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The British river of the future: How climate change and other social and economic pressures might affect two contrasting lowland river ecosystems

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ABSTRACT

The effects of changing climate on northern and southern English rivers (the Yorkshire Ouse, and Thames respectively) were examined in relation to water quality and biological health throughout the food chain. The CLASSIC hydrological model, driven by output from the Hadley Centre climate model (HadCM3), based on IPCC low and high CO_2 emission scenarios were used as the basis for the analysis. The approach taken is descriptive and comes via an "expert system" analysis with many areas of environmental and freshwater aquatic biological sciences being brought together. Compared to current conditions, the CLASSIC model predicted lower flows for both rivers in all seasons except winter. Such an outcome would lead to longer residence times with elevated nutrient, organic and biological contaminant concentrations, doubling in some cases if sewage treatment is not significantly improved. Greater opportunities for phytoplankton growth will arise, and this may be significant in the Thames. Warmer winters and milder springs will favour riverine birds and increase recruitment of many coarse fish species. However, warm, slow flowing, more shallow water would increase the incidence of fish diseases. These changing conditions would make southern UK rivers a less favourable habitat for Atlantic salmon (*Salmo salar*). Accidental or deliberate introductions of alien macrophytes and fish may change the balance of species in the rivers. In some areas, it is possible that a concurrence of different pressures may give rise to the loss of ecosystem services. An increasing demand for water in Southern UK due to an expanding population, a possible reduced flow due to climate change, together with the Water Framework Directive obligation to maintain water quality, will put extreme pressure on river ecosystems such as the Thames.

Keywords: Climate change, Ecosystem, Phytoplankton, Fish

Contents

1. Introduction

The potential impact of climate change on the natural environment has and continues to be an important subject of study and planning in the UK for a range of governmental (Hopkins et al., 2007; Mitchell et al., 2007) and non-governmental agencies such as the Forestry Commission (Broadmeadow and Ray, 2005), Royal Society for the Protection of Birds (Huntley et al., 2007), and Butterfly Conservation Trust (Fox et al., 2007). However, the potential impacts on the lowland river ecosystem as a whole have so far received little attention, although there are plenty of grounds for concern. The worldwide reduction in freshwater biodiversity to date is believed to have exceeded that in terrestrial, or marine environments (Jenkins, 2003). This reduction is believed to be closely related to declining river flows (Oberdorff et al., 1995; Xenopoulos et al., 2005). The pressure on freshwater systems is predicted to increase not only due to possible climate change scenarios, but also due to increasing human demands (Alcamo et al., 2007).

This review was initiated by climate change and hydrological modelling exercises followed by a two day workshop involving a wide range of experts. Two lowland rivers were modelled, the Thames in Southern England and the Yorkshire Ouse in Northern England. The workshop examined how potential changes to regional climate, hydrology, and chemistry might affect the biology of the river, including habitats, phytoplankton, macrophytes, viruses, bacteria, macroinvertebrates, native and invasive fish, fish disease and riverine bird communities. Some consideration on how the river ecosystem could be evaluated economically and socially was also carried out. Whilst this review focuses on two British rivers with their own particular circumstances of geology, hydrology and human development, all the issues addressed in this review will be relevant to most rivers throughout Europe. This study is not an exhaustive review of all river wildlife, their interactions, and possible climate-induced changes, nevertheless it is probably the most comprehensive to date. Instead the aim was to identify some of the big issues which will have a major effect on the typical lowland river ecosystem in the future, and, in particular, suggest what research will be needed in the years to come.

2. Physical description of the catchments and climate change

2.1. Climate change scenarios for the rivers

Most climate models agree that the trend of increasing temperatures due to anthropogenic influences will continue to 2080 and beyond, although there is less agreement on precipitation trends (Wilby and Harris, 2006). The diversity of precipitation scenarios and their outcomes has been previously reviewed for the Yorkshire Ouse by Bouraoui et al. (2002) and by Wilby and Harris (2006) for the Thames. The Bouraoui et al. (2002) study used the HadCM2 general climate model (GCM) and predicted lower flows in the Ouse in two of the summer months but higher flows in the other months. Wilby and Harris (2006) compared the CGCM2 (Canada), CSIRO (Australia), ECHAM4 (Germany) and HADCM3 (UK) GCM scenarios for precipitation and evaporation in the Thames catchment, and using two regional hydrological models concluded that lower flows would become more frequent. For this review, the scenarios have been made by the HadCM3 GCM driven by low and high IPCC emissions scenarios and downscaled in space using the Hadley Centre regional climate model (RCM). These are termed the UKCIP02 scenarios. These models are the basis for much current climate change planning in the UK. It should be noted that the UKCIP02 scenarios present a relatively dry picture for the UK. Some GCMs driven by the same emissions data suggest less summer drying than the UKCIP02 scenarios and these would produce quite different flow scenarios for these two catchments. The UKCIP02 scenarios have been used to provide a benchmark for this review, acknowledging that they do not span the full range of possible changes in the future climate for these two catchments. It should be noted that not only is climate change likely to change the annual, or seasonal rainfall totals, but also the dynamics of the individual rainfall events. For example, some scenarios suggest future summers that are, on average, drier than they are now will experience a higher proportion of the seasonal total in more intense events. Couple this with drier soil conditions and the potential risk of summer flooding might increase despite a reduction in average rainfall. The UKCIP02 scenarios for the UK suggest that where winter rainfall is predicted to increase this will be a feature both of an increase in the number of rain days, and partly from an increase in rainfall intensity due to the milder temperatures increasing the potential for increased water vapour content in the air.

Flow data were estimated for the two catchments using driving data derived from current climate conditions (1961-1990) using a standard catchment rainfall runoff model, CLASSIC: (Crooks and Naden, 2007). The same model was used to derive flows driven by the UKCIP02 low and high emission scenarios. Percentage changes in the key flow data for the different seasons were then calculated by difference.

River residence times were estimated from river velocity (calculated from river flow using a general relationship for the UK for the River Aire and from a specific relationship available for the River Thames) and river length. Thus, predications could be made for each flow estimate. The approach to water quality variables was very simple. It was assumed that future concentrations of nutrients could be estimated by scaling present concentrations by the changes in flow predicted under climate change scenarios for each season. This is a reasonable approximation for soluble reactive phosphorus (SRP) and ammonium (NH_4), which are mostly controlled by dilution of point sources in the main river, and silica (Si), which has a strong baseflow component (resulting from local geology). However, nitrate (NO_3) concentrations are linked to both point and diffuse sources. Diffuse NO_3 sources in autumn and winter are strongly influenced by the magnitude and frequency of winter storm flows which are not accounted for in these calculations. A further complication for Si is that in-stream uptake from diatoms in spring seems to control Si concentrations and this could buffer predicted future concentration rises (Neal et al., 2000; Jarvie et al., 2002; Neal et al., 2006a). The concentrations measured most recently within these studies were taken as "current values" and these were then scaled by the amount of river flow available for dilution in future scenarios compared to that available today (Tables 1 and 2).

2.1.1. Summary of modelled predictions for the Thames

- Flow is predicted to decline under all scenarios, seasons, and regimes. In particular, flow could drop by a third to a half in summer and autumn, leading to some potentially very long residence times.
- High flow events are also likely to decline in magnitude under all seasons and regimes, by as much as 50% plus in autumn.
- Winter river water temperatures could rise by 1.5-3 ^{o}C from the current typical 5 ^{o}C. Mean summer temperatures could rise by 3-5 ^{o}C, giving a mean summer water temperature of 20.5-22.5 ^{o}C compared to the current 17.5 ^{o}C.
- Annual mean concentrations of nutrients could rise by a third (based only on changes in available dilution).
- Slight decrease in incoming solar radiation in winter but predicted increase in all other seasons, particularly summer with an 8-17% increase.

2.1.2. Summary for the Yorkshire Ouse

- No significant change in mean flow in winter, otherwise decline under all scenarios, seasons, and regimes. This would give modest increases in residence time: flow could drop by over a third in summer and autumn.

- High flow events also likely to decline in magnitude under all seasons except winter, by as much as 70% plus in autumn in the high emission scenario.
- Winter river water temperatures could rise by 1.5-3 ^{o}C from the current typical 5 ^{o}C. Mean summer temperatures could rise by 2-4 ^{o}C, giving a mean summer water temperature of 19-21 ^{o}C compared to the current 17 ^{o}C.
- Annual mean concentrations of nutrients could double (ignoring biological transformations).
- Slight decrease in incoming solar radiation in winter but predicted increase in all other seasons, particularly summer with an 8-15% increase.

It should be noted that these hydrological scenarios are subject to considerable uncertainty, reflecting the limitations of any modelling exercise of this type. In particular, the sensitivity of low flows to increasing temperatures and changing rainfall patterns is likely to be complex and spatially variable with differing responses in rivers draining impermeable catchments from those sustained largely by groundwater outflows. Flow records for rivers in the Thames and Ouse basins generally indicate that low flows over the last decade have been characterised by considerable year-on-year variability (Hannaford and Marsh, 2006). These hydrological scenarios have not specifically examined the risk of particular headwater streams drying out in summer. It would be fair to say that in impermeable catchments, headwater reaches of streams that do not receive discharges such as sewage effluent, are likely to dry out more frequently then at present, events which would have dramatic effects on river biota.

The general picture from this particular climate scenario for 2080 is that water in both the Thames and Ouse is that flows will be reduced with consequently increased sedimentation rates, the water will stay in the river for longer, be warmer, and have a considerably higher solute concentrations (due to reduced dilution) then now.

2.2. Hydrological descriptions

2.2.1. River Thames catchment

The average rainfall for the Thames catchment is 690mm/yr of which around 440mm is lost through evaporation, leaving an average runoff of 250mm/yr. The Thames basin, in southern England, covers an area of 13,000 km2 and has a population density approaching 1000 people/km^2 (Evans et al., 2003). The greatest elevation of the headwaters is no more than 300 m above sea level (Marsh and Lees, 2003) and runs for 240 km from its Gloucestershire origin to the tidal limit at Teddington. London's water supply accounts for over 70% of the total water demand in the catchment, and is equivalent to over 30% of the average flow in the lower Thames, rising to over 50% during drought years. This level of abstraction represents an exceptionally high proportion of the mean runoff In relation to other medium and large river basins, both within the UK and internationally, this. The Thames catchment embraces a number of very different river and regime types (urban and other responsive rivers contrasting with spring-fed streams). Each type is likely to respond differently to climatic or land-use changes.

The provision of suitable river habitats is a vital factor in the biodiversity that a river can sustain. A graphic and obvious example is the comparison between a canal and a river. A key factor is the interaction between water flow and the structure of the channel. Archaeological evidence suggests man has been altering the physical nature of the Thames channel since at least Stone Age times (Wilson, 1987). These changes have included the building of mill races, weirs, locks, channel straightening and dredging. The floodplain has been developed extensively for agriculture and in some cases is urbanised, which has resulted in the destruction of side channel and wetland habitats. Data from Brookes et al. (1983) indicate that the navigable Thames was subject to extensive Ministry of Agriculture, Fisheries and Food (MAFF)-funded capital and maintenance works during the mid 20th Century. Data from the Environment Agency indicates that 60% of the River Habitat Surveys on the Thames (excluding 1st order streams) are classified as significantly or severely modified with only 7% remaining as pristine or semi-natural.

The main stem of the Thames has a relatively deep channel and consists of a series of sections divided and ponded by weirs and sluices. As the sluices are operated to maintain depth, and width varies little, the effects of changing flow on water velocity are accentuated. Improved weir design and increased channel capacities have moderated flood risk (in the lower Thames). In addition, there is no compelling long-term trend in flood magnitude (Marsh and Hannaford, 2007). In a warming world, the aggravating role of snowmelt (and frozen ground) on flood risk is now greatly diminished and if summer soils remain drier for longer, the winter flood season may decrease in length (Kay et al., 2006). However, the economic vulnerability to flooding continues to increase as the floodplain development continues to grow (EA, 2007).

In water resource terms, a considerable proportion of the flow is already abstracted in summer (sometimes up to 2/3), leading to little room for manoeuvre (Hannaford and Marsh, 2006). The winter recharge season is vital and when it is below requirement leads to repercussions throughout the rest of the year, as demonstrated during the 2004-06 drought (Marsh, 2007). Tributaries of the Thames draining the clay vales appear more vulnerable to climate change because they do not benefit from the major baseflow support deriving from the extensive limestone and Chalk outcrops below Oxford.

Although there has been no decline in naturalised low flows in the Thames (at Teddington) over the last 100 years, the predicted 2080 Q95 low flows for the Thames (Table

1) are reasonable, and fall within the historically recorded range (similar naturalised flows were recorded in the 1890s and 1940s).

2.2.2. Yorkshire Ouse catchment

The Yorkshire Ouse (all subsequent mention of the Ouse refers to the Yorkshire Ouse) and its associated tributaries form the Northern limb of the Humber catchment, which provide the greatest quantity of freshwater to the North Sea of all British rivers (Jarvie et al., 1997). The Ouse drains 3500 km^2 and is fed by a number of tributaries rising in the Pennines and North Yorkshire Moors with an elevation of 600-700 m above sea level (Jarvie et al., 1997; Marsh and Sanderson, 1997; Bouraoui et al., 2002). Mean annual natural runoff for the Ouse is around twice that of the Thames, but it is less heavily exploited; there are, however, a significant number of important public water-supply reservoirs in the catchment (Marsh and Sanderson, 1997). The Ouse has a long history of navigation, being used at least since Roman times, two thousand years ago, and again was extensively developed for commercial traffic in the 17th and 18th Centuries and subject to MAFF-funded land drainage and flood defence works in the 20th Century.

The major tributaries (Derwent, Swale, Ure, Nidd and Wharfe) rise in wet moorland headwaters and drain through rural areas with a low population density. Catchment annual rainfall is around 870 mm, but there is considerable regional variation, with 2000 mm in the uplands to 600 mm lower in the catchment (Marsh and Sanderson, 1997; Bouraoui et al., 2002). Clay is the major soil in the catchment followed by clay loam and sandy loam (Bouraoui et al., 2002). The high rainfall, relative low temperatures and poor, shallow soils of these areas provide largely low quality grazing for agriculture (Jarvie et al., 1997). With its high rainfall in its upland tributaries, clay soils, and relatively steep elevation the Ouse has a considerably more responsive flow regime than the Thames; it is prone to rapid and large fluctuations in discharge with a range of 3 to over 300 m^3/s (Nunn et al., 2007b). The absence of any substantial baseflow component in the flow of the Yorkshire Ouse implies a particularly vulnerability to any increase in the frequency of hot, dry summers.

3. Nutrients

Given our current knowledge of nutrient delivery to, and behaviour within rivers, how might this influence the nutrient predictions for the Thames and Ouse predicted on the basis of scaling alone (Tables 1 and 2)? A recent study of 54 UK lowland rivers has indicated that point (sewage effluent) rather than diffuse (agricultural) are the most important sources of P in terms of eutrophication risk (Jarvie et al., 2006). Whilst many of the larger sewage treatment plants have a phosphorus stripping stage, this is not true of the more numerous smaller trickling filter works, which are particularly relevant in rural areas. It should also be noted that current P stripping technology does not completely eliminate P from the effluent (Neal et al., 2005). Thus, where population increases are expected, such as SE England, so an increase in P delivery to rivers will also occur. The ‘self-cleansing’ capacity of rivers to remove P may be limited or even reversed under severely eutrophic conditions and high organic matter loading, due to the reductive dissolution of Fe-P complexes (Jarvie et al., 2008; Withers and Jarvie, 2008).

N is present within many rivers as nitrate but also as ammonium and nitrite with the major sources being diffuse, from the land, and atmospheric (e.g. ammonia deposition) (Neal et al., 2006b). Predicting N changes in rivers is particularly difficult because of the many biological interactions it undergoes. Higher rates of N mineralization during the warmer drier summers would result in a greater build-up of nitrogen in the soils (Randall and Mulla, 2001; Whitehead et al., 2002), although this might be partially compensated by higher rates of plant uptake. Actually, long-term records of streamwater quality have shown that dry summers result in high rates of diffuse source nitrogen delivery when the drought breaks (Whitehead et al., 2006), and future climate scenarios indicate increased diffuse-source N and P fluxes during the autumn and winter periods (Bouraoui et al., 2002). A recent study in Denmark indicated that although N retention in rivers would increase, these losses are likely to be considerably less than the increase in nitrate delivery to the river under future climate change scenarios (Andersen et al., 2006). Whitehead et al. (2006) have shown that higher rates of nitrification would result in reductions in within-river ammonium concentrations, but conversely higher nitrate concentrations, as the ammonium is converted into nitrate.

Thus, studies of nutrient dynamics to date suggest that the N and P scenarios for climate change conditions (Table 1 and 2) are likely to tend towards under- rather than over-estimation.

Many British lowland rivers are already considered 'hyper-eutrophic' (as judged by current chlorophyll levels and high nutrient concentrations (Hilton et al., 2006; Neal et al., 2006b), but what might such increases mean for water quality? The predicted nitrate concentrations for 2080 exceed the EU drinking water standards of 11.3 mg-N/L in winter and autumn under both the low and high -emission scenarios (Tables 1 and 2). Extended periods with high nitrate concentrations could limit the use of Thames river water for public potable supplies.

4. Wetlands

UK wetlands are important both for the biodiversity they support (Merritt, 1994) and the services they perform for mankind, such as nutrient removal (Fisher and Acreman, 2004), and flood reduction (Acreman et al., 2003).

The River Thames catchment contains a wide range of wetlands due to the diverse nature of its geology, such as the alluvial floodplains along the River Cherwell, those on the gravel river terraces around Cricklade and those on Chalk, such as around the Lambourn catchment (Acreman et al., 2003). The Ouse catchment contains major blanket peats in the Pennines and North Yorkshire Moors, and floodplains through the Vale of York and the Derwent Ings, which are of international importance under the (Ramsar) Convention on Wetlands.

There are three important types of wetland that must be considered in the Thames and Ouse catchments:

- Rain-fed wetland, such as raised mire and blanket peats, where the wetland soil water table is controlled by rainfall and evaporation
- River-fed wetland, such as a floodplain margins, where the wetland soil water table is controlled by river level
- Groundwater-fed wetlands, such as fens, where the wetland soil water table level is controlled by the groundwater levels in underlying or adjacent aquifers

In a study of the potential impacts of climate change on rain and river-fed wetlands it was concluded that increased evaporation and reduced rainfall would cause a reduction in the soil water tables at an important part of the plant growing season (Acreman et al. (submitted). Such impacts range from minor in northern Scotland and Wales, to significant in south east England. Consequently, wetlands in the Thames catchment are likely to suffer greater desiccation that those in the Ouse catchments. Rain-fed wetlands are likely to be more significantly impacted than river-fed wetlands.

The impacts on groundwater-fed wetlands, will be strongly related to location in the country which would suggest less impact on the sandstone and limestone aquifers (South West, Midlands and North) but a greater reduction in water levels in the southern Chalk and thus increased stress for their associated wetlands (Bloomfield et al., 2003).

Overall, the outlook for many wetland habitats in Southern and Central England is unfavourable, possibly leading to a reduction in the biodiversity and amenity value associated with them. In northern England, wetlands are less vulnerable.

5. Human enteric viruses

Faecal-oral transmission of enteric viruses may cause more than half of all episodes of human gastroenteritis (vomiting and diarrhoea) in the developed world (Moore et al., 1993). Transmission may be via food, fomites, direct contact between hosts, exposure to river water, or more frequently virus contaminated drinking water. The economic cost of infections is difficult to calculate accurately. Approximately 9.5 million cases of gastroenteritis occur annually in England (20 per cent of the population), with 1.5 million cases presenting to their Doctor (FSA, 2000). – For these 1.5 million cases, using figures from the Office of National Statistics (2008) on the cost of a GP visit (£100) and one day lost from work (£96) this would represent around £290 million per annum cost based on the average salary.

Most human waterborne viral infections are caused by rotaviruses (Reoviridae), astroviruses (Astroviridae), adenoviruses (Adenoviridae), noroviruses (Calicicviridae) or various members of the Picornaviridae family (Carter, 2005). The viruses enter watercourses at point sources via effluent from sewage treatment plants or leakage from septic tanks and sewers. Though some such as noroviruses may be derived from animal slurry (Mattison et al., 2007). Many survive sewage treatment, giving levels of between 1 and 10000 plaque forming units (pfu) per 100 L of receiving water (Scipioni et al., 2000), and 1-20 pfu per 1000 L of potable water (Payment et al., 1997). Presently, baseline data are not available for human enteric viruses in water. Existing US and EU regulations only require assessment of microbiological water quality by counts of faecal coliform, and total coliform bacteria and enterococci. Coliphage counts have been proposed as better indicators of human viral pollution by the U.S.-Environmental Protection Agency (EPA). However neither coliforms, enteroccocci nor coliphage always reflect the risk from human viruses (Geldenhuys and Pretorius, 1989). Quantification of risks will require environmental and experimental standardised measurement of enteric virus presence, survival and transport through sewerage systems, and ground and river water.

Rivers and lakes are reservoirs for enteric viruses. Virus concentrations in water may increase in British rivers with reduced dilution and increased residence times. Associated increased sedimentation rates may reduce virus spread from any point source, but increase local survival (Green and Lewis, 1999). Countering this, enteric virus inactivation times in water vary widely, but all will be reduced by increased temperature and UV irradiation. These factors will probably have differential effects on the virus population, for example double-stranded DNA adenoviruses are relatively insensitive to UV (Gerba et al., 2002). Changes in human behaviour such as recreational bathing in warmer waters will also play a part in future exposure and is likely to increase the frequency of gastroenteric infections (Schijven and Husman, 2005). To summarise, we have very little suitable information to judge whether there will be an increasing human health issue with enteric viruses and water, but it is a concern that deserves further consideration and research.

6. Bacteria

When considering bacteria in rivers and the consequences of climate change, it is important to note that bacteria are generally robust, capable of assimilating and degrading a multitude of substrates under both aerobic and anaerobic conditions, and that changing their environment illicits responses at either a cell, population or community level that can be immediate (seconds) or long-term.

It is important to consider ‘bacteria’ with respect to both their environmental contribution and as potential pathogens to a variety of hosts, including humans. However, their role as pathogens is often perceived as greater than their environmental role as their health impacts are more visible than those of the ecologically more significant and numerically dominant environmental microbes that carry out essential ecological services.

6.1. Biogeochemical cycling

Environmental bacteria drive biogeochemical cycling and underpin the majority of the earth’s biological processes (Hurst et al., 2007). Temperature is a key environmental factor, yet the predicted rises in temperature are within the growth range of the majority of most environmental bacteria. As with most biological systems, if it gets warm then the bacterial activity will increase and bacteria will also respond to any changes in nutrient levels caused by increased inputs or reduced river dilution. Considerable functional redundancy exists: i.e. the number of species performing the same ecological function in a community is often high, as many different bacterial species can perform the same task (e.g. denitrification; Gaston, 1996). Therefore climate change may illicit a community response, but the general ecological services will remain. Regarding the processes, an increase in organic nutrients to rivers may be in prospect due to greater biological productivity from plants (terrestrial and riverine) and algae due to more prolonged sunlight and warmer temperatures. The breakdown of these natural organic products, predominantly by bacteria and fungi, may lead to more O_2 consumption and CO_2 production in the river bed. It is not clear whether generally lower dilutions, with proportionally higher carbon loadings, microbial activity and warmer temperatures, would lead to significantly lower dissolved oxygen levels (through enhanced respiration) in the future. However, lower oxygen levels for longer periods in rivers would certainly represent an additional stress for many species of fish and macroinvertebrates. Indeed increased stress tends to lead to greater susceptibility to disease in fish and often breeding constraints, resulting in lower size classes (Winfield et al., 2008).

6.2. Human bacterial pathogens

Pathogens are of concern to issues relating to water purification, use of recreational water and sewage treatment, including use of river water for irrigation. Each of the factors which contribute to the pathogen life cycle, such as the source, transport, exposure and susceptibility will be influenced by the many environmental changes associated with climate change. Clinically and subclinically affected individuals shed their pathogens into a general pathogen pool, and in addition they also contribute faecal bacteria that are of concern to other groups (e.g. humans, *Campylobacter* spp. derived from animal slurry; Bates and Phillips, 2005). Land-use, water run off and animal practices in the catchment contribute a vast number of pathogens into this pool. In some cases the pathogens derived from one group affect another (e.g. *Mycobacterium avium* subspecies *paratuberculosis* derived from Johne's diseased animals affect humans; Pickup et al., 2005; Pickup et al., 2006). In general, bacterial pathogens which survive in water and sediments after deposition, can be resuspended into the water column and retain their pathogenicity for long periods (Barker and Brown, 1994; Pickup et al., 2005; Mura et al., 2006; Ohno et al., 2008). In some cases as with *Legionella* spp., elevated temperatures may enhance survival (Nguyen et al., 2006). Considering future changes in waterborne disease in the Netherlands, Schijven and Husman (2005) proposed greater exposure due to a probable increase in water related recreation and suggested inactivation of pathogens by temperature was only significant in water bodies with residence times greater than a month.

In summary, pathogen issues will increase with climate change, whereas the affect on bacterial processes involved in biogeochemical cycling will most likely be neutral. However, potentially greater carbon inputs and more rapid microbial breakdown could lead to increased oxygen depletion in some parts of rivers, causing additional stress to many species of aquatic wildlife.

7. Phytoplankton

Environmental factors that control phytoplankton biomass in lowland rivers include flushing, surface light, underwater light, temperature, sedimentation and grazing rate (Garnier et al., 1995). All these may alter, directly, or indirectly (e.g. grazing), as a result of climate change. Nutrient levels are probably saturating for most of the time in most lowland rivers (Hilton et al., 2006), although transient nutrient-limitation is possible, particularly for silica (Skidmore et al., 1998). Any entry of coloured DOC to waters will worsen light penetration through the water and cause a decrease in productivity. It is acknowledged that contol of phytoplankton populations by grazing or lysis is still not well understood. It has been argued that the large and efficient grazers which can be very important in lakes are not suited to rivers with their short residence times (Garnier et al., 1995). Lysis due to viral, bacterial, or fungal infections may have led to the abrupt termination of blooms in the Seine catchment (Garnier et al., 1995). Assessing whether grazers could effectively limit large algal blooms is not straight forward to predict. Simple zooplankton, such as rotifers, which are believed to be the most efficient grazers of phytoplankton in rivers, are themselves prey for higher organisms (Gosselain et al., 1998). Successful grazing of the small-cell algae (<20 μm), may simply cause the proliferation of large cell members (>20 μm) of the algal community which are not grazed by the small zooplankton, thus leading only to a change in community structure (Ruse and Love, 1997; Gosselain et al., 1998).

Aside from these general factors affecting algal cell growth, and death, local geographic factors may also be surprisingly important in determining the extent of phytoplankton blooms. In a study of chlorophyll-a in rivers in Eastern England, the strongest relationship was seen with catchment area and flow, rather than nutrient concentration (Neal et al., 2006b). The importance of residence time was reinforced by the chlorophyll-a content of a canal being up to six times greater than that of the neighbouring rivers. The permeable sub-catchments of the Thames, which have a less dense network of feeder streams and ditches were found to have lower chlorophyll a concentrations compared to the more impermeable sub-catchments. This is believed to relate to the feeder streams and ditches acting as important nursery sites for algal inoculae (Neal et al., 2006b). Low gradients along the River Thames and the abundance of weirs locks and canals, exacerbate this water residence time issue. Moreover, canals and reservoirs alongside the Thames can provide algal inocula to the rivers (Neal et al., 2006b). While hydraulic flushing can be a major loss factor, on occasions greater phytoplankton biomass has been observed in rivers than had been predicted from on the basis of river velocity and phytoplankton doubling rates. In the River Severn Reynolds (2000) suggested that population predictions for phytoplankton cannot be made on the assumption of rivers being purely plug flow systems, and that slow flowing regions, or ‘dead zones’, were important in maintaining the biomass in the main channel.

From the predicted changes to flow and nutrients (Tables 1 and 2), some suggestions can be made: In winter, the forecast increase in water temperature might promote a modest increase in the level of phytoplankton, but the response will be constrained by light levels. In spring, the forecast increase in water temperature, reduced flows and increased surface light is likely to increase phytoplankton biomass and the spring increase will probably take place earlier. Thus, more primary production would be occurring earlier in the season. This could be substantial as this period coincides with the main bloom period for diatoms which grow more rapidly than other groups of phytoplankton until limited by silica concentration (Garnier et al., 1995).

In summer, the forecast increase in surface light and reduction in flushing rate will tend to promote phytoplankton productivity, but the increase in water temperature is likely to decrease net rates of production in optically deep water because it will increase rate of respiration. Increased temperature may also promote loss rates due to a proportionate increase in rates of grazing. Of concern is that the warm, very slow flowing conditions favour blue green, also known as cyanobacteria, which are associated with the production of microcystin toxins (Ruse and Love, 1997). In autumn, the forecast slight reduction in flushing rate and increase in surface light will tend to increase phytoplankton biomass.

Overall, our current knowledge suggests these climate change scenarios will promote additional phytoplankton growth where residence times are predicted to increase, with the Thames being particularly vulnerable. Notwithstanding their key roll as primary producers, and their potential to contribution to eutrophication, there are still considerable uncertainties over the magnitude of the response we can expect from the phytoplankton community.

8. Macroinvertebrates

Macroinvertebrates are a numerically very diverse group of organisms which play an important intermediate role in the river food chain. It is known that the species composition of the overall community is very sensitive to environmental conditions and this has led to their being used by scientists as indicators of water quality, such as in the RIVPACS model (Wright et al., 1984). It has been argued that an increase in water temperature, through climate change, will be a less important driver of species change than other indirect factors. For example, improvements in BOD and discharge in southern chalk streams caused a more significant change in invertebrate communities over the period 1989-2007 than did a 2 ºC increase in winter temperature (Durance and Ormerod, 2009). And there is some evidence that at higher altitudes, species rich, circum-neutral head waters may be more affected by warming than acidic headwaters (Durance and Ormerod, 2007), supporting the hypothesis that any direct effect of climate change may only be apparent in the absence of other stressors. However, changes have been reported in the invertebrate community of the Upper Rhône in France, related to increasing temperatures and reduced discharge, rather than due to other environmental changes (Daufresne et al., 2004).

Oxygen concentration and sedimentation are particularly important influencing factors for species composition. As already discussed, both are predicted to change under the influence of lower flows. Thus, it would be predicted that limnophilic macroinvertebrate taxa (i.e. characteristic of slower flowing/still water) will increase in prevalence in the lower reaches, which are again associated with lower oxygen concentrations. Droughts, such as have occurred in chalk streams in southern UK in the past, is a drastic challenge for macroinvertebrates. However, past examples have shown that when the flow returns so do macroinvertebrates although the species composition may then be different from previously (Boulton, 2003).

The extent of change in the macroinvertebrate communities in the Thames will be moderated by the ground water component to base flow which will buffer any reduction in summer precipitation, and by high winter flows in the Ouse, which will remove accumulated sediment.

The predicted climate change, changes to habitat and water quality will undoubtedly affect macroinvertebrate species composition. From a regulatory point of view, where biological water quality indices are weighted in favour of larger, longer-lived macroinvertebrates which thrive in high O_2, low organic nutrient environments, we can expect a decline in such scores as these conditions change.

9. Macrophytes

Aquatic macrophytes already respond adequately in the most part to large changes in environmental conditions through out the year. Changes in incident irradiance, temperature, water velocity, dissolved gases and nutrient availability influence macrophyte growth rates, biomass accumulation, flowering times, seed production (and likelihood of germination), relationships with other species in the community, and the success of vegetative reproductive strategies.

Increases in water temperature and nutrients will probably favour the growth of epiphytic algae and bacteria on submerged macrophytes (Hilton et al., 2006). Increases in boundary layer thickness, perhaps somewhat earlier in the growing season than now, may reduce growth and resource capture by macrophytes, resulting in a loss of competitive ability of native species and an increase in the dominance of sub-tropical type introduced species. "Native" macrophytes have upper temperature limits above which growth ceases. There are a number of potential causes for this, including disease, physiological malfunction and suffocation. Periods of drought in streams are a drastic challenge to macrophytes and have been known to permanently change the species composition even after the return of normal flow conditions (Boulton, 2003).

Elevated CO_2 concentration will benefit the majority of C_3 macrophytes using Rubisco as the main enzyme for carbon acquisition. Evolved systems to use HCO_3^- have energy costs, as do most other enzyme-based systems of concentrating carbon. Alleviation of the need to use other forms of carbon may confer advantages on CO_2 users.

Increased growth of floating macrophytes at the expense of the extant submerged species dominated flora, will probably become more noticeable. This may be already happening with the dominance of non-native amphibious species such as *Hydrocotyle ranunculoides* and *Myriophyllum aquaticum* in northern Europe, with increased prevalence of tropical species such as *Eichhornia crassipes* in south eastern Europe.

In summary, the main physiological and ecological functions of aquatic macrophytes will probably remain unaltered within the predicted limits, but the species contributing to these functions may change. The speed of change will probably be a mixture of punctuated dramatic change and gradual replacement of species.

10. Fish

10.1. General climate effects

A reasonable amount of research has already been devoted to the issue of how climate change has impacted fish and fisheries. For example, it has been suggested that the distributions of various species of fish in the North Sea have shifted in latitude or depth, or both, over the last 25 years, as a consequence of increased sea temperature (Perry et al., 2005), to be replaced by warmer-water species (Genner et al., 2004). However, whereas the impact of climate change on marine fish and fisheries has received a considerable amount of attention, due to their economic importance, the situation with regard to European freshwater fish is markedly understudied (FSBI, 2007). Nevertheless, the lessons from studies of marine fish and fisheries are probably relevant to freshwater fish, with the strong proviso that unlike marine fish species, each population of freshwater fish is confined to its particular river catchment (though each species often exist in many catchments), and hence the fish cannot readily move. They cannot significantly migrate north, to cooler rivers (as rivers warm); they would have to be transported there by man. This lack of mobility of freshwater fish populations could mean they are threatened much more by climate change than are marine fish species. It has been argued that declining river flows represent the greatest worldwide threat to fish biodiversity and local extinctions can be expected (Xenopoulos et al., 2005).

Fish are ectotherms: in most species, body temperature is essentially the same as that of the surroundings water at the time. Temperature is thus a major controlling factor in all physiological process, from the molecular (e.g. Brian et al., 2008) through to the ecological (such as growth and reproduction). Each species has its own distinct thermal niche, where it can optimise its physiological, behavioural, and ecological performance. As rivers warm, fish are likely to find themselves living in environments outside their optimal thermal ranges. In response, and if they can, populations will probably move. For example, in a period of 20 years the water temperature in the upper River Rhone (in France) rose 1.5 ºC, leading to the progressive replacement of more northern, cold water species (e.g. dace) by the more southern fish species (e.g. chub, barbel; Daufresne et al., 2004). Perhaps similar changes in species distributions may already be occurring in the River Thames and River Ouse? Not only will fish populations move (if they can), but spawning is likely to occur earlier in the year (e.g. Gillet and Quetin, 2006), and growth rates will probably increase, with an anticipated increase in food supply contributing to this consequence. Based on the recent realisation that many species of fish have temperature-dependent sex differentiation (e.g. Goto-Kazeto et al., 2006), it is even possible that a rise in water temperature will alter the sex ratios of fish populations. As would be expected based on the above, not only will temperature affect the physiology of individual fish, but it will also have an effect at the population level, with recruitment correlated with water temperature (Grenouillet et al., 2001).

Recent assessments of the strength of the cyprinid fisheries on the River Ouse support some of these likely consequences of climate change. Reviewing the recruitment success of three species of cyprinids using 15 years of historic data, Nunn et al (2003) concluded that warmer water temperatures had contributed to the survival of juvenile fish. This increased survival was believed to be related to better growth of fish due to greater food production. Most freshwater fish in the U.K. spawn in the spring (April to June): a situation true for the River Ouse (Nunn et al., 2007a). Thus, Fry and juvenile fish are present in the river through the spring and summer. These small fish are very susceptible to high flow rates during this period and the absence of high flow events may be the critical factor controlling recruitment (i.e. survival of young fish) on the River Ouse (Nunn et al., 2007b). Thus, analysis of cyprinid fish populations in the River Ouse supports the idea that if climate change leads to higher water temperatures and less frequent high flow rates in spring and summer, some fish populations will benefit.

In summary, responses of freshwater fish to direct climate change are likely to be quite complex, and hence difficult to predict accurately (FSBI, 2007). There are likely to be winners and losers (see section on Atlantic salmon below). Populations of cold-adapted fish, such as the various species of salmonids, may encounter occasional (or even regular) temperature regimes close to or even at their thermal limits, and hence suffer. However, the majority of freshwater fish found in the U.K., such as the species that dominate the Rivers Thames and Ouse, could well respond positively to predicted water temperature increases. As long as other factors (such as chemicals, or an increased prevalence of existing diseases) do not adversely affect populations, then increased growth and reproductive success could lead to increased production.

10.2. The challenge of increasing concentrations of chemical contaminants

It is important to keep in mind that the magnitude of any effect caused by a microorganic chemical contaminant will depend on its concentration. So, with lower flows predicted, at least for spring, summer and autumn (Table 1), this will lead to less dilution of sewage effluents (and their associated microorganic contaminants), then the concentrations would rise, and greater effects would be expected. Young fish hatch from eggs, and undergo development, during the summer. Sex determination occurs at this time, and the process is known to be affected by one class of microorganics, namely the estrogenic chemicals (Colborn et al., 1993). If concentrations of estrogenic chemicals in rivers rose in the summer, then it is likely that the incidence and severity of intersexuality would rise. Lower concentrations at other times of the year probably will not reverse the effect. Under mean annual flow conditions it is currently predicted that about a third of English rivers have levels of estrogenic chemicals sufficient to cause some endocrine disruption in fish (Williams et al., 2009). This level of exposure is not evenly spread around the country. Fish are most under threat in cathchments with a high human population and low rainfall characteristics density. The Thames catchment would fall into the more exposed category with a daily dilution per head of 1.7 m^3/d·capita, whilst the Yorkshire Ouse is under less pressure at 18.2 m^3/d·capita based on annual mean flows (Williams et al., 2009). Thus, higher incidences of endocrine disruption, as well as possibly other disruptive effects caused by pharmaceuticals, will be an increasing threat in the future in regions like the Thames, Anglian and Midlands regions, unless further measures to improve the quality of effluent are taken.

10.3. Changes to fish disease patterns

Diseases in wild fish populations are caused by a variety of pathogens and occasionally cause acute mortalities where dead or dying fish are observed (Bakke and Harris, 1998). More commonly, debilitating chronic infections, most frequently parasitic infections, in juvenile and adult fish result in the increased likelihood of predation or inability to capture food items. Proliferative kidney disease (PKD) caused by the myxozoan parasite *Tetracapsuloides bryosalmonae* has been strongly associated with salmonid declines in Switzerland and mortalities in wild salmon in Norway (Sterud et al., 2007; Wahli et al., 2007). The disease is endemic through out much of the United Kingdom, including the Ouse catchment but the effect of PKD on wild salmonids in this region is currently unknown (Peeler et al., 2008).

Long-term datasets on the parasites of juvenile cyprinids exist for the River Ouse catchment (Longshaw, 2004). Data on roach, chub, dace and minnow collected between 1993 and 2006 from 28 sites in the greater Yorkshire region, combined with information on the seasonality and development of infections in juveniles and environmental and population data strongly suggest that disease can be an important factor affecting year class strength (Longshaw et al., submitted).

Bacterial and viral infections of fish are likely to be strongly correlated with environmental changes, with a general increase in the severity of infection of recognised endemic fish pathogens. Those that currently have a higher temperature threshold (for disease expression or infection) may be able to establish and proliferate more readily. In addition, some exotic pathogens with high temperate thresholds (e.g. *Lactococcus garviae*) are more likely to establish if introduced. Other species may emerge as pathogens and become established. Local adaptations and short-term evolutionary changes are more likely to occur in bacterial and viral agents, compared with parasitic infections.

Predicted increases in temperature, residence times and nutrient concentrations together with decreases in water flow will impact on all hosts directly, altering fish distribution and immunocompetence and disease susceptibility. Increase in mean temperatures will potentially lengthen the period of infectivity for some pathogens, affecting virulence and transmission rates. Increased numbers of invertebrates as a result of the increased levels of nutrients provides will have an impact on disease transmission since they act as intermediate hosts for several parasite groups.

Potential movements of new hosts into the River Ouse catchment may also introduce new pathogens into the region and naïve hosts may suffer losses. Although difficult to predict which pathogens may become established, aquatic animals introductions into any catchment need to be carefully monitored and controlled and legislation is in place for this. Introduction to inland waters in England and Wales are regulated by the Environment Agency, under Section 30 of the Salmon and Freshwater fisheries Act 1975. This requires that stock are screened for a range of parasites prior to movement. The risk of introducing novel pathogens through international trade is limited by a combination of legal provisions such as the Aquatic Animal Health Regulations 2009, EC Regulation 708/2007 and the Import of Live Fish Act 1980.

It may be concluded that some of the changes predicted to occur in UK rivers over the next fifty to a hundred years will lead to shifts in endemic fish disease dynamics and may facilitate the emergence of new pathogens. These changes are expected to be detrimental in most cases to the fish host.

10.4. Invasive fish species

People are the main vector of freshwater fish movements across river basins or countries (Gozlan, 2008a, 2008b). The general understanding is that the ever-increasing need for food, sport or hobbyist fish is a major driver of freshwater fish introductions. The situation in England clearly illustrates this, as the number of non-native fish species found in the wild in any particular region is directly linked with the number of live fish imported into that region. There is a direct correlation between live fish imports and human population density (Copp et al., 2007), with aquaculture believed to be particularly important (Welcomme, 1988; De Silva et al., 2006). Any future increase in human population in the south-east of England would therefore suggest we can expect further introductions of non-native fish in this region, including the Thames.

10.4.1. What are likely to be the successful fish invaders in England?

Recently, the profiling of traits involved in the establishment of non-native species in England showed that propagule pressure (number and frequency of introductions) is the main criteria for predicting successful establishment (Copp et al., 2007; Gozlan, 2008a). However, in England, it is the size of fish eggs (i.e. <1.4 mm), which best discriminates invasive species in the wild. This is illustrated with species such as Zander *Sander lucioperca*, topmouth gudgeon *Pseudorasbora parva*, sunbleak *Leucaspius delineatus*, and pumkinseed *Lepomis gibbosus*. None of these species in itself presents a major risk for the native communities, with the possible exception of topmouth gudgeon, and even with this species the risk is more likely to be related to an emerging disease (Gozlan et al., 2005; Gozlan, 2008a) than in a direct impact of the fish. The fish communities of the Thames and Ouse mainly consist of coarse fish species and these rivers do not host endemic or rare species. Heavy re-stocking of coarse fish species such as roach *Rutilus rutilus*, bream *Abramis brama*, rudd *Scardinius erythrophtalmus*, and dace *Leciscus leuciscus* is common practice.

10.4.2. What are the fish introductions of the future?

The rate of introductions will probably level off in the future as a result of educational efforts and the development of risk assessment policies (Andersen et al., 2004; Copp et al., 2005; Sutherst et al., 2007; Baker et al., 2008). However, future non-native fish introductions are likely to be coarse fish species coming from our main donor regions (Asia, Eurasia, North America), which are subject to high propagule pressure and are temperature tolerant. Research based on Food and Agriculture Organisation datasets on aquaculture production per year has highlighted eight species as candidates for future introduction under a climate change scenario. Three species were classified as slow spreading, namely channel catfish *Ictalurus punctatus*, black bullhead *Ameirus melas* and North African catfish *Clarias gariepinus*, three as fast spreading, namely bighead carp *Aristichthys nobilis*, black carp *Mylopharyngodon piceus* and pond loach *Misgurnus anguillicaudatus* and a further two species as fast spreading nuisance species, namely bluegill *Lepomis macrochirus*, and black bass *Micropterus salmoides* (ALARM).

Overall, these species have a history of ecological impacts including predation, habitat degradation, and displacement of the endemic species in eight to twenty seven percent of introductions outside their native range.

10.5. Unique issues for the salmonids

The Atlantic salmon and brown trout (*Salmo trutta*) are the two species of native salmonids in UK rivers. This is a high profile species, often considered “the king of the fishes”. Salmonids are worthy of special note because of their anadromous habit of migrating to salt water for their adult lives and the resultant requirements to exist within or pass through the entire river corridor at some point in their lives. In Europe, Atlantic salmon are found in rivers and in the ocean from northern Portugal in the south to Norway, Iceland and Russia in the north. The species has been in decline in most of Europe for the last 50 years. This decline has been most dramatic in the south of its range. Atlantic salmon, and the anadromous form of brown trout (seatrout) disappeared from the river Thames and Yorkshire Ouse in the 19th century and despite more than two decades of effort to re-introduce them to the river Thames there is still no naturally spawning population present. Resident populations of brown trout do however exist in many of the upper tributaries of these rivers and Atlantic salmon are present in many rivers throughout Southern England, and therefore we should consider what issues might arise for them. To assess the overall future for salmonids it is necessary to examine the vulnerability of the different life stages to climate change effects.

10.5.1. Spawning

Salmonid egg survival has been under pressure through heavy siltation of spawning gravels especially in the low gradient lowland rivers including the Southern Chalk streams. The transport of silt through the river is partly a function of flood magnitude and frequency but its source, or supply, are probably more dependent on management activities rather climate change. Egg survival is temperature dependent. Highest egg survival in brown trout is at 10-12 ºC (Ojanguren and Brana, 2003). Egg survival is compromised at temperatures over 14 ºC, but given that groundwater is often a cooling source of river water in the south, water temperatures generally will not exceed 14 ºC under current scenarios, and therefore this may only represent an occasional local problem.

10.5.2. Juveniles and river resident adults

During drought years stranding of juvneile salmonids especially trout has been a cause of mortality in chalk rivers and this may become more prevalent. Upper incipient lethal thermal tolerances for Atlantic salmon have been recorded as 27.8 ºC, and those for brown trout are thought to be about 3 ºC lower (Elliott, 1991). Current temperature forecasts expect summer air temperatures to commonly reach 30 ºC and mean water temperatures to reach 20-22.5 ºC on the Thames (Table 1). As with spawning, climate change will probably not result in mass mortalities other then at an occasional, local level. But in the Thames catchment, and indeed in many other rivers, the natural distribution of trout is extended in a downstream direction with extensive stocking for commercial angling. The region of river where this activity is possible will shrink as flow decreases and temperatures increase, bringing summer temperatures close to the lethal limit in areas of the river where temperature refuges are less prevalent (less groundwater influence, and less shading). This could have a significant commercial impact, as the alternative coarse and grayling fishing activities tend to command lower capital and rental values.

10.5.3. Migration stages for anadromous salmonids.

There are two downstream migrations that take place, one in the autumn from the natal stream to the estuarine zone (Pinder et al., 2007) and a bigger migration in the spring from the natal zone to the sea. These migration periods are characterised by high mortality from predation pressure (Kennedy and Greek, 1988) and there is evidence that the timing of reaching the sea is important to subsequent survival (Larsson, 1977). There is a behavioural element to migration, where the emigrating smolts tend to migrate during floods. Thus, a decline in spring flood frequency may reduce survival. Counter to this, increased temperatures will have the effect of increasing smolt size through increased growth rates and since predation mortality is negatively correlated with size, this will have a beneficial impact on smolt mortality. On balance it would be expected that years without spring flood events will increase mortality.

The greatest threat to anadromous salmonids probably lies in the upstream migration phase. To enter the river these fish must pass through the tidal and lower reaches of rivers. These regions are often characterised by increased levels of pollutants, de-oxygenation, and high temperatures during the summer months. Migratory salmonids are resticting entry to freshwater through these regions during hot dry summers (Solomon and Sambrook, 2004). Fish whose migration is delayed tend to spend long periods in the estuary and then fail to enter freshwater, possibly through a missed physiological opportunity. Once in the river, entry to the most upper natal regions requires the occurrence of high flow events (Webb and Hawkins, 1989). If the frequency of such events decreases in future, it may result in less of the upper reaches of rivers being seeded with juveniles. The net effect of this will be shrinkage of freshwater habitat used and further pressure on salmonid populations, although the river resident forms of brown trout may afford this species a greater resilience.

10.5.4. Conclusion for the salmonids

The salmonid life-history, with the temporal co-existence of many cohorts inhabiting both freshwater and marine environments, will provide some protection from many of the adverse conditions that climate change will bring. But the increased occurrence of unfavourable temperature and flow conditions may result in more extinctions, or reductions, in size of individual populations at a local level. The threat to populations is probably greatest when a combination of factors come together, particularly increased pollution (reduced dilution), and increased incidence of disease (warmer water). Overall, climate change predictions seem likely to increase the pressure on this species. Given its currently modest population levels in Southern England, this is a cause for concern.

10.6. Fish summary

Notwithstanding the climate change scenarios, whilst we maintain water and flow in our rivers, fish populations will remain, but their composition is likely to change. Some coarse fish populations may indeed increase, although this will be balanced against more favourable conditions for disease transmission. Because of the popularity of fishing, introductions of alien species are likely to continue, but a significant concern here is that they may introduce novel diseases over which our native fish may have limited immunity. A serious concern is that lower flows may elevate concentrations of toxic, or disruptive, chemicals to levels where serious effects on fish populations may occur. Whilst predicted climate changes may not result in a knock out blow for the Salmon and brown trout, it will increase the pressure on their weak Southern UK populations.

11. Riverine birds

Temperature-induced changes in breeding physiology could change the timing and length of the breeding season and, crucially, alter the abundance and phenology of food supplies (Crick, 2004; Visser et al., 2004; Both and Visser, 2005). If birds cannot adjust their timing to such changes, consequent mismatching of supply and demand may reduce both breeding success and survival (Both et al., 2006; Drever and Clark, 2007; Durant et al., 2007). For migrants, mismatching will be exacerbated by conditions on the wintering grounds and temperature-induced effects on the timing and progress of migration (Jenni and Kéry, 2003; Anthes, 2004;

Beale et al., 2006; Jonzen et al., 2006). Stresses due to mismatching will be exacerbated by both low and excessive flow rates, the frequency of extreme weather, pollution and disturbance. However, warmer winters could improve annual survival (Newton, 1998; Saether et al., 2000). Population increases in some species could have consequences for other components of the ecosystem, including fish and macrophytes (Vaneerden et al., 1995; Carss and Marquiss, 1996; Newson et al., 2006). Catchment-scale effects may be further influenced by geographical-scale changes in species breeding and wintering ranges (Rehfisch et al., 2004; Huntley et al., 2007).

Flood events can destroy nests, reduce food supplies and increase foraging difficulties, but such events are within the range of normal experience and may also offer novel, although usually short-lived, foraging opportunities (Poiani, 2006). Once conditions return to normal, recovery should be rapid. Increased frequency of extreme events may be more problematic (Taylor and O'Halloran, 2001). Prolonged drought and low flows are likely to be more serious at the population level and will interact with pollution status (Vickery, 1991; Sorenson et al., 1998). Loss of aquatic vegetation and invertebrates would have a direct negative impact on many water birds (Vickery, 1991) and could also have wider indirect effects. For example, a loss of emergent flies could affect riverine woodland passerines such as Pied Flycatchers, *Ficedula hypoleuca*, and wet habitats have been identified as key resources for several declining farmland bird species (Field and Anderson, 2004; Peach et al., 2004).

With a few exceptions, water bird populations in the UK seem to be doing well (Table 3). Warmer winters with less ice glazing may currently favour over-winter survival and outweigh other possibly deleterious effects of climate change. Thus land use change, habitat loss, reduction of habitat quality and disturbance effects due to increasing human population pressure, especially in the south and south east, are likely to be of more immediate concern for water bird populations than those directly related to climate change. To separate the effects of climate change from those of other factors would require in-depth fieldwork. The Dipper, *Cinclus cinclus*, would be one obvious candidate for such work because of existing knowledge of its physiology, diet, ecology and behaviour, especially in relation to acidification (e.g. Ormerod and Tyler, 1993; Tyler and Ormerod, 1994). It is also one of the few riverine birds for which there is current evidence (eight day advancement of lay date over the last 35 years) of a direct effect of climate change (Sparks et al., 2006).

12. The economic and human dimensions of climate change impacts on British rivers

Water scarcity is exacerbated as its demand increases, and its availability reduces. Forecasts suggest that water demand in the UK is expected to continue to increase in the future, due to increases in population, per capita consumption and economic development. The Thames catchment has been described as one of the most exploited in the world (Evans et al., 2003; Rodda, 2006). Further, despite this already limited water resource, there are continuing economic and social demands for increased housing in the region (SEERA, 2006). At the same time, this climate-change induced reduction in water availability will increase water stress in this already dry part of the country. Furthermore, warmer dryer conditions will give rise to increases in demand for water to maintain agriculture, for example in the Anglian region, in the East of England, it has been predicted that a 30% increase in the volume of water will be needed to irrigate the same area of crops in 2050. This trend is expected to gradually spread west and north (Henriques et al., 2008).

All of these pressures will potentially translate into less quantity and quality of water for the environment. However, under the European Union Habitat Directive (HD) and Water Framework Directive (WFD), the priority is to protect the environment to ensure *site integrity* on HD sites, and *good ecological status* in water bodies. Complying with this legislation will imply higher costs to the water sector, as it will have to invest in the technology needed to reduce water loss such as leakage, and provide more water resources (e.g. desalination, water storage), together with more extensive sewage treatment in some cases. In addition, many of these developments will generate a net increase in CO_2 emissions, and the costs associated with these emissions will have to be included in the total. Thus, the overall costs to the consumer and UK economy associated with water will undoubtedly increase, perhaps substantially so.

When weighing up the competing demands of avoiding environmental damage and reducing water abstractors' costs it is essential that the *Total Economic Value* of water is not underestimated. For example, an aesthetically pleasing river environment nearby makes an attractive place to live and work, and so influences land and house values. Often there may be a substantial tourist industry associated with a river system, and it must not be forgotten that in the UK in particular, angling is an enormously popular sport with £1.18 billion of angler gross expenditure, which generated £980 million of household income and over 37,000 jobs across England and Wales in 2005 (EA, 2007). Focusing on the salmonids alone, if the associated angling were to cease in the Southern regions of Britain, £65 million would be lost each year, resulting in a net loss of £24 million in terms of household income, as well as a loss of over 800 jobs (EA, 2007). This figure of £65 million refers only to losses in expenditure directly associated with the described loss of fish species. It is important to note that this estimate represents only a proportion of the total overall loss of economic value that would be associated with such a loss of species in the Southern regions.

Methods of determining most appropriate strategies for mitigation of, and adaptation to, climate change will need to be developed. This may lead us into the unfamiliar territory of having to select those species, or aquatic and riparian attributes, which provide the highest benefits. This will depend on the value of the goods and services generated by them (including the existence value), which, as with any other scarce (i.e. economic) resource, will depend on both their uniqueness (substitution level) and their resilience to climate change. These complex socio-political and economic issues relating to the impacts of climate change, and our potential to adapt to it, are all areas in need of significant further interdisciplinary research.

13. Conclusions

13.1. So what will the lowland British river of the future look like?

It is necessary to remember that no climate change model can provide a certain picture of the future. The HadCM3 model suggests a drier future for our locations than today, and this review has attempted to think through the implications of such a change. A summary of the individual potential changes to wildlife is given in Table 4. The climate scenarios used in this review suggest lowland British rivers in central and southern regions will have less water and be warmer than before. Unless there is a drastic reduction in nutrients, for much of the year the rivers will probably be a darker shade of green than they are now. Providing flows are maintained and the water is not over-abstracted, rivers will remain ‘open for business’ as ecosystems. However, the species composition will undoubtedly change. A number of wetland environments, particularly those depending on rain water or river water, are likely to decline. It is fortunate that many of the rivers in southern England are groundwater fed, as this provides both relatively resilient base flow and a moderation of water temperature change. Surface water dominated rivers are more at risk from prolonged periods of minimal precipitation, but they are more numerous in northern UK, where the climatic changes are predicted to be less. We can be sure that consumers, particularly in the South-East, will have to pay more for their water as it becomes a scarce commodity and the costs of maintaining quality increases. However, there are a number of ‘wild cards’ which could yet have drastic effects on the river ecosystem which need further analysis:

- Might current organic microcontaminants, such as oral contraceptives, with reduced dilution exceed a threshold concentration that would cause widespread declines in fish populations in rivers with high associated human populations such as the Thames?
- Might alien species bring new pathogens that infect and overwhelm native species in rivers such as the Thames and Ouse?
- Might a dry summer, following an extremely dry winter, stop flow in the Thames and lead to catastrophic eutrophication?
- Might higher carbon loadings in river bed-sediments dangerously deplete oxygen levels in some slow flowing rivers?

13.2. What next?

13.2.1. Science

The origin for an examination, such as this, of how a river ecosystem might change as climate changes, is a regional climate model linked to river flow predictions. Thus, it is vital that the abilities of such models to predict current and past flows are thoroughly tested, to ensure we have the highest confidence in using them to predict our future. From this review it is clear that within the individual biological disciplines there remain considerable gaps in our knowledge, to say nothing of our ignorance of ecosystem interactions in rivers. These gaps reduce the confidence we can give to our predictions of how the biology of a lowland river will respond to climate change. Without a significant increase in research funding and direction, our ability to predict how such important ecosystems will respond to climate-driven environmental impacts will remain weak. Integrated studies involving climate change modellers, hydrologists, hydromorphologists, chemists, biologists and economists working closely together are particularly needed, but to achieve this will require a change in the mindset of both scientists and funders. Although it is invidious to make comparisons, we would argue that the UK, and particularly southern English aquatic environments, are more in danger of decline due to climate change than any other natural environment in the country. A river, its wildlife and associated services cannot move north as conditions change

13.2.2. Policy and management

It would seem that even if the world were to reduce carbon emissions, the UK will experience a prolonged period of climate change (Lowe et al., submitted). There is a danger that increasing demands for water (described by some as the new oil) in a future where water resources may well decline, and a desire to continue to meet high water quality standards, is a circle we may not be able to square. Over-exploitation, leading to areas of stagnant water, would be potentially catastrophic for riverine wildlife. Should we accept that trying to maintain high water quality standards as dilution falls may be both economically unacceptable and not in the best interests of the wider environment? Wildlife is more able to accept lower quality water, than no water at all. A mature and pragmatic debate is needed between environmental scientists, regulators, water companies and planners to ensure that UK lowland rivers, with their rich ecosystems and high economic value, will be able to adapt to environmental change. It may well require unpalatable decisions to be taken by all parties.

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Table 1-River Thames (221 km main stem to tidal limit)

		Typical hydraulic residence time (d)		Mean SRP† (μg/L)*	Mean Nitrate-N (μg/L)*	Mean NH$_4$ (μg/L)*	Typical mean Si (μg/L)*	Mean Water temperature (^{o}C)	Incoming shortwave radiation (W/m^2)	Q95[+] flow (m^3/s)	Q5 flow[++] (m^3/s)
		Mean Flow	Q95[+]								
Now	Winter*[2]	7	31	324	9330	161	4440	6.2	46.4	32.3	269.0
	Spring	9	30	403	8301	182	2871	11	152.8	33.2	196.0
	Summer	17	41	835	6828	85	4262	17.5	209.2	24.2	81.9
	Autumn	20	47	831	7301	79	5324	12.5	90.4	21.4	149.0
2080 Low emission scenario (UKCIP)	Winter	10	47	440	13000	220	6000	7.5	46.3	21.5	263.0
	Spring	11	38	480	9900	220	3400	12.5	159.9	26.3	178.0
	Summer	24	59	1100	9300	120	5800	20.0	227.3	17.1	56.2
	Autumn	29	69	1200	10500	110	7700	14.5	96.1	14.6	67.6
2080 High emission scenario (UKCIP)	Winter	10	56	500	14000	250	6800	8.5	46.1	17.8	258.0
	Spring	13	43	540	11000	240	3800	14.0	168.2	23.5	170.0
	Summer	28	73	1400	11000	140	6900	22.0	244.3	13.8	46.8
	Autumn	34	82	1400	12500	140	9100	16.5	101.5	12.2	55.6

*Information from R. Thames at Howbery Park, Wallingford. This could be informed by predicted land use changes in due course. But at this stage future concentration predictions would be based on a pro-rata predicted change;

†SRP soluble reactive phosphorus;

*[2] Winter taken to mean Dec, Jan, and Feb;

[+] Q95 Flow exceeded 95% of the time, for example might occur in dry summer conditions;

[++] Q5 flow exceeded 5% of the time, for example very high flows in winter.

Table 2-Yorkshire Ouse (120 km main stem to tidal limit)

		Typical hydraulic residence time (d)		**Mean SRP (μg/L)***	**Mean Nitrate-N (μg/L)***	**Mean NH_4 (μg/L)***	**Typical mean Si (μg/L)***	**Mean Water temperature (°C)**	**Incoming shortwave radiation (W/m^2)**	**Q95 flow (m^3/s)**	**Q5 flow (m^3/s)**
		Mean Flow	**Q95**								
Now	Winter*[2]	2.3	4.9	136	4781	32	2241	4.3	39.6	20.2	210
	Spring	2.9	5.3	253	4062	33	643	8.8	146.1	12.6	139
	Summer	3.6	6.7	493	2709	67	1198	17.2	198.3	5.61	67.3
	Autumn	2.9	7.9	373	2352	63	2211	10.4	80.2	5.55	167
2080 Low emission scenario (UKCIP)	Winter	2.3	5.1	130	4700	31	2200	5.5	39.2	19	220
	Spring	2.9	5.4	270	4300	35	690	10.5	152.5	11.8	130
	Summer	4.0	6.9	700	3900	96	1700	19.5	213.7	4.53	31.6
	Autumn	3.3	8.6	570	3600	96	3400	12.5	84.7	3.96	132
2080 High emission scenario (UKCIP)	Winter	2.3	5.3	130	4600	31	2200	7.0	38.7	17.5	230
	Spring	3.0	5.6	290	4700	38	740	12.0	158.6	10.9	127
	Summer	4.2	7.2	870	4800	120	2100	21.5	228.2	3.8	19.3
	Autumn	3.7	8.8	880	5500	150	5200	14.5	88.93	3.15	114

*Information from R. Ouse at York. This could be informed by predicted land use changes in due course. But at this stage future concentration predictions would be based on a pro-rata predicted change.

Table 3-Current population trends in UK aquatic birds (data from BTO web site, 19.03.07)

Species	Trend
Mute Swan	Increasing
Mallard	Increasing
Shelduck	Increasing
Cormorant	Increasing
Oystercatcher	Increasing
Goosander	Long-term increase
Red-breasted Merganser	Long-term increase, recent shallow decline
Coot	Long-term increase, recent shallow decline
Grey Heron	Moderate increase; stable in Wales
Tufted Duck	Shallow increase
Great Crested Grebe	Shallow increase
Moorhen	Stable or shallow increase
Common Scoter	Stable, increasing in Scotland after previous decline
Kingfisher	Fluctuating, no general trend
Dipper	Fluctuating, no general trend
Sedge Warbler	Fluctuating, no general trend
Sand Martin	Fluctuating, no general trend
Swallow	Fluctuating, no general trend
Reed Warbler	Fluctuating, uncertain
Little Grebe	Stable, but possible decline on rivers, uncertain

Pied Flycatcher	Possible decline, uncertain
Grey Wagtail	Shallow decline
Common Sandpiper	Moderate decline

Table 4-Summary table of predicted changes to riverine wildlife

Organism examined	**Challenge**	**Effect**	**Probablility**	**Hazard?**
Enteric pathogenic virus	Reduced flow, less dilution in summer	Increase of viral concentration	Possible	Yes
	Change in human behaviour, more people bathe in rivers in summer	Greater exposure to enteric viruses	Possible	Yes
	Warmer water and more sunlight	Greater inactivation of RNA type viruses	Possible	Beneficial
Pathogenic bacteria	Similar to viral pathogens	Survival of some pathogens will be reduced, others enhanced	Possible	Neutral?
Biogeochemical processes	More nutrients and carbon arriving in the river	Greater O_2 consumption and CO_2 generation	Possible	Will play a role in changing the habitat conditions and affecting higher organisms
Phytoplankton	Greater coloured DOC released into rivers from more productive organic rich soils	Reduced light penetration reduces growth	Possible	No
	More sunlight/warmth	More growth	Possible	Yes (eutrophic problems, or stimulating to toxic cyanobacteria)
	Lower flows	More growth	Possible	Yes
	Conditions favour greater predation	Reduced growth	Possible	No

Macroinvertebrates	Lower flows, change in DO, sedimentation, and food source	Decreases in rheophilic taxa and increases in limnophilic taxa	Likely	Neutral
Macrophytes	Warmer water and lower flows encourage growth of epiphytic algae	Reduced growth of native species. May favour alien sub-tropical species	Possible	Some
	Elevated atmospheric CO_2	Favours the community which utilises CO_2 rather than HCO_3	Possible	Neutral
Fish (other than Salmon)	Warmer temperatures	Better recruitment of juvenile fish	High	Beneficial
	Less high flow events	Better recruitment of juvenile fish	High	Beneficial
	More disease transmission (warmer water, less volume)	Reduce recruitment of juvenile fish	Possible	Yes
	Exotic disease introduced from alien fish	Reduced population levels in susceptible species. Local extinctions	Possible	Yes
	Higher concentrations of harmful chemicals from sewage effluent	Reduced fertility and population effects from endocrine disrupters. Other disruptive chemicals may also cause damage if less dilution	Very likely in Southern and Central England unless we invest further in sewage treatment	Yes

Salmon	Similar as for other fish	But warmer temperatures and low flow not helpful to its needs	Possible	More pressure for a species already in difficulty in Southern UK
Birds	Warmer winters	Better winter survival	High	Beneficial
	Less high flow events in nesting season	Better survival for young	Possible	Beneficial (but some chance of changes in food supply)
	Earlier onset of spring	Bird breeding out of synch with food source	Already a problem in some species	Yes, for some species
	Loss of macroinvertebrate, plant food sources due to flow change effects, or greater chemical pollution	Reduced survival and breeding success; possible loss of species from affected sites	Possible, but difficult to predict; likely to be highly species-specific	Yes
	Increase in macroinvertebrate food source (warmer, nutrient rich rivers)	Increased survival, possible population growth, espec. of herbivores, but excessive nutrient load detrimental	Possible	Complex, may be beneficial or detrimental depending on circumstances and degree of eutrophication