights into changes that may be related to, for example, increased temperatures due to climate change (e.g. Nõges & Järvet, 2005; Gillet & Quétin, 2006). Here, it was demonstrated that there was substantial variation in the growth of these fish over a 30 year period that were able to be at least partially explained by changes in abiotic parameters. For roach, there were significant temporal changes that were at least partly explained by shifts in abiotic parameters. For much of the period, temperature appeared to be the key determinant of roach growth (as per the prediction, Section 3.1) but more recently, the reduction in orthophosphate loading in the river following phosphate stripping (so indicating a shift to less eutrophic conditions) appeared to have a major slowing effect on the growth rates of roach. As anecdotal evidence strongly suggests the performance of the river's roach fishery (based on catch and release angling) has declined in recent years (Chapter 1), their growth rate decline may have inhibited individuals from attaining large sizes and so caused the decreased presence of specimen roach in angler catches.

Whilst the role of river productivity in determining growth rates tends to be overlooked (especially in ages above 0), studies on lacustrine roach populations have found strong causal associations between biological productivity and roach growth rates. For example, Persson (1983) found slow roach growth rates when diet was mainly composed of detritus and algae due to a shortage of animal food. Cryer *et al*., (1986) found both juvenile and adult roach had depressed growth when their prey populations (primarily zooplankton) were depressed. In combination, this suggests that river productivity may actually be ecologically significant in determining roach growth rates and population dynamics, particularly in systems that have previously been subjected to high nutrient loadings that are now being significantly reduced. This also suggests that water quality improvements will result in a range of consequences for riverine fish communities, from shifts in the strength of inter-specific interactions such as competition, through to more subtle changes, such as in the expression of life history traits. Further research into prey availability and stomach content analysis of 0 group roach in the River Wensum would be recommended.

Other studies suggest that roach tend to dominate fish communities in eutrophic waters (e.g. Willemsen, 1980; Winfield, 1992; Kennedy, 1996; Lappalainen *et al*., 2001), with this dominance being adversely impacted when water quality improvements occur (Cowx & Broughton, 1986), although information on their corresponding growth rates tend to be lacking. Moreover, growth (and recruitment) studies of riverine roach populations have tended to focus on the role of density-independent, abiotic factors (e.g. Mills & Mann 1985; Nunn *et al*. 2003, 2007;

Britton *et al*. 2004). Periods of elevated growth tend to be significantly associated with the direct and/or indirect effects of increased temperature (Mills & Mann 1985).

That temperature was able to explain much of the variation in the growth of all species in the more eutrophic, pre-phosphate stripping period is consistent with other studies that demonstrate significant relationships between faster growth rates and increased temperatures (Kitchell *et al*., 1977; Magnuson *et al*., 1979). For roach, this relationship is apparent at both large spatial scales, such as over their biogeographic distribution where the relationship is non-linear (Lappalainen *et al*., 2008), and within individual rivers, where the growth of juvenile fish is significantly correlated to water temperatures, resulting in annual variability that impacts recruitment patterns (Nunn *et al*., 2003, 2007; Britton *et al*., 2004).

Although decreases in growth rate early in life is usually associated with an increased lifespan (Metcalfe & Monaghan, 2003) and a corresponding ability to attain larger sizes than fast growing fish (Britton, 2007), this was not apparent within the dataset. Whilst it was beyond the scope of this study to also determine whether the other traits of the roach population, such as survivorship, age at maturity and fecundity, were also impacted by reduced orthophosphate levels, this may be considered likely given these traits are more closely linked to size than age (Kirkpatrick, 1984). Thus, it is suggested that this shift to less eutrophic conditions in the river was likely to have had a profound effect on their life history traits, with not only slower growth but also later maturity and reduced fecundity at age.

For dace, although some significant differences in lengths at age were apparent between surveys, mean values in 2006 were similar to those from the 1983 scale ageing data. That growth rates of dace in the pre and post phosphate stripping periods was not significantly different may be a reflection of prey choice, being mainly carnivorous in both juvenile and adult stages (Weatherley, 1987).

When compared with roach and dace, the growth of chub appeared to be less variable and with the exception of temperature in the pre-phosphate stripping period, did not show any significant relationships with the abiotic parameters. This may be partially explained by their multiple spawning strategies in riverine habitats (Nunn *et al.*, 2002; Hladik & Kubecka, 2003; Fredrich *et al.*, 2003) which have been detected in the River Wensum (Bolland *et al*., 2007). The multiple spawning strategy is also the most logical explanation for the higher than expected back-calculated length at age 1 ranging between 60 and 80mm (Fig. 3.1). In this instance it is likely that the first annulus has been missed during the ageing process. This reproductive trait is selected as it confers advantages through reduced spawning stress, reduced competition for spawning grounds, reduced spawning mortality, increased longevity and elevated fecundity (Mann, 1976; Karlsen *et al.*, 1995). However, as it results in an extended spawning period, larvae may emerge as early as June and as late as August of each year (Nunn *et al.*, 2002). Thus, fish at the end of their first year of life show considerable variance in their lengths (irrespective of abiotic factors) which then has a significant influence on their subsequent growth over their lifetime. Fish of smaller lengths at age 1 producing smaller annual growth increments throughout life compared with the larger individuals in the cohort (Bolland *et al*., 2007). Thus, this reproductive strategy has important implications for the growth of chub over their life span and may have inhibited further elucidation of how the abiotic factors influenced their growth.

3.5 Conclusions

In summary, the growth rates of these three cyprinid fish were revealed to be significantly variable over time, with much of this variability in roach able to be explained by environmental parameters, especially temperature, and in more recent years, by a shift to less eutrophic conditions. This roach growth suggests the anthropogenic pressure of organic enrichment (and reversal) was an important driver of change, with shifts in water quality potentially having important ecological consequences for fish populations that may then negatively impact aspects of fishery performance.

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Chapter 4. Factors affecting the temporal variation in the recruitment rate of roach in the River Wensum

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4.1 Introduction

Populations of cyprinid fishes in temperate lowland rivers tend to be dominated by small numbers of year classes that are over-represented in the population (Mills & Mann, 1985). These relatively strong year classes are important because they may comprise a substantial proportion of the population (Mills & Mann, 1985) and so, for example, contribute strongly to the spawning stock (Britton *et al*., 2004). Strong year classes tend to be produced when a range of biotic and abiotic factors combine to make conditions sufficiently favourable in the first year of life of the cohort to maximise larval and juvenile survival rates (Grenouillet *et al*., 2001; Nunn *et al*., 2003). These factors appear strongly associated with weather, particularly those of temperature and rainfall (Mills & Mann, 1985; Britton *et al*., 2004; Nunn *et al*., 2007).

Summers that are relatively cool tend to produce 0 group cohorts that recruit weakly into the population, with the converse for warm summers (Mills & Mann, 1985; Britton *et al.*, 2004). These patterns have also been related to the growth of fish in the year class during their first year of life, with strong recruitment positively correlating with the faster growth rates and larger body lengths of fish that occur in warmer summers (Nunn *et al.*, 2007, 2010). River discharge has also been reported as important in regulating recruitment rates through causing increased mortality and displacement during episodes of elevated discharge (Nunn *et al.*, 2007). Indeed, Nunn *et al.*, (2003) argued that whilst temperature may determine potential recruitment strength, discharge determines the actual strength. However, these studies on cyprinid recruitment have tended to focus on relatively large rivers with high flow rates and variable discharge patterns, such as the Yorkshire Ouse, England (Nunn *et al*., 2003, 2007) and the River Rhône, France (Piffady *et al*., 2010).

To date, studies of roach recruitment in rivers of less variable discharge, such as chalk rivers that have relatively stable hydrology, have received less recent attention, with few other studies other than those outlined by Mills & Mann (1985) on the River Frome, Dorset. Thus, temporal trends in recruitment and the factors affecting the recruitment processes of the roach population of the River Wensum are determined in this chapter. Through the scale analysis process fish were aged alongside their associated year class, with some individuals from the initial surveys corresponding to the 1970 year class. The objective of this chapter was to identify their long-term (1970 to 2006) recruitment pattern in relation to climatic factors, hydrology and growth in the first year of life. Scale ageing data from the Wensum in 1983 possessed roach up to 13 years old from the 1970 year class, hence growth rates from 1970 to 2006 were available. It was predicted that years characterised by higher than average temperatures and lower than average flow rates produced 0 group fish of relatively large sizes and resulted in relatively strong recruitment of the 0 group cohort. These cohorts would then be highly represented in subsequent population samples and have higher values of year class strength.

4.2 Materials and Methods

4.2.1 Study area

This study was conducted on the same reach as Chapter 3 (sites 1 to 18, Table 2.1, Figure 2.1), where channel dimensions ranged from 7 to 25 m in width and 0.5 to 3 m in depth (Table 2.1). Data was available from surveys conducted in 1986, 1990, 1994, 1997, 2003, 2006 and 2008 (Section 2.2.1). Scale data obtained from the National Fish Laboratory archives was also used, providing additional information regarding growth rates of roach captured from the Wensum in 1983, 1989 and 1991. Note the recruitment rates of dace were not determined due to issues of a lack of year classes represented in some later surveys than impacted analysis, and chub were not determined as samples tended to be dominated mainly by fish over the age of 5 years old, with relatively low number of juvenile fish that made determination of an accurate mortality rate difficult (Equation 4.1).

4.2.2 Calculation of Year Class Strength

As detailed in Chapter 3.2.2 the data used in this chapter were taken from the scales taken from each fish during the fish surveys that were removed from their archive and aged in 2009 on a projecting microscope. The data used in this chapter from the process was the estimated age of each fish in each survey as it enabled the year class of the fish to be recorded, the number of fish in each age and year class and the measured distance to the first annulus and the scale radius to provide the back-calculated length at age 1 to be determined (Section 3.2.1; Francis, 1990). Variation in recruitment between 1970 and 2006 was then able to be estimated using the year class strength (YCS) method of Cowx & Frear (2004). This method has the capability of showing the dominance of certain year classes in the population structure and is determined by back-calculating the number of fish (N_0) that would have been recruited to the population at time t_0 (Cowx & Frear, 2004), assuming constant mortality throughout life (Equation 4.1). Although mortality is known to be higher in the juvenile life stages, this was irrelevant for this procedure because a comparative index of YCS was generated based on mortality in >1 year old fish:

$N_0 = N_t \exp Z_t$ (Equation 4.1)

where Z = Total mortality rate

N_0 = Numbers in starting population

N_t = Numbers at time t

t = time

Year class strength was then calculated as the number of fish recruited divided by the mean number recruited from all year classes, multiplied by 100. The YCS values for each year class per sample were then expressed as standardized residuals, where the residual was calculated as the difference between the YCS value for that year class and the mean YCS for the sample. Where a year class was present in two surveys, the mean YCS standardised residual for each year class was determined.

Mean values above zero thus represented strong recruitment, values below zero represented weaker recruitment.

Once the mean YCS per year class had been determined, the influence of the abiotic variables on YCS was tested. The relationship between YCS and temperature was tested by using estimates of water temperature. Water temperature data (as degree-days > 12ºC) were determined as described in Section 3.2.3. The influence of river flow on YCS was tested by obtaining daily flow data within the study reach (Section 3.2.3) and constructing the flow duration curve, and determining the annual number of flow-days above the mean annual flow (Nunn *et al*., 2003) and coefficient of variation of flow per year (CV/ standard deviation/ mean flow).

The final test was to test YCS against the mean back-calculated length at age 1 (Section 3.2.1) to identify whether growth in the first year of life had a significant influence on recruitment success. Statistical tests were completed in SPSS v16.0 and 17.0, testing for normality was completed prior to using parametric tests, ANOVA tests were used only when Levene's test indicated equal variances between the groups (indicated by $P > 0.05$), and error bars represent 95 % confidence limits unless stated otherwise.

4.3 Results

The YCS output revealed the long-term recruitment pattern of roach in the River Wensum study area (Section 3.2.1; Figure 2.1) was short periods of strong recruitment, generally two or three consecutive years, interspersed by several years of poorer recruitment (Figure 4.1). The relationship between degree-days >12 ^{o}C and year class strength was then also positive and significant (linear regression: R^2 = 0.36, $F_{1,33}$ = 10.97, P < 0.01; Figure 4.2).The flow duration curve revealed a relatively stable hydrological regime with a mean daily flow of 2.77±2.10 $m^{-3}s^{-1}$ (Figure 4.3); comparison with the duration curve for the Yorkshire Ouse of Nunn *et al*., (2007) reveals considerable differences, with flows in the Ouse exceeding 10 $m^{-3}s^{-1}$ for approximately 80 % of the time, compared with 5 % for the Wensum. The association between the number of flow days above the annual mean flow and YCS was not significant (linear regression: R^2 = 0.01, $F_{1,33}$ = 0.01, P > 0.05, Figure 4.4). There was also no significance between flow CV and YCS (linear regression: R^2 = 0.02, $F_{1,33}$ = 0.72, P > 0.05). As temperature and river flow may be closely related for a given year due to their association with weather, multiple linear regression then tested YCS against both degree-days >12 ^{o}C and annual flow days above the mean. Degree-days >12 ^{o}C was the only significant variable in the model (R^2 = 0.31, $F_{2,32}$ = 7.05, P = 0.03; degree-days: standardised β = 0.58, P = 0.01; flow-days: standardised β = 0.20, P = 0.22). This multiple regression model was then used to test YCS against mean monthly temperature and flow for June, July, August and September of each year. These revealed the models were only significant in July and August, with water temperature the only significant explanatory variable (Table 4.3). For each month, the relationship between water temperature and flow was not significant (linear regression, P > 0.05).

The relationship between length at age 1 and YCS was then tested by using the back-calculated lengths at age 1 data. There was a significant relationship between age-at-capture and back-calculated length at age 1 (linear regression: R^2 = 0.24; $F_{1,558}$

= 66.99, P < 0.01), with smaller fish at age 1 tending to be longer-lived. Decreased levels of orthophosphate have also been shown to influence growth of roach at above age 1 in the river (Chapter 3). Thus, to control for the influence of both age at capture and orthophosphate in the relationship between length at age 1 and YCS, ANCOVA was used. This revealed a significant association between length at age 1 and year class strength, with mean lengths in strong year classes being significantly smaller (R^2 = 0.29, $F_{1,33}$ = 11.39, P < 0.01; Figure 4.5). Both covariates were significant in the model (P < 0.05). The lengths at age 1 were also compared by grouping the data into weak (mean value below 0) and strong (mean value above 0) year classes and using ANCOVA outputs to test for differences between the groups using pair wise comparisons with Bonferroni adjustments for multiple comparisons. Mean-adjusted fish lengths from ANCOVA were then significantly smaller in strong year classes (mean adjusted difference = 2.53 ± 0.65 mm; P < 0.01).

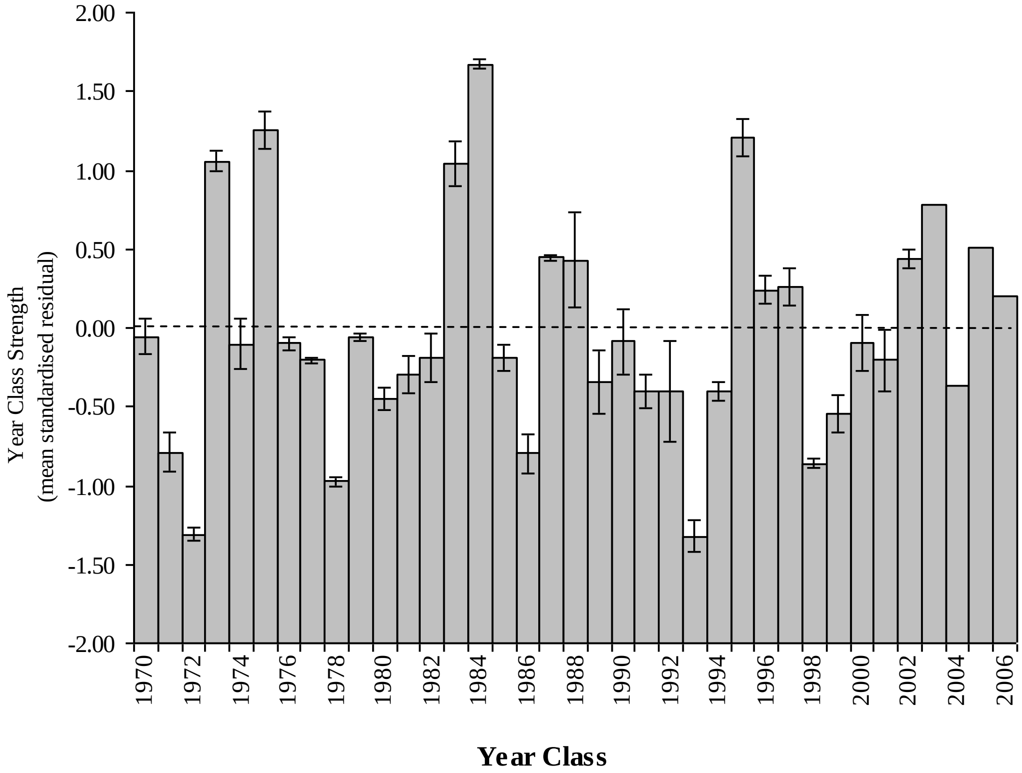

Figure 4.1 Mean year class strengths of roach in the River Wensum between 1970 and 2006.

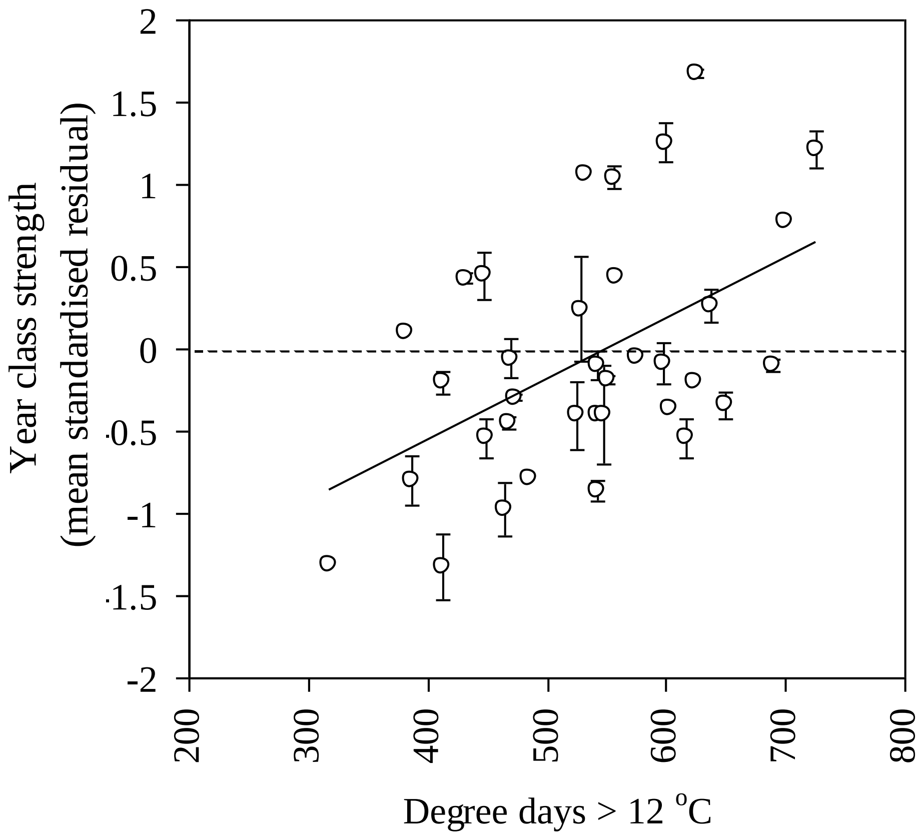

Figure 4.2 Relationship of YCS with annual water temperature, expressed as degree-days > 12 ^{o}C.

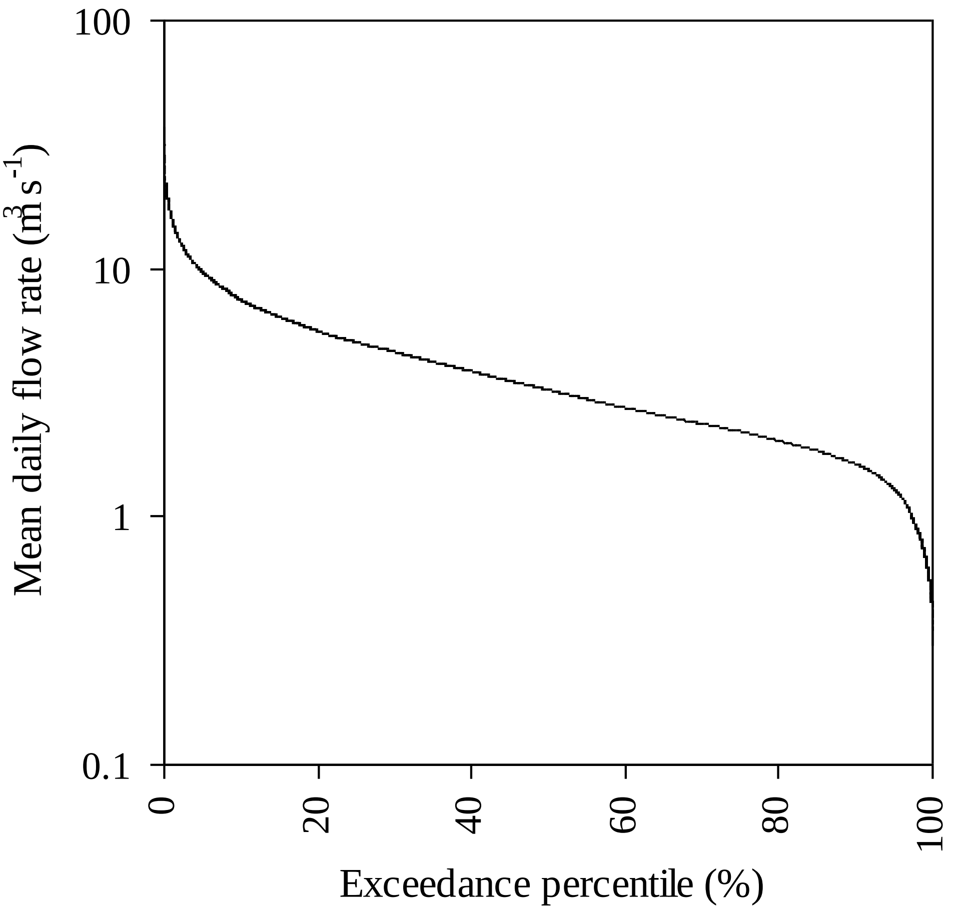

Figure 4.3 Flow duration curve of the River Wensum 1970 to 2004.

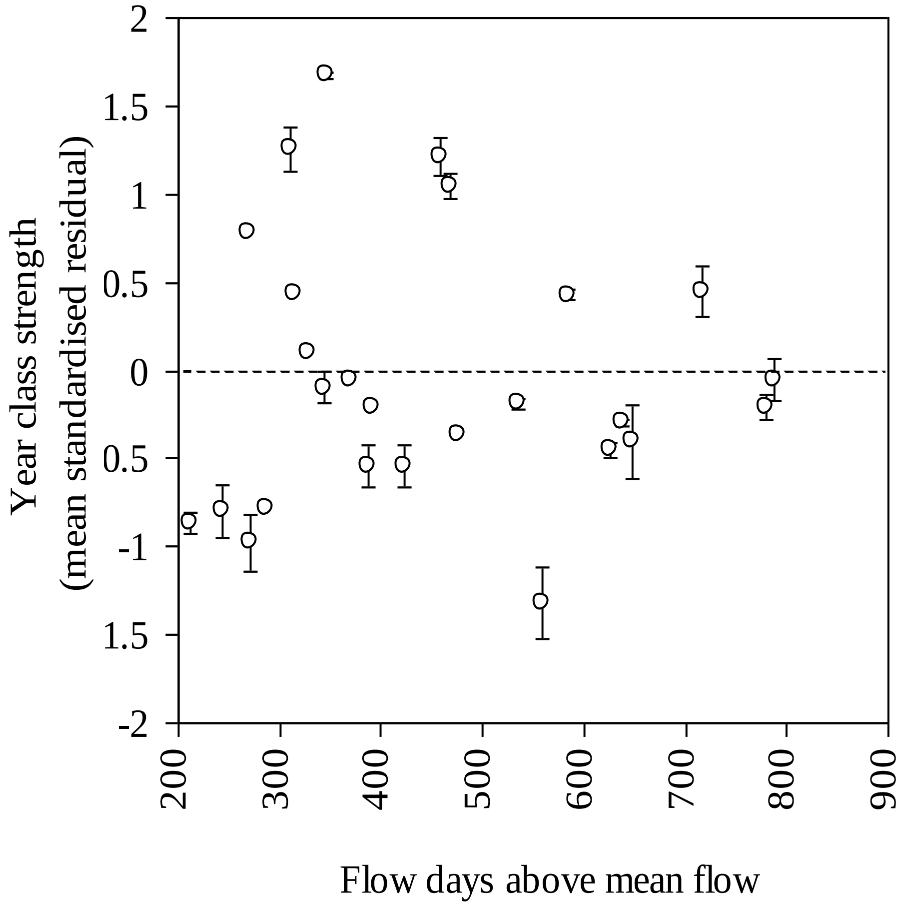

Figure 4.4 Relationship of YCS with annual flow, expressed as the number of flow days above the basal rate.

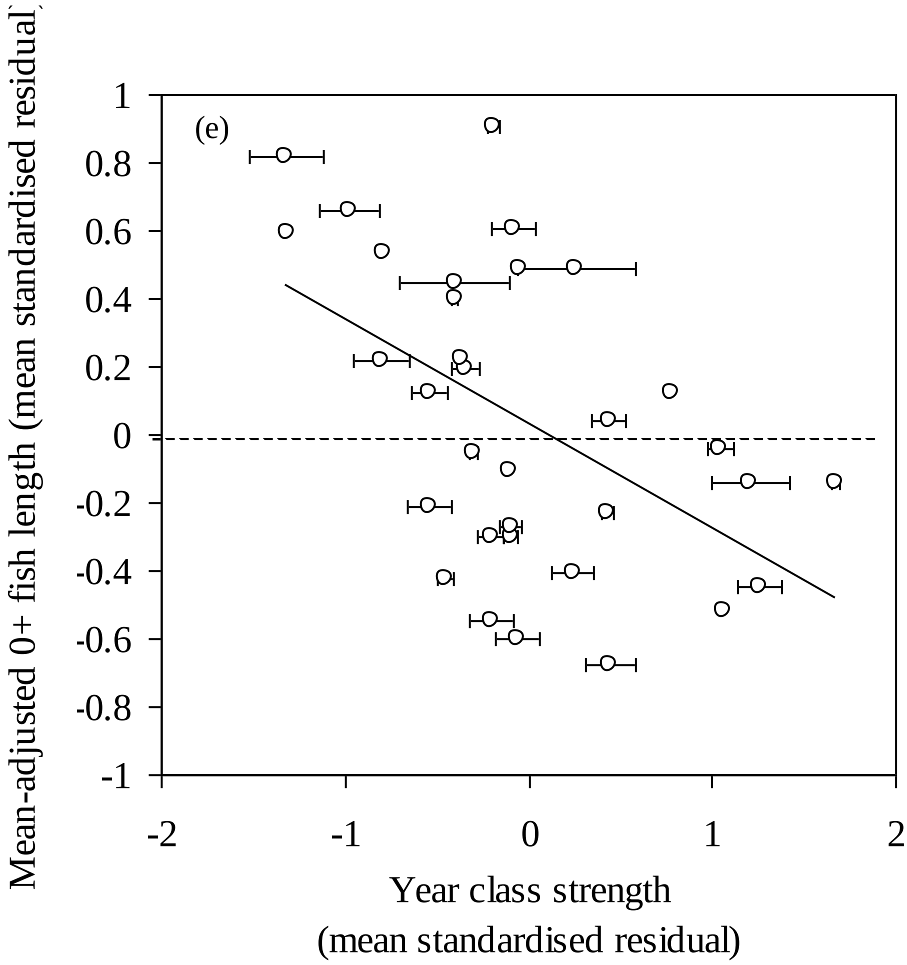

Figure 4.5 Relationship of mean-adjusted length at age 1 of the year classes with their YCS. Solid lines represent the significant relationship between the variables according to linear regression ($P < 0.05$). Horizontal dashed lines denote the position of zero on the Y-axis.

Table 4.1. Outputs of multiple regression models testing the effect of mean monthly temperature and mean river flow between June and September of each year on year class strength between 1970 and 2004. β = values of the standardised beta coefficient.

	Overall regression model			Mean water temperature (^{o}C)		Mean flow (m^3s^{-1})	
	R^2	$F_{2,32}$	*P*	β	*P*	β	*P*
June	0.10	1.95	> 0.05	0.30	> 0.05	0.21	> 0.05
July	0.24	5.05	0.01	0.51	< 0.01	0.26	> 0.05
August	0.42	11.33	< 0.01	0.66	< 0.01	0.11	> 0.05
September	0.02	0.27	> 0.05	0.12	> 0.05	0.07	> 0.05

4.4 Discussion

Long-term population data from the adult roach population revealed years of strong recruitment were infrequent and were related to years of higher temperatures. That river discharge had no apparent influence on recruitment success is in contrast to most studies that suggest periods of elevated discharge in critical periods can have sufficient deleterious effects on 0 group fish abundance to result in weaker recruitment (Grenouillet *et al*., 2001; Nunn *et al*., 2003, 2007; 2010). The lack of relationship between discharge and recruitment in the River Wensum was likely to be connected to its relatively stable hydrology, as the difference between the Q10 and Q90 flows was only 4.2 $m^{-3}s^{-1}$ and the maximum flow recorded over a 35 year period was only 31.40 $m^{-3}s^{-1}$. By contrast, Nunn *et al*. (2003, 2007) demonstrated that the Yorkshire Ouse, a river where periods of high flow have negative consequences for cyprinid recruitment, has a discharge rate ranging between 3 and 300 $m^{-3}s^{-1}$, with Johnson *et al*., (2009) revealing a 38-fold difference between the Q5 and Q95 flows of the river. Thus, the highly variable hydrological regime has substantial effects on the survival of the 0 group cohorts (Nunn *et al*., 2003). These findings are also corroborated by other studies that demonstrate hydrological variables play a key role in the recruitment of cyprinid fishes in lotic systems (e.g. Cattaneo *et al*., 2001; Konecna *et al*., 2009; Olden & Naimen, 2010; Piffady *et al*., 2010) and even lentic systems (Kahl *et al*., 2008). Thus, the relatively stable hydrology of the River Wensum that is provided through its chalk geology may provide its 0 group roach cohorts with an apparent buffer from the deleterious effects of large, relatively rapid increases in discharge that are observed in other temperate rivers.

The only significant abiotic variable on the recruitment strength of the roach cohorts in this study was temperature. Whilst this is a common finding in cyprinid recruitment studies, this tends to correspond with the increased growth of fish within the 0 group cohort that promotes their survival and subsequent recruitment into the adult population (Mills & Mann, 1985; Nunn *et al.*, 2003; 2007). Yet, in this study, there was a negative relationship between mean back-calculated length at age 1 and recruitment strength, even when the effects of the age at capture of the fish had been accounted for in the analysis. This negative correlation, whilst being counter-intuitive, may have resulted from the higher 0 group fish densities - that would be apparent in years that produce strong year classes - resulting in increased competition within the cohort as it may be that their habitat is limited (Chapter 5). Irrespective, this suggests fish length at the end of the first growth season was not an important determinant of the proportion of the 0 group fish that successfully over-wintered, presumably because of the negligible effect of flow that has been already outlined.

4.5 Conclusion

In conclusion, the factors determining the recruitment pattern of roach in the River Wensum was primarily temperature dependent, with years of warmer temperatures resulting in stronger recruitment. Fish length at age 1 and aspects of river flow were not, however, important determinants of recruitment success. Thus, factors affecting the recruitment success of roach in temperate lowland rivers appear to be context dependent, with variation in patterns between rivers being determined by climatic factors and their specific interactions of river geology, hydrology and biology.

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Chapter 5. Interactions of 0 group roach with the littoral habitat of the River Wensum and the effects of river management

5.1 Introduction

It was established in Chapter 4 that the recruitment of roach into the adult population was environmentally determined, with years of strong recruitment having a high dependency on water temperature. Strong recruitment is dependent upon the number of 0 group fish surviving their first year of life, with critical periods affecting their mortality rate and so the number of surviving fish (Nunn *et al*., 2003; 2007a). Whilst no relationship was detected between flow and year class strength (Chapter 4), the role of physical habitat may still be a limiting feature for YoY fishes in the river. Indeed, environmental conditions, such as river discharge rates and macrophyte cover may still be important in determining the amount of available habitat for the 0 group cohort (Souchon, 1994; Lamouroux *et al*., 1999). Habitat for these life stages tend to be areas of slack water that provide areas of refuge from predation, even for rheophilic species like European barbel that only tend to seek faster water flows once body lengths above 50 mm are achieved (Britton *et al*., 2011). Even in the River Wensum, it may still be the case that brief episodes of elevated discharge may increase mortality and displacement in some years, even though this could not necessarily be detected within the adult fish data in Chapter 4. Indeed, critical periods such as this are common in the early life of the cohort when the larval stages have low swimming abilities (Catteneo *et al*. 2001; Grenouillet *et al*., 2001; Nunn *et al*., 2003, 2007a; Piffady *et al*., 2010). Moreover, the ability to differentiate between the effects of elevated discharge in the recruitment process may also be difficult to separate from its effect on water temperature, given that this will be reduced during inclement weather in the early summer (Nunn *et al*., 2003).

The relationship between the 0 group fish cohorts and their available habitat is important in the context of not only environmental conditions and river discharge but also river management (Section 1.3.3). For example, long-term flood management methods tend to involve channel straightening that has the general effect of reducing the area of favourable larval and juvenile habitat in the littoral areas, with this often compensated by increasing the availability of connected off-channel refuges (Nunn *et al*., 2007b, 2010; Janac *et al*., 2010). In some rivers, excessive macrophyte growth in the main channel elevates flood risk and so weed cutting programmes are executed, despite their usefulness as a source of refugia for 0 group fish (Jurajda, 1995; Copp, 1997). For example, a study on the Great River Ouse in Eastern England showed that weed cutting had a substantial consequence for the river biota generally as well as the 0 group fish specifically (Garner *et al*., 1996). Prior to weed-cutting, a significant relationship between 0 group fish, macrophyte cover and zooplankton density was found, with elevated densities of zooplankton and fish in the macrophyte zone. The removal of much of this macrophyte cover through weed cutting resulted in a rapid decline in the mean densities of zooplankton present as a result of increased washout that was accompanied by increased 0 group fish displacement, predation and starvation. This resulted in reduced growth rates in the fish as their diet shifted from zooplankton to the less nutritious detrital aufwuchs (Garner *et al*., 1996). Other studies have examined the diet of 0 group roach and have all concluded that variations in zooplankton prey abundance is found to influence the initial growth rates of roach larvae, with shifts from small invertebrates to one dominated by detrital aufwuchs, found to offer minimal nutritional value and is of poor digestibility (Persson, 1983; Garner *et al*., 1996; Mann & Bass, 1997 & Nunn *et al*., 2007b). Thus, river management schemes, such as those that reduce flood risk through channel straightening and weed removal may be a significant factor of the 0 group fish survival rates and so also upon the recruitment success of the cohort.

Consequently, the aim of this chapter is to build on the recruitment data from the adult roach produced in Chapter 4 by looking at the 0 group fish population of the River Wensum in relation to habitat and river management strategies. Objectives were to (i) determine the important micro-habitat variables that determine the presence and abundance of 0 group roach in the littoral zone; and (ii) determine the effect of weed cutting (as a river management exercise) and its associated disturbance on the distribution and abundance of the 0 group roach.

5.2 Materials and methods

5.2.1 Study area

The study was carried out at five sites on the River Wensum, within a 40 km stretch between Bintree (52°46’57.05”N, 0°57’37.94”E) and Hellesdon (52°38’25.49”N, 1°14’58.03”E) where the rivers dimensions vary from 10 to 25m in width and 0.5 to 3m in depth (Table 5.1; Fig. 5.1). Unsympathetic river management schemes in the last century have resulted in changes in channel form and function throughout the watercourse via; straightening, dredging, loss of backwaters causing reduced lateral connectivity between the river and its floodplain, and regular removal of in-stream habitat such as woody debris and macrophyte control.

Table 5.1. Location and frequency of River Wensum point abundance electrofishing surveys, 2007 to 2008 with X denoting survey conducted. The site number refers to those on Figure 2.1.

		2007					2008				
		Jul	Aug	Sept	Oct	Nov	Jul	Aug	Sept	Oct	Nov
6	U/S Bintree Mill	X	X	X	X	X	X	X	X	X	X
9	Swanton Morley	X	X	X	X	X	X	X	X	X	X
11	Lyng Pits	X	X	X	X	X	X	X	X	X	X
12	U/S Lenwade Mill	X	X	X	X	X	X	X	X	X	X
18	Hellesdon Rd (Albert's)	X	X	X	X	X	X	X	X	X	X

5.2.2 Juvenile fish sampling and data analysis

Point abundance electric fishing was used to assess the relationship between 0 group fish and littoral habitat variables. This method was used in preference to micromesh seine netting due to the lack of littoral areas suitable for seine netting arising from channelization (*cf.* Cowx *et al*., 2001). For example, there were few suitable backwaters and shallow bays present for sampling. To optimise the opportunity to representatively capture the 0 group fish population at each point, the electric fishing gear was specifically adapted to catching these fish using the method of Copp & Garner (1995). This covered the use of a 10cm diameter anode ring and a 20 metre long cathode to reduce energy loss from the area. A Honda EU 10i, 1.0 KW electrofishing generator was used with an Electrocatch control box, producing approximately 0.5 to 1.0 amps of Pulsed Direct Current at 50 Hz. This enabled an effective fishing area around the anode of approximate radius 0.5 m. The surveys were generally conducted monthly from July to November between the years of 2007 and 2008 and comprised the fishing in each location of 60 random points per site, as in the study by Garner (1997) it was suggested that to produce reliable estimates, a minimum of 50 points is required. Sampling took place in the littoral areas of the river as these habitats tend to be favoured by 0 group fish (Copp & Garner 1995; Pilcher & Copp, 1997; Welcome & Cowx, 1998; Copp 2010). Two additional point abundance samples also took place in August 2009 prior and subsequent to weed-cutting operations. Access issues meant these surveys were restricted to being completed in daylight hours only, so diel patterns were unable to be determined (Copp, 2010). Each point was fished for a standard period of 10 seconds and all fish immobilized within the electric field were captured with a hand net. These fish were then identified (species, larval stage, juvenile) and measured (nearest mm). The environmental variables of depth (m), flow ($m^{-3}s^{-1}$), estimated macrophyte cover (%), substrate and location (GPS) were then recorded.

5.2.3 Effect of weed cutting on juvenile fish

During the juvenile fish sampling surveys of 2007 and 2008 (Table 5.1) a stark contrast in presence and abundance of juvenile fish prior to and subsequently after annual weed-cutting practice took place, was observed. Consequently, to test the effect of weed-cutting on the juvenile fish populations of the river in August 2009, two separate point abundance surveys were conducted in a 1.6 km reach of the study area at Lenwade (52°43'10.47"N, 1°05'43.11"E), where the dimensions of the river ranged from 15 to 20m in width and 0.5 to 3m in depth, in what is an impounded stretch of the river (Site 12; Table 5.1, Fig. 5.1). The first survey was conducted 24 hours prior to a weed-cutting operation and the second was conducted 24 hours following that weed-cutting operation. Additional surveys had been intended to take place every week for one month following weed-cutting operations, however following organisational change within the Environment Agency this was not possible and only one survey 24 hours after weed-cutting took place. In both surveys, 120 point samples were taken due to the reach length of weed-cut being approximately twice the length of a typical point abundance survey for the river (1.6 km stretch). Data for each point was also recorded, as outlined above.

5.2.4 Data analysis

The data from the point abundance surveys were analysed for the habitat variables affecting roach presence and abundance during daylight hours. For analysis of their presence/absence, logistic regression was used to test for a relationship between the probability of capturing at least one roach in a point sample, measured as the binary yes (detection) or no (non-detection), against the depth, flow and macrophyte cover of those points. This revealed the significant variables contributing to the determining of their presence in a point and enabled the probability of capture (P) to be determined from P = $e^{(a+bF+cM)}$ / 1+ $e^{(a+bF+cM)}$ (Equation 1; Britton *et al*; 2011), where *a*, *b* and *c* were the regression coefficients of the habitat variables flow (F) and cover (M) (*cf*. Results). From this model, the habitat variables required to have a high probability of capturing at least one roach from a point were determined and displayed on a contour plot. In the points where roach were present, multiple regression analysis was then used to identify the variables that explained most of the variation in the model through looking at the standardized β values. For the point samples from the pre and post weed-cutting in 2009, changes in the habitat variables of the points were tested using ANOVA and Mann-Whitney U tests (depending on the distribution of the data) followed by testing of changes in the proportion of points with roach present and their abundance. All statistics were completed in SPSS v16.0. Parametric tests were used only after successfully testing for normality.

5.3 Results

5.3.1 Overview of point sample data

During the point abundance sampling for the 0 group component, a total of 10 fish species were encountered, with a typical survey of the river possessing around 5 species (Table 5.2). At the majority of the survey sites, minnow *Phoxinus phoxinus* was the most abundant juvenile species present with other cyprinid species encountered infrequently. Roach were present in only 6.2 % of the 2163 points sampled. Other species occasionally encountered during sampling included stoneloach *Barbatula barbatula*, bullhead *Cottus gobio*, three spined-stickleback *Gasteroseus aculeatus*, gudgeon *Gobio gobio*, pike *Esox lucius* and perch *Perca fluviatilis*. Monthly length frequency distributions for roach, dace and minnow for the lower most survey site (No. 18) are included in Appendix 2. Given the amount a data collected, this site was chosen at random to display length-frequencies.

Table 5.2. Fish species present during point abundance surveys at the 5 sites surveyed during 2007 and 2008 on the River Wensum. X denotes confirmed presence of species at given site. Site numbers in brackets denote location in Table 2.1 and Figure 2.1.

Sites	**Bintree Mill**		**Swanton Morley**		**Lyng Pits**		**U/S Lenwade Mill**		**Hellesdon Rd**	
Fish	(6)		(9)		(11)		(12)		(18)	
species	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**	**2007**	**2008**
Roach	X	X	X	X	X	X	X	X	X	X
Dace			X	X			X	X	X	X
Chub			X	X	X	X	X	X	X	X
Bullhead			X	X						
Stoneloach			X	X			X	X		
3 Spined Stickleback	X	X			X	X				
Minnow	X	X	X	X					X	X
Gudgeon			X	X	X	X				
Perch									X	X
Pike	X	X								

5.3.2 Relationship of 0 group roach with littoral habitat features

Across all of the point samples (n = 2163), roach were only caught in 133 points. The fish captured were generally above 25 mm and either larval stage 5 or the juvenile stage, with mean fish length generally increasing with sampling month (Appendix 2). There were significant differences in the environmental variables between the points in which 0 group roach were present and absent. Points with fish were deeper (mean 1.07 vs. 0.99m; ANOVA $F_{1,2163} = 6.20$, $P < 0.02$), slower flowing (mean 0.03 vs.

$0.06\ m^3\ s^{-1}$; ANOVA $F_{1,2163} = 21.56$, $P < 0.01$) and had increased macrophyte cover (median 60 vs. 5 % Mann Whitney U test Z = -19.52, $P < 0.01$). As these relationships were independent of fish length (Regression, $P > 0.05$) and larval/juvenile stage (ANOVA, $P > 0.05$) then data from monthly samples were combined for the subsequent habitat-based analyses.

The use of these point sample data in logistic regression revealed that both flow and macrophyte cover were significant variables in the model, but depth was not significant (Model 1, Table 5.3). Consequently, depth was omitted and the model was run again; flow (*F* in Equation 1) and macrophyte cover (*M* in Equation 1) remained significant in the model (Model 2, Table 5.3). These were then used in Equation 1 to give the probability of recording at least 0 group roach in a point sample according to flow and macrophyte cover. It revealed that the probability of a roach being present in a point was only above 0.80 (i.e. 80 %) when flow was below $0.34\ m^{-3}s^{-1}$ in conjunction with macrophyte cover being above 60 % (Fig. 5.2). Validation of the model through calculation of the probability of capture in the points where roach were actually present and absent revealed that the median probability in points where roach were captured was 0.86 compared to 0.01 where roach were not captured, with the difference being significant (Mann Whittney U test: Z=-18.79, $P < 0.01$). Thus, the model was considered robust. In the points where roach were present, multiple regression revealed that variation in their abundance was mainly explained by macrophyte cover, where points with increased cover had significantly increased abundance (Table 5.4). The variables of depth and flow were not significant variables in this model (Table 5.4).

5.3.3 Effect of weed cutting on the littoral habitat and presence and abundance of 0 group roach

The effect of weed-cutting on the characteristics of the point samples was marked. Although there were no significant differences in the mean depth and flow of the points pre and post-cutting (ANOVA: depth $F_{1,239} = 0.67$, $P > 0.05$; flow $F_{1,239} = 0.14$, $P > 0.05$), there was a significant reduction in macrophyte cover (pre-cut median: 60 %, post-cut: 30 %; Mann Whitney U test Z =-6.54, $P < 0.01$). In the point-samples prior to weed-cutting, 39 of 120 points had 0 group roach present (32.5 %), whereas this reduced to 21 of 120 points post cutting (17.4 %). In the points where they were present, their abundance was significantly higher in the pre-cut samples compared with the post-cut samples (mean 3.61 ± 2.3 vs. 2.2 ± 0.9; ANOVA $F_{1,58} = 6.79$, $P < 0.02$).

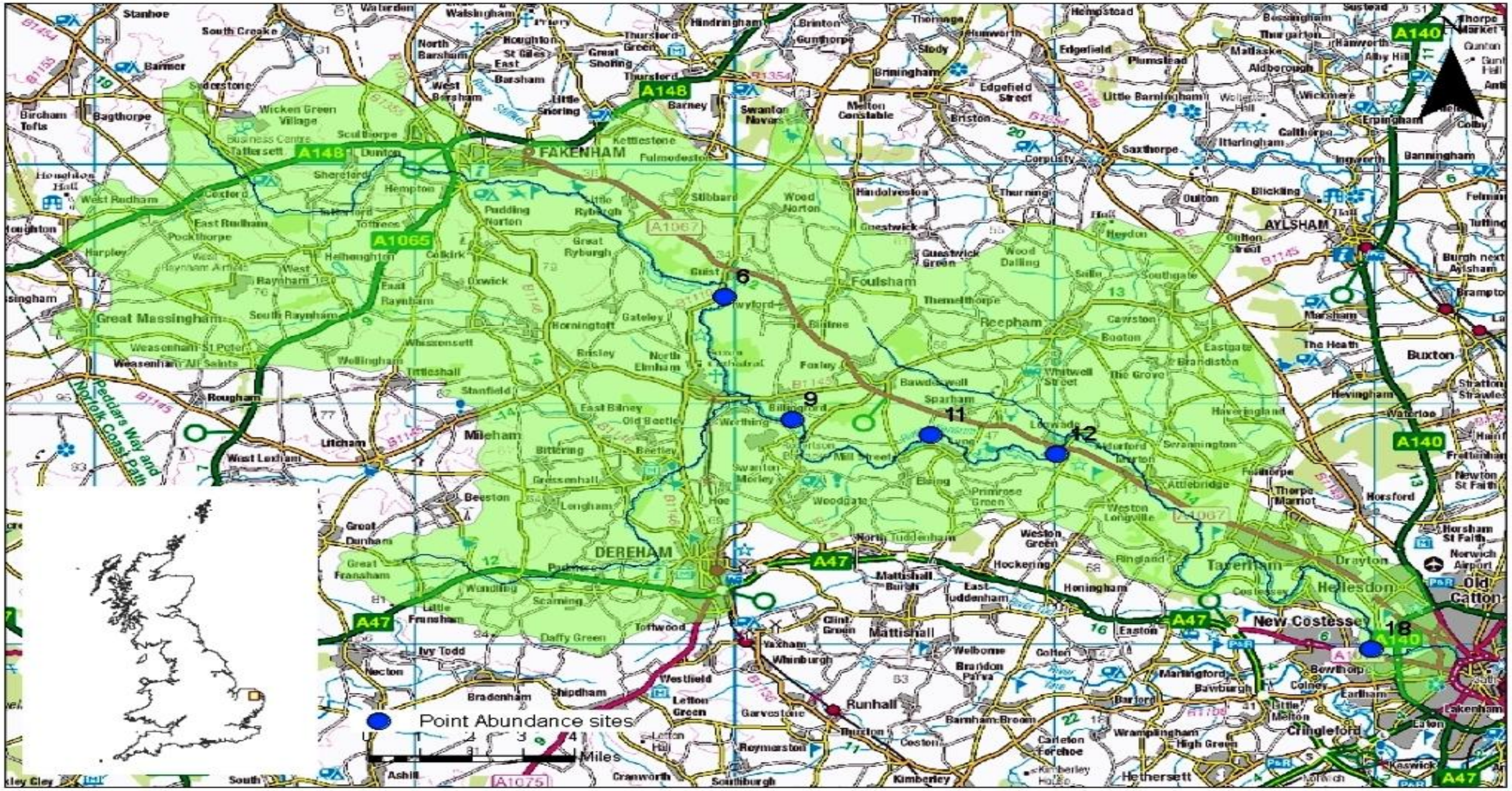

Figure 5.1. Site locations of the point abundance surveys on the River Wensum; numbers relate to Table 5.1. The area shaded in green shows the drainage area of the catchment.

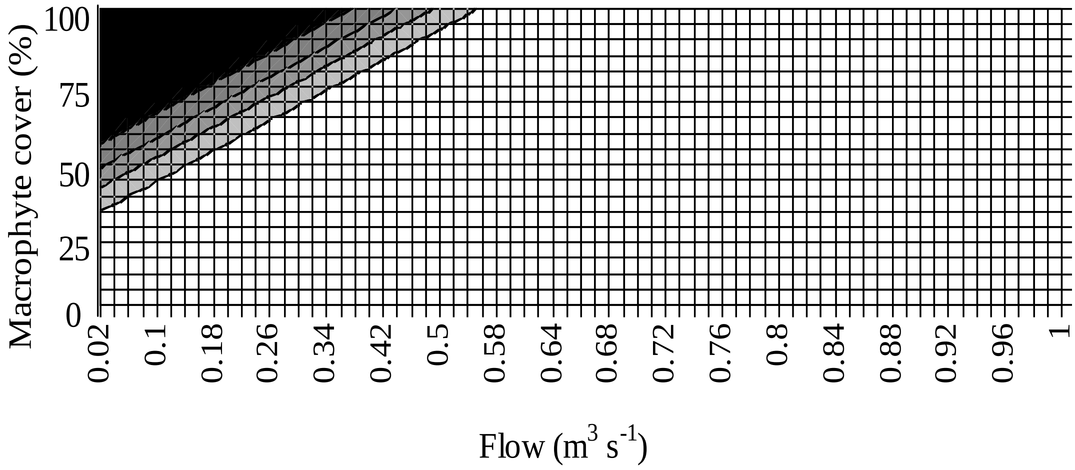

Figure 5.2 Contour plot of predicted probability of capturing a 0 group roach according to the variables of flow and macrophyte cover, where colours represent: white $P < 0.19$; light grey: $P = 0.20$ to 0.39; medium grey: $P = 0.40$ to 0.59; dark grey: $P = 0.60$ to 0.79; black $P = 0.80 - 0.99$.

Table 5.3. Logistic regression coefficients and their statistical significance for the environmental variables of the point samples, where values in (2) were used in equation 1 to calculate the probability of capturing a 0 group roach at a point sample according to values of the variables.

Model	Variable	Symbol in equation 1	Coefficient	Standard error	*P*
(1)	Constant	n/a	- 5.90	0.31	< 0.01
Flow (*F*), depth	Flow	n/a	-16.53	4.52	< 0.01
and macrophyte	Cover	n/a	0.13	0.01	< 0.01
cover (*M*).	Depth	n/a	0.26	0.44	0.55
(2)	Constant	a	- 5.65	0.45	< 0.01
Flow (*F*) and	Flow	b	-15.82	4.31	< 0.01
macrophyte	Cover	c	0.13	0.01	< 0.01
cover (*M*).					

Table 5.4 Outputs of multiple regression analysis for the contribution of flow, depth and macrophyte cover to the number of 0 group roach sampled from points (excluding points where roach were absent).

Overall model: $R^2 = 0.07$; $F_{3,129} = 3.25$; $p < 0.03$		
Variable	β (standardised)	*p*
Flow	-0.096	0.28
Depth	0.126	0.16
Macrophyte cover	0.229	< 0.01

5.4 Discussion

5.4.1. The importance of physical habitat for 0 group fish

The survival and recruitment of 0 group fish through critical periods occurring during their early life stages have been suggested as the major determinants of recruitment strength (Mills & Mann, 1985; Garner *et al*., 1996; Nunn *et al*., 2007a, 2010). In the study of a regulated stretch of the River Great Ouse, Copp (1997) observed that the common place practice of weed-cutting for navigation and flood risk management purposes was detrimental to the survival and recruitment of young fish through removal of refuge from flow and predators and the associated food source. Following weed-cutting operations, a significant decrease in the frequency of samples in the main channel containing fish was observed suggesting their downstream displacement. In the River Wensum, to prevent the backing-up of water during episodes of high flows, removal of in-channel obstructions such as large woody debris has been a commonplace management activity by the Environment Agency and its predecessor organisations for many years. The importance of woody debris as habitat and refuge for small fish, and the impact of its removal demonstrated by Angermeier & Karr (1984) who found significant associations between the presence of woody debris and fish, with avoidance of areas lacking such habitat features.

In the River Wensum, macrophyte cover was shown to be the most influential variable in determining both the probability of a 0 group roach being present during the daylight hours in a point sample and their abundance at a point. Thus, it may be that in years of elevated temperatures, there is increased macrophyte cover available for 0 group roach enhancing their survival but reducing their growth through density dependant mechanisms such as increased competition for food (*cf*. Chapter 4). This, however, must remain speculative given that it was unable to be tested explicitly within the study. Moreover, it is acknowledged that a shortcoming in this aspect of the study is the lack of opportunity to determine the diel activity of the 0 group cohort; in darkness, an increased fish abundance and greater spatial dispersion may have been apparent and have been related to other habitat variables. For example, the study by Copp (2010), observed the shortcoming of the point abundance sampling method in daylight hours through inadequately representing benthic and nocturnal species, instead finding increased sample densities of 0 group fish during hours of darkness.

The importance of macrophyte cover to the presence and abundance of the 0 group roach cohorts over two successive years, and the deleterious effects of the weed-cutting that was observed, strongly suggests that recruitment rates in the river have been adversely impacted by unsympathetic weed cutting regimes. Given that the point sampling data already suggested that only a small proportion of the marginal areas of the river were suitable nursery habitat (low flow, high macrophyte cover), then any habitat disruption would be a concern from a recruitment perspective. Indeed, marginal macrophytes are known refuges from flow for phytoplankton, zooplankton and fish (Copp 1990; Mann & Bass 1997) and their removal through physical cutting for reducing flood risk is common practice in many lowland rivers in England (Frigburg, 2009). Despite the deleterious consequences for both invertebrate and 0 group fish populations, indiscriminate weed cutting that leaves only small buffer areas remains common. It must however be acknowledged that within the scope of study only one point abundance electro fishing survey subsequent to weed-cutting operations was conducted with no further repeat surveys. This is a shortfall of the study as although weed-cutting was confirmed as deleterious to the presence and abundance of 0 group roach, it is not known if fish were displaced due to habitat disturbance or displacement through removal of habitat. Consequently, and following Garner *et al*. (1996), it is recommended that more experimental weed cutting trials are conducted in the River Wensum to identify how modified practices may reduce the risk of 0 group fish displacement and mortality, and enhance subsequent recruitment success.

In order to maintain fish populations in modified and regulated river systems, suitable spawning and nursery habitat, and in- and off-river refuges are of vital importance (Mills & Mann, 1985; Jurajda, 1999; Nunn *et al*., 2007b). It is recognised that water bodies maintaining lateral connectivity with their floodplains enhance the successful recruitment of riverine fish populations through increased availability of food sources such as plankton that cannot persist in flowing conditions and refuge from high flows (Nunn *et al*., 2007b). The importance of suitable nursery habitat to the 0 group cohort was further highlighted in Copp (1997) where in the River Great Ouse the absence of side-channels and natural backwaters meant the only off-river refuges available were man-made marinas which were found to be heavily utilized by juvenile fishes. However the limited size of the connection between the main river and such marinas compromised their use, as the young fish may be have been unable to find these during seasonal flooding events.

The point abundance surveys completed here suggested that suitable nursery habitat was limiting as only 6 % of sampling points in the littoral zone were occupied by juvenile roach (in daylight hours). Thus, this suggests the majority of habitat present within the littoral zone was inappropriate as nursery habitat. Section 4.3 revealed that years of strong recruitment were associated with years of elevated temperature that were negatively correlated with mean lengths at age 1. Thus, this nursery habitat limitation may be causing more intense competition for food resources for the juvenile roach in the river and resulting in their depressed growth in years of high abundance and survival (and so subsequent recruitment). Further investigation into available food resources and competition are therefore necessary.

5.5 Conclusion

To conclude, this chapter revealed nursery habitat was limiting for juvenile roach in the river, with these habitats best described by their macrophyte cover. The river management scheme of weed cutting revealed a deleterious effect on juvenile roach. Although it could not be ascertained whether this was just a short-term impact, other studies suggest that longer term consequences are also apparent.

5.6 References

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Chapter 6. Discussion

6.1 Overview

6.1.1 Water quality

"By the late 19th Century water-borne diseases were rife and the beauty of the river (Wensum) destroyed" (Countryside Agency, 2006).

The location of the River Wensum in Eastern England that provides a relatively rural catchment means that the water quality of the river has never experienced the type of industrial pollution experienced by rivers such as the Trent and Don (Amisah & Cowx 2000a,b). Nevertheless, it was noted in Chapter 2 that deterioration in the water quality of the Wensum had been evident, particularly in relation to the input of the nutrients phosphate and nitrate. The phosphate levels in the river only began to decrease in the 1990s as improvements to sewage treatment works, particularly phosphate stripping, resulted in significantly decreased inputs thereafter. This decrease in phosphate levels is a common and desirable effect of such improvements to sewage effluents (Jarvie *et al*. 2000; Wade *et al*. 2002).

Improvements to the nitrate levels in the river have been more difficult to reduce, with much of this likely to result from diffuse pollution occurring via agricultural practises. Whilst some improvements have been apparent, nitrate levels remain elevated. Nevertheless, the river today is cleaner and less eutrophic when compared to the 1960s, 70s and 80s having consequences on aspects of the fish community (Section 6.1.2).

Monitoring of the status of the River Wensum now falls under the Water Framework Directive, 2000 (WFD). Within the WFD, there is the stipulation that all inland, estuarial and coastal waters must aim to achieve “good ecological status” by 2015. More than 80 % of water bodies in England and Wales currently fail and are likely to still fail in 2015 to achieve this status, (Postnote, 2008). The River Wensum is included in the 80 % of water bodies that will fail to meet this required status. There are three parts to the classification of a water body; ecological, chemical and hydro-morphological designation. Any status that is less than ‘good’ is considered to be failing. Ecological classification takes into account the biological status of four key elements; diatoms, macrophytes, invertebrates and fish. Although much improved in recent years, the Wensum is currently failing for diatoms and fish, is designated as ‘heavily modified’ (as such is only able to meet good ecological potential) and has a chemical failure for the presence of isoproturon. The reasons for failure of ecological status according to fish relates primarily to sites where the abundance of roach and dace were lower (and were occasionally zero) than the abundances predicted according to their environmental and water chemistry characteristics (Environment Agency, 2011a). The decline in dace populations of the river has already been detected in this thesis and the roach population has been noted as being influenced by a number of environmental factors that may be influencing their cyclic patterns of abundance (Section 6.1.2)

6.1.2. Adult fish populations

A series of changes and shifts in the spatial and temporal relationships of the Wensum fish community have occurred between 1986 and 2009 (*cf*. Chapter 2) with fish abundances apparently responding to, for example, shifting environmental conditions. Most recent surveys suggest a significant decline in the presence and abundance of eel and dace, with chub increasingly present. Also noted was the significant increase in both density and biomass of pike in the river following phosphate stripping. Although not substantiated, it is possible that this occurrence is coincident with increased water clarity due to fewer nutrients entering the waterbody, thus facilitating their sight feeding predatory behaviour and ultimately, their fitness. Further analysis of water quality parameters such as suspended solids (mg l^{-1}) and chlorophyll a (μg l^{-1}) would be good indicators of temporal changes in turbidity. This could be examined alongside changes in the abundance and growth rates of perch and pike.

Contrary to the views and anecdotal opinions of anglers, the electric fishing surveys suggested the population abundance of roach has not changed significantly between 1986 and 2009. Indeed, abundances in 2009 were similar to those of the 1980s and early 1990s. There are similar instances of reported declines in angler catches not always being matched by patterns in the fish population or even the angler catch data (e.g. Cowx *et al.*, 1986; Lyons *et al.*, 2007). There were, however, two aspects that may have provided this perception of roach population decline:

(i) The climate-driven, cyclical nature of their recruitment success would have resulted in temporally variable roach abundance and as the abundance of roach in the angler catchable cohort (generally fish of > 120 mm) would have consequently changed over time then so would the angler catch rates. This cyclic pattern of recruitment in roach is common in temperate riverine cyprinid fish generally, although in other rivers, growth of the 0 group fish and episodes of high flows can have a stronger role in determining recruitment success (e.g. Grenouillet *et al*., 2001; Nunn *et al*., 2003, 2007).

(ii) The somatic growth rates of roach temporally and significantly declined over the study period, with individuals now growing slower than in the 1970s, 80s and early 90s. This slowing of growth would inhibit individuals growing to 'specimen' sizes and given that the Wensum was previously famed for these roach, rather than for its roach population generally, then it may be the paucity of these fish that is being most noticed by anglers. The significant changes observed in roach growth suggests the anthropogenic pressure of organic enrichment (and reversal post 1996) were important drivers of change, with shifts in water quality potentially having important ecological consequences for fish populations that may then negatively impact aspects of fishery performance through inhibiting individuals from attaining their former specimen sizes.

6.1.3 Juvenile fish populations and habitat

Successful years of recruitment in the River Wensum were largely temperature driven (*cf*. Chapter 4), with warmer years resulting in stronger recruitment despite the significantly smaller mean sizes of the recruits - a counter-intuitive outcome (Grenouillet *et al*., 2001; Nunn *et al*., 2003; 2007a). This reduced growth in good recruitment years may be indicative of a lack of suitable littoral and nursery habitat for juvenile cohorts that resulted in a situation where a strong spawning year for roach resulted in higher competition for resources, decreasing their growth but not necessarily impacting their recruitment (density-dependent growth but density-independent survival). To substantiate this theory further, stomach content analysis of the 0 group component in relation to fork length and aspects of physical habitat would be useful and may confirm the hypothesis that sub-optimal physical habitat is present in the Wensum for juvenile fish.

The presence and abundance of the 0 group roach was significantly associated with areas of increased macrophyte cover and deeper, slow flowing water where the fish could take refuge from the main flow. This was found to be in accordance with aspects of Garner's (1996) study of the River Great Ouse in Cambridgeshire, Eastern England, that described the optimum habitat conditions for determining juvenile roach presence as 1m in depth, with a coarse substratum, negligible velocity and presence of floating and submerged broadleaved cover. That only 6 % of points throughout the 2-year point abundance sampling period had 0 group roach present in the Wensum suggests that nursery habitat may have been a limiting factor constraining the overall population. Furthermore, an experiment on current weed-cutting practices within the river revealed a deleterious effect on the presence and abundance of 0 group roach through removal of macrophyte habitat, associated cover and food supply. Additional investigation is strongly recommended here to further the findings of weed-cutting activities and ascertain if the effect observed in this study was caused through initial disturbance of weed-cutting or through removal of habitat and therefore displacement. Moreover, investigation into diel patterns of juvenile density within the Wensum would be valuable to compare distribution and abundance of juveniles in daylight hours (the focus of this study) to those of darkness (Copp, 2004).

In order to maintain fish populations in modified and regulated river systems, suitable spawning and nursery habitat, and in- and off-river refuges, are of vital importance (Mills & Mann, 1985; Jurajda, 1999; Nunn *et al*., 2007a). It is recognised that water bodies maintaining lateral connectivity with their floodplains enhance the successful recruitment of riverine fish populations through increased availability of food sources such as plankton that cannot persist in flowing conditions and refuge from high flows (Nunn *et al*., 2007b). The importance of suitable nursery habitat to the 0 group component was further highlighted in Copp (1997) where in the River Great Ouse the absence of side-channels and natural backwaters meant the only off-river refuges available were man-made marinas which were found to be heavily utilized by juvenile fishes.

6.2 Management recommendations and implications

This study has demonstrated that much of the issue relating to roach in the River Wensum may be explained by a combination of changes in the nutrient status of the river and natural fluctuations in aspects such as climatic factors. These have resulted in roach remaining relatively abundant in some reaches of the river - as numerous as the 1980s but also sometimes resulting in failure of good ecological status in the Water Framework Directive. These roach are now, however, generally slower growing and less likely to reach angler 'specimen' size (1 kg). For juvenile roach, habitat also appeared limiting, with few areas in the littoral zone of the river providing optimum areas for refugia and especially when in-stream macrophytes are cut. Consequently, the aim of this particular section is to identify how some of these aspects may be remedied within current river management practises and aspects such as the Water Framework Directive.

6.2.1. Water Framework Directive legislation

The effect that the shift to less eutrophic conditions following improving water quality has been well documented within this study. Although roach growth is reduced as a result, importantly now the river achieves the General Quality Assessment grade, although this has now been superseded by EU Water Framework Directive legislation for phosphate concentrations (Environment Agency, 2011b). Levels are set to decrease further still under Habitats Directive legislation for Special Areas of Conservation (SAC) rivers before 2015 (Riley, 2010). As such, any suggestions to increase phosphate inputs as a means to improve roach growth is not a desired or feasible management option. Sustainable management options to help improve roach populations would therefore be to improve, restore and create adequately sized and suitable areas for important life-stages of the roach (e.g. spawning, larval and juvenile stages, adult over-wintering).

Physical modification to the River Wensum over the years, whether via straightening, removal of meanders or loss of backwaters, combined with insensitive river management practices such as dredging, macrophyte removal and removal of woody debris, have been contributed to the relative lack of suitable habitat available for the 0 group roach. This in turn means that in years when environmental factors are favourable to recruitment success, this too is perturbed by increased intraspecific competition within the cohort for sufficient resources, highlighted by the smaller mean lengths of roach at age 1 present in stronger year classes. Should the 0 group component successfully recruit and survive into adulthood, recent growth per each annual increment is also perturbed compared to annual incremental growth obtained prior to phosphate stripping, due in part to reduced productivity from improved water quality and to lack of nutritional food supply able to persist in conditions within the main channel. The limited areas of lateral connectivity and minimal off-river refuges where appropriate food sources such as zooplankton populations can develop and persist within the water column, often means that fish utilize the abundant aufwuchs that have little nutritional value (Garner *et al*., 1996; Mann & Bass, 1997; Nunn *et al*., 2007b). In order to test the possibility of this occurrence within the River Wensum it is recommended that stomach content analysis of 0 group fish in relation to food availability in marginal areas is examined. Furthermore, it is recognised under WFD that the river is heavily modified and failing to meet good ecological potential, highlighted through the depressed observed densities of roach and dace. Improvements to the current failing fish element are unlikely to be achieved without channel form and function and issues first being addressed.

6.2.2 Sustainable management options

This study has highlighted the most significant factors responsible for recent survey catches and the status of the River Wensum roach population and the fishery it supports being the complex interactions between abiotic and biotic factors that were exacerbated by limited suitable habitat for critical life stages. This limited habitat relates to the main river management activity in the catchment of flood defence operations. Ideally, any flood preventative works should be completed in a manner that provides flood protection but minimises the damage to the fish habitat. Past modifications are currently being addressed through the River Wensum Restoration Strategy to facilitate restoring the physical functioning of the river enabling it to sustain the wildlife and fisheries characteristic of a Norfolk chalk river (Environment Agency, 2008).

The management recommendations that follow are designed to improve and create habitat within the river that is lacking at present with the overall aim of improving the overall abundance of the roach population which in turn will help rectify the current failing fish status.

- *Creation of off-river refuges*

In light of the knowledge that suitable juvenile habitat appears to be limited in the river, the creation of widespread off-river refuges help provide greater areas of suitable habitat. Currently, few stretches along the river possess adequately sized off-river areas and where they are available they are often poorly connected. Previous attempts have been made to create off-river refuges for juvenile fish in the River Wensum including Schemes at Swanton Morley and Attlebridge (Figure 2.1) where enhancement has taken place. Although better than nothing, these off-river refuges are very limited in their distribution and are therefore likely to have minimal effect, particularly in high flow events when juveniles would be unlikely to locate such areas. Widespread provision of these areas would create suitable nursery habitat for juveniles to grow and potentially reach larger sizes at the end of their first year of life. Connection of man-made water-bodies where habitat is lacking has been found to be of benefit to enhance juvenile recruitment (Nunn *et al*., 2007a). The size range of zooplankton species able to persist in off-river refuges was also found to be greater than that present in main river stretches, providing suitable prey items for the various developmental stages of juvenile fish species, thus enhancing their recruitment success (Nunn *et al*., 2007a).

Alongside control methods, including human disturbance; roost removal, automated scarecrows and shooting to scare, the creation of fish refuges and addition of in-channel features offering overhead cover could potentially be of use in the provision of cover and protection from avian predators. The suspected increase in predation of cyprinid fishes in the Wensum by cormorants *Phalacrocorax carbo carbo* and *Phalacrocorax carbo sinensis* has been widely rumoured by anglers, with the reported ‘decimation’ of river and adjacent lake stocks being of increasing concern (Paisley, 2011). As a response to lobbying from Angling Trust campaigners, calling for action to limit the impacts of cormorants on fisheries all over the UK, Fisheries Minister Richard Benyon has ordered a review into current controls on cormorant numbers (Angling Trust, 2012). Nevertheless, studies on cormorant predation on riverine fish stocks rarely demonstrate unequivocal damage to stocks due to the complexity of factors influencing riverine fish population dynamics and the utilisation of multiple foraging sites by the birds (Britton *et al*., 2002, 2003; Davies *et al*., 2003). Thus, evidence that cormorants have adversely impacted the roach population of the Wensum is lacking, is currently only anecdotal and is not supported by fish population data.

- *Re-connection with floodplain and lowering of banks*

Re-connecting the river with it's floodplain through lowering of banks and allowing the river to naturally meander and utilize the floodplain is a widely regarded restoration technique proven to increase habitat diversity and thus potentially improve fish stocks. If the channel was able to overtop into surrounding marginal land during peak flows, natural off river refuges would be present where young fish could escape such conditions thus preventing their displacement downstream (Copp, 1997; Bass *et al*., 1997; Nunn *et al*., 2007a). For example on the village green at Ringland (Figure 2.1) the Wensum is not constrained to the channel and is therefore able to regularly flood. During peak events a shallow, slack-water refuge is created and can frequently be observed to be densely occupied (personal observation). It would therefore be beneficial to the Wensum fishery as a whole to create more of these areas where possible throughout the length of the waterbody. However, given the importance of the adjacent land for both agriculture and urban settlement, then it is debatable as to whether this is feasible option.

- *Addition of in-channel habitat features*

The addition of woody debris could be a significant improvement to uniform reaches lacking habitat diversity. Use by various age classes within cyprinid populations is well documented (Angermeier & Karr, 1984; Everett & Ruiz, 1993; Robertson & Crook, 1999), offering cover from predators, refuge from flow in the areas of slack water created immediately downstream, as well as potential spawning substrate. It is recognised that woody debris can be beneficial to the in-stream biota in many ways through variation of flow and shape of the channel, and creating physical habitat for many species of plants, invertebrates and fish. The Environment Agency promotes its use in river restoration projects, as a rapid and cost-effective method for creating or restoring morphological diversity as required under WFD, assisting rivers in achieving good ecological status or potential. It creates lower water velocity upstream and encourages deposition of fine sediments in marginal zones, ideal habitat for juvenile brook lamprey *Lampetra planeris*, and emergent vegetation important for fly life. Fish refuges during flooding are created, whilst the scour pools and areas of slack water are important during drought. Furthermore, the importance of woody debris to regulate flow is likely to increase as a result of climate change, with greater flow variability predicted from lower summer flows to more rapid and extreme floods (Environment Agency, 2012).

- *Habitat enhancement in straightened sections*

The creation and enhancement of riffle and pool sequences to reaches with limited habitat and flow diversity have been proven as a worthwhile restoration technique, being of benefit to both rheophilic species (e.g. chub, dace and barbel) that require riffles for spawning and limnophilic species able to take refuge in the deeper, slower flowing waters (e.g. roach). Flow deflectors in stretches where diversity is lacking aid the narrowing of the channel, creating flow diversity through increase of current immediately downstream of the narrowing with small pools scoured out further downstream (River Restoration Centre, 1999). In 2010, the restoration and re-connection of a meander loop in the River Wensum, previously by-passed and straightened during the 1950s, transformed the previously low fish abundance in the reach to a diverse habitat for a variety of chalk stream communities including fish, macrophytes and invertebrates. Post-work electric fishing surveys confirmed the presence of 11 fish species (n = 384) compared to 8 fish species (n = 31) in the survey undertaken prior to the works commencing. (Environment Agency, 2011c).

- *Less harmful annual river maintenance practices*

The flood defence maintenance practice of weed-cutting was shown to be deleterious to the presence and abundance of 0 group roach in the Wensum (Chapter 4). With growth in the early life stages found to be already limited through inadequate nursery habitat, this annual practice occurring at a critical time of year for cohorts is likely to affect their survival and recruitment. The study by Garner *et al*., (1996) found that the removal of the macrophyte zone during weed-cutting operations resulted in rapid decline in zooplankton populations resulting from increased wash-out, predation and starvation. This too was followed by rapid decline in the growth rate of roach, forced to feed on the less nutritious aufwuchs. It is therefore important that this practice is conducted as sensitively and un-intrusively as possible. Reducing impacts of weed-cutting to 0 group fish is recommended through ensuring operations are only undertaken after being deemed absolutely necessary in the interest of flood risk management. Similarly if off-river refuges were more widespread throughout the river, the impact of weed-cutting might not be so detrimental, through other suitable habitat being available to 0 group fish.

The practice of de-silting, whilst no longer widespread, is also slowly becoming recognised as detrimental to both channel form and function, and the biota present, with restoring original channel features aimed at self regulation preferable to harsh maintenance practices. The WFD recognises the impact of past river management on current aquatic communities, with the impetus focussing on ‘un-doing’ much of the over-zealous works that until recently were commonplace activities.

6.3 Final comments

A true reflection of fish populations within the River Wensum prior to the impacts of any anthropogenic modification is unattainable due the absence of evidence pre-dating the impact of human activity on the catchment. What was apparent throughout the study was that the river is physically, chemically and biologically very different today than even 50 years ago. Whilst it has been determined that roach face a challenging existence in the river from both biotic and abiotic factors, it is possible to mitigate against at least some of these through provision of suitable habitat that will encompass their various life stage requirements.

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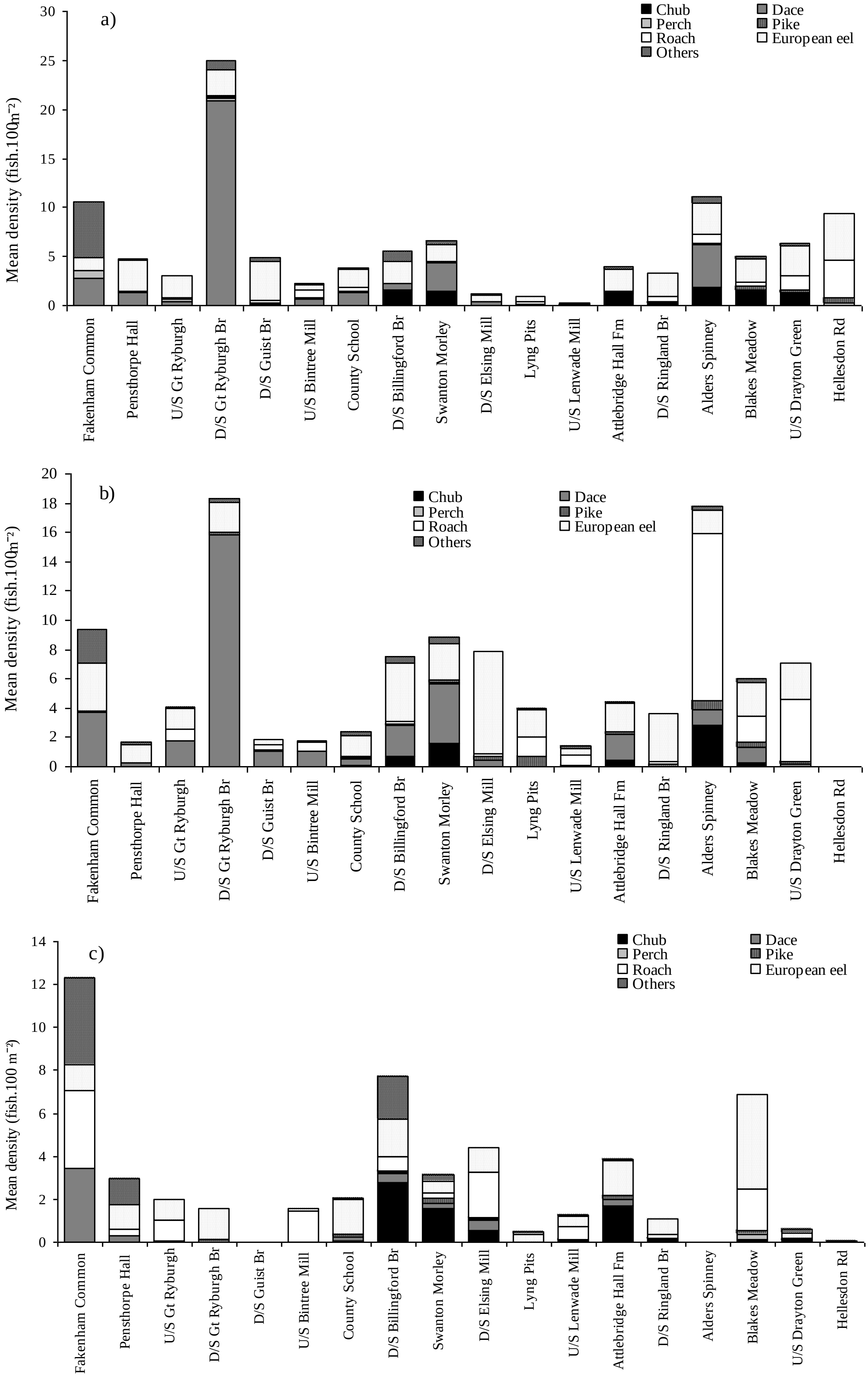
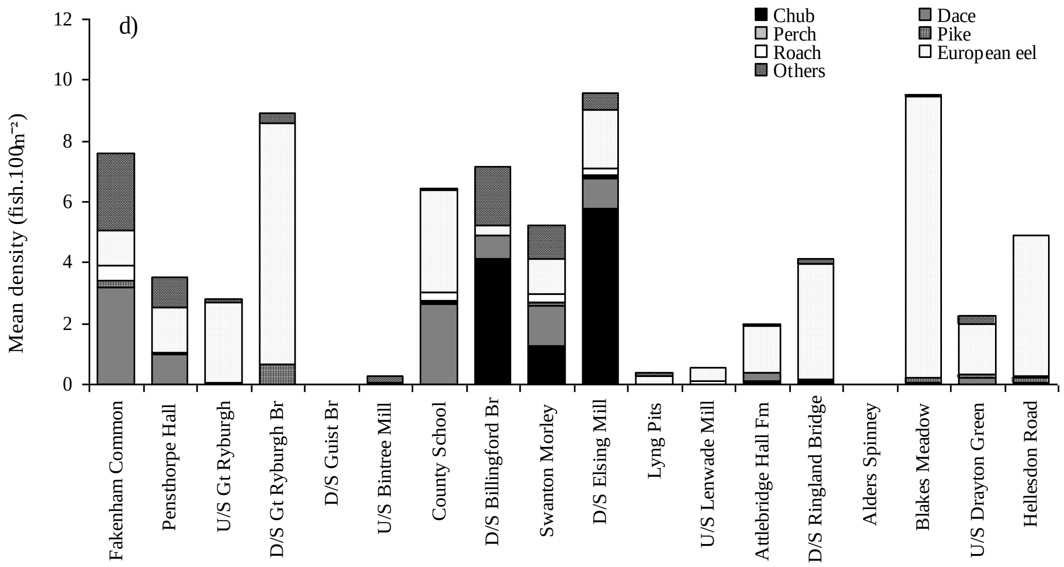
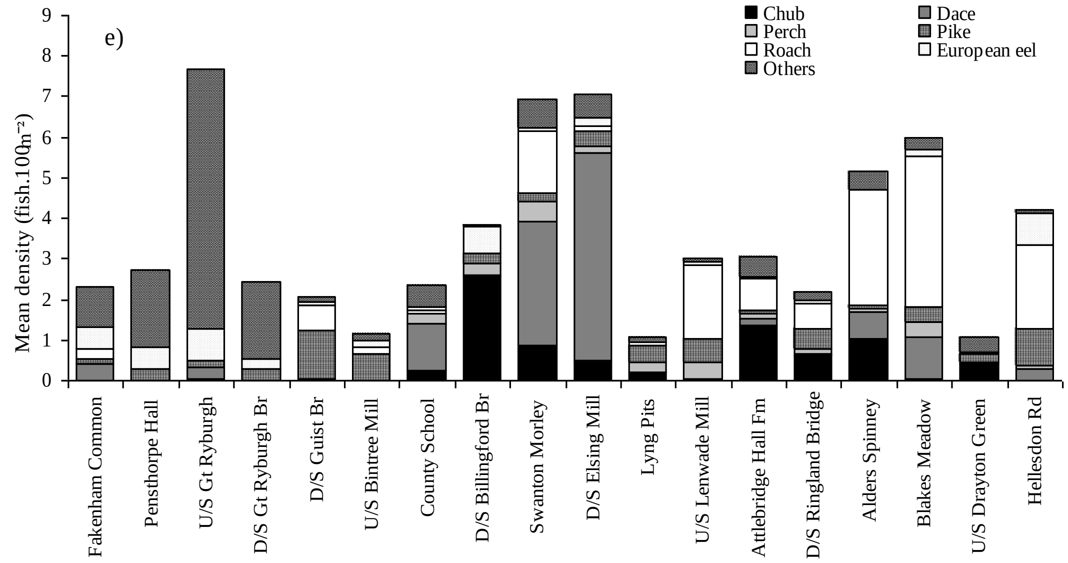
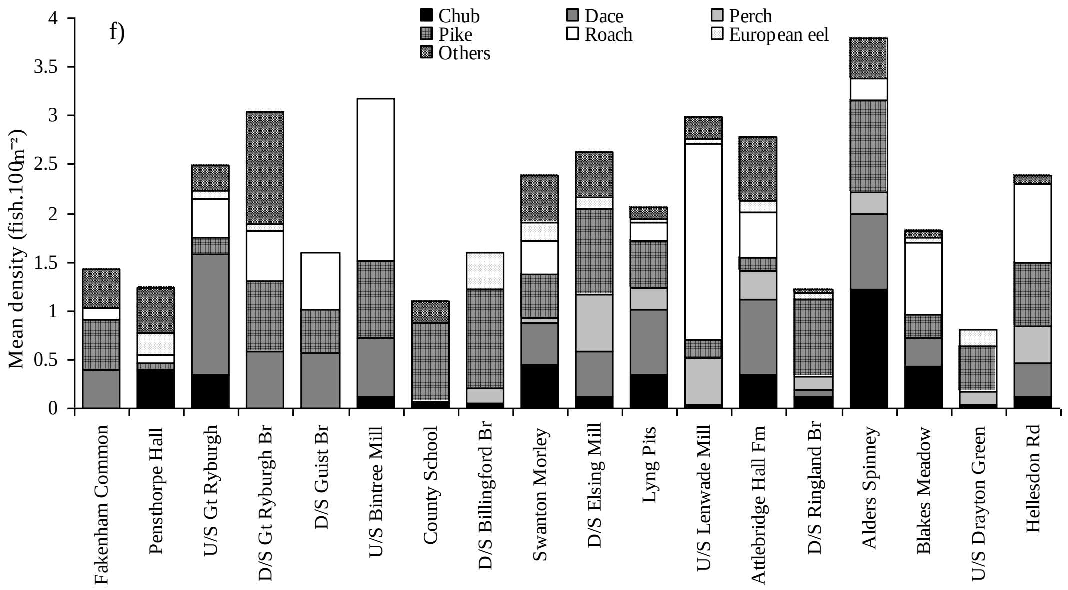
Appendix 1a.



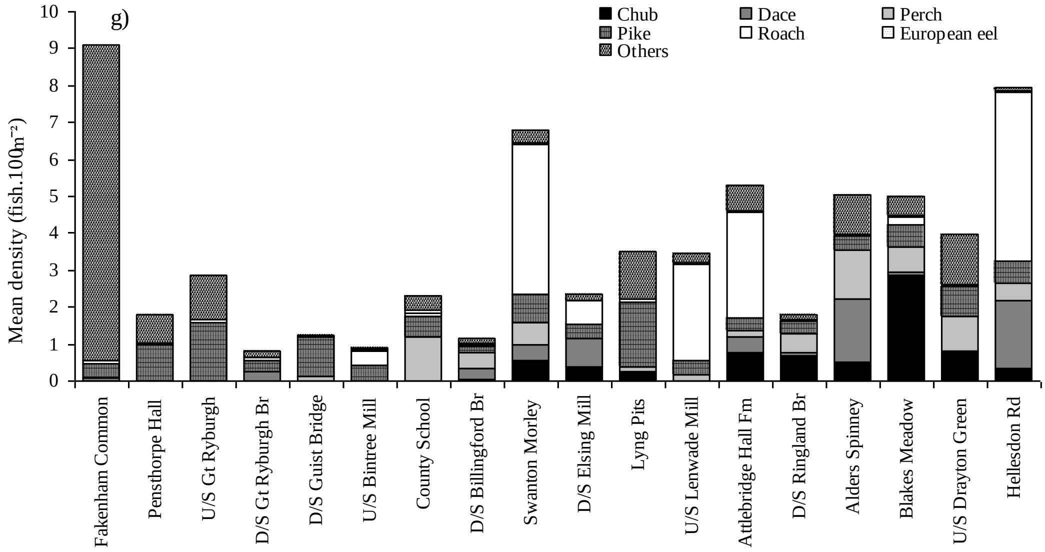
Estimated mean density of fish species (>99mm), site by site on the River Wensum (a) 1986, (b) 1990 and (c) 1994.





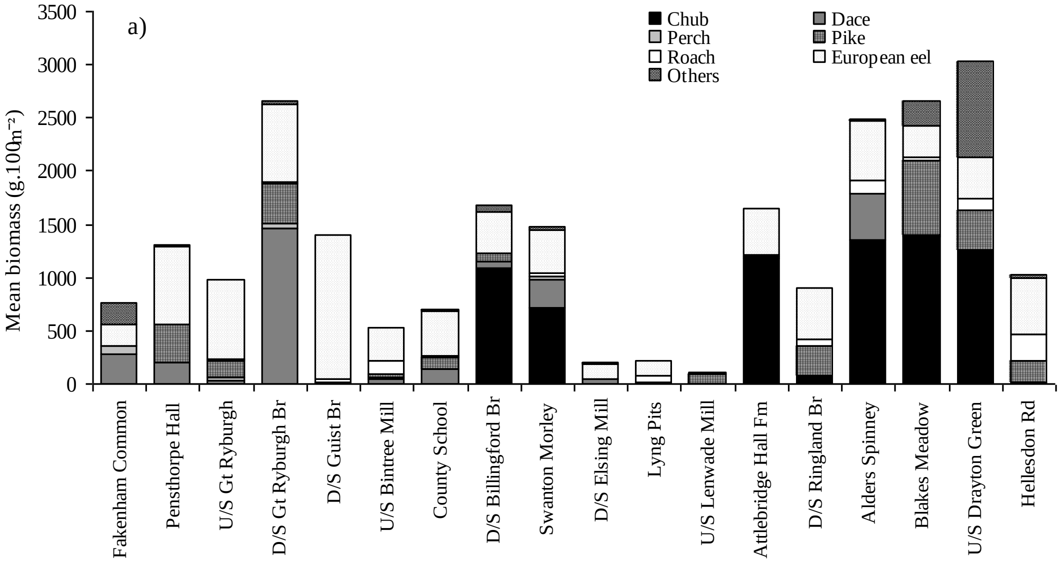


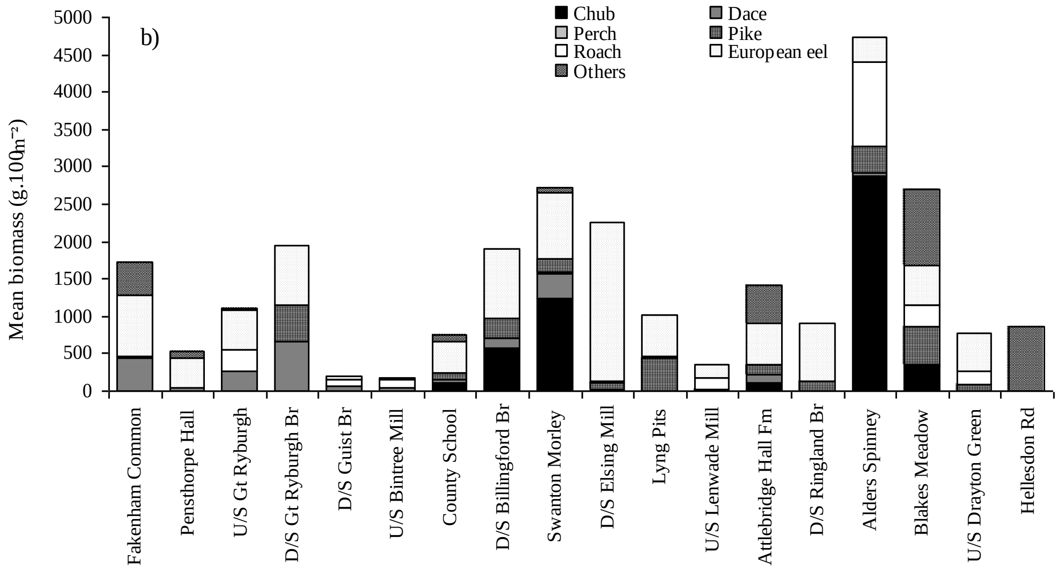
Estimated mean density of fish species (>99mm), site by site on the River Wensum (d) 1997, (e) 2003 and (f) 2006.

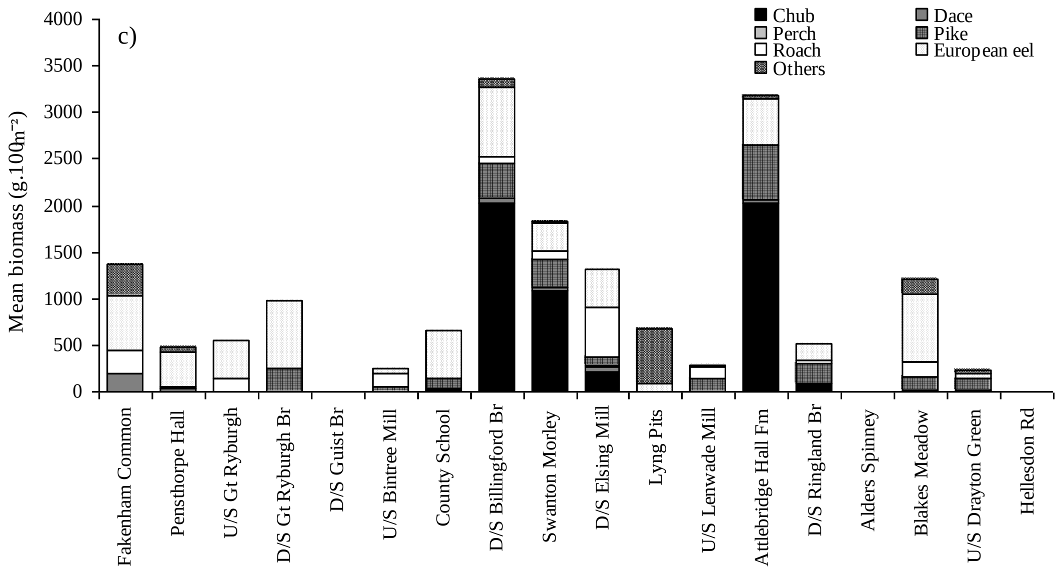


Estimated mean density of fish species (>99mm), site by site on the River Wensum (g) 2009.

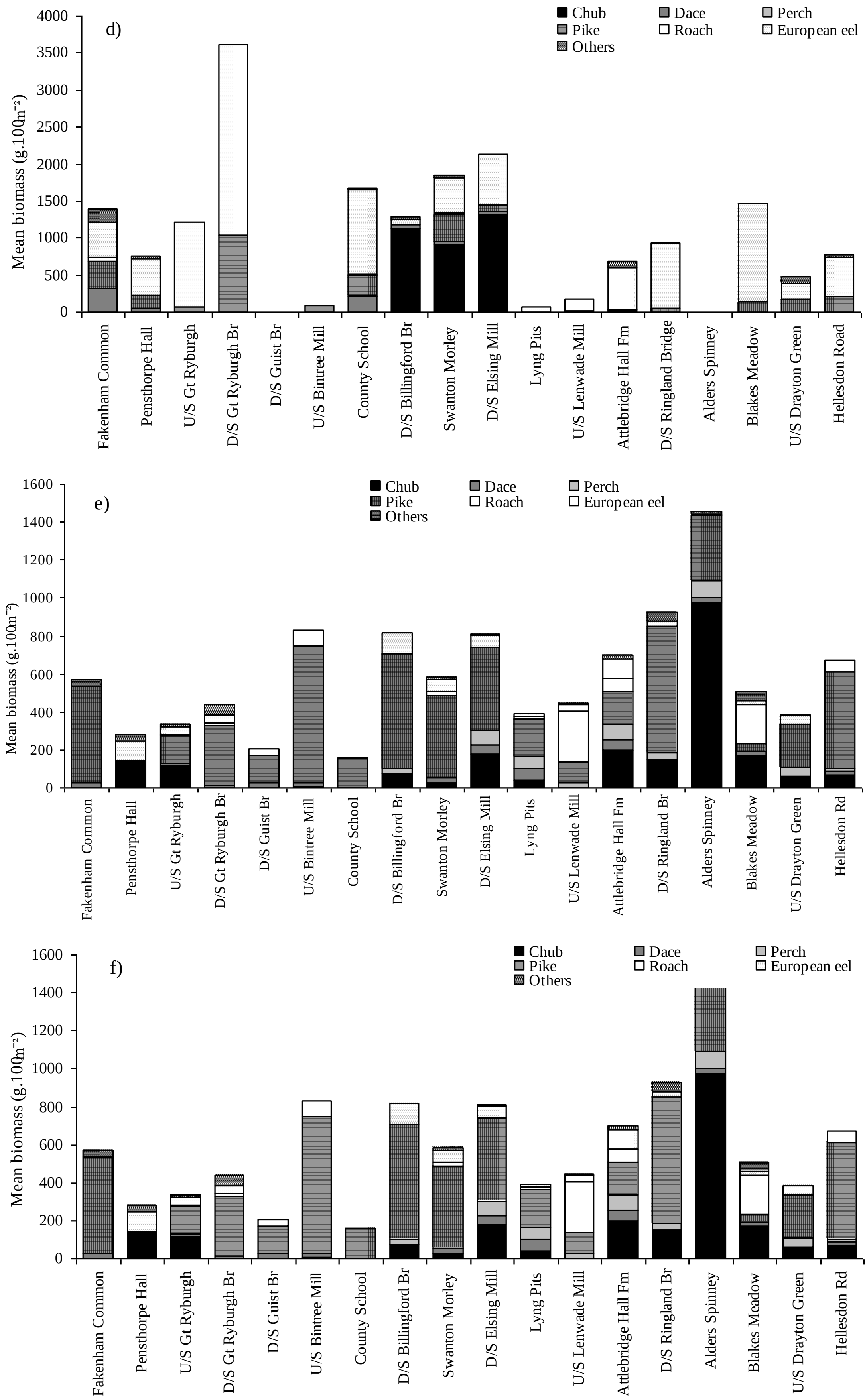
Appendix 1b.



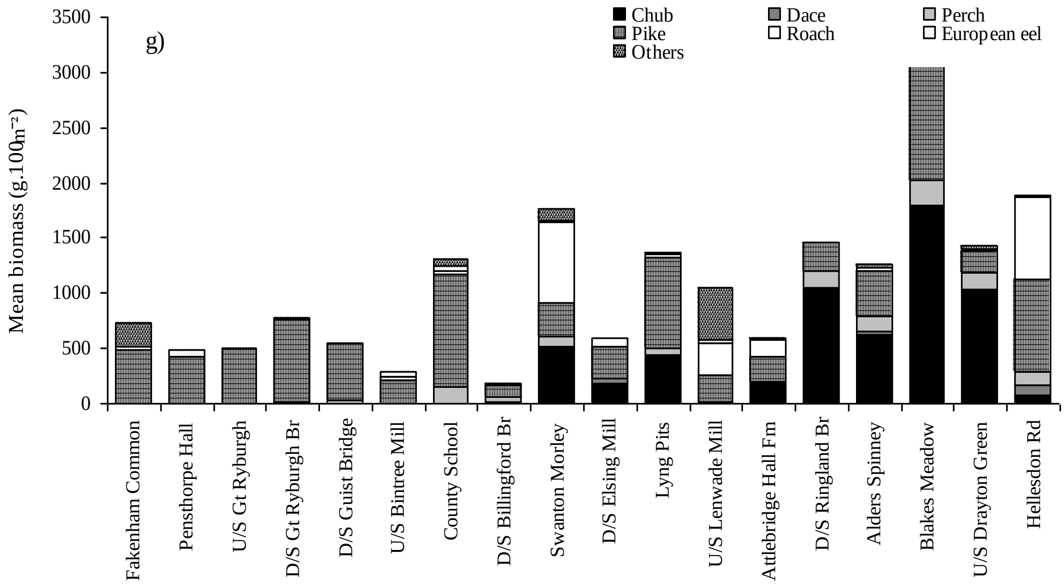




Estimated mean biomass of fish species (>99mm), site by site on the River Wensum (a) 1986, (b) 1990 and (c) 1994.

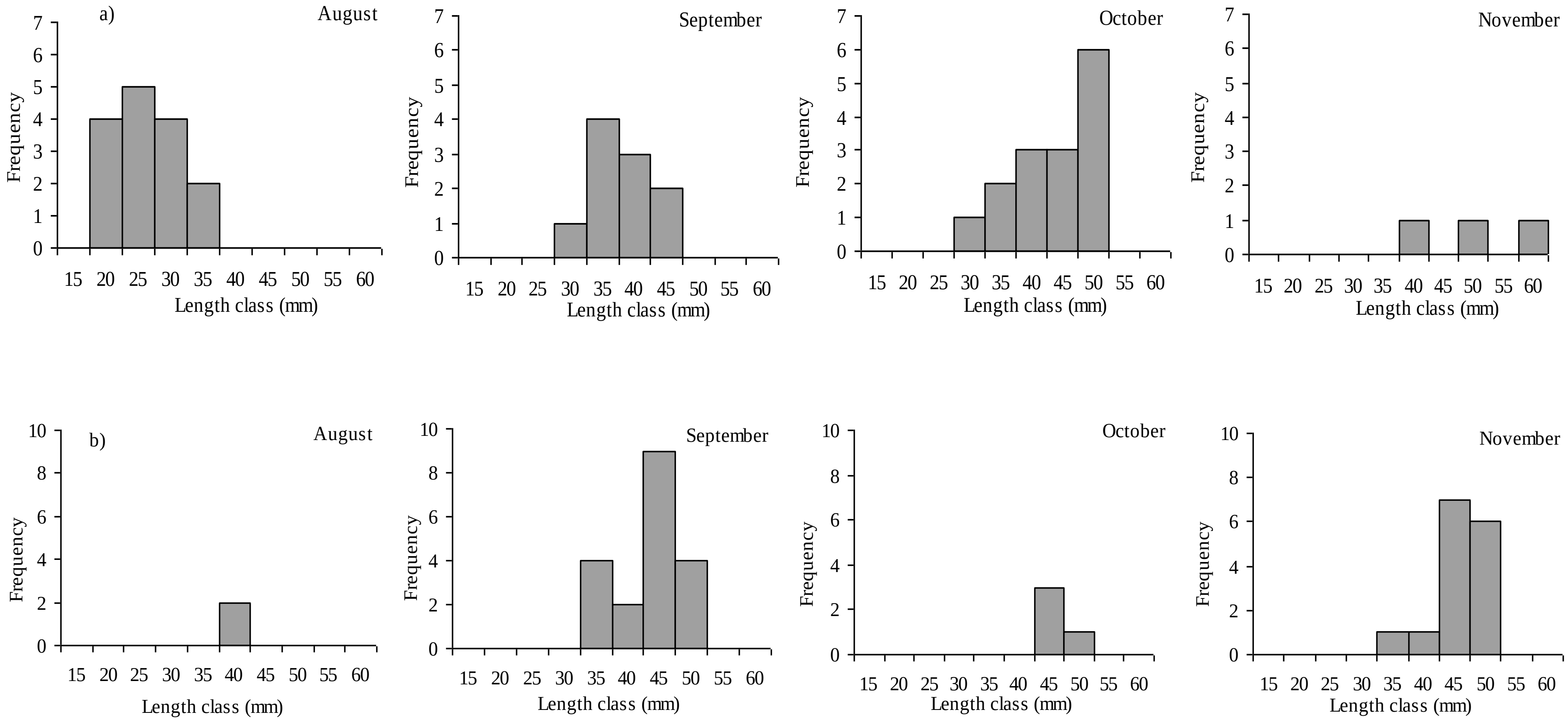


Estimated mean biomass of fish species (>99mm), site by site on the River Wensum (d) 1997, (e) 2003 and (f) 2006.

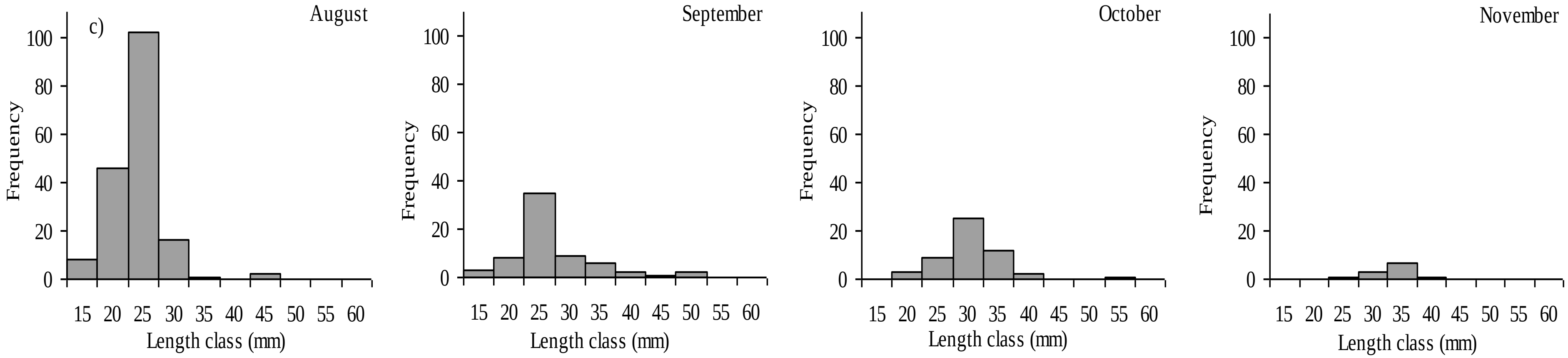


Estimated mean biomass of fish species (>99mm), site by site on the River Wensum (g) 2009.

Appendix 2.



Appendix 2a-b. Length frequency distributions of (a) roach and (b) dace sampled during point abundance surveys on the River Wensum at Hellesdon Rd (Albert's), site 18, Figure 5.1 during 2007.



Appendix 2c. Length frequency distributions of (c) minnow sampled during point abundance surveys on the River Wensum at Hellesdon Rd (Albert’s), site 18, Figure 5.1 during 2007.