

# *The implications of climate change for the water environment in England*

Article

Published Version

Creative Commons: Attribution 3.0 (CC-BY)

Open Access

Arnell, N. ORCID: <https://orcid.org/0000-0003-2691-4436>, Halliday, S., Battarbee, R. W., Skeffington, R. and Wade, A. ORCID: <https://orcid.org/0000-0002-5296-8350> (2015) The implications of climate change for the water environment in England. *Progress in Physical Geography*, 39 (1). pp. 93-120. ISSN 1477-0296 doi: 10.1177/0309133314560369 Available at <https://centaur.reading.ac.uk/39250/>

It is advisable to refer to the publisher's version if you intend to cite from the work. See [Guidance on citing](#).

Published version at: <http://dx.doi.org/10.1177/0309133314560369>

To link to this article DOI: <http://dx.doi.org/10.1177/0309133314560369>

Publisher: Sage

All outputs in CentAUR are protected by Intellectual Property Rights law, including copyright law. Copyright and IPR is retained by the creators or other copyright holders. Terms and conditions for use of this material are defined in the [End User Agreement](#).

[www.reading.ac.uk/centaur](http://www.reading.ac.uk/centaur)

**CentAUR**

Central Archive at the University of Reading

Reading's research outputs online



# The implications of climate change for the water environment in England

Progress in Physical Geography  
2015, Vol. 39(1) 93–120  
© The Author(s) 2015  
Reprints and permission:  
[sagepub.co.uk/journalsPermissions.nav](http://sagepub.co.uk/journalsPermissions.nav)  
DOI: 10.1177/0309133314560369  
[ppg.sagepub.com](http://ppg.sagepub.com)



**Nigel W. Arnell and Sarah J. Halliday**

University of Reading, UK

**Richard W. Battarbee**

University College London, UK

**Richard A. Skeffington and Andrew J. Wade**

University of Reading, UK

## Abstract

This paper reviews the implications of climate change for the water environment and its management in England. There is a large literature, but most studies have looked at flow volumes or nutrients and none have considered explicitly the implications of climate change for the delivery of water management objectives. Studies have been undertaken in a small number of locations. Studies have used observations from the past to infer future changes, and have used numerical simulation models with climate change scenarios. The literature indicates that climate change poses risks to the delivery of water management objectives, but that these risks depend on local catchment and water body conditions. Climate change affects the status of water bodies, and it affects the effectiveness of measures to manage the water environment and meet policy objectives. The future impact of climate change on the water environment and its management is uncertain. Impacts are dependent on changes in the duration of dry spells and frequency of ‘flushing’ events, which are highly uncertain and not included in current climate scenarios. There is a good qualitative understanding of ways in which systems may change, but interactions between components of the water environment are poorly understood. Predictive models are only available for some components, and model parametric and structural uncertainty has not been evaluated. The impacts of climate change depend on other pressures on the water environment in a catchment, and also on the management interventions that are undertaken to achieve water management objectives. The paper has also developed a series of consistent conceptual models describing the implications of climate change for pressures on the water environment, based around the source-pathway-receptor concept. They provide a framework for a systematic assessment across catchments and pressures of the implications of climate change for the water environment and its management.

---

## Corresponding author:

Nigel W Arnell, University of Reading, Agriculture Building, Earley Gate, Reading RG6 6AR, UK.

Email: [n.w.arnell@reading.ac.uk](mailto:n.w.arnell@reading.ac.uk)

**Keywords**

climate change, water quality, river flows, groundwater, estuaries, lakes, water framework directive

**I Introduction**

Across many parts of the world the water environment is facing increasing challenges. Loadings of nutrients have increased significantly, air pollution has caused surface water acidification, a wide variety of pollutants are discharged to water courses and abstractions from rivers and groundwater have affected flow regimes. As of 2009, only 44% of rivers in the 27 member states of the European Union, plus Norway, were classified as being of 'good' or 'high' ecological status (European Commission, 2012), and in some regions less than 10% of rivers met this standard. However, water managers are well aware of these pressures, and have implemented improvement measures. For example, whilst 4% of rivers and lakes in Saxony, Germany, were classified as being of good status in 2009, by 2015 it is anticipated that this will increase to 14% (Spanhoff et al., 2012). Climate change poses an additional challenge. It has the potential to affect the water environment through changes to water quantity and quality and freshwater biodiversity, and to influence the effectiveness of management measures required to restore water quality. A major assessment of the probable impact of climate change on European lakes, rivers and wetlands has been conducted recently (Kernan et al., 2010) and George (2010) examined the potential impact of climate change on the nutrient status of European lakes, but a thorough systematic study of the impact of climate change on the water environment in England has yet to be carried out.

This paper presents a high level review of the potential consequences of climate change for the water environment in England, with a particular emphasis on implications for the delivery of water management objectives. It

is based on a review of published literature produced for the Department for Environment, Food and Rural Affairs (Defra) (Arnell et al., 2014a), and combines evidence from published case studies with scientific first principles. A significant amount of work has been done and published. Many processes are understood in principle if not adequately captured by models but, as the review shows, there are substantial gaps. In particular, studies have been undertaken in a relatively small subset of environments and it is therefore difficult to generalise to produce national-scale assessments. This paper summarises the current knowledge of potential impacts in England, and proposes a series of conceptual models to frame future catchment or national-scale assessments. It develops the review produced by Whitehead et al. (2009a) by considering all types of water bodies, by considering potential impacts from first principles and observations as well as model results, by explicitly considering implications for water management and finally by proposing generalised conceptual models.

**II The water environment: current and future pressures***Managing the water environment*

The dominant driver for the management of the water environment in England, and indeed the rest of the European Union (EU), is the Water Framework Directive (WFD: 2000/60/EC), adopted in 2000. This drew together a number of previous directives, and its primary objective is to provide 'good' status for all European water bodies by set deadlines (2015, 2021 or 2027 depending on affordability and feasible system recovery times).

'Good' is interpreted in terms of ecological and chemical status, and the status of designated 'protected areas'. These designated protected areas consist of drinking water protected areas (DrWPAs), nutrient sensitive areas (nitrate vulnerable zones and areas downstream of urban waste water treatment sites), shellfish waters, bathing waters, and sites with unique and valuable habitats (Natura2000 sites). WFD objectives are delivered through periodic river basin management plans (RBMPs), which specify actions (known as the 'programme of measures') to be taken by a wide range of stakeholders. The first round of RBMPs was published in 2009, and the second round is due to be produced by the end of 2015. Water managers also have a duty to reduce pollution from specified substances to surface water and groundwater to maintain regulatory standards. They also have an operational responsibility to respond to, and reduce risks from, individual polluting incidents.

The water environment comprises both surface and groundwater bodies. Surface water bodies are rivers, lakes, transitional waters and coastal waters. Transitional waters are bodies of surface water in the vicinity of river mouths which are partly saline but substantially influenced by freshwater flows; most are estuaries and rias, but there are some coastal lagoons. Coastal waters are within one nautical mile of the coast, and can therefore be affected by inflows of surface and groundwater from the land, typically from small catchments (because the largest rivers enter the sea through estuaries). More broadly, the 'water environment' is often interpreted to include those terrestrial ecosystems which are influenced by the volume and quality of water, largely because the interventions which may be necessary to maintain their status come through water management. This paper focuses on surface and groundwater bodies, and does not consider explicitly water-dependent terrestrial ecosystems such as wetlands.

The regulatory policy drivers are summarised in Table 1. Most are focused around the definition of the status of a water body, based on a very wide range of chemical, biological and, for groundwater bodies, quantitative indicators (there are dozens of chemical indicators, although not all are measured or relevant for each water body). Threshold values are defined separately for each indicator based either on values deemed to be indicative of 'good' status (based on observations), or on toxicological limits. Different threshold values may be defined for different types of water body (river, lake, etc.), and for different categories of each water body type. Quantitative indicators are not defined for the Natura2000 sites because of their diversity, and status is based on expert judgement. In all these cases, the aims of water management are to allow water bodies to maintain or achieve a defined status, to prevent deterioration and, for groundwater bodies, reverse significant adverse trends. Compliance is therefore measured in terms of the water body status. The regulatory approach for nutrient sensitive zones is slightly different. In these cases, 'sensitive areas' are defined on the basis of chemical and biological indicators, and specific management approaches must be implemented in these areas (for example, relating to the application of nitrogen by farmers and the treatment of sewage effluent). Compliance under these regulations is measured in terms of the implementation of these interventions, not in terms of the quality of the receiving water – although this will typically be addressed by the other regulations.

### *Current pressures on the water environment in England*

There are seven main current pressures on the water environment in England, and Table 2 maps these onto the regulatory framework in Table 1:

**Table 1.** Regulatory policies affecting the water environment in England.

Policy instrument	Reference	Description
Water Framework Directive (WFD)	2000/60/EC	Defines status of surface water bodies in terms of ecological status (biological and physico-chemical status) and chemical status (specific chemicals). Defines status of groundwater bodies in terms of quantity and chemical quality
Marine Strategy Framework Directive (MSFD)	2008/56/EC	Defines status of marine waters in terms of qualitative descriptors covering ecology, chemistry and the physical environment
<b>Protected areas</b>		
Drinking water protected areas (DrWPAs)	Article 7, WFD	Defines status on basis of specific chemical determinands: a DrWPA is 'at risk' if treatment is needed to meet drinking water standards
Shellfish waters	Shellfish Directive 2006/113/EC; under WFD from 2014	Define status on basis of specific chemical and microbial determinands
Bathing waters	Bathing Waters Directive 2006/7/EC	Define status on basis of specific microbial determinands
Nutrient sensitive zones: nitrate vulnerable zones (NVZs)	Nitrates Directive 91/676/EC	NVZs based on nitrate concentrations; specific management actions necessary within NVZs
Nutrient sensitive zones: urban waste water treatment	Urban Waste Water Treatment Directive 91/276/EEC	Sensitive waters based on eutrophication risk or nitrate concentrations, and include designated shellfish and bathing waters; specific management actions necessary within sensitive waters
Natura2000	Habitats Directive 92/43/EEC	Water-dependent ecosystems, sensitive to changes in water volume or quality. Objective is to maintain status
<b>Pollution control</b>		
Priority substances	WFD Article 16, Annex X substances, as defined in Environmental Quality Standards Directive 2008/105/EC	Define status on basis of 33 specific chemical determinands
Groundwater pollution	Groundwater WFD Daughter Directive 2006/118/EC	Define status on basis of pesticides, nitrate, salinity and specific chemical determinands

**Table 2.** Relationship between pressures on the water environment and regulatory policies.

	Nutrient enrichment and eutrophication	Organic enrichment	Pollution from organic contaminants and toxic chemicals	Acidification	Over-abstraction from rivers and groundwater	Invasive species
Water Framework Directive	■	■	■	■	■	■
Marine Strategy Framework Directive	■		■			■
Drinking water protected areas	■		■			
Shellfish waters		■	■			
Bathing waters			■			
Nitrate vulnerable zones	■					
Urban waste water treatment	■					
Natura2000 sites	■		■	■	■	■
Pollution from priority substances			■			
Groundwater pollution	■		■			

- eutrophication and nutrient enrichment (primarily due to nitrogen and phosphorus species);
- organic pollution leading to increased oxygen demand from species inhabiting freshwater habitats (organic enrichment);
- pollution from organic contaminants (including pesticides, herbicides and microbial pathogens) and toxic chemicals;
- acidification (from sulphur and nitrogen deposition and their legacies);
- over-abstraction from rivers and groundwater;
- morphological changes to water bodies (erosion, sedimentation and channel modification);
- invasive species affecting species interactions and biodiversity.

As of 2013, 21% of rivers, 26% of lakes, 16% of transitional waters and 33% of coastal waters in England were classified as having ‘good’ ecological status under the WFD, and in 2010

38% of groundwater bodies were classified as having good status. Most of the rivers that fail to achieve good ecological status do so largely because of excessive nutrients (mostly phosphorus concentrations) adversely affecting biological communities, morphological modifications to the river channel (such as obstructions to fish movement) and sedimentation affecting fish and invertebrate communities. Eutrophication and excess nutrients are also the dominant causes for lakes, transitional and coastal waters failing to achieve good ecological status. The groundwater bodies that fail to achieve good status do so for a combination of reasons including eutrophication (particularly high nitrate concentrations) and also because over-abstraction affects the volume of surface waters.

Around 30% of the surface water DrWPAs in England and Wales, and 70% of groundwater DrWPAs were classified as 'at risk' in 2013 because additional treatment may be needed to meet drinking water standards (Environment Agency, 2013a). The dominant reasons for 'at risk' status for surface water DrWPAs are excessive pesticide concentrations, poor water colour (due to high dissolved organic carbon) and high algal concentrations due to excessive nutrients. High nitrate concentrations are by far the main reason why groundwater DrWPAs are at risk (Environment Agency, 2013a). Virtually all of England's bathing and shellfish waters meet basic quality standards, but only 81% and 34%, respectively, meet the stricter 'guideline' standards. All these failures are due to excessive faecal coliform concentrations.

Failure to achieve target status is therefore due to a variety of drivers, mostly ultimately related to various dimensions of water chemistry. Excessive concentrations of nutrients and pollutants derive from both point and diffuse sources.

### *Climate change*

By 2050, mean winter temperatures in England are projected to rise by approximately 1.1 to

3.2°C (with a central estimate of 2.1°C) and mean summer temperatures could be 1.2 to 4.2°C (central estimate 2.5°C) higher than in 1961 to 1990 (UKCP09: Murphy et al., 2009). Mean winter precipitation could increase by 2 to 28% (central estimate 13%) and mean summer precipitation could change by between -36% and +4% (central estimate -16%). Table 3 shows the variation in the potential impact on average seasonal temperature and precipitation across England, and illustrates the large amount of uncertainty even assuming one scenario for future emissions. The frequency of intense rainfall events is likely to increase, as a warmer atmosphere can hold more water. Warmer and drier conditions *on average* during summer could be expected to lead to more frequent hot dry summers.

Sea level is projected to rise by approximately 18–26 cm by 2050 (relative to 1990) in south-east England, and sea surface temperatures to increase by of the order of 0.2–0.3°C per decade (suggesting an increase of 1.6–2.4°C by 2050 relative to 1961–1990). The salinity of the seas around England is likely to reduce by 2050, particularly in the North Sea, but changes in estuaries will be strongly affected by changes in river flows. Stratification in estuaries is likely to increase slightly, and the duration of stratification in summer to increase (Statham, 2012). There is currently considerable uncertainty on potential changes in the circulation in the coastal zone.

### *Other pressures on the water environment*

By the mid-2030s, the population of England is projected to increase by between 6.5 and 9.6 million over the 2012 level (Office of National Statistics, 2013). This will have two effects on the water environment. First, demand for water resources will likely increase, although the effect will depend on future per capita water use; the Environment Agency (2013b) projects changes in demand in England and Wales by 2050 under different scenarios ranging from a decrease of 28% to an increase of 49% (relative



**Table 3.** UKCP09 climate change projections for the 2050s, assuming medium emissions (mean is shown with 10th and 90th percentile in brackets). The change is relative to the 1961–1990 mean.

Region	Temperature (°C)		Precipitation (%)	
	Winter	Summer	Winter	Summer
East of England	2.2 (1.1–3.4)	2.5 (1.1–3.9)	14 (1–24)	–16 (–36–1)
London	2.2 (1.1–3.4)	2.7 (1.2–4.2)	14 (2–29)	–19 (–36–6)
North-east of England	2.0 (1.0–3.0)	2.5 (1.2–4.1)	11 (3–26)	–15 (–36–1)
North-west of England	1.9 (1.1–3.1)	2.6 (1.2–4.1)	13 (1–24)	–18 (–30–1)
South-east of England	2.2 (1.2–3.2)	2.3 (1.2–4.4)	11 (2–27)	–19 (–37–6)
South-west of England	2.1 (1.1–3.4)	2.7 (1.1–3.9)	17 (1–24)	–20 (–36–1)
West Midlands	2.1 (1.1–3.2)	2.6 (1.3–4.6)	13 (4–38)	–17 (–42–7)
Yorkshire and Humber	2.2 (1.2–3.5)	2.3 (1.3–4.6)	11 (2–32)	–19 (–41–7)
<b>Average</b>	<b>2.1 (1.1–3.3)</b>	<b>2.5 (1.2–4.2)</b>	<b>13 (2–28)</b>	<b>–16 (–36–4)</b>

to 2008). Population growth and demand growth is most likely to occur in south-east England, the driest area of the UK. Second, increased population would lead to increased discharges of sewage effluent to treatment works and the water environment, although the effects of this would depend on changes to water treatment practices.

The water environment may also be affected by future changes in land cover and use. Increased urbanisation and a potential increase in the area of land devoted to biofuels may affect river flow regimes and recharge through altering flow and recharge generation processes, but potentially the greatest effect of land use change is on water chemistry. Fertiliser use in the UK is currently declining (Defra, 2014) and overall pesticide use is also declining (although the areas receiving pesticide applications are increasing) (The Food and Environment Research Agency, 2013), but many factors affect pesticide and fertiliser use so it cannot be assumed that current trends will continue and there is a legacy of nutrient pollution which will continue to affect water quality for decades. Changes to farming practices have the potential to alter loads and affect the mechanisms by which material reaches the water course.

### III Potential effects of climate change on the water environment

#### Introduction

Table 4 lists the refereed papers (as of May 2014) which consider explicitly the implications of future climate change for the water environment in the UK, categorised by major pressure. Some of the papers cover several pressures (for example both river flows and nutrients), and some papers consider some pressures en route to estimating impacts on other pressures (for example, whilst there have been few published papers dealing specifically with the effects of future climate change on river water temperature in the UK, most of the studies looking at nutrients and oxygen depletion incorporate potential changes in temperature). The papers do not necessarily represent separate studies (some times different aspects of the same project are reported in several papers), but most include some form of quantitative analysis. The table does not include studies which have examined past associations between variability in weather or climate and the water environment, unless they specifically considered implications for the future. Government and water management agencies have also commissioned and published reports into various aspects of climate change and the water environment.

**Table 4.** Published papers and reports into the potential effects of future climate change on the water environment in England.

	Rivers	Groundwater	Lakes	Transitional and coastal waters
Volume	<p>Arnell (1992a, 1992b, 2003, 2004, 2011); Arnell and Reynard (1996); Arnell et al. (2014b); Bell et al. (2012); Boorman and Sefton (1997); Calder et al. (2009); Charlton and Arnell (2014); Christierson et al. (2012); Chun et al. (2009); Cloke et al. (2010); Diaz-Nieto and Wilby (2005); Fowler and Kilsby (2007); Fung et al. (2013); Jin et al. (2012); Kay and Jones (2012); Ledbetter et al. (2012); Limbrick et al. (2000); Lopez et al. (2009); New et al. (2007); Pilling and Jones (1999a, 1999b); Prudhomme and Davies (2009a, 2009b); Prudhomme et al. (2003, 2010, 2012, 2013a, 2013b); Remesan et al. (2014); Reynard et al. (2001); Sanderson et al. (2012); Sefton and Boorman (1997); Thompson (2012); Werritty (2002); Wilby (2005, 2006); Wilby and Harris (2006); Wilby et al. (2006a); Environment Agency (2006, 2009); Rance et al. (2012); Reynard et al. (2005, 2009); UKWIR (1997, 2002, 2007)</p>	<p>Bloomfield et al. (2003); Cooper et al. (1995); Herrera-Pantoja and Hiscock (2008); Holman (2006); Holman et al. (2009); Jackson et al. (2011); UKWIR (1997, 2002, 2007)</p>		
Water temperature	<p>Orr et al. (2014); Environment Agency (2007a)</p>		<p>Arvola et al. (2010); George (2007); George et al. (2004, 2007); Jones et al. (2010)</p>	<p>Edwards et al. (2006); Maier et al. (2012); Statham (2012)</p>
Nutrients and eutrophication	<p>Astaraie-Imani et al. (2012); Bouraoui et al. (2002); Crossman et al. (2013); Dunn et al. (2012); Ferrier et al. (1995); Jin et al.</p>	<p>Stuart et al. (2011)</p>	<p>Anderson et al. (2012); Battarbee et al. (2012); Bennion et al. (2012); Blenckner et al. (2010); Carvalho and Kirika (2003); Carvalho et al.</p>	<p>Edwards et al. (2006); Friocourt et al. (2012); Peperzak (2005); Statham (2012)</p>

(continued)

**Table 4.** (continued)

	Rivers	Groundwater	Lakes	Transitional and coastal waters
	(2012); Whitehead et al. (2006, 2009a, 2009b, 2013); Wilby et al. (2006a); Environment Agency (2008a); ADAS (2004); Hutchins et al. (2013); Rance et al. (2012); UKWIR (2000, 2001, 2006)		(2012); Curtis et al. (2014); Elliott (2012); Elliott et al. (2005, 2006); Elliott and May (2008); George et al. (2010); Howard and Easthope (2002); Jones et al. (2011); Moore et al. (2010); Moss et al. (2011); Thorne and Fenner (2011); Thackeray et al. (2008); Hutchins et al. (2013); UKWIR (2000, 2001)	
Organic enrichment and oxygen depletion	Astaraië-Imani et al. (2012); Cox and Whitehead (2009)		Foley et al. (2012)	
Dissolved organic carbon	Tang et al. (2013); Worrall et al. (2004)		Monteith et al. (2007, 2014)	
Pollutants	Bloomfield et al. (2006); Foulds et al. (2014); Macleod et al. (2012); Curtis et al. (2014); Monteith et al. (2014); UKWIR (2004)	Bloomfield et al. (2006)		
Acidification	Evans et al. (2008); Helliwell and Simpson (2010); Curtis et al. (2014); Monteith et al. (2014)		Battarbee et al. (2014); Curtis et al. (2014); Monteith et al. (2014); Wright et al. (2006)	
Sediments and morphology	Coulthard et al. (2012); Lane et al. (2007); Lewin and Macklin (2010); Macklin and Lewin (2003); Macklin and Rumsby (2007); Mullan (2013); Mullan et al. (2012); Whitehead et al. (2009b)			Karunaratna (2011); Environment Agency (2010)
In-stream habitats	Johnson et al. (2009); Durance and Ormerod (2007, 2009); Gauld et al. (2013); Graham and Harrold (2009), Walsh and Kilsby (2007); Whitehead et al. (2009b); Brown et al. (2012); CEFAS (2004, 2012); Environment Agency (2005a, 2005b, 2007b, 2008b, 2009); Natural England and RSPB (2014)		Elliott and Elliott (2010); Griffiths (2007); Hopkins et al. (2011); Jeppesen et al. (2012); McKee et al. (2002); Winfield et al. (2008a, 2008b, 2010, 2012)	Callaway et al. (2012); Cheung et al. (2012); Fuji and Raffaelli (2008); Goodwin et al. (2013); Hawkins et al. (2009); Heath et al. (2012); Hiscock et al. (2004); Jackson and McIlvenny (2011); Jones et al. (2013); Lee (2001); Nicolas et al. (2011); Rombouts et al. (2012); Pinnegar et al. (2012)

These too are shown in Table 4; note that the list includes some scoping studies. Some of these studies have also been presented in the refereed literature.

Key conclusions from the overview of the literature are:

- very few papers have considered biological aspects of water quality in rivers, with most focused on water chemistry;
- there have been far more papers on surface waters than groundwater;
- there has so far been very little published research on potential changes in sediment properties and river and lake morphology;
- most of the chemical water quality papers concentrate on nitrogen and phosphorus dynamics;
- there is little literature on coastal and transitional waters;
- published studies do not explicitly consider policy-relevant determinands – with the exception of nitrogen and phosphorus;
- virtually all projections of the potential effect of climate change in rivers use models, whilst most of the studies in lakes rely on experimental or observational evidence on sensitivity to change;
- studies have largely focused on a small number of case study catchments or water bodies;
- few studies have so far used the UKCP09 climate projections, with most utilising earlier projections.

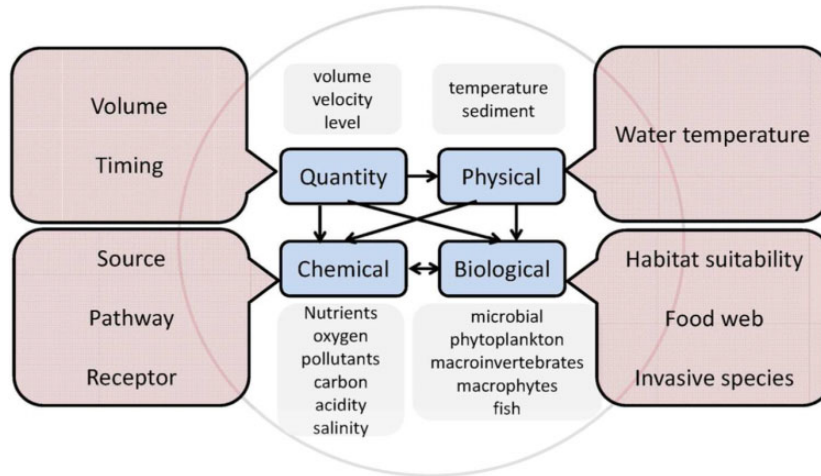
Figure 1 presents a conceptual model of the effects of climate change on the water environment, based on the literature shown in Table 4 and first principles. The water environment in a water body is characterised by the quantity of water (and its variation over time), together with its physical, chemical and biological properties that form ecosystems. The two key physical properties are temperature and sediment concentration. The chemical

properties are a function of the materials dissolved in the water or present in sediments, and the biological characteristics are defined by the assemblage of plants and animals in the water body and their interaction. There are links between these different components. Chemical, biological and physical characteristics may depend on water temperature, many chemical changes in a water body are driven by microbial processes and both chemical composition and physical properties affect biology.

Climate change affects these four components of the water environment differently but – crucially – all together at the same time, as ecosystems. Changes in weather regimes will affect the volume and timing of river flows, inflows to lakes, transitional waters and the coastal zone and the amount of groundwater recharge. Increases in air temperature affect water temperature and the thermal structure of standing water. Changes in the chemistry of water bodies will be determined by changes in the *sources* of material, *pathways* by which material reaches the water body, and processes within the water body itself – the *receptor*. The biological characteristics of a water body will be affected not only by changes in hydrological, physical and chemical characteristics, but also by changes in habitat suitability, food-web structure and the presence of invasive species. Climate change will be superimposed onto other changes in the catchment. In a given catchment, these land use changes or changes in management practices may be more significant for the water environment than climate change alone (as shown, for example, by Crossman et al., 2013). In the uplands, air pollution and its legacy may remain the dominant control on water quality for many headwaters.

### *Hydrological changes*

***Change in the volume and timing of river flows.*** Many studies (Table 4) have assessed the implications of climate change for river flow



**Figure 1.** The impact of climate change on the water environment.

regimes in England. All have used catchment hydrological models with several generations of climate scenario; there have so far been few studies of hydrological changes under the UKCP09 projections (Christierson et al., 2012; Kay and Jones, 2012; Charlton and Arnell, 2014). Three key conclusions from the studies in Table 4 are (i) that impacts on river flow regimes may be substantial (with summer flows potentially declining by around 30% by the 2020s: Christierson et al., 2012), (ii) that there is considerable uncertainty in projected impacts, largely due to uncertainty in projected changes in climate as represented by different climate scenarios, and (iii) different types of catchment respond differently to the same climate scenario. There is a clear distinction between the effects of climate change in groundwater-dominated catchments and those with more responsive hydrological regimes, and there is a difference in response between wet upland catchments and drier lowland catchments due to the different baseline water balances. There are of course a number of caveats with these studies. Different hydrological models could produce different changes, although this effect is probably smaller than the considerable range between scenarios. More significantly, most climate scenarios, as currently applied

in catchment-scale impact studies, do not explicitly incorporate potential changes in the characteristics of daily rainfall or changes in the year to year variability in rainfall. They may therefore underestimate the potential effects of climate change on the variability in river flows over time.

Climate change also has the potential to alter river flow generation processes, although this has not yet been assessed in any studies in England. For example, warmer, drier conditions in summer could lead to changes to soil structure (for example cracking), which could change the nature of hydrological response to subsequent rainfall. Such changes are not incorporated into the current generation of hydrological models used to estimate climate change impacts.

**Change in groundwater recharge.** Ground water in England is typically recharged during winter, when soil moisture deficits are minimal (recharge also can occur in other seasons when soil moisture deficits are eliminated). In general, warmer temperatures will lead to a reduction in the recharge season (starting later and finishing earlier), but this may be exaggerated or offset by changes in seasonal rainfall totals; recharge may therefore either increase or decrease (Herrera-Pantoja and

Hiscock, 2008; Jackson et al., 2011). As with river flow generation, recharge processes may be affected by climate change. During very intense rainfall, or when soils are saturated for prolonged periods, recharge may occur rapidly through 'fast' recharge routes (such as macropores and fissures).

### *Changes in physical properties*

***Change in water temperature.*** River temperature is a key determinant of water quality that affects chemical and biological processes. At low-frequency time-scales, such as monthly, empirical relationships are often used to determine water temperatures from air temperatures (Orr et al., 2014). However, at the time-scale at which biogeochemical processes operate, simple empirical relationships are not appropriate and do not provide any detail of the thermal regime experienced by aquatic organisms. Water and air temperature are not well correlated at a fine temporal scale (Webb et al., 2008) because the thermal regime of the river is affected by factors such as radiation and evaporative heat fluxes, heat transfer to/from the streambed and mixing of groundwater inputs, as well as water management practices (e.g. Caissie et al., 2007; Webb et al., 2008; Williams and Boorman, 2012).

The effects of climate change on lake water temperature profiles depend not only on the change in temperature and energy balance, but also on the characteristics of the lake, including its depth and degree of mixing (Arvola et al., 2010). Higher temperatures and increased emissions of long-wave radiation generally increase lake water temperature at the surface, but stimulate earlier and more persistent stratification so thermal profiles through the lake will change (George et al., 2007). Lake temperature changes are most influenced by changes in winter and night-time air temperatures (Jones et al., 2010). The incidence and length of winter ice cover will diminish.

***Sea level rise and saline intrusion.*** In principle, a rise in sea level could lead to increased

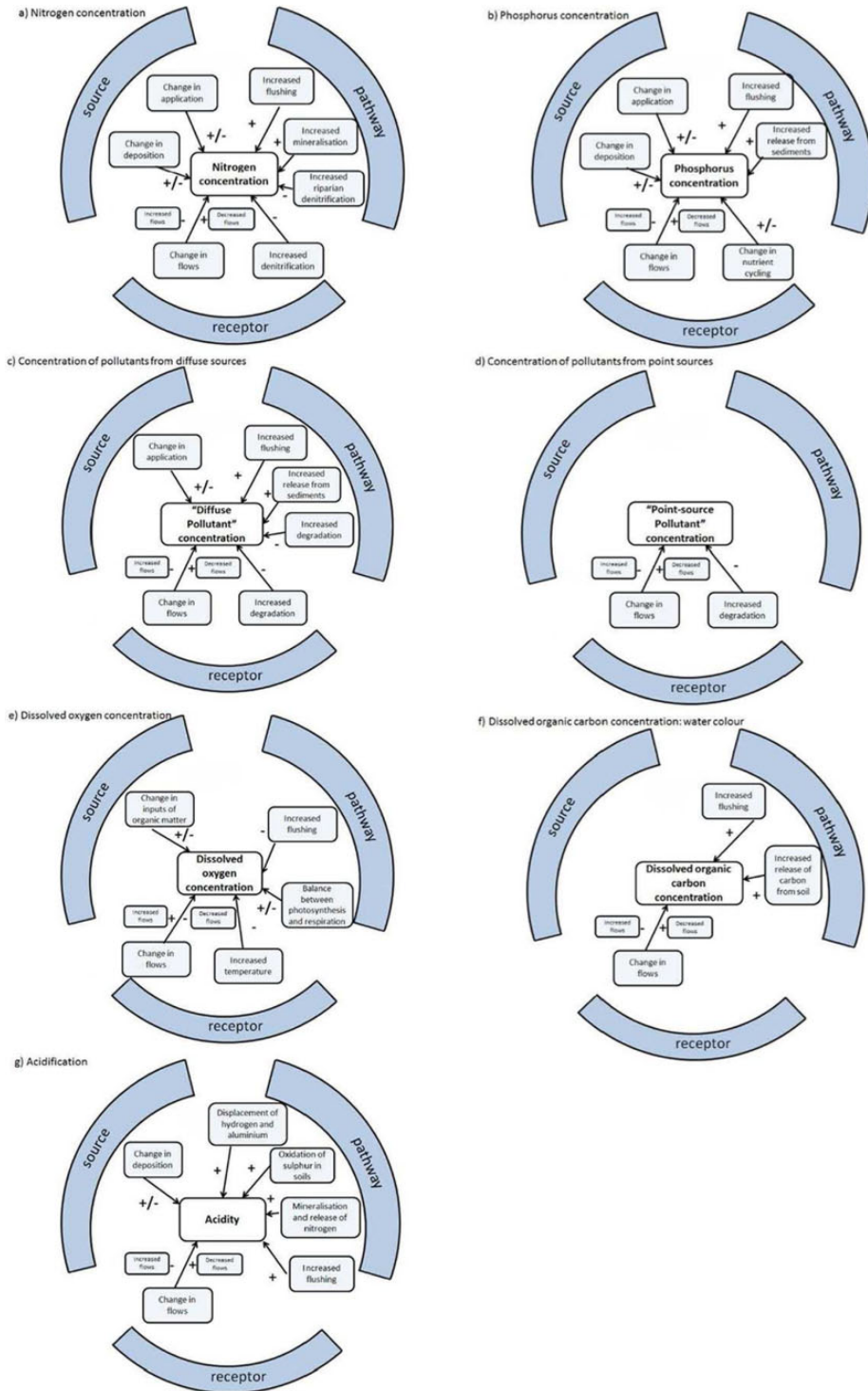
saline intrusion into coastal aquifers, although the effect will vary locally depending on factors such as local hydraulic gradients and the amount of abstraction from the aquifer (Ferguson and Gleeson, 2012). Sea level rise will also affect saline intrusion along estuaries, with the extent of the effect depending on local gradients and tidal patterns.

***Morphology and sediment.*** Changes in river flow regimes have the potential to affect patterns of erosion and deposition within river channels, lakes and estuaries. An increased frequency of intense rainfall events could also generate additional sediment loads. There have been many fluvial geomorphology studies showing how erosion and sedimentation have varied over the past in relation to climatic variability (e.g. Lewin and Macklin, 2010; Macklin and Rumsby, 2007), indicating that English rivers are sensitive to climatic change. However, there has so far only been one published quantitative study in England into the potential for river channel response to future climate change (Lane et al., 2007); it showed that changes in sediment delivery to the channel could be more important than changes in hydrological regime. Three studies (Coulthard et al., 2012; Mullan, 2013; Mullan et al., 2012) have demonstrated the increased risk of soil erosion and therefore sediment delivery due to increased frequency of intense rainfall. For lakes, increased erosion leads to increased sediment accumulation rates and the acceleration of hydrosere development, especially in the littoral zone. Within estuaries, changes in river inflows together with changes in sea level may alter patterns of erosion and sedimentation, but again there has been little published research (see Karunarathna, 2011; Uncles et al., 2013).

### *Implications for pressures on the water environment*

Regulation and compliance in the water environment is largely focused around the linked





**Figure 2.** The impact of climate change on pressures on the water environment: sources, pathways and receptors.

chemical and biological characteristics of a water body; a biological 'fail' frequently has a chemical cause. Figure 1 suggests that impacts on chemical characteristics are dependent on changes in sources, pathways and receptors. Figure 2 presents generalised models of the impacts of climate change on chemical characteristics and therefore also biological pressures on the water environment, in terms of changes to sources, pathways and receptors. The models indicate the direction of impact. The magnitude of impact, and the relative importance of the different drivers, will vary with local context (and it is significant that many of the relationships can be either positive or negative); not every change will occur, or be important, everywhere. The models have been developed through a combination of reasoning from first principles and evidence from observational (mostly in lakes) and numerical modelling studies presented in Table 4.

#### ***Eutrophication and nutrient enrichment.***

Eutrophication is the ecosystem response to an excess of nutrients, primarily phosphorus and nitrogen, and it is manifest in increased algal growth, often characterised by blooms of phytoplankton ('algal blooms'), changes in ecosystem structure and function. Climate change has the potential to affect the release of nutrients from catchment soils, the transport of nutrients to water courses, biogeochemical processes within water courses and, via changes in flows, dilution and hence concentrations; it affects sources, pathways and receptors. Figures 2a and 2b present models of the impacts of climate change on the concentrations of the two principal nutrients, nitrogen and phosphorus.

Most nitrogen species come from agricultural land as non-point sources, although drainage from sewage treatment works and septic tanks can make significant contributions in some catchments. In the uplands, high nitrate concentrations in surface waters can be the result of atmospheric deposition and leaching from catchment soils saturated by decades of

nitrogen deposition from fossil fuel combustion and agriculture. Changes in precipitation intensity and distribution have the theoretical potential to alter atmospheric deposition rates of pollutant nitrogen. Historically, most phosphorus has come from industrial and domestic sources as point sources from sewage effluent, but with the increasing effluent treatment standards an increasing proportion derives from agricultural land; the balance varies between catchments and the level of effluent treatment. With no change in land use, it is possible that changes in agricultural growing conditions due to climate change could lead to changes – increases or decreases – in the agricultural application of nitrogen and phosphorus to the soil.

Higher soil temperatures and changes in seasonal rainfall and temperature patterns will alter catchment nutrient processing and nitrification in the riparian zone. Changes in the moisture status of the soil are likely to increase mineralisation, leading to increased availability of nitrate for delivery to streams. Increased storm events may also increase the delivery of nutrient loads and sediment from agricultural land through increased flushing, which would mobilise and transport soil particles and associated nutrients to river systems. Increased storm events, especially in summer, could also result in more frequent incidences of combined sewer overflows. These events result in highly polluted water, including untreated sewage, discharging directly into receiving water bodies.

With the projected changes in UK precipitation, it is anticipated that many river systems will see a reduction in summer flows. This would reduce the dilution capacity of system receptors resulting in higher nutrient concentration, particularly in point-source dominated catchments. In addition to reducing receptor dilution capacity, lower summer flows will result in longer water residence times, increasing the potential for eutrophication and the development of algal blooms.



Increased temperatures and lower summer flows may, however, enhance denitrification, potentially lowering riverine nitrogen concentrations, but the effects will depend on the size of the catchment and hence residence times. Changes in nutrient uptake by primary producers (mainly algae) and releases by decomposition may also affect both nitrogen and phosphorus concentrations in water bodies, and a range of chemical phosphorus cycle processes (including direct assimilation, adsorption/desorption and co-precipitation are temperature-dependent). In groundwater-fed catchments, the increased importance of groundwater contributions during low flow periods in the summer could also result in elevated river nitrate concentrations due to historic contamination. In river systems which have experienced historic contamination, remobilisation of within-channel phosphorus has also been observed during storm events, as a result of increased water velocity. In addition, higher temperatures or lower oxygen concentrations in river water may also increase phosphorus release rates from the bed-sediment.

The relative importance of these potential changes to sources, pathways and receptors will vary between catchments. For example, simulations projected increases in summer nitrate concentrations in the River Kennet due to reduced dilution (Whitehead et al., 2006), but reductions in summer nitrate concentrations in the River Thames because increased denitrification offset the reduced dilution effect (Jin et al., 2012).

Altered freshwater fluxes of nutrients, principally nitrogen and phosphorus, will also impact upon estuaries and coastal waters. There is also good evidence (Statham, 2012) that the ratio of nitrogen and phosphorus to silicon has increased in estuaries over time (because of increased anthropogenic loadings of nitrogen and phosphorus), leading to the risk that phytoplankton blooms will consist of potentially toxic cyanobacteria or dinoflagellates rather than diatoms. Submarine groundwater discharges can

be important contributors to transitional waters in the UK (e.g. Jickells, 2005), especially for nitrogen. In some areas, depending on the geological setting, there is a large pool of nitrate in groundwater, and climate change-driven hydrological changes leading to a changed flux from this pool may alter considerably nitrogen fluxes into transitional waters.

Increased nutrient loading from upstream as a result of increases in winter precipitation and summer storms would also impact upon eutrophication in lakes, and changes to processes, especially enhanced nutrient recycling within lakes, may further promote eutrophication (Moss et al., 2011). Warmer, drier summers, longer water residence time and earlier and more stable stratification causing reduced hypolimnetic oxygen concentration in deeper, stratifying lakes may lead to increased algal growth (Foley et al., 2012). Phenological change, especially differential earlier growth of some species, may lead to possible mismatches of life-cycles and to complex impacts on lake communities and lake ecosystem functioning. A change in food-web structure and lake functioning caused by rising water temperature can lead potentially to changes in the composition of fish populations and an increase in fish abundance causing increased predation on zooplankton populations and increased algal growth. For shallow lakes, this may also be accompanied by a shift in aquatic plant community composition towards floating plants, dense algal blooms and a decrease in night-time oxygen concentrations, potentially leading to fish kills (Moss et al., 2011).

***Pollution from organic contaminants and toxic chemicals.*** Pollution of water bodies can come from organic contaminants (including microbial contaminants and waterborne pathogens such as faecal indicator organisms (FIOs)) or toxic substances (including heavy metals and persistent organic pollutants (POPs)). These come both from agriculture (from pesticides, fungicides, fertilisers, silage and animals), and

**Table 5.** Key pollutants affecting compliance with water quality standards.

Category	Primary sources
Nutrients	Agriculture: diffuse Urban: point
Microbial	Agriculture: diffuse Domestic: point
Pesticides and herbicides	Agriculture: diffuse Urban: point
Industrial and domestic chemicals	Industry / urban: point
Transport-derived combustion products	Transport: point, but through drainage system rather than sewage system
Metals	Legacy spoil tips and sediments: diffuse
Endocrine disruptors	Industry / domestic: point
Nano particles	Industry / domestic: point
Pharmaceuticals	Domestic: point Agriculture: diffuse

from a range of industrial, domestic and transport processes. Pollutants are transported along the river network to lakes and estuaries, and can enter the food chain through uptake by benthic invertebrates leading to bioaccumulation in the tissues of fish and shellfish populations; the shellfish waters directive is specifically concerned with this. Table 5 summarises the key types of pollutants that can or could affect compliance with chemical water standards, identifying primary sources and describing whether those sources are point or diffuse. Point and diffuse pollutants will be affected differently by climate change (Figures 2c and 2d).

Total inputs of point-source pollutants (mostly from industry and domestic sources) will be unaffected by climate change, but the application of pesticides and herbicides by farmers may be influenced by the effect of climate change on crop growth. Although the emissions of toxic metals and POPs are now controlled, toxic substances stored in soils and in sediments in the river bed continue

to be transported along water courses through leaching and erosion processes. Increased incidences of combined sewer overflows due to more intensive heavy rainfall events could result in highly polluted untreated waters, containing heavy metals and hydrocarbon based pollutants, discharging directly into receiving water bodies (Rügner et al., 2014).

Increased delivery of diffuse pollutants to rivers and groundwater may result from the anticipated changes in extreme events, with storm events resulting in increased flushing and the remobilisation of contaminated materials (Foulds et al., 2014), until the source becomes exhausted. However, higher temperatures will likely increase the volatilisation and degradation of pesticide residues both in the soil and in surface waters, and this will have the effect of reducing pesticide loads (Bloomfield et al., 2006). Changes in runoff generation processes – for example through increased soil cracking – could alter pathways by which pesticides reach water courses and groundwater.

Pollutant concentrations in rivers will also be affected by changes in the volume of river flows. Reductions in summer flows would increase concentrations, whilst higher flows in late autumn, winter and early spring would reduce concentrations; the effect depends on when the pesticides are applied or pollutants discharged. Higher water temperatures may also potentially affect pesticide concentrations in receiving waters through changing degradation rates.

***Organic enrichment and oxygen depletion.*** Reduced dilution effects and increased flushing of organic material from land would increase biochemical oxygen demand (BOD) in rivers and consequently lower dissolved oxygen concentrations (Cox and Whitehead, 2009; Figure 2e). Increased flow velocities due to higher flows would increase reaeration, and lead to increased dissolved oxygen concentrations. Higher water temperature will also reduce the amount of dissolved oxygen in rivers and lakes

and as the oxygen depletion rate is more temperature sensitive than the reaeration rate this will also contribute to dissolved oxygen reductions. Dissolved oxygen concentrations will also depend on the balance between photosynthesis and respiration processes in the water body. In addition, algal blooms can exert a significant control over seasonal and diurnal patterns in dissolved oxygen levels and in the hypolimnion of stratifying lakes. The importance of such dynamics may increase under climate change as eutrophication and algal bloom formations become more widespread.

Higher temperatures reduce the water solubility of oxygen and may make stratification in estuaries more intense (Rabalais et al., 2009) which, in conjunction with higher primary productivity and enhanced nutrient inputs, may lead to increased risk of anoxic zones developing. These will have a considerable effect on both organism distribution and biogeochemical cycling.

**Dissolved organic carbon.** As upland waters recover from the impact of acid deposition, dissolved organic carbon (DOC) concentrations are increasingly affecting the colour of surface waters (Monteith et al., 2007); this colour needs to be removed before water can be supplied to consumers. Higher temperatures may further increase the release of DOC from soil (Figure 2f). The greatest effect of climate change is likely to be through changes in the frequency of short-duration drought events (during which DOC accumulates) followed by heavy rainfall which flushes accumulations to the water course (Tang et al., 2013). Changes in flow would also, of course, affect dilution.

**Acidification.** Surface water acidification remains a major issue in the UK, particularly within upland systems. However, long-term monitoring under the Upland Waters Monitoring Network (UWMN) is now indicating that almost all monitored streams and lakes are in recovery (Curtis et al., 2014). The impact of climate change on the recovery process is still

uncertain but it is possible that pathways in acidified catchments can be significantly affected (Figure 2g). For example, an increased deposition of sea salts due to potentially increased winter storminess would displace hydrogen and aluminium from soil exchange sites, leading to increased acidification. An increased summer drought frequency would lead to increased mineralisation of nitrogen, placing additional acid stress on water courses, and could lead to the oxidation of legacy sulphur retained by anaerobic peaty soils and therefore increased sulphate-dominated acid pulses. As with the other pressures, changes in flow volume will affect dilution.

**Overview.** There are some common themes across all the pressures. These include the effect of changes in the volume and timing of flows and recharge on the dilution of loads in water bodies (a reduction in flow of 40% increases concentrations by 66.7% with the same load), the likely effect of an increased frequency of flushing events on short-term discharges to water bodies, and the potential effects of changes in the catchment affecting pathways by which material reaches rivers, lakes, coastal waters and groundwater. The relative importance of these different changes will vary between catchments, as will the relative importance of climate and other changes on the water environment.

### *Implications for habitat suitability and invasive species*

**Habitats and biodiversity.** Water body habitats, and the biodiversity of these habitats, are affected by the pressures outlined above – eutrophication, organic enrichment, pollution, acidification, morphological change (and abstraction of water) – but are also potentially directly affected by changes in the volume and timing of river flows and lake water levels particularly, and by changes in water temperature. Most research in inland waters (Table 4) has

concentrated so far on implications for macro-invertebrate communities (e.g. Durance and Ormerod, 2007, 2009) and salmonid fish in rivers (Walsh and Kilsby, 2007) and lakes (e.g. Elliott and Elliott, 2010).

Increasing water temperatures in rivers and lakes may significantly affect freshwater biological assemblages by altering species distributions and abundance through changes in metabolic rates, feeding, migration patterns and physiological harm at different life-cycle stages. Many species, such as salmonid and bullhead species, have thermal limits that determine the success of spawning, migration and survival. Warming could also lead to less suitable conditions for cold and cool-water-adapted species (including high conservation value taxa such as Arctic charr (*Salvelinus alpinus*)), isolating them in increasingly confined headwaters and lakes (Winfield et al., 2008a, 2010). Thermal refuges may be further compromised by oxygen depletion resulting from nutrient enrichment. The thermal tolerances of species can also be lowered by other climatic driven changes in the riverine environment, such as lower water levels and reduced dissolved oxygen concentrations. Other freshwater species, including some macroinvertebrates, can only tolerate a narrow range of temperature, meaning they are highly susceptible to any changes in riverine thermal regime. Reductions in river flows may also restrict access to refugia which aquatic organisms may have historically used, and changes in the river morphology, such as siltation and culverting, may also limit the refugia available.

Temperature increases are likely to impact on the distribution of aquatic plants and animals in transitional and coastal waters (Callaway et al., 2012). Much ecological modelling relating to climate change in coastal waters has focused on water temperature (e.g. Jones et al., 2013; Rombouts et al., 2012). Mobile organisms are likely to move northwards as temperatures rise. The distribution of exploited fish species round the UK is also changing (Nicolas et al., 2011;

Heath et al., 2012), with the pattern being consistent with temperature rise. However, it is also clear that patterns of change will be more complex than a simple northerly shift in species, because if keystone species are affected, then there could be widespread changes in community structure and composition. There are likely to be interactions between temperature rise and other driving forces. Marine ecosystems are often dominated by organisms with planktonic life history stages, and are thus sensitive to alterations in coastal circulation patterns. Harmful algal blooms in the North Atlantic and North Sea are potentially affected by changes in circulation, and particularly stratification.

**Invasive species.** Higher water temperatures and lower flows may result in changes in the distribution and survival of native aquatic organisms, as outlined above. However, these environmental changes will also make the UK aquatic environment increasingly susceptible to the invasion of non-native species or increase in prevalence of existing invasives. The invasion of non-native species is a serious environmental concern as they can have significant detrimental impacts on native species through competition, predation, herbivory, habitat alteration, disease and genetic effects such as hybridisation. For example, the invasion of non-native crayfish species, long-clawed or Turkish crayfish (*Astacus leptodactylus*) and North American signal crayfish (*Pacifastacus leniusculus*), are impacting on native crayfish, white-clawed/Atlantic stream crayfish (*Austropotamobius pallipes*), through competition, and invasion of non-native grass carp (*Ctenopharygdon idella*) is adversely affecting the native macrophyte communities in rivers (Hill et al., 2005).

The potential for invasion varies between water bodies, with the greatest potential in coastal and transitional waters. In inland water bodies, invasive plant species are most likely to be introduced by human action intentionally and unintentionally moving propagules.

## IV Implications for water management

The WFD does not explicitly mention climate change in either the setting of standards or the assessment of risks, although the 2009 RBMPs for England (and Wales) do include highly-generalised qualitative assessments of the effects of climate change on pressures on the water environment. Wilby et al. (2006b) identified five potential implications of climate change for the WFD. The first is on the characterisation of water bodies (different standards are applied to different classes), but in practice it is unlikely that climate change will mean that water bodies in England will change character (Environment Agency, 2007c) because characterisation is largely based on geological and physical properties such as size, altitude and exposure.

The second potential implication of climate change (Wilby et al., 2006b) is on the risk of water bodies failing to meet regulatory compliance objectives. Table 1 listed the main regulatory drivers on compliance, and it was noted that in most cases compliance was based on the status of water bodies. Climate change has the potential to alter water body status, and therefore compliance – and the general direction of change is to increase risks of non-compliance with objectives. The evidence from the literature shows that these risks will vary from one catchment or water body to another.

Wilby et al.'s (2006b) third implication of climate change was for the effectiveness of the programmes of measures incorporated within RBMPs to achieve water environment objectives. For example, with higher water temperatures and lower diluting flows, planned improvements to effluent treatment and controls on diffuse pollution might become less effective. In order to maintain compliance, it may therefore be necessary to further develop and implement measures to maintain the quality of water bodies, but a key implication of the

literature evidence, again, is that this would depend on local conditions. Whitehead et al. (2006) demonstrated that it was technically feasible to offset through a suite of measures the effects of climate change on nutrient concentrations (and therefore compliance) in a lowland chalk stream, but did not evaluate costs and other barriers. Some of the consequences of climate change (for example the effects of higher water temperature) may be difficult to avoid through adaptations to water management approaches. In such cases, climate change could imply an unavoidable regulatory failure – or that the standards of what is deemed to be 'acceptable' or 'good' would need to be changed.

Wilby et al.'s (2006b) fourth implication of climate change was for monitoring, and in particular for the maintenance of long-term monitoring for trend detection and the selection of reference sites used to define 'good' status. Their final implication was for the river basin planning process under the WFD; climate change adds uncertainty to potential future risks and the effectiveness of response measures, for example, and many land use measures that are being considered to address climate change (for example relating to soil protection, agricultural production and biofuel production) will affect the water environment.

## V Conclusions

This review has identified the extent of our understanding of the way climate change might affect a range of dimensions of the water environment in England. There is a large literature on potential impacts (over a 100 papers in the refereed literature), but most studies have looked at flow volumes or nutrients, and none have considered explicitly the implications of climate change for the delivery of water management objectives. Most of the studies in lakes and estuaries have been based on observations made over long periods and have inferred future



changes from past climatic variability, whilst most of the studies of changes in flows and nutrients in rivers have used numerical simulation models. Studies have been undertaken in a very small number of locations (catchments, lakes or estuaries), and it is clear that the impacts of climate change will depend on local conditions – including the extent of pressures on the water environment. It is therefore difficult to extrapolate from the catchment to the national scale for an overall assessment of the implications of climate change for the water environment and compliance with regulatory objectives. Nevertheless, it is possible to conclude that climate change has the potential to pose risks to water management, in two main ways: it affects the status of water bodies (and therefore compliance), and it affects the effectiveness of catchment and in-stream measures to manage the water environment and meet policy objectives. However, the magnitude of this risk depends on local conditions. The interpretation, measurement and definition of WFD status is also potentially affected by a changing climate.

The impact of climate change on the water environment – and therefore the risks posed to water management – is uncertain, for five reasons. First, future changes in relevant aspects of weather and climate are uncertain, and may not be represented in current generation climate scenarios. Changes in most chemical determinands (and therefore biological systems), for example, are strongly dependent on changes in the duration of dry spells and frequency of intense ‘flushing’ events. Second, whilst there is a good qualitative understanding of potential ways in which systems may change, some of the interactions between components of the water environment are poorly understood and new high-frequency observations are giving new insights into system dynamics (Wade et al., 2012). Third, predictive models are currently only available for some components of the water environment, and these models have

parametric and structural uncertainty which has not yet been fully explored. Fourth, climate change is not the only pressure affecting catchments, and how climate change affects the water environment in a place will depend on other land use and management pressures. Finally, the future consequences of climate change will depend on the management actions taken to respond not only to climate change, but also to the other evolving pressures.

The paper has also developed a series of consistent conceptual models describing the implications of climate change for pressures on the water environment, based around the source-pathway-receptor concept. The models have been largely constructed from first principles, but have been informed by the results of observational and modelling studies. They provide a framework for a systematic assessment across catchments and pressures of the implications of climate change for the water environment and its management.

### Acknowledgements

We gratefully acknowledge the helpful support and comments of Dr Debbie Coughlin and Stuart Kirk (Defra), Dr Glenn Watts (Environment Agency) and Professor Stephen Maberley (CEH).

### Funding

This work was supported as part of a scoping study funded by the UK Department for the Environment, Food and Rural Affairs (Defra), under contract WT1540.

### References

- ADAS (2004) *Scoping study of potential impacts of climate change on nutrient pollution from agriculture*. Defra Final Report Project CC0378.
- Anderson NJ, Foy RH, Engstrom DR, et al. (2012) Climate forcing of diatom productivity in a lowland, eutrophic lake: White Lough revisited. *Freshwater Biology* 57: 2030–2043.
- Arnell NW (1992a) Factors controlling the effects of climate change on river flow regimes in a humid

- temperate environment. *Journal of Hydrology* 132: 321–342.
- Arnell NW (1992b) Impacts of climatic change on river flow regimes in the UK. *Journal of the Institution of Water and Environmental Management* 6: 432–442.
- Arnell NW (2003) Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: Future streamflows in Britain. *Journal of Hydrology* 270: 195–213.
- Arnell NW (2004) Climate-change impacts on river flows in Britain: The UKCIP02 scenarios. *Water and Environment Journal* 18: 112–117.
- Arnell NW (2011) Uncertainty in the relationship between climate forcing and hydrological response in UK catchments. *Hydrology and Earth System Sciences* 15: 897–912.
- Arnell NW and Reynard NS (1996) The effects of climate change due to global warming on river flows in Great Britain. *Journal of Hydrology* 183: 397–424.
- Arnell NW, Halliday SJ, Battarbee RJ, et al. (2014a) *The consequences of climate change for the water environment in England: An assessment of the current evidence*. Report to Defra, contract WT1540. Research Note 5, Walker Institute for Climate System Research, University of Reading.
- Arnell NW, Charlton MB and Lowe JA (2014b) The effect of climate policy on the impacts of climate change on river flows in the UK. *Journal of Hydrology* 510: 424–435. 10.1016/j.jhydrol.2013.12.046.
- Arvola L, George G, Livingstone DM, et al. (2010) The impact of the changing climate on the thermal characteristics of lakes. In: George G (ed) *Impact of Climate Change on European Lakes*. Dordrecht: Springer, pp. 85–101.
- Astaraie-Imani M, Kapelan Z, Fu G, et al. (2012) Assessing the combined effects of urbanisation and climate change on the river water quality in an integrated urban wastewater system in the UK. *Journal of Environmental Management* 112: 1–9.
- Battarbee RW, Anderson NJ, Bennion H, et al. (2012) Combining limnological and palaeolimnological data to disentangle the effects of nutrient pollution and climate change on lake ecosystems: Problems and potential. *Freshwater Biology* 57: 2091–2106
- Battarbee RW, Shilland EM, Kernan M, et al. (2014) Recovery of acidified surface waters from acidification in the United Kingdom after twenty years of chemical and biological monitoring (1988–2008). *Ecological Indicators* 37, Part B: 267–273.
- Bell VA, Kay AL, Cole SJ, et al. (2012) How might climate change affect river flows across the Thames Basin? An area-wide analysis using the UKCP09 Regional Climate Model ensemble. *Journal of Hydrology* 442: 89–104.
- Bennion H, Carvalho L, Sayer CD, et al. (2012) Identifying from recent sediment records the effects of nutrients and climate on diatom dynamics in Loch Leven. *Freshwater Biology* 57: 2015–2029.
- Blenckner T, Elliott A, Markensten H, et al. (2010) Modeling the effects of climate change on the seasonal dynamics of phytoplankton. In: George G (ed) *Impact of Climate Change on European Lakes*. Dordrecht: Springer, pp.275–292.
- Bloomfield JP, Gaus I and Wade SD (2003) A method for investigating the potential impacts of climate-change scenarios on annual minimum groundwater levels. *Journal of the Chartered Institution of Water and Environmental Management* 17: 86–91.
- Bloomfield JP, Williams RJ, Goody DC, et al. (2006) Impacts of climate change on the fate and behaviour of pesticides in surface and groundwater: A UK perspective. *Science of the Total Environment* 369: 163–177.
- Boorman DB and Sefton CEM (1997) Recognising the uncertainty in the quantification of the effects of climate change on hydrological response. *Climatic Change* 35: 415–434.
- Bouraoui F, Galbiati L and Bidoglio G (2002) Climate change impacts on nutrient loads in the Yorkshire Ouse catchment (UK). *Hydrology and Earth System Sciences* 6: 197–209.
- Brown I, Ridder B, Alumbaugh P, et al. (2012) *CCRA risk assessment for the biodiversity and ecosystem services sector*. UK 2012 Climate Change Risk Assessment, Defra.
- Caissie D, Satish MG and El-Jabi N (2007) Predicting water temperatures using a deterministic model: Application on Miramichi River catchments (New Brunswick, Canada). *Journal of Hydrology* 336: 303–315.
- Calder IR, Nisbet T and Harrison JA (2009) An evaluation of the impacts of energy tree plantations on water resources in the United Kingdom under present and future UKCIP02 climate scenarios. *Water Resources Research* 45. DOI: 10.1029/2007wr006657.

- Callaway R, Shinn AP, Grenfell SE, et al. (2012) Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems* 22: 389–421.
- Carvalho L and Kirika A (2003) Changes in shallow lake functioning: response to climate change and nutrient reduction. *Hydrobiology* 506/509: 789–796.
- Carvalho L, Miller C, Spears BM, et al. (2012) Water quality of Loch Leven: Responses to enrichment, restoration and climate change. *Hydrobiologia* 681: 35–47.
- CEFAS (2004) *Salmonid migration and climate change*. Defra Final Report Project SF0230. Defra.
- CEFAS (2012) *What are the impacts of non-native fish on freshwater ecosystems?* Defra Project SD0248. Defra.
- Cheung WWL, Pinnegar J, Merino G, et al. (2012) Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems* 22: 368–388.
- Charlton MB and Arnell NW (2014) Assessing the impacts of climate change on river flows in England using the UKCP09 climate change projections. *Journal of Hydrology* 519: 1723–1738.
- Christierson BV, Vidal JP and Wade SD (2012) Using UKCP09 probabilistic climate information for UK water resource planning. *Journal of Hydrology* 424: 48–67.
- Chun KP, Wheeler HS and Onof CJ (2009) Streamflow estimation for six UK catchments under future climate scenarios. *Hydrology Research* 40: 96–112.
- Cloke HL, Jeffers C, Wetterhall F, et al. (2010) Climate impacts on river flow: Projections for the Medway catchment, UK, with UKCP09 and CATCHMOD. *Hydrological Processes* 24: 3476–3489.
- Cooper DM, Wilkinson WB and Arnell NW (1995) The effect of climate change on aquifer storage and river baseflow. *Hydrological Sciences Journal* 40: 615–631.
- Coulthard TJ, Ramirez J, Fowler HJ, et al. (2012) Using the UKCP09 probabilistic scenarios to model the amplified impact of climate change on drainage basin sediment yield. *Hydrology and Earth System Sciences* 16: 4401–4416.
- Cox BA and Whitehead PG (2009) Impacts of climate change scenarios on dissolved oxygen in the River Thames, UK. *Hydrology Research* 40: 138–152.
- Crossman J, Whitehead PG, Futter MN, et al. (2013) The interactive responses of water quality and hydrology to changes in multiple stressors, and implications for the long-term effective management of phosphorus. *Science of the Total Environment* 454–455: 230–244.
- Curtis CJ, Battarbee RW, Monteith DT, et al. (2014) The future of upland water ecosystems of the UK in the 21st century: A synthesis. *Ecological Indicators* 37, Part B: 412–430.
- Defra (2014) The British survey of fertiliser practice: Dataset. Available at: [www.gov.uk/government/statistical-data-sets/british-survey-of-fertiliser-practice-data-set](http://www.gov.uk/government/statistical-data-sets/british-survey-of-fertiliser-practice-data-set) (accessed 29 May 2014).
- Diaz-Nieto J and Wilby RL (2005) A comparison of statistical downscaling and climate change factor methods: Impacts on low flows in the River Thames, United Kingdom. *Climatic Change* 69: 245–268.
- Dunn SM, Brown I, Sample J, et al. (2012) Relationships between climate, water resources, land use and diffuse pollution and the significance of uncertainty in climate change. *Journal of Hydrology* 434–435: 19–35.
- Durance I and Ormerod SJ (2007) Climate change effects on upland stream macroinvertebrates over a 25-year period. *Global Change Biology* 13: 942–957.
- Durance I and Ormerod SJ (2009) Trends in water quality and discharge confound long-term warming effects on river macroinvertebrates. *Freshwater Biology* 54: 388–405.
- Edwards M, Johns D, Leterme S, et al. (2006) Regional climate change and harmful algal blooms in the northeast Atlantic. *Limnology and Oceanography* 51: 820–829.
- Elliot JA (2012) Is the future blue-green? A review of the current model predictions of how climate change could affect pelagic freshwater cyanobacteria. *Water Research* 46: 1364–1371.
- Elliott JA and May L (2008) The sensitivity of phytoplankton in Loch Leven (UK) to changes in nutrient load and water temperature. *Freshwater Biology* 53: 32–41.
- Elliott JA, Thackeray SJ, Huntingford C, et al. (2005) Combining a regional climate model with a phytoplankton community model to predict future changes in phytoplankton in lakes. *Freshwater Biology* 50: 1404–1411.
- Elliott JA, Jones ID and Thackeray SJ (2006) Testing the sensitivity of phytoplankton communities to



- changes in water temperature and nutrient load, in a temperate lake. *Hydrobiologia* 559: 401–411.
- Elliott JM and Elliott JA (2010) Temperature requirements of Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*) and Arctic charr (*Salvelinus alpinus*): Predicting the effects of climate change. *Journal of Fish Biology* 77: 1793–1817.
- Environment Agency (2005a) *Effect of climate change on salmon fisheries*. Science Report W2-047/SR.
- Environment Agency (2005b) *Preparing for climate change impacts on freshwater ecosystems (PRINCE): Literature review and proposal methodology*. Science Report SC030300/PR.
- Environment Agency (2006a) *The impacts of climate change on severe droughts*. Science Report SC040068/SR3.
- Environment Agency (2006b) *Incorporating climate change in river typologies for the Water Framework Directive*. Science Project Record SC030301.
- Environment Agency (2007a) *Climate change impacts and water temperature*. Science Report SC060017/SR.
- Environment Agency (2007b) *Preparing for climate change impacts on freshwater ecosystems (PRINCE)*. Science Report SC030300/SR.
- Environment Agency (2007c) *Incorporating climate change in typologies: Results*. Science Project Record SC030301.
- Environment Agency (2008a) *Potential impacts of climate change on river water quality*. Science Report SC070043/SR1.
- Environment Agency (2008b) *Evaluating climatic effects on aquatic invertebrate in southern English rivers*. Science Report SC070046.
- Environment Agency (2009) *Applying probabilistic climate change information to strategic resource assessment*. Science Report SC050045.
- Environment Agency (2010) *Vulnerability of estuaries to sea level rise – stage I: A review*. Report SC080016/R1.
- Environment Agency (2013a) *Drinking water protected areas. Challenges and choices*. Summary Factsheet.
- Environment Agency (2013b) *Current and future water availability: addendum. A refresh of the case for change analysis*. Environment Agency, December.
- European Commission (2012) *Report from the Commission to the European Parliament and the Council on the Implementation of the Water Framework Directive (2000/60/EC)*. River Basin Management Plans, November.
- Evans CD, Reynolds B, Hinton C, et al. (2008) Effects of decreasing acid deposition and climate change on acid extremes in an upland stream. *Hydrology and Earth System Sciences* 12: 337–351.
- The Food and Environment Research Agency (2013) UK pesticide usage surveys. Available at: [www.fera.defra.gov.uk/landUseSustainability/surveys/index.cfm](http://www.fera.defra.gov.uk/landUseSustainability/surveys/index.cfm) (accessed 2 September 2014).
- Ferguson G and Gleeson T (2012) Vulnerability of coastal aquifers to groundwater use and climate change. *Nature Climate Change* 2: 342–345.
- Ferrier RC, Whitehead PG, Sefton C, et al. (1995) Modelling impacts of land use change and climate change on nitrate-nitrogen in the River Don, North East Scotland. *Water Research* 29: 1950–1956.
- Foley B, Jones ID, Maberly SC, et al. (2012) Long-term changes in oxygen depletion in a small temperate lake: Effects of climate change and eutrophication. *Freshwater Biology* 57: 278–289.
- Foulds SA, Brewer PA, Macklin MG, et al. (2014) Flood-related contamination in catchments affected by historical metal mining: An unexpected and emerging hazard of climate change. *Science of the Total Environment* 476: 165–180.
- Fowler HJ and Kilsby CG (2007) Using regional climate model data to simulate historical and future river flows in northwest England. *Climatic Change* 80: 337–367.
- Friocourt YF, Skogen M, Stolte W, et al. (2012) Marine downscaling of a future climate scenario in the North Sea and possible effects on dinoflagellate harmful algal blooms. *Food Additives and Contaminants Part A: Chemistry Analysis Control Exposure & Risk Assessment* 29: 1630–1646.
- Fuji T and Raffaelli D (2008) Sea-level rise, expected environmental changes and responses of intertidal benthic macrofauna in the Humber estuary, UK. *Marine Ecology Progress Series* 371: 23–35.
- Fung F, Watts G, Lopez A, et al. (2013) Using large climate ensembles to plan for the hydrological impact of climate change in the freshwater environment. *Water Resources Management* 27: 1063–1084.
- Gauld NR, Campbell RNB and Lucas MC (2013) Reduced flow impacts salmonid smolt emigration in a river with low-head weirs. *Science of The Total Environment* 458–460: 435–443.
- George DG (2007) The impact of the North Atlantic oscillation on the development of ice on Lake Windermere. *Climatic Change* 81: 455–468.

- George DG (ed) (2010) *The Impact of Climate Change on European Lakes*. Dordrecht: Springer.
- George DG, Maberly SC and Hewitt DP (2004) The influence of the North Atlantic oscillation on the physical, chemical and biological characteristics of four lakes in the English Lake District. *Freshwater Biology* 49: 760–774.
- George DG, Hurley M and Hewitt D (2007) The impact of climate change on the physical characteristics of the larger lakes in the English Lake District. *Freshwater Biology* 52: 1647–1666.
- George DG, Jarvinen M, Noges T, et al. (2010) The impact of the changing climate on the supply and recycling of nitrate. In: George G (ed) *Impact of Climate Change on European Lakes*. Dordrecht: Springer, pp.161–178.
- Goodwin CE, Strain EMA, Edwards H, et al. (2013) Effects of two decades of rising sea surface temperatures on sublittoral macrobenthos communities in Northern Ireland, UK. *Marine Environmental Research* 85: 34–44.
- Graham CT and Harrod C (2009) Implications of climate change for the fishes of the British Isles. *Journal of Fish Biology* 74: 1143–1205.
- Griffiths D (2007) Effects of climatic change and eutrophication on the glacial relict, *Mysis relicta*, in Lough Neagh. *Freshwater Biology* 52: 1957–1967.
- Hawkins SJ, Sugden HE, Mieszowska N, et al. (2009) Consequences of climate-driven biodiversity changes for ecosystem functioning of North European rocky shores. *Marine Ecology Progress Series* 396: 245–259.
- Heath MR, Neat FC, Pinnegar JK, et al. (2012) Review of climate change impacts on marine fish and shellfish around the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems* 22: 337–367.
- Helliwell RC and Simpson GL (2010) The present is the key to the past, but what does the future hold for the recovery of surface waters from acidification?. *Water Research* 44: 3166–3180.
- Herrera-Pantoja M and Hiscock KM (2008) The effects of climate change on potential groundwater recharge in Great Britain. *Hydrological Processes* 22: 73–86.
- Hill M, Baker R, Broad G, et al. (2005) *Audit of non-native species in England*. English Nature Report 662. English Nature.
- Hiscock K, Southward A, Tittley I, et al. (2004) Effects of changing temperature on benthic marine life in Britain and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems* 14: 333–362.
- Holman IP (2006) Climate change impacts on groundwater recharge-uncertainty, shortcomings and the way forward? *Hydrogeology Journal* 14: 637–647.
- Holman IP, Tascone D and Hess TM (2009) A comparison of stochastic and deterministic downscaling methods for modelling potential groundwater recharge under climate change in East Anglia, UK: Implications for groundwater resources management. *Hydrogeology Journal* 17: 1629–1641.
- Hopkins K, Moss BR and Gill AB (2011) Increased ambient temperature alters the parental care behaviour and reproductive success of the three-spined stickleback (*Gasterosteus aculeatus*). *Environmental Biology of Fishes* 90: 121–129.
- Howard A and Easthope MP (2002) Application of a model to predict cyanobacterial growth patterns in response to climatic change at Farmoor Reservoir, Oxfordshire, UK. *Science of the Total Environment* 282: 459–469.
- Hutchins M, Elliot A, Caillouet L, et al. (2013) *Understanding the effects of climate change on water quality: A case-study assessment on rivers and lakes in England*. Defra Final Report Project WT0972.
- Jackson AC and McIlvenny J (2011) Coastal squeeze on rocky shores in northern Scotland and some possible ecological impacts. *Journal of Experimental Marine Biology and Ecology* 400: 314–321.
- Jackson CR, Meister R and Prudhomme C (2011) Modelling the effects of climate change and its uncertainty on UK chalk groundwater resources from an ensemble of global climate model projections. *Journal of Hydrology* 399: 12–28.
- Jeppesen E, Mehner T, Winfield IJ, et al. (2012) Impacts of climate warming on the long-term dynamics of key fish species in 24 European lakes. *Hydrobiologia* 694: 1–39.
- Jickells T (2005) External inputs as a contributor to eutrophication problems. *Journal of Sea Research* 54: 58–69.
- Jin L, Whitehead PG, Futter MN, et al. (2012) Modelling the impacts of climate change on flow and nitrate in the River Thames: Assessing potential adaptation strategies. *Hydrology Research* 43: 902–916.
- Johnson AC, Acreman MC, Dunbar MJ, et al. (2009) The British river of the future: How climate change and human activity might affect two contrasting river ecosystems in England. *Science of the Total Environment* 407: 4787–4798.
- Jones I, Sahlberg J and Persson I (2010) Modelling the impact of climate change on the thermal

- characteristics of lakes. In: George G (ed) *Impact of Climate Change on European Lakes*, Dordrecht: Springer, pp.103–120.
- Jones ID, Page T, Elliott JA, et al. (2011) Increases in lake phytoplankton biomass caused by future climate-driven changes to seasonal river flow. *Global Change Biology* 17: 1809–1820.
- Jones MC, Dye SR, Fernandes JA, et al. (2013) Predicting the impact of climate change on threatened species in UK waters. *Plos One* 8. DOI: 10.1371/journal.pone.0054216.
- Karunaratna H. (2011) Modelling the long-term morphological evolution of the Clyde Estuary, Scotland, UK. *Journal of Coastal Conservation* 15: 499–507.
- Kay AL and Jones RG (2012) Comparison of the use of alternative UKCP09 products for modelling the impacts of climate change on flood frequency. *Climatic Change* 114: 211–230.
- Kernan M, Moss B and Battarbee RW (eds) (2010) *Climate Change Impacts on Freshwater*. Oxford: Wiley Blackwell.
- Lane SN, Tayefi V, Reid S, et al. (2007) Interactions between sediment delivery, channel change, climate change and flood risk in a temperate upland environment. *Earth Surface Processes and Landforms* 32: 429–446.
- Ledbetter R, Prudhomme C and Arnell NW (2012) A method for incorporating climate variability in climate change impact assessments: Sensitivity of river flows in the Eden catchment to precipitation scenarios. *Climatic Change* 113: 803–823.
- Lee M (2001) Coastal defence and the habitats directive: Predictions of habitat change in England and Wales. *Geographical Journal* 167: 139–156.
- Lewin J and Macklin MG (2010) Floodplain catastrophes in the UK Holocene: messages for managing climate change. *Hydrological Processes* 24: 2900–2911.
- Limbrick KJ, Whitehead PG, Butterfield D, et al. (2000) Assessing the potential impacts of various climate change scenarios on the hydrological regime of the River Kennet at Theale, Berkshire, south-central England, UK: An application and evaluation of the new semi-distributed model, INCA. *Science of the Total Environment* 251: 539–555.
- Lopez A, Fung F, New M, et al. (2009) From climate model ensembles to climate change impacts and adaptation: A case study of water resource management in the southwest of England. *Water Resources Research* 45. DOI: 10.1029/2008wr007499.
- Lowe JA, Howard TP, Pardaens A, et al. (2009) *UK Climate Projections Science Report: Marine and Coastal Projections*. Exeter: Met Office Hadley Centre.
- Macklin MG and Lewin J (2003) River sediments, great floods and centennial-scale Holocene climate change. *Journal of Quaternary Science* 18: 101–105.
- Macklin MG and Rumsby BT (2007) Changing climate and extreme floods in the British uplands. *Transactions of the Institute of British Geographers* 32: 168–186.
- Macleod CJA, Falloon PD, Evans R, et al. (2012) Chapter two: The effects of climate change on the mobilization of diffuse substances from agricultural systems. *Advances in Agronomy* 115: 41–77.
- McKee D, Hatton K, Eaton JW, et al. (2002) Effects of simulated climate warming on macrophytes in freshwater microcosm communities. *Aquatic Botany* 74: 71–83.
- Monteith DT, Stoddard JL, Evans CD, et al. (2007) Dissolved organic carbon trends resulting from changes in atmospheric deposition chemistry. *Nature* 450: 537–540.
- Monteith DT, Evans CD, Henrys PA, et al. (2014) Trends in the hydrochemistry of acid-sensitive surface waters in the UK 1988–2008. *Ecological Indicators* 37: 287–303.
- Moore K, Jennings E, Allott N, et al. (2010) Modelling the effects of climate change on the supply of inorganic nitrogen. In: George G (ed.) *Impact of Climate Change on European Lakes*. Dordrecht: Springer, pp.179–197.
- Moss B, Kosten S, Meerhoff M, et al. (2011) Allied attack: Climate change and eutrophication. *Inland Waters* 1: 101–105.
- Mullan D (2013) Soil erosion under the impacts of future climate change: Assessing the statistical significance of future changes and the potential on-site and off-site problems. *Catena* 109: 234–246.
- Mullan D, Favis-Mortlock D and Fealy R (2012) Addressing key limitations associated with modelling soil erosion under the impacts of future climate change. *Agricultural and Forest Meteorology* 156: 18–30.
- Murphy JM, Sexton DMH, Jenkins GJ, et al. (2009) *UK Climate Projections Science Report: Climate Change Projections*. Exeter: Met Office Hadley Centre.
- Natural England and RSPB (2014) *Climate Change Adaptation Manual*. Peterborough: Natural England and RSPB.

- New M, Lopez A, Dessai S, et al. (2007) Challenges in using probabilistic climate change information for impact assessments: An example from the water sector. *Philosophical Transactions of the Royal Society A: Mathematical Physical and Engineering Sciences* 365: 2117–2131.
- Nicolas D, Chaalali A, Drouineau H, et al. (2011) Impact of global warming on European tidal estuaries: Some evidence of northward migration of estuarine fish species. *Regional Environmental Change* 11: 639–649.
- Office of National Statistics (2013) National population projections, 2012-based Statistical Bulletin. Available at: [www.ons.gov.uk](http://www.ons.gov.uk) (accessed 22 September 2014).
- Orr HG, Simpson GL, des Clers S, et al. (2014) Detecting changing river temperatures in England and Wales. *Hydrological Processes*. DOI: 10.1002/hyp.10181.
- Peperzak L (2005) Future increase in harmful algal blooms in the North Sea due to climate change. *Water Science and Technology* 51: 31–36.
- Pilling C and Jones JAA (1999) High resolution climate change scenarios: Implications for British runoff. *Hydrological Processes* 13: 2877–2895.
- Pilling CG and Jones JAA (2002) The impact of future climate change on seasonal discharge, hydrological processes and extreme flows in the Upper Wye experimental catchment, mid-Wales. *Hydrological Processes* 16: 1201–1213.
- Pinnegar J, Watt T and Kennedy K (2012) *CCRA risk assessment for the marine and fisheries sector*. UK 2012 Climate Change Risk Assessment. Defra.
- Prudhomme C and Davies H (2009a) Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK. Part 1: baseline climate. *Climatic Change* 93: 177–195.
- Prudhomme C and Davies H (2009b) Assessing uncertainties in climate change impact analyses on the river flow regimes in the UK. Part 2: future climate. *Climatic Change* 93: 197–222.
- Prudhomme C, Jakob D and Svensson C (2003) Uncertainty and climate change impact on the flood regime of small UK catchments. *Journal of Hydrology* 277: 1–23.
- Prudhomme C, Wilby RL, Crooks S, et al. (2010) Scenario-neutral approach to climate change impact studies: Application to flood risk. *Journal of Hydrology* 390: 198–209.
- Prudhomme C, Young A, Watts G, et al. (2012) The drying up of Britain? A national estimate of changes in seasonal river flows from 11 Regional Climate Model simulations. *Hydrological Processes* 26: 1115–1118.
- Prudhomme C, Crooks S, Kay AL, et al. (2013a) Climate change and river flooding: Part 1 classifying the sensitivity of British catchments. *Climatic Change* 119: 933–948.
- Prudhomme C, Kay AL, Crooks S, et al. (2013b) Climate change and river flooding: Part 2 sensitivity characterisation for British catchments and example vulnerability assessments. *Climatic Change* 119: 949–964.
- Rabalais NN, Turner RE, Díaz RJ and Justic RJ. (2009) Global change and eutrophication of coastal waters, *ICES Journal of Marine Science: Journal du Conseil* 66: 1528–1537.
- Rance J, Wade SD, Hurford AP, et al. (2012) *Climate change risk assessment for the water sector*. Evidence Report. Defra Project GA0204. HR Wallingford and CEH.
- Remesan R, Bellerby T and Frostick L (2014) Hydrological modelling using data from monthly GCMs in a regional catchment. *Hydrological Processes* 28: 3241–3263.
- Reynard NS, Prudhomme C and Crooks SM (2001) The flood characteristics of large UK rivers: Potential effects of changing climate and land use. *Climatic Change* 48: 343–349.
- Reynard NS, Crooks SM and Kay AL (2005) *Impact of climate change on flood flows in river catchments: final report*. R&D Technical Report W5-032/TR Defra/EA Flood and Coastal Erosion Risk Management R&D Programme. Defra.
- Reynard NS, Crooks S, Kay AL, et al. (2009) *Regionalised impacts of climate change on flood flows*. R&D Technical Report FD2020/TR Defra/EA Flood and Coastal Erosion Risk Management R&D Programme. Defra.
- Rombouts I, Beaugrand G and Dauvin JC (2012) Potential changes in benthic macrofaunal distributions from the English Channel simulated under climate change scenarios. *Estuarine Coastal and Shelf Science* 99: 153–161.
- Rügner H, Schwientek M, Egner M, et al. (2014) Monitoring of event-based mobilization of hydrophobic pollutants in rivers: Calibration of turbidity as a proxy for particle facilitated transport in field and laboratory. *Science of the Total Environment* 490: 191–198.
- Sanderson MG, Wiltshire AJ and Betts RA (2012) Projected changes in water availability in the United Kingdom. *Water Resources Research* 48. 10.1029/2012wr011881.

- Sefton CEM and Boorman DB (1997) A regional investigation into climate change impacts on UK streamflows. *Journal of Hydrology* 195: 26–44.
- Spanhoff B, Dimmer R, Friese H, et al. (2012) Ecological status of rivers and streams in Saxony (Germany) according to the Water Framework Directive and prospects for improvement. *Water* 4: 887–904.
- Statham PJ (2012) Nutrients in estuaries: An overview and the potential impacts of climate change. *Science of the Total Environment* 434: 213–227.
- Stuart ME, Goody DC, Bloomfield JP, et al. (2011) A review of the impact of climate change on future nitrate concentrations in groundwater of the UK. *Science of the Total Environment* 409: 2859–2873.
- Tang R, Clark JM, Bond T, et al. (2013) Assessment of potential climate change impacts on peatland dissolved organic carbon release and drinking water treatment from laboratory experiments. *Environmental Pollution* 173: 270–277.
- Thackeray SJ, Jones ID and Maberly SC (2008) Long-term change in the phenology of spring phytoplankton: Species-specific responses to nutrient enrichment and climatic change. *Journal of Ecology* 96: 523–535.
- Thompson JR (2012) Modelling the impacts of climate change on upland catchments in southwest Scotland using MIKE SHE and the UKCP09 probabilistic projections. *Hydrology Research* 43: 507–530.
- Thorne O and Fenner RA (2011) The impact of climate change on reservoir water quality and water treatment plant operations: A UK case study. *Water and Environment Journal* 25: 74–87.
- UKWIR (1997) Effects of climate change on river flows and groundwater recharge: guidelines for resource assessment. Report 97/CL/04/1.
- UKWIR (2000) Review of river and reservoir water quality models for predicting effects of climate change. Report 00/CL/06/1.
- UKWIR (2001) Modelling the effects of climate change on water quality in rivers and reservoirs. Report 01/CL/06/2.
- UKWIR (2002) Effect of climate change on river flows and groundwater recharge: UKCIP02 scenarios, Report 03/CL/04/2.
- UKWIR (2004) Review of the microbial implications of climate change for the water industry. Report 04/DW/02/32.
- UKWIR (2006) Effects of climate change on river water quality. Report 05/CL/06/4.
- UKWIR (2007) Effect of Climate Change on River Flows and Groundwater Recharge, A Practical Methodology. Synthesis Report 07/CL/04/10.
- Uncles RJ, Stephens JA and Harris C (2013) Towards predicting the influence of freshwater abstractions on the hydrodynamics and sediment transport of a small, strongly tidal estuary: The Devonshire Avon. *Ocean & Coastal Management* 79: 83–96.
- Wade AJ, Palmer-Felgate EJ, Halliday SJ, et al. (2012) Hydrochemical processes in lowland rivers: Insights from in situ high-resolution monitoring. *Hydrological and Earth System Sciences* 16: 4325–4342.
- Walsh CL and Kilsby CG (2007) Implications of climate change on flow regime affecting Atlantic salmon. *Hydrology and Earth System Sciences* 11: 1127–1143.
- Webb BW, Hannah DM, Moore RD, et al. (2008) Recent advances in stream and river temperature research. *Hydrological Processes* 22: 902–918.
- Werritty A (2002) Living with uncertainty: Climate change, river flows and water resource management in Scotland. *Science of the Total Environment* 294: 29–40.
- Whitehead PG, Wilby RL, Butterfield D, et al. (2006) Impacts of climate change on in-stream nitrogen in a lowland chalk stream: An appraisal of adaptation strategies. *Science of the Total Environment* 365: 260–273.
- Whitehead PG, Wilby RL, Battarbee RW, et al. (2009a) A review of the potential impacts of climate change on surface water quality. *Hydrological Sciences Journal* 54: 101–123.
- Whitehead PG, Wade AJ and Butterfield D (2009b) Potential impacts of climate change on water quality and ecology in six UK rivers. *Hydrology Research* 40: 113–122.
- Whitehead PG, Crossman J, Balana BB, et al. (2013) A cost-effectiveness analysis of water security and water quality: Impacts of climate and land-use change on the River Thames system. *Philosophical Transactions of the Royal Society Series A: Mathematical, physical and engineering sciences* 371: 20120413–20120413.
- Wilby RL (2005) Uncertainty in water resource model parameters used for climate change impact assessment. *Hydrological Processes* 19: 3201–3219.
- Wilby RL (2006) When and where might climate change be detectable in UK rivers? *Geophysical Research Letters* 33: L19407.



- Wilby RL and Harris I (2006) A framework for assessing uncertainties in climate change impacts: Low-flow scenarios for the River Thames, UK. *Water Resources Research* 42: W02419.
- Wilby RL, Whitehead PG, Wade AJ, et al. (2006a) Integrated modelling of climate change impacts on water resources and quality in a lowland catchment: River Kennet, UK. *Journal of Hydrology* 330: 204–220.
- Wilby RL, Orr HG, Hedger M, et al. (2006b) Risks posed by climate change to the delivery of the Water Framework Directive objectives in the UK. *Environment International* 32: 1043–1055.
- Williams RJ and Boorman DB (2012) Modelling in-stream temperature and dissolved oxygen at sub-daily time steps: An application to the River Kennet, UK. *Science of The Total Environment* 423: 104–110.
- Winfield IJ, Fletcher JM and James JB (2008a) The Arctic charr (*Salvelinus alpinus*) populations of Windermere, UK: Population trends associated with eutrophication, climate change and increased abundance of roach (*Rutilus rutilus*). *Environmental Biology of Fishes* 83: 25–35.
- Winfield IJ, James JB and Fletcher JM (2008b) Northern pike (*Esox lucius*) in a warming lake: Changes in population size and individual condition in relation to prey abundance. *Hydrobiologia* 601: 29–40.
- Winfield IJ, Hateley J, Fletcher JM, et al. (2010) Population trends of Arctic charr (*Salvelinus alpinus*) in the UK: Assessing the evidence for a widespread decline in response to climate change. *Hydrobiologia* 650: 55–65.
- Winfield IJ, Fletcher JM and James JB (2012) Long-term changes in the diet of pike (*Esox lucius*), the top aquatic predator in a changing Windermere. *Freshwater Biology* 57: 373–383.
- Worrall F, Harriman R, Evans CD, et al. (2004) Trends in dissolved organic carbon in UK rivers and lakes. *Biogeochemistry* 70: 369–402.
- Wright RF, Aherne J, Bishop K, et al. (2006) Modelling the effect of climate change on recovery of acidified freshwaters: Relative sensitivity of individual processes in the MAGIC model. *Science of the Total Environment* 365: 154–166.