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Review

The British river of the future: How climate change and human activity might affect two contrasting river ecosystems in England

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ABSTRACT

The possible effects of changing climate on a southern and a north-eastern English river (the Thames and the Yorkshire Ouse, respectively) were examined in relation to water and ecological quality throughout the food web. The CLASSIC hydrological model, driven by output from the Hadley Centre climate model (HadCM3), based on IPCC low and high CO_2 emission scenarios for 2080 were used as the basis for the analysis. 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 (by up to a month in the Thames), with nutrient, organic and biological contaminant concentrations elevated by 70–100% pro-rata, assuming sewage treatment effectiveness remains unchanged. 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 the recruitment of many coarse fish species. However, warm, slow-flowing, shallower water would increase the incidence of fish diseases. These changing conditions would make southern UK rivers in general a less favourable habitat for some species of fish, such as the Atlantic salmon (*Salmo salar*). Accidental or deliberate, introductions of alien macrophytes and fish may change the range of species in the rivers. In some areas, it is possible that a concurrence of different pressures may give rise to the temporary loss of ecosystem services, such as providing acceptable quality water for humans and industry. An increasing demand for water in southern England due to an expanding population, a possibly 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.

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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 UK and European lowland river ecosystem as a whole have so far received little attention, although there are plenty of grounds for concern (Heino et al., 2009). 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, but also due to increasing human demands (Alcamo et al., 2007). More recently, reductions in water quality are now also being predicted in a warming UK (Whitehead et al., 2009).

Looking across the UK, the UKCIP02 report (Hulme et al., 2002) predicted that southern and eastern England will experience the most dramatic climate change in terms of increased temperatures and reduced precipitation. What might this mean for rivers in those regions? To help focus and provide a backdrop for this review, the climatic impacts on hydrology and chemistry were modelled for the contrasting catchments of the Thames in southern England, and the Yorkshire Ouse in north-eastern England. These potential changes to flow, temperature, sunlight and chemical composition were used as a guide to help judge how a range of different aquatic organisms, from microscopic to macroscopic, might respond. The intention was to cover as broad a trophic range as possible, and to include many of the most significant groups within the river ecosystem. Some consideration as to how river ecosystems as a whole could be evaluated, both economically and socially, was also given. Whilst this review uses two British rivers, with their own particular circumstances of geology, hydrology and human development, as a guide, the issues addressed in this review will be relevant to most lowland rivers throughout Europe. This review aims to identify some of the big issues, or even unpleasant surprises, which could have major impacts on some British river ecosystems in the future. What these possible changes imply for research and policy is also assessed in this review.

2. Physical description of the catchments and climate change

2.1. Deriving 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) and New et al. (2007) 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 (Hulme et al., 2002). These models are the basis for much current climate change planning in the UK. The UKCIP02 scenarios present a relatively dry picture for the UK which is not shared by all GCMs. Thus, 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 that 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. Where winter rainfall is predicted to increase, this will be a feature both of an increase in the number of rain days, and from an increase in rainfall intensity due to the milder temperatures increasing the potential for increased water vapor 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.

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

		Typical hydraulic residence time (d)		Mean SRP[b] (μg/L)[c]	Mean nitrate-N (μg/L)[c]	Mean NH_4 (μg/L)[c]	Typical mean Si (μg/L)[c]	Mean water temperature (°C)	Incoming shortwave radiation (W/m^2)	Mean flow (m^3/s)	Q95[a] flow (m^3/s)	Q5 flow[d] (m^3/s)
		Mean flow	Q95[a]									
Now	Winter[e]	7	31	324	9330	161	4440	6.2	46.4	113	32.3	269.0
	Spring	9	30	403	8301	182	2871	11	152.8	79	33.2	196.0
	Summer	17	41	835	6828	85	4262	17.5	209.2	43	24.2	81.9
	Autumn	20	47	831	7301	79	5324	12.5	90.4	37	21.4	149.0
2080 Low emission scenario (UKCIP)	Winter	10	47	440	13000	220	6000	7.5	46.3	83	21.5	263.0
	Spring	11	38	480	9900	220	3400	12.5	159.9	67	26.3	178.0
	Summer	24	59	1100	9300	120	5800	20.0	227.3	32	17.1	56.2
	Autumn	29	69	1200	10500	110	7700	14.5	96.1	26	14.6	67.6
2080 High emission scenario (UKCIP)	Winter	10	56	500	14000	250	6800	8.5	46.1	74	17.8	258.0
	Spring	13	43	540	11000	240	3800	14.0	168.2	60	23.5	170.0
	Summer	28	73	1400	11000	140	6900	22.0	244.3	26	13.8	46.8
	Autumn	34	82	1400	12500	140	9100	16.5	101.5	22	12.2	55.6

[a] Q95 Flow exceeded 95% of the time, for example might occur in dry summer conditions.
[b] SRP soluble reactive phosphorus.
[c] Concentration information from R. Thames at Howbery Park, Wallingford average of period 1999–2002. Concentrations for 2080 based on a pro-rata predicted change.
[d] Q5 Flow exceeded 5% of the time, for example very high flows in winter.
[e] Winter taken to mean Dec, Jan, and Feb.

It is acknowledged 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 than at present, which would have dramatic effects on river biota.

River residence times were estimated from river length and water velocity. The water velocity was calculated from river flow using a general relationship for the UK for the River Aire (Round et al., 1998) and from a specific relationship available for the River Thames (Whitehead and Williams, 1984). Thus, predictions 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. N and P nutrients are vital for sustaining algal and macrophyte growth in rivers. This is a reasonable approximation for soluble reactive phosphorus (Jarvie et al., 2006) and ammonium (NH_4), which are mostly controlled by dilution of point sources in the main river, and also silica (Si), which has a strong baseflow component (resulting from local geology). Of course, further human population growth may increase this load. Nitrate (NO_3) behaviour is more complex both because of its varying sources (both point and diffuse) and of its transformations to other nitrogen forms. Research suggests that 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) and notwithstanding plant uptake, dry summers still result in high rates of diffuse source nitrogen getting into rivers when the drought breaks (Whitehead et al., 2006). A recent study in Denmark indicated that although N retention in rivers would increase, this loss would still be exceeded by the increase in nitrate delivery to the river under future climate change scenarios (Andersen et al., 2006). Thus, Tables 1 and 2 should provide a reasonable starting point for nutrient chemistry, but there is some likelihood of underestimation.

2.2. Current and future picture for hydrology and chemistry in the Thames

The annual average rainfall for the Thames basin is 690 mm (1961–1990), of which around 440 mm is lost through evaporation, leaving an average runoff of 250 mm/yr. The Thames basin, in southern England, covers an area of 13,000 km^2 and has a population density approaching 1000 people/km^2 (Evans et al., 2003). The greatest

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)	Mean flow (m^3/s)	Q95 flow (m^3/s)	Q5 flow (m^3/s)
		Mean flow	Q95									
Now	Winter	2.3	4.9	136	4781	32	2241	4.3	39.6	66	20.2	210
	Spring	2.9	5.3	253	4062	33	643	8.8	146.1	32	12.6	139
	Summer	3.6	6.7	493	2709	67	1198	17.2	198.3	14	5.61	67.3
	Autumn	2.9	7.9	373	2352	63	2211	10.4	80.2	31	5.55	167
2080 Low emission scenario (UKCIP)	Winter	2.3	5.1	130	4700	31	2200	5.5	39.2	67	19	220
	Spring	2.9	5.4	270	4300	35	690	10.5	152.5	30	11.8	130
	Summer	4.0	6.9	700	3900	96	1700	19.5	213.7	10	4.53	31.6
	Autumn	3.3	8.6	570	3600	96	3400	12.5	84.7	20	3.96	132
2080 High emission scenario (UKCIP)	Winter	2.3	5.3	130	4600	31	2200	7.0	38.7	68	17.5	230
	Spring	3.0	5.6	290	4700	38	740	12.0	158.6	28	10.9	127
	Summer	4.2	7.2	870	4800	120	2100	21.5	228.2	8	3.8	19.3
	Autumn	3.7	8.8	880	5500	150	5200	14.5	88.93	13	3.15	114

*Concentration information from R. Ouse at York (average of period 1986–1990). Concentrations for 2080 based on a pro-rata predicted change.

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. The Thames catchment embraces a number of very different river and regime types, from urbanised responsive rivers to spring-fed streams. Each type is likely to respond differently to climate change pressures. Tributaries draining the clay vales appear to be more vulnerable to climate change, because they do not benefit from the major baseflow support from the limestone and Chalk outcrops below Oxford. 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 catchment contains a wide range of wetlands including those on the alluvial floodplains (along the River Cherwell), on the gravel river terraces (around Cricklade) and those on Chalk, (around the Lambourn catchment) (Acreman et al., 2003).

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). The winter recharge season is vital and when it is below requirement, this leads to repercussions throughout the rest of the year, as demonstrated during the 2004–06 drought (Marsh, 2007).

The current and 2080 modelled hydrological behaviour and chemical changes for the Thames are shown in Table 1, and can be summarised as follows:

- 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.
- The duration of high flow events is also likely to decline in magnitude under all scenarios and regimes, by as much as 50% plus in autumn.
- Winter river water temperatures could rise by 1.5–3 °C, from the current typical 5 °C. For the Thames there is currently a 12-fold difference between Q95 to Q5, but under our most extreme climate change scenario this variation increases to 21-fold. This increased range is due to a lowering in the predicted Q95 low flows compared to today (Table 1).

2.3. Current and future picture for hydrology and chemistry in the Yorkshire Ouse

The Yorkshire Ouse (from here all subsequent mention of the Ouse refers to the Yorkshire Ouse) and its associated tributaries form the northern limb of the Humber catchment and 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). Catchment annual rainfall is around 870 mm, but there is considerable regional variation, from 2000 mm in the uplands to 600 mm lower in the catchment (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 is, however, a significant number of important public water supply reservoirs in the catchment (Marsh and Sanderson, 1997). 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. The major tributaries (Derwent, Swale, Ure, Nidd and Wharfe) rise in wet moorland headwaters and drain through rural areas with a low population density. With its high rainfall in 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, ranging from 3 to over 300 m^3/s (Nunn et al., 2007). The absence of any substantial baseflow component in the flow of the Ouse implies a particular vulnerability to any increase in the frequency of hot, dry summers.

The current and 2080 modelled hydrological behaviour and chemical changes for the Thames are shown in Table 2, and can be summarised as follows:

- There is no significant change in mean flow in winter, but otherwise there is a decline in mean flow 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.
- The duration of high flow conditions declines in magnitude in spring, summer and autumn, but slightly increases in winter.
- Winter river water temperatures could rise by 1.5–3 °C from the current typical 5 °C. Mean summer temperatures could rise by 2–4 °C, giving a mean summer water temperature of 19–21 °C compared with the current 17 °C.
- Annual mean concentrations of nutrients could double (ignoring biological transformations).
- There is a slight decrease in incoming solar radiation in winter, but a predicted increase in all other seasons, particularly in summer, with an 8–15% increase.

Natural flow variability, based on the last 30 years of data for the Ouse, is currently 38-fold based on the difference between Q95 to Q5 figures, but under our most extreme climate change scenario this variation increases to 74-fold (Table 2). This increased range is due primarily to a halving in the predicted Q95 low flows compared to today (Table 2).

2.4. Influence of land use change

Human activities will have an impact on the quantity and quality of water in our rivers. Increases in population, such as those planned in the South East (SEERA, 2006; New et al., 2007) cause a water loss through abstraction and then a return through sewage discharge, with their added nutrient and chemical contaminant loads at different points in the catchment. Development of urban centres on flood plains increases the risk of flooding following extreme rainfall events (Wheater, 2006). Unlike domestic consumption, where most of the abstracted water is returned to the catchment in the form of treated sewage effluent, irrigation is predominantly consumptive and involves a net loss through crop evapotranspiration. Although irrigation accounts for only a small proportion of total direct abstraction, its use is increasing due to consumer demand for premium quality produce (Knox et al. (2000)). Recent forecasts suggest that agricultural demand could increase by 25–180% by the 2050s, depending on the socio-economic scenario (Weatherhead and Knox, 2000; Henriques et al., 2008). More intensive agriculture is associated with risks of greater nutrient contamination, although it is not clear if the risk of runoff will be greater during fertiliser application periods than it is now. An intensification in agriculture in headwater zones may lead to a loss of riparian vegetation, leading to increased light penetration and warmer temperatures and thus increased algal biomass and community composition (Heino et al., 2009). In summary, whilst there is considerable uncertainty in predicting human activity 70 years into the future, its influence is likely to exacerbate, rather than contradict, the hydrological and chemical changes (Tables 1 and 2) predicted on the basis of climate change.

3. Predicting biotic responses to climate change scenarios for the Thames and Yorkshire Ouse in 2080

The general picture that emerges from modelled climate scenarios for 2080, for the Thames and Ouse, is that flows will be reduced (with consequently increased sedimentation rates), water will stay in the river for longer, be warmer, and have considerably higher solute concentrations (due to reduced dilution) then now (Tables 1 and 2). These predictions on hydrology and chemistry have been used as a guide (but not exclusively so) to assist predicting how aquatic organisms might respond in southern and north-eastern UK. In many cases the assessments on the behaviour of aquatic organisms cannot be specific to these catchments, since we know little of their current status. A range of aquatic organisms from different trophic levels is now examined and the results summarised in Table 4.

3.1. Human pathogenic microorganisms

An indirect effect of climate change and human behaviour may be more human exposure to pathogenic organisms from water. Whilst the vast majority of morbidity and mortality caused by waterborne enteric pathogens (viruses, bacteria and protozoa) occurs in the developing world, as many as 19.5 million illnesses due to waterborne infection are believed to occur in the US each year (Reynolds et al., 2008). In the UK it has been estimated that currently 1.5 million patients with gastroenteritis (vomiting and diarrhoea) present to their doctor annually (FSA, 2000), although it is not clear, at present, what proportion of these infections result from exposure to river water or contaminated drinking water. Water is known to be the main source of enteric infections caused by the protozoans *Crytosporidium* and *Giardia* (Pruss, 1998).

Human enteric pathogens transmitted via the faecal–oral route enter watercourses at point sources via effluent from sewage treatment plants or septic tanks. Humans come into contact with surface water through recreation and also via the use of river water for irrigation (Tyrrel et al., 2006). However, some, such as noroviruses, *Crytosporidium*, *Campylobacter* spp. and *Mycobacterium avium* subspecies *paratuberculosis*, may be derived from animal slurry or water runoff from agricultural land (Bates and Phillips, 2005; Pickup et al., 2005, 2006; Mattison et al., 2007). In general, bacterial and protozoan pathogens which survive in water and sediments 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). Although highly variable (days to weeks), enteric viruses also have relatively long half-lives in water (Carter, 2005). Currently, EU regulations only require assessment of microbiological water quality by counts of faecal coliform, and total coliform bacteria and enterococci. However such counts do not reflect the risk from human viruses (Geldenhuys and Pretorius, 1989), and levels of between 1 and 10,000 pfu (plaque-forming units) per 100 L of receiving water (Scipioni et al., 2000), and 1–20 pfu per 1000 L potable water have been observed (Payment et al., 1997). Notably, the infectious dose of some enteric viruses may be only 1–10 pfu (Leclerc et al., 2002).

Absolute numbers of enteric pathogens may increase in British rivers with reduced dilution and increased residence times (Tables 1 and 2). Associated increased sedimentation rates may reduce pathogen spread from point sources, but increase local survival (Green and Lewis, 1999). Countering this, enteric virus survival times will be slightly decreased by higher temperatures and UV irradiation. For bacteria, it has been suggested that inactivation due to temperature changes will be significant only in water bodies with residence times greater than a month (Schijven and Husman, 2005). For some bacteria, such as *Legionella* spp., elevated temperatures may actually enhance survival (Nguyen et al., 2006). Recreational bathing in warmer waters will also play a part in future exposure and is likely to increase the frequency of human enteric infections (Schijven and Husman, 2005).

On balance, the projected changes in river ecology are likely to result in an increase in human exposure to enteric pathogens, but we currently have little suitable information to judge the magnitude of the increase, or to predict which pathogenic organisms are likely to increase the most. Application of high throughput molecular techniques may prove useful for monitoring (Lemarchand et al., 2004). More such infections might be expected in the Thames, rather than the Ouse, on the basis of their respective population densities and higher southern temperatures.

3.2. Bacteria and 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 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, in response 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 riverbed. It is not clear whether generally lower dilutions, with proportionally higher organic carbon concentrations, 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).

In summary, the effect 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.

3.3. 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. Importantly, nutrient levels are considered to be saturating for most of the time, in most lowland rivers (Hilton et al., 2006), although transient nutrient-limitation is possible for silica (Skidmore et al., 1998). Any entry of coloured dissolved organic carbon (DOC) to waters will worsen light penetration through the water and cause a decrease in productivity. Assessing whether grazers could effectively limit large algal blooms is not straightforward 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 algae (>20 μm), thus leading only to a change in community structure (Ruse and Love, 1997; Gosselain et al., 1998). Perhaps viral, bacterial, or fungal infections may play a role in controlling algal blooms, as has been suggested for the Seine catchment (Garnier et al., 1995).

Aside from these general factors affecting algal cell growth and death, local geographic factors will also be important in determining the extent of phytoplankton blooms. In a study of chlorophyll-a in rivers in eastern England, including the Ouse, the strongest relationship was seen with catchment area and flow, rather than nutrient concentration (Neal et al., 2006). The importance of residence time was reinforced by the chlorophyll-a content of a canal being up to six times greater than that of 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 inocula (Neal et al., 2006). Low gradients along the 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., 2006). Whilst hydraulic flushing can be a major loss factor, on occasions greater phytoplankton biomass has been observed in rivers than predicted. This is purely on the basis of mean river velocity, due to the presence of slow-flowing regions, or 'dead zones', maintaining the biomass in the main channel (Reynolds, 2000).

From existing studies we can compare the phytoplankton productivity of the Thames and Ouse. In a comparative study of the Thames and Humber basins, it is possible to compare mean chlorophyll-a values (1993–97) for the Ouse (22 μg/L) and Thames (17 μg/L upstream of Wallingford) (Neal et al., 2006). The catchments at these points have relatively similar areas, with the Ouse being 3315 km^2 and the Thames above Wallingford 3445 km^2. However, whilst the Ouse and Thames may be similarly productive, area for area, the Thames is longer and slower-flowing (see Tables 1 and 2), and further down the catchment higher algal values have been recorded, such as 160 μg/L in the 1980s below Reading (Young et al., 1999), and up to 270 μg/L below Reading in 1975 (Whitehead and Hornberger, 1984).

Overall, current data suggests that these climate change scenarios (Tables 1 and 2) will promote additional phytoplankton growth above present levels, the Thames being particularly vulnerable with its longer residence time. 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). Notwithstanding their key roll as primary producers, and their potential contribution to eutrophication, there is still considerable uncertainty over the magnitude of the response we can expect from the phytoplankton community.

3.4. Macroinvertebrates

Macroinvertebrates are a numerically very diverse group of organisms, which play an important intermediate role in the river food web. It is known that the species composition of the overall community is very sensitive to environmental conditions, and this has led to their use as indicators of water quality, such as in the RIVPACS model (Wright et al., 1984). Overall, it appears that a northward shift of many aquatic macroinvertebrates can already be detected, when comparing species distributions of the 1970s with those of the 1990s (Hickling et al., 2006). Direct effects of climate change, such as increasing temperature, can have an effect on invertebrate abundance and composition, and this has already been noted in Wales (Durance and Ormerod, 2007) and the Upper Rhône in France (Daufresne et al., 2004). Similarly, reductions in flow can have a direct effect (Daufresne et al., 2004; Durance and Ormerod, 2009). Even where other important stressors are present, such as acidity, the influence of climate, such as the North Atlantic oscillation, can be related to the persistence and stability of invertebrate communities (Bradley and Ormerod, 2001).

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 lower river reaches. Droughts, such as those that have occurred in chalk streams in southern England in the past, dramatically change the environment for macroinvertebrates. However, past examples have shown that when the flow returns, so do the aquatic macroinvertebrates, although species composition may be different from previously (Boulton, 2003).

Overall, the extent of change in macroinvertebrate communities in the Thames will be moderated by the groundwater 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, together with 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 (that thrive in high O_2, low organic nutrient environments), we can expect declines in such water quality scores.

3.5. Macrophytes

Aquatic macrophytes already adapt to large changes in environmental conditions throughout the year. Changes in irradiance, temperature, water velocity, dissolved gases and nutrients will all influence macrophytes.

Warmer water, more nutrients and slower flows will have adverse effects on a number of species. Increases in boundary-layer thickness induced by lower flows, combined with higher water temperatures, may reduce growth and resource capture by submerged macrophytes (Black et al., 1981; Madsen and Sandjensen, 1991). This would result in a loss of competitive ability in species dependant on the C_3 pathway, and an increase in the dominance of sub-tropical type alien species, which tend to have C_4 type carbon physiology, or floating leaves, which reduce dependence on the limiting concentration of dissolved CO_2 in water (Madsen and Sandjensen, 1991). Similarly, submerged macrophytes could also be suppressed by the growth of epiphytic algae and bacteria (Hilton et al., 2006). Thus, an increase in the growth of floating macrophytes over submerged species would be expected (Madsen and Sandjensen, 1991). This may already be happening with the dominance of non-native amphibious species such as *Hydrocotyle ranunculoides* and *Myriophyllum aquaticum* in northern Europe (Newman, pers. obs. 2004), with increased prevalence of tropical species such as *Eichhornia crassipes* in south-western Europe (Moreira et al., 1999).

'Native' macrophytes have upper temperature limits above which growth ceases (e.g. *Ranunculus penicillatus* var. *calcareus* photosynthetic rate declines at pH 7.5 above 23.5°C due to an inhibition of enzyme activity responsible for HCO_3^- transport across the plasmalemma (Newman, 1991). Periods of drought in streams 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, as CO_2 in water is a critical limiting factor (Raven, 1984). Evolved systems to use HCO_3^- have energy costs, as do most other enzyme-based systems of concentrating carbon, e.g. C_4 systems (Madsen and Sandjensen, 1991) and CAM (Keeley, 1996). Alleviation of the need to use other forms of carbon may confer advantages on obligate CO_2 users (C_3 carbon physiology).

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.

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 in late summer and early autumn, an important part of the plant-growing season (Acreman et al., 2009). 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 than those in the Ouse catchments. Rain-fed wetlands are likely to be more significantly impacted than river-fed wetlands. 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 (in the 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 without human intervention to protect their function and water supply, possibly leading to a reduction in the biodiversity and amenity value associated with them. In northern England, wetlands are predicted to be less vulnerable.

3.6. Fish

3.6.1. Introduction

Fish face a range of environmental challenges both from man's activities and from direct and indirect climate change effects (Ormerod, 2003). Man's direct effects include the introduction of alien species, over-exploitation, habitat fragmentation and declines in habitat quality. As noted above, both the Thames, and to a lesser extent the Ouse, have had considerable man-made ‘improvements’ over the years. Direct and indirect climate change potential effects include those on water temperature, oxygen content, flow, prey and predators, chemical contaminants, and disease. Flow, or rather reduced flow, will influence all of these factors negatively and a relationship has been demonstrated between declining worldwide river flows and reductions in fish biodiversity (Xenopoulos et al., 2005). Low flows in summer, with their attendant higher pollutant concentrations and lower oxygen levels, have been linked with migratory salmonids declining to travel through the estuary to freshwater in the UK (Solomon and Sambrook, 2004). However, it is worth noting that reduced high flow events can be beneficial. Juvenile fish are very susceptible to loss in high flow events (Nunn et al., 2007), and a reduction in such occurrences would enhance recruitment (i.e. survival of young fish). The River Thames fishery is dominated by cyprinid fishes, such as roach (*Rutilis rutilis*), bream (*Abramis brama*) and chub (*Leuciscus cephalus*), plus some perciform fishes (e.g. perch, *Perca fluviatilis*). The lower reaches of the River Ouse contain a fixed coarse and trout fishery, whereas the upper reaches are dominated by salmonids. The coarse fish species in the lower reaches are very similar to those in the River Thames. The salmonids fishes in the upper reaches are predominantly Atlantic salmon (*Salmo salar*), Brown trout (*Salmo trutta*) and grayling (*Thymallus thumallus*). The following review of fish will focus on temperature, chemicals, disease all of which are strongly influenced by changes in flow.

3.6.2. Temperature-related effects

Fish are ectotherms: in most species, body temperature is essentially the same as that of the surrounding 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). As rivers warm, some fish species are likely to find themselves living in environments outside their optimal thermal ranges. In response, and if they can, populations will move to cooler pockets of water (Breau et al., 2007), but failing that they may disappear altogether. For example, in a period of 20 years the water temperature in the upper River Rhône (in France) rose 1.5 °C, 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). 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 to water temperature (Grenouillet et al., 2001).

Recent assessments of the strength of the cyprinid fisheries on the 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.

3.6.3. Impact 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 (Tables 1 and 2), this will lead to less dilution of sewage effluents (and their associated microorganic contaminants), so 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 catchments with a high human population density and low rainfall. The Thames catchment would fall into the more threatened category, with a daily dilution per head of 1.7 m^3/d/capita, whilst the 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 sewage effluent are taken.

3.6.4. Changes to fish disease patterns

Diseases in wild fish populations are caused by a variety of pathogens which occasionally cause acute mortalities where dead or dying fish are observed (Bakke and Harris, 1998). More commonly, debilitating chronic infections, most frequently parasitic infections, result in the increased likelihood of predation, or the 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 throughout 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 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 (Feist and Longshaw, 2008).

Bacterial and viral infections of fish 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. Predicted increases in temperature, residence times and nutrient concentrations, together with decreases in water flow, will impact on all hosts directly, altering fish distribution, immunocompetence and susceptibility. An 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 will have an impact on disease transmission, since they act as intermediate hosts for several parasite groups. Potential movements of new hosts into rivers may also introduce new pathogens into the region and naïve hosts may suffer losses.

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.

3.6.5. Invasive fish species

People are the main vector of freshwater fish movements across river basins or countries (Gozlan, 2008a,b). 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). Projected increases in human population in the south-east of England imply that further introductions of non-native fish in this region, including into the Thames, will occur.

Recent studies have shown that the successful establishment of non-native species in England is related to propagule pressure (number and frequency of introductions) (Copp et al., 2007; Gozlan, 2008b) and also to the size of the fish eggs (i.e. <1.4 mm). 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 present a major risk for the native communities in themselves, 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, 2008b) than in a direct impact of the fish.

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. A lot has been leant about the factors influencing the success, or failure, of both accidential and intentional introductions (Garcia-Berthou, 2007), and this has included consideration of future introductions under a climate change scenario. Some introduced species, such as bighead carp *Aristichthys nobilis*, black carp *Mylopharyngodon piceus* and pond loach *Misgurnus anguillicaudatus*, are known to be fast spreading, whereas others such as bluegill *Lepomis macrochirus*, and black bass *Micropterus salmoides* can be both fast spreading and a nuisance. Overall, these species have a history of adverse ecological impacts including predation, habitat degradation, and displacement of the endemic species in a significant proportion of introductions outside their native range. Introductions of species such as these, which may well thrive in the English rivers of the future, could have dramatic effects on the current native fish populations.

3.6.6. 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. The Atlantic salmon and brown trout are highly prized by anglers, and hence receive considerable conservation efforts. However, neither species is currently particularly common (relative to other species of fish) in either the Thames, or Ouse. Overall, future climate change seems likely to further exacerbate the decline of these species. 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.

Table 3
Current population trends in a selection of important UK riverine birds (data from BTO web site, 19.03.07) * = species likely to be typical of both river systems; **Upper Ouse, unlikely in Thames.

Species	Trend
*Mute Swan	Increasing
*Mallard	Increasing
*Shelduck	Increasing
Goosander	Long-term increase
*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
*Kingfisher	Fluctuating, no general trend
**Dipper	Fluctuating, no general trend
*Sand Martin	Fluctuating, no general trend
*Reed Warbler	Fluctuating, uncertain
*Little Grebe	Stable, but possible decline on rivers, uncertain
*Grey Wagtail	Shallow decline
Common Sandpiper	Moderate decline

3.7. Riverine birds

The riverine bird species likely to be typical of the Thames and the Yorkshire Ouse are as indicated in Table 3. Some of the other species might also occur sporadically or occasionally, but most likely in the winter or during the migration period. For breeding birds, temperature-induced changes in 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) and such effects might be expected to be more marked at northern latitudes (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, although some evidence suggests increased mortality in years with flood events (Lebreton et al., 1992). 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

Table 4
Summary table of predicted changes to riverine wildlife.

Organism examined	Challenge	Effect	Probability	Impact on Thames?	Impact on Ouse?
Enteric pathogenic virus	Reduced flow, less dilution in summer	Increase of viral concentration	Possible	Could be negative for health	Less risk than Thames
	Change in human behaviour, more people bathe in rivers in summer	Greater exposure to enteric viruses	Possible	Could be negative for health	Less risk than Thames
	Warmer water and more sunlight	Greater inactivation of RNA type viruses	Possible	Beneficial	Beneficial
Pathogenic bacteria	Similar to viral pathogens	Survival of some pathogens will be reduced, others enhanced	Possible	Neutral?	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 for higher organisms	Will play a role in changing the habitat conditions for higher organisms
Phytoplankton	Greater coloured DOC released into rivers from more productive organic rich soils	Reduced light penetration reduces growth	Possible	Reduced algal growth	Reduced algal growth
	Lower flows and more sunlight/warmth	More growth	Possible	Yes (eutrophic problems, or stimulating to toxic cyanobacteria)	Less of a problem for shorter catchment with less residence time
	Conditions favour greater predation	Reduced growth	Possible	Beneficial	Beneficial
Macroinvertebrates	Lower flows, change in DO, sedimentation, and food source	Decreases in rheophilic taxa and increases in limnophilic taxa	Likely	Neutral	Neutral
Macrophytes	Warmer water and lower flows encourage growth of epiphytic algae	Reduced growth of native species. May favour alien sub-tropical species	Possible	Change expected	Change expected
	Elevated atmospheric CO_2	Favours the community which utilises CO_2 rather than HCO_3	Possible	Neutral	Neutral
Fish	Warmer temperatures	Better recruitment of juvenile fish	High	Beneficial	Beneficial
	Less high flow events	Better recruitment of juvenile fish	High	Beneficial	Beneficial
	More disease transmission (warmer water, less dilution)	Reduce recruitment of juvenile fish	Possible	Negative impact	Negative impact
	Exotic disease introduced from alien fish	Reduced population levels in susceptible species. Local extinctions	Possible	Negative impact	Negative impact
	Higher concentrations of harmful chemicals from sewage effluent (less dilution)	Reduced fertility and population effects from endocrine disrupters and other disruptive chemicals	Likely in many parts of England without improvements in sewage treatment	Negative impact	Less of a problem due to lower human population
Birds	Warmer winters	Better winter survival	High	Beneficial	Beneficial
	Less high flow events in nesting season	Better survival for young	Possible	Beneficial (but some chance of changes in food supply)	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	Problem for some species	Problem for some species
	Changes in plant and macroinvertebrate food sources	Changes in survival and breeding success rates	Possible, but difficult to predict; likely to be highly species-specific	May be beneficial or detrimental depending on circumstances	May be beneficial or detrimental depending on circumstances

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 (Durance and Ormerod, 2007). 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). For example, riverine macroinvertebrates are key to its distribution and abundance, and detrimental effects of acidification on availability are further exacerbated by increasing water temperature (Durance and Ormerod, 2007). 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).

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

Water demand is expected to rise in line with population growth, increasing personal wealth and economic development, whilst at the same time its quantity is predicted to decline in many parts of the world due to climate change (Alcamo et al., 2007). Given its exposed location with respect to the magnitude of expected climate change in UKCIP02 (Hulme et al., 2002), the Thames region is an area of particular concern. The Thames catchment has been described as already one of the most exploited in the world (Evans et al., 2003; Rodda, 2006). Of course, as a commodity becomes scarcer, so its value, and hence its cost, to the consumer will increase. Apart from increasing demand and increasing scarcity, another factor that will raise costs for the consumer is the demand to maintain, or increase the quality of the waterbodies themselves. 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, including greater levels of sewage treatment. 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.

What is the cost if a particular waterbody is over-exploited to the extent that the ecosystem is damaged, and species lost? An attractive and biodiverse river has a surprisingly large number of connections with our economy. For example, an aesthetically pleasing river environment nearby makes an attractive place to live and work, and 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, generating £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).

Unfortunately, in the future the twin pressures of climate change and increasing human demand may force us to make compromises in the extent of protection we extend to our water courses. 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. To help value and hence protect our aquatic freshwater heritage further, co-operative efforts between economists and environmental scientists will be necessary.

5. Conclusions

5.1. 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 both in the South and North East 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 England, 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 and which need further analysis, for example:

- 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?

5.2. What next?

5.2.1. 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 within 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 in the UK, 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.

5.2.2. 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., 2009). 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 the UK's lowland rivers, with their rich ecosystems and high economic value, will be able to adapt to environmental change. It may well require unpalatable decisions by all parties.

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