A climate change report card for water

Working technical paper

Climate change and water in the UK – past changes and future prospects

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Abstract

Climate change is expected to modify rainfall, temperatures and catchment hydrological responses across the world, and adapting to these water-related changes is a pressing challenge. This paper reviews the impact of climate change on water in the UK and looks at projections of future change. The natural variability of the UK climate makes change hard to detect; only historical increases in air temperature can be attributed to climate change, but over the last fifty years more winter rainfall has been falling in intense events. Future changes in rainfall and evapotranspiration could lead to changed flow regimes and impacts on water quality, aquatic ecosystems and the water available for use by people. Summer flows may decrease on average, but floods may become larger and more frequent. Water quality may decline as a result of higher water temperatures, lower river flows and increased algal blooms. Water demand may increase in response to higher summer temperatures, placing additional pressure on water resources. These changes affect many parts of everyday life, emphasising the importance of long-term adaptation that takes these possible changes into account.

Key words

Climate change, climate change impacts, water environment, hydrology, water demand, water use, water quality, adaptation.

1 Introduction

Observed climate change over recent decades has been linked with changes in the global hydrological cycle, including increased atmospheric water content and changing precipitation patterns (Bates et al. 2008, Allan 2011). It has been suggested that many of the most severe global impacts of climate change may be mediated by water (Stern 2006) and that rivers may be among the ecosystems most sensitive to climate change (Millennium Ecosystem Assessment 2005, Ormerod 2009, Kernan et al. 2010). It is also anticipated that further warming will intensify the hydrological cycle, leading globally to more floods and droughts (Bates et al. 2008, Rockström et al. 2009, Giorgi et al. 2011) and increased exposure to water resources stress, even under the most stringent emissions mitigation scenarios (Arnell et al. 2011, 2013).

Regionally, the impact of climate change on the past and future water cycle is less clear. In part this is because historical change in hydroclimatic datasets is hard to distinguish, as hydrological systems exhibit a high noise to signal ratio (Wilby 2006) and trends may be masked by random variation (Kundzewicz and Robson 2004) or natural cycles. Projections of climate change at a regional level show considerable variability, with different climate models or model parameterisations disagreeing even about the sign of change in variables such as precipitation in some regions and seasons (Bates et al. 2008). However, it is at the regional level that most steps towards adaptation will be taken, and these require a good understanding of the scale and scope of possible change and the uncertainties associated with regional projections.

This paper addresses one of the possible barriers to climate change adaptation in the UK: reliable, clear information about the current and possible future impact of climate change on the water cycle. This paper is organised as follows. Section 2 provides a summary of the evidence of changes to the UK water cycle, looking mainly at the last half of the twentieth century and the first decade of the twenty-first century. Section 3 looks at projected changes through the rest of the first half of the twenty-first century. In Section 4 we consider the implications for adaptation, identify research gaps and draw conclusions.

2 Historical changes to the water sector in the UK

Here we review the changes that have already occurred in the UK, concentrating on evidence of links to climate change. This part of the paper starts with rainfall and evapotranspiration. These lead to river flows and groundwater levels, which in turn affect river and groundwater temperature and quality. Aquatic ecosystems respond to river flows, water quality and temperature, as well as light availability and competition between species. Water supply and agricultural demand are included to illustrate the impact of climate change on people and their lives.

In examining the existing impact of climate change the problems of detection and attribution must be addressed. In a guide for the Intergovernmental Panel on

Climate Change (IPCC), Hegerl et al. (2010) define detection as “the process of demonstrating that climate or a system affected by climate has changed in some defined statistical sense” and attribution as “the process of evaluating the relative contributions of multiple causal factors to a change or event with an assignment of statistical confidence.” Attribution methods include *direct attribution* of changes to external forcing and *associative attribution*, where changes in the observed impact are compared with observed changes in climate. In both cases, it is important to consider confounding factors; unless all other possible causes for an observed change can be ruled out, the change should not be attributed to climate change.

Throughout this section we try to be clear about the attribution of observed changes. It should be noted that a lack of attribution to climate change could be for a number of reasons; there may be no link with climate change, there may have been no investigation of the link, or the observed change may actually be associated with climate change but it may not be possible to identify this with any confidence (in other words, a false negative).

2.1 Precipitation and evapotranspiration

Rainfall (or more properly, precipitation) and evapotranspiration together drive the water balance, and quantification of the two forms the basis of modern hydrology (Blackie and Eeles 1985).

The England and Wales Precipitation (EWP) series includes monthly totals from January 1766[1] (Alexander and Jones 2001), and has been shown to be suitable for use in a wide range of studies across the UK (Croxton et al. 2006). Annual average rainfall has not changed significantly through this series, but there is an increasing trend in winter rainfall, although with little change over the last fifty years (Jenkins et al. 2008). It seems that more winter rain is falling in intense events (Osborn and Hulme 2002, Jenkins et al. 2008, Burt and Ferranti 2011, Jones et al. 2012), with the changes being most significant in long-duration events (five to 10 days) (Fowler and Kilsby 2003). Long summer events also show increased rainfall intensity (Jones et al. 2012). There is also some evidence that the within-year clustering of extreme rainfall events has increased in recent years (Jones et al. 2012). There is insufficient evidence to suggest a link between climate change and these changes in precipitation and some authors have suggested that at the UK scale such a link may not be apparent until the 2050s in most regions (Fowler and Wilby 2010).

Evapotranspiration includes both direct evaporation to the atmosphere from soil and water surfaces, and transpiration from trees and other plants. Direct measurement of evapotranspiration is not practical at a catchment scale, but there are several methods for calculating potential evapotranspiration from meteorological variables (Shuttleworth 2007). Potential evapotranspiration (PE) is an estimate of the maximum volume of water that could pass to the atmosphere if there is no limit to supply. Actual evapotranspiration (AE) is constrained by water availability (usually

[1] Available from http://www.metoffice.gov.uk/hadobs/hadukp/

soil moisture), and cannot be greater than PE. Temperature-based methods for estimating PE have a long history, dating back to the 1940s (Penman 1948, Thornthwaite 1948) but evapotranspiration is more properly considered a function of the energy balance, humidity and wind speed (Monteith 1965, Allen et al. 1998).

There are few studies of historical changes in evapotranspiration in the UK, with no large scale studies. Burt and Shahgedanova (1998) calculate evaporation from 1815 to 1996 for a site in Oxford, finding increases in PE but decreases in AE over the period studied. Temperature trends can be used to infer changes in potential evapotranspiration: temperature presents a reasonable, but not perfect, correlation with evapotranspiration (see, for example, Dai (2011) and Sheffield et al. (2012) for a discussion of the impact of different PE formulations on drought indices), though it is not clear that the relationship will remain constant in a changing climate. Karoly and Stott (2006) conclude that it is likely that there has been a human contribution to warming in the Central England Temperature (CET) series[2]. CET has increased by about a degree Celsius since 1980 (Jenkins et al. 2008). On this basis, it might be reasonable to hypothesise that UK PE has also increased over the same period, but there is no formal study to confirm this.

2.2 River flows and groundwater levels

River flows and groundwater levels represent the integrated response of hydrometeorological processes (principally precipitation and evapotranspiration) acting on a catchment. The UK has an exceptionally dense river gauging and groundwater level network[3], essential for the detection of changes and trends (Hannah et al. 2011). However, there are few records from before the 1960s, catchment change and water use affects many of the sites, and poor quality and missing data is a problem for the estimation of low and high extremes of both river flow and groundwater level.

Groundwater levels are highly variable in both space and time, and there have been no large scale studies of historical changes in groundwater levels across the UK. Holman et al. (2011) investigate links between three long English groundwater records and three indices of atmospheric circulation (including the North Atlantic Oscillation, NAO). In some periods there are strong links between groundwater levels and circulation indices, but at other times the links are weak or non-existent, perhaps illustrating the complex and dynamic nature of the relationship between climate and groundwater levels in the UK. No links have been made between UK groundwater levels and climate change.

There are more large scale studies of changes in UK river flow, mainly concentrating on the “benchmark network” of sites where the net impact of human disturbance on flow regimes has been relatively minor (Bradford and Marsh 2003). Hannaford and Buys (2012) find a high degree of spatial variability in seasonal flow trends from 1969

[2] Available from http://www.metoffice.gov.uk/hadobs/hadcet/
[3] Available from the National Water Archive http://www.ceh.ac.uk/data/nwa.htm

to 2008, as well as different trends for high and low flows within and between seasons. In the winter half of the year (September to March) there are increasing high flows across the whole of the UK. In contrast, there is no obvious trend in low flows in winter across the UK, though in the west the increasing high flows are accompanied by a decrease in low flows. There is a weak trend towards decreasing spring flows since 1960, particularly in lowland England, and a mixed picture in summer. The UK trend towards increasing winter flows is confirmed for Scotland from 1970 to 1996 by Werrity (2002). These changes in flow have not been attributed to climate change.

Changes in flood magnitude and frequency are of considerable practical interest, because floods can have a serious impact on people and businesses. Again, most studies concentrate on the period after 1960, because of the increased number of reliable records. Hannaford and Marsh (2008) find increases in high flow magnitude and duration from the 1960s to the 2000s, especially in the uplands of the north and west. In contrast, few trends are apparent in the English lowlands, though Hannaford and Buys (2012) find greater evidence for increasing high flows in some lowland catchments over the same period. Regional studies confirm increasing high flows since about 1960, particularly in upland areas of Scotland (Black 1996, Werrity 2002), Wales and the West Midlands (Dixon et al. 2006, MacDonald et al. 2010, Biggs and Atkinson 2011). Hannaford and Marsh (2008) caution that these recent increases in high flows are not necessarily seen if trends are analysed against longer records, confirmed by Marsh and Hannaford (2008) for the River Avon in the English Midlands, and Marsh and Harvey (2012) for the River Thames in south-east England. Long chronologies of UK floods (MacDonald et al. (2006) for the Tay, Scotland, MacDonald and Black (2010) for the Yorkshire Ouse) show that there were also large floods before the instrumented record. Similarly, based on long reconstructed flood occurrence series extending back to the late 1800s, Wilby and Quinn (2013) find evidence of pronounced interdecadal variability in flooding across the UK. Recent changes in average flood magnitude and frequency have not been attributed to climate change. The only formal attribution work is for the unusual flood event of autumn 2000 (Kay et al. 2011, Pall et al. 2011) which is thought to have been more likely as a result of greenhouse gas forcing, though even here the two different studies offer different interpretations of the increased probability attributed to the forcing.

In contrast to floods, little work has addressed changes in low flow across the UK. Hannaford and Marsh (2006) find little evidence of trends in low flow between 1960 and the early 2000s. In contrast, Stahl et al. (2010) find decreases in low and summer flow in some UK catchments over the 1962 to 2004 period, though it is possible that this result is influenced by the droughts at the end of the sequence in 2003 and 2004. Marsh et al. (2007) demonstrate that some of the droughts of the nineteenth century were longer and more severe than those of the twentieth century, but there is no evidence of trends in drought occurrence or magnitude in the UK.

In summary, there is little evidence of climate change-induced trends in groundwater levels or low flows across the UK. There are signs of increases in high flows and floods since 1960, particularly in the uplands of the north and west, but analysis of longer records suggests that recent flood magnitudes and frequencies are not unusual. Changes in river flows and groundwater levels have not been attributed to climate change.

2.3 River and groundwater temperature, quality and ecosystems

Along with flow, water temperature is one of the most important influences on ecosystem state in rivers and streams (Caissie 2006, Webb et al. 2008), exerting a direct control on parts of the lifecycle of a genus such as trout (*salmo*) (Wherly et al. 2007) and affecting water quality, with most chemical and bacteriological processes operating faster at higher temperatures (Whitehead et al. 2009). River water temperature is controlled by energy and hydrological fluxes at the air-water and water-riverbed interfaces (Hannah et al. 2008). River water temperature varies seasonally and diurnally in response to the dominant solar forcing, with day-to-day thermal variability in response to weather conditions and flow change.

For the UK there are very few studies of long-term changes in river water temperature. Webb and Walling (1992) report rising temperatures in the River Exe, south-west England, from 1977 to 1990. Langan et al. (2001) find no trend in annual water temperatures from 1968 to 1997 in a small catchment in north-east Scotland, but report increases in mean daily maximum temperature in winter and spring, and increased average temperatures in spring. These are tentatively associated with increasing air temperature, possibly linked through a reduction in the amount of snow in the catchment. Durance and Ormerod (2007) suggest that water temperature in upland mid-Wales increased by around 1.5 °C in both forest and moorland streams between 1981 and 2005 when corrected for variation in the North Atlantic Oscillation (NAO). Des Clers et al. (2008) report an average increase in water temperature of around 0.3 °C per decade across England and Wales between 1990 and 2006, based on an assessment of sampled temperature data from around 3000 sites. At some sites, though, water temperature fell over this period.

There is very little information about changes in groundwater temperature in the UK. Stuart et al. (2010) investigate groundwater temperature from the Environment Agency's archive of about 3700 monitoring sites, but conclude that the measurements are probably unreliable, suggesting that sample temperatures had adjusted to ambient air temperature during the measurement process.

River water quality is influenced by water temperature, hydrological regime, nutrient status, point source and diffuse discharges, mobilisation of toxic substances and acidification potential (Whitehead et al. 2009), making the detection and attribution of change difficult. Pollution from point source discharges and toxic substances has decreased in recent years, mainly as a result of tighter regulation and the introduction of tertiary treatment at sewage treatment works (Jarvie et al. 2006, Neal et al. 2010), but there is a long history of increasing nutrient levels in UK catchments (Whitehead et al. 2009), mainly related to changes in land-use and fertiliser application (Whitehead 1990, Bennion et al. 2012). Upland catchments have begun to recover from acidification since the 1980s, as a result of reductions in sulphur emissions (Wright et al. 2005). There is some evidence that climate change may affect lake acidity through spatial and temporal variations in precipitation altering the predominance of flow pathways and of changes in lake water quality by temperature effects on biochemical processes (Koinig et al. 1998, Monteith et al., 2001). Dissolved organic carbon (DOC) concentrations have doubled across the UK since the 1980s (Monteith et al. 2000, Freeman et al. 2001, Evans et al. 2001, 2005, Worrall et al. 2003, 2004), possibly linked to reductions in sulphur deposition or a reduction in soil respiration due to drought (e.g. Watts et al. 2001, Clark et al. 2005, Monteith et al. 2007). Changes in UK river water quality have not been linked to climate change, instead being driven by changes in land-use and point sources (Howden et al. 2010).

The most significant impact on UK groundwater quality in the last half of the twentieth century was the intensification of agriculture and the consequent impact on groundwater quality from diffuse pollution, in particular from nitrate (Shand et al. 2007). Such changes are thought to be greater than any direct effects from climate change (Stuart et al. 2011) and there have been no studies linking historic groundwater quality changes to climate change.

Fresh waters are considered to be among the most sensitive of all ecosystems to the effects of climate change (Durance and Ormerod 2007, 2009), partly because of changes in water temperature and flow, but also because most river organisms are ectotherms (their body temperatures are controlled by their surroundings). However, establishing long-term climate effects on freshwater organisms and ecological processes is difficult. It requires long, systematic records to detect change and there are also many confounding factors that affect biodiversity and ecosystem form and function; these include flow variation, improving or declining water quality, habitat degradation and invasive species. Even where climate change is the underlying cause of local extinction, this may not occur as a direct response to climate but to other related factors, such as loss of host or pollinator species or changes in pathogens or competitors (Cahill et al. 2013). More than 30 years of data collection at the Llyn Brianne Stream Observatory in mid-Wales has shown a decrease in invertebrate abundance in spring of around 20% for every 1 °C temperature rise (Durance and Ormerod 2007). Durance and Ormerod (2010) suggest that the loss of *Crenobia alpina* (a planarian or flatworm) in the Llyn Brianne catchment was a response to a prolonged positive North Atlantic Oscillation (NAO) between 1989 and 1994, though they caution that it is difficult to identify the exact climatic causes leading to such local extinctions. Clews et al. (2010) suggest that warmer, drier summers may explain reductions in salmon and brown trout populations in the Welsh Wye catchment between 1985 and 2004. Increased spates may destroy habitats and extended low flow conditions can cause both scouring and siltation (Meyer et al., 1999, Wright et al., 2004). Altered environmental conditions may result in the loss of taxa thereby allowing non-native species to enter river-systems (Verdonschot et al., 2010).

In summary, there is some evidence that UK river water temperatures may be increasing as a result of climate change, but no research to link other changes in water quality with climate change. There is some evidence that ecosystems are responding to changes in water temperature.

2.4 Water use

In the UK, water is used in households, agriculture, and industry, with power generation and public water supply the two largest water uses. As the climate changes, water use may also change, but the links between water use (sometimes called “demand”) and weather and climate are complex, with social and economic changes also driving changes in water use (Watts 2010, Wade et al. 2013). This section concentrates on public water supply and agriculture as the links to climate are clearest and most research has concentrated on these areas.

Water supply planning considers the risk of supply failure that results from reduced availability and increased demand for water during droughts (e.g. Hall et al. 2012, Watts et al. 2012). There is no evidence for a change in the magnitude or frequency of droughts in the UK over the twentieth century, though some nineteenth century droughts were longer and more severe than those of the twentieth century (Marsh et al. 2007). Water demand is partly linked to temperature, with greater water demand on hot days (Herrington 1996, Downing et al. 2003, Parker and Wilby 2013) so demand might be expected to have already increased with increasing average temperature. However, there is no research to confirm this, which may be because the signal is too small to distinguish compared to the many other factors that influence demand.

Irrigated crops cover only a small area of the UK (150,000 hectares even in a dry year (Knox et al. 2009)) and irrigation uses less than 2% of water abstracted in England and Wales (Weatherhead and Howden 2009). However, irrigation is needed mainly in the summer and in the driest parts of the UK, which means that locally it can exert a significant pressure on the water environment (Hess et al. 2010). Weatherhead and Knox (2008) estimate that demand for irrigation water, corrected for weather variation, grew at an underlying average rate of over 2% per year between 1982 and 2005. Much of this growth appears to be due to increased irrigation on high value crops, partly to assure quality standards, and as the demand is corrected for weather variation, this increase in water use cannot be associated directly with climate change (Weatherhead and Knox 2008). Disentangling the effects of non-climate factors on agricultural water use complicates such analyses (Knox et al. 2010).

2.5 Summary of impacts

This section of the paper illustrates some of the problems in trying to understand the impact of climate change in the UK. Changes in air and river water temperatures and in rainfall patterns have been observed over the last fifty years. Air temperature increases have been attributed formally to climate change, and water temperature changes may be linked to the same processes that have changed air temperature, though water temperature is only partly dependent on air temperature. Changes in rainfall patterns have not been linked to climate change, and the impact of climate change on river flows and groundwater levels has not yet been detected. This suggests that adaptation to climate change will need to start before formal attribution of changes; for example, Fowler and Wilby (2010) estimate that it is at least a decade before climate change induced changes in winter extreme rainfall can be detected in south west England, with later detection for other seasons and regions of the UK. The next section of this paper looks at the possible impact of climate change on water in the UK over the first half of the 21st century.

3 Possible changes to the UK water cycle through the 21st century

The impact of climate change on the water environment of the UK has been the subject of much research, perhaps reflecting both the scale and impact of possible change and the way that water and everyday life are inextricably linked, not only in the UK but in most of the world (e.g. Sofoulis 2005). In evaluating possible changes, it is essential to consider uncertainty in climate projections. Uncertainties in climate prediction come from three main sources: internal variability of the climate system, model uncertainty, and emissions uncertainty (Hawkins and Sutton 2009). For many regions, including western Europe, natural climate variability is the biggest source of uncertainty for up to thirty years ahead, with greater uncertainty in precipitation projections than temperature projections (Hawkins and Sutton 2011). Model uncertainty – the way that different GCMs simulate changes in climate for a given radiative forcing – then becomes the most important source of uncertainty (Hawkins and Sutton 2011). Ignoring the uncertainty in climate projections could lead to inappropriate adaptation measures; for this reason, it is often suggested that the results of a range of climate models are used in any adaptation study (e.g. Hawkins and Sutton 2011). The UK Climate Projections 2009 (UKCP09, Murphy et al. 2009), on which many recent UK climate impact studies are based, address this problem by using a Bayesian statistical framework to generate a probabilistic ensemble of climate projections that combine climate variability and model structural uncertainty for three separate emissions scenarios (Murphy et al. 2008). This allows an explicit understanding of the possible range of climate change, though the range remains constrained by the processes represented in the climate models used in the assessment.

The UK is fortunate in having access to a growing academic literature on climate change impacts, much of which covers some aspect of water or the water environment. Much of the work on possible impacts takes as its basis the UK climate projections, either in the assessment from 2002 (UKCIP02, Jenkins et al. 2002) or from 2009 (UKCP09, Murphy et al. 2009). With few exceptions, impact studies tend to be location specific (e.g. Wilby et al. 2006, Johnson et al. 2009, Cloke et al. 2010) or demonstrations of possible approaches that could be used more widely (e.g. New et al. 2007, Lopez et al. 2009, Fung et al. 2013). UK-scale assessments have been conducted for river flows (Christiersen et al. 2012, Prudhomme et al. 2012), droughts (Blenkinsop and Fowler 2007, Vidal and Wade 2009, Burke et al. 2010, Rahiz and New 2013), extreme rainfall (Fowler et al., 2007, Fowler and Ekström, 2009), and floods (Prudhomme et al. 2013a, 2013b).

This section follows the same structure as section 3 and looks mainly towards the 2050s, with some information about changes over the remainder of the 21st century. The 2050s represent a reasonable planning horizon for many parts of the water environment; for example, it may take 20 years or more to plan, design and build a new reservoir (Wilby and Davies 1997).

3.1 Rainfall and evapotranspiration

The previous generation of UK climate projections, known as UKCIP02 (Jenkins et al. 2002), presented a relatively simple picture of increasingly warmer, wetter winters and hotter, drier summers through the 21st century, suggesting, for example, that by the 2080s virtually every summer may be hotter and drier than 2001. UKCP09 (Murphy et al. 2009) takes a broader view of uncertainty, giving ranges of possible change. This assessment suggests that annual average rainfall may change little by the 2080s, with the 10th to 90th percentile range between a 16% reduction and a 14% increase for the medium emissions scenario. Seasonal precipitation changes may be greater. In winter, UKCP09 projects the biggest increases to be along the west coast, with a median change of +33% (10th to 90th percentile range +9 to +70%). In contrast, small decreases are seen in Scotland in winter (10th to 90th percentile range -11 to +7%). In summer, UKCP09's biggest median change of about -40% is in southern England (10th to 90th percentile range -65 to -6%), with little change in northern Scotland (10th to 90th percentile range -8 to +10%). It will be noted that, by definition, there is a 20% chance of values being outside the ranges quoted. Fowler and Ekström (2009) examine changes in extreme rainfall using a range of Regional Climate Models (RCMs), finding increases in winter, spring and autumn extreme precipitation by the 2080s, with increases ranging from 5 to 30% depending on region and season. Summer changes are less clear, and changes in short-duration (sub-daily) rainfall events remain unclear, as current climate models are unreliable at these scales (Fowler et al. 2007).

UKCP09, in common with most RCMs and GCMs, does not offer direct estimates of future evapotranspiration. It is possible to use output from climate models to calculate PE using one of the many formulae that exist, but this can be problematical. The more physically-based methods are considered most accurate (e.g. Allen et al. 1998) but GCMs do not project all climate parameters with equal reliability, raising the question of whether it is better to use physically-based methods with uncertain data, or empirical methods with more certain data (Kingston et al. 2009). It is clear that different methods lead to different projections of potential evapotranspiration, at scales from local (Kay and Davies 2008) to global (Kingston et al. 2009).

What does this mean for the UK? Estimates of changes in PE vary depending on both GCMs and PE methods. Penman-Monteith estimates generally show increases in PE by the 2050s (Prudhomme et al. 2012) and the 2080s (Kay and Davies 2008). Patterns of increase vary seasonally: Kay and Davies (2008) find that some months can show small decreases in PE using the Penman-Monteith formulation, but annual changes range from +6 to +56%. Temperature-based PE estimates for the UK show a similar range (e.g. Kay and Jones 2012) but tend towards increases throughout the year (e.g. Kay and Davies 2008, Christiersen et al. 2012). All of these studies assume that meteorological variables alone control PE, but vegetation type and growth is also relevant. In an attempt to understand part of the role of vegetation, Bell et al. (2011) allow surface resistance to vary, simulating the closure of plant stomata under higher atmospheric CO_2 concentrations, and find much lower increases in PE; this suggests that there is a need for more work on feedbacks between climate change, land-cover and PE.

3.2 River flows and groundwater levels

Much attention has been paid to possible changes in flow as a result of climate change. Most studies concentrate either on long-term changes in average flow, or on changes in flood flow. Many studies approach this problem by scaling historic rainfall and potential evapotranspiration time series, referred to as a perturbation or delta change approach (Prudhomme et al. 2002, Fowler et al. 2007a). This has the effect of maintaining current sequencing of wet and dry events but changing their magnitude. Identification of the scaling factors for a river catchment or other area of interest requires downscaling from a GCM, for which a variety of different methods exist, often giving different hydrological results (Fowler et al. 2007a). Combined with the uncertainty in hydrological modelling (e.g. New et al. 2007), this means that projections of changes in UK flow cover a wide range, though as the range of uncertainty is poorly sampled this is probably not the full range of possible outcomes (Hall 2008, Arnell et al. 2013).

Site-specific studies often consider a range of different GCMs, emissions scenarios and sometimes hydrological model parameterisations. Wilby et al. (2006) look at a range of GCMs and emissions scenarios for the Kennet, southeast England, with some GCMs giving small reductions in summer flow but others leading to increases; medium and high flows increase in all the GCMs investigated. Johnson et al. (2009) use the UKCIP02 change factors (Jenkins et al. 2002) to examine changes in flow in the Yorkshire Ouse, northeast England, and the Thames, southeast England. They find reductions in low and high flow at both locations, but they note that the climate model used is considered dry. Cloke et al. (2010) look at changes in river flow in the Medway, southeast England, investigating 10 different RCM results and a range of hydrological model parameterisations. They find reductions in flow, especially in summer, where flows are reduced by 50% by the 2060s. Lopez et al. (2009) use a large ensemble of climate projections for the River Exe in southwest England, comparing these to a range of different GCMs. Most models show a reduction in summer flows by the 2030s, with more models projecting increases in winter flows than decreases. Lopez et al. (2009) caution against relying on these results, as the study is aimed at exploring the use of large ensembles rather than estimating changes in flow. Indeed, much catchment-specific work is aimed at exploring new approaches (e.g. Wilby et al. 2011, Fung et al. 2013), and it is hard to generalise from specific studies that use different GCMs and have different objectives.

Two recent studies look at the impact of climate change on monthly and seasonal river flows across the UK. Christiersen et al. (2012) use the UKCP09 climate ensemble to model flows in the 2020s at 70 locations across the UK, choosing sites where the catchment is thought to be broadly undisturbed by artificial influences (Bradford and Marsh 2003). The approach uses a stratified sampling method to reduce the 10,000 member ensemble of change factors from UKCP09 to a more manageable 20 sets of factors intended to represent the distribution of the original ensemble. The ensemble approach allows Christiersen et al. (2012) to draw conclusions about the range of possible changes in flow. The median projection is a reduction in spring (MAM) and summer (JJA) flows, a mixed picture in autumn (SON) and small increases in winter (DJF) flows across the UK. The greatest reductions in flow are in August, with a median projection of up to 30% reduction compared to the 1961-90 baseline. For most seasons the 25th to 75th percentile range spans a range from lower to higher flows; the exception is for the summer where most sites have a reduction in flow even at the 75th percentile. This distribution leads Christiersen et al. (2012) to some confidence in a reduction in summer flows across the UK by the 2020s.

Prudhomme et al. (2012) use a different approach to examining changes in flow across Britain (Northern Ireland is omitted from their study) by the 2050s. Their model is a generalised rainfall-runoff model parameterised on catchment characteristics (Young 2006) which means that it is possible to model natural flows at all the reaches across the country. Such a model needs spatially coherent climate projections; Prudhomme et al. (2012) use the 11 RCMs that form part of the basis of UKCP09 (Cloke et al. (2010) used 10 of these 11 RCMs). These provide scenarios of possible change to which it is not possible to assign probabilities, but which give some sense of spatial variability in change that cannot be gathered from the probabilistic approach of Christiersen et al. (2012). Prudhomme et al. (2012) find a mixed picture of changes in winter flow in England and Wales, with changes of -20 to +40%. In Scotland in winter the changes are smaller, in the range of +/- 20%. In spring (MAM) most of the scenarios have reduced flows across the UK, with reductions of up to 40%, but three of the eleven show increases in flow of up to 60% in central England. In summer, there is a more consistent picture of reduced flows across most of the scenarios with reductions of up to 80% especially in the north and west. However, even in summer a few scenarios have small increases in flow in some areas, most notably northeast Scotland in one scenario, and southeast England in another. Autumn changes, like spring, are mixed, with a range of -80% to +60%, with decreases appearing most frequently in southern England. Annual average flows change little across the century.

It seems that the results of Christiersen et al. (2012) and Prudhomme et al. (2012) are broadly consistent, given the different time horizons, but this is perhaps not surprising as both are derived from the same RCM results. Overall, summer flows seem more likely to reduce through the century across Britain, but Prudhomme et al. (2012) demonstrate that increases remain possible, even if less likely than decreases in flow.

Changes in drought frequency and severity are perhaps the most important question for water supply, but neither Christiersen et al. (2012) nor Prudhomme et al. (2012) are able to consider such changes, both because the change factor approach can only scale historic weather sequences and because GCMs and therefore RCMs are not good at representing the processes that lead to the persistence of extended dry weather across northern Europe (Murphy et al. 2009). Long droughts lasting two years or more are particularly important for water supply in the UK (Marsh et al. 2007, Watts et al. 2012). Blenkinsop and Fowler (2007) consider precipitation-deficit droughts in six different RCMs for the 2080s. Short summer droughts are projected to increase except in Scotland and Northern Ireland, though these results are uncertain. Changes in longer droughts are even more uncertain, but the longest droughts are projected to become shorter and less severe in most of the RCMs. Blenkinsop and Fowler (2007) caution that climate models may not be able to simulate persistent low rainfall events, making it difficult to draw conclusions about long droughts. In an apparently contradictory finding, Vidal and Wade (2009) use a slightly different definition of precipitation deficit drought, and find an increase in long droughts in southeast England by the end of the century. Vidal and Wade (2009) agree with Blenkinsop and Fowler (2007) that uncertainty is great, and that water supply planners need to consider a range of possible future droughts. Burke et al. (2010) look at droughts from 3 to 18 months duration and find an overall increase in droughts of all duration through the 21st century, though with a wide spread that spans decreases as well as increases in drought frequency. As an example, the possible frequency of a drought like 1976 (Doornkamp et al. 1980) by the end of the 21st century could range from the current frequency (perhaps 1 in 100) to 1 in 10 years (Burke et al. 2010). Rahiz and New (2013) consider the spatial coherence of future droughts, suggesting that by the end of the century droughts may be more coherent, with a higher probability of droughts occurring in different areas at the same time.

Changes in flood magnitude and frequency are just as interesting and important as changes in drought occurrence, but they are equally difficult to assess. There are two main approaches (Wilby et al. 2008); inference from projections of extreme precipitation, or downscaling from GCMs followed by hydrological simulation. Fowler et al. (2007b) use a multimodel ensemble to look at changes in extreme rainfall, dividing the UK into nine regions. Median changes indicate an increase of 10 to 20% on 1961-90 extreme rainfall values by 2071, with more confidence about changes in 10 day values than in 1 or 2 day extremes, though Fowler et al. (2007b) report considerable uncertainty in all of these changes. Fowler and Wilby (2010) confirm these projected increases in extreme rainfall across the UK in autumn and winter. Prudhomme et al. (2010) look at changes in 20 year return period floods for the 2080s for two British catchments, using an approach that uses a rainfall-run-off model to examine the sensitivity of catchment floods to changes in rainfall and temperature, and then plots changes from multiple GCMs on this sensitivity surface. While many of the GCMs lead to increases in the magnitude of the 20-year flood, most would be contained within a 20% allowance. However, some GCMs suggest that floods could grow beyond this limit by the 2080s, with greater changes for a catchment in the northwest than the southeast. Prudhomme et al. (2013a, 2013b) extend this study to more catchments across Britain, confirming the importance of catchment climatic and physical characteristics in determining how floods respond to climate change. Bell et al. (2012) use a distributed hydrological model to examine changes in flood in the Thames catchment, southeast England, using the 11-member RCM ensemble also used by Prudhomme et al. (2012). Towards the bottom of the catchment, Bell et al. (2012) report that for the 2080s, the average estimated change in modelled 20-year return period flood peaks is +36% with a range of -11% to +68%.

Changes in rainfall and evapotranspiration will also affect groundwater recharge and groundwater levels, though there have been relatively few studies in the UK and, as yet, no consistent national assessment. Jackson et al. (2011) use 13 different GCMs to investigate changes in recharge in a chalk aquifer in southeast England. The ensemble average suggests a 5% reduction in recharge by the 2080s, with a range extending from a 26% decrease to a 31% increase. There may be more winter recharge but it may take place over a shorter period. Other studies are based on the UKCIP02 climate scenarios (Jenkins et al. 2002). Herrera-Pantoja and Hiscock (2008) suggest that annual recharge could fall by up to 20% by the 2080s in the chalk in East Anglia, and by 7% in the Devonian and Carboniferous Limestone in Scotland. There has been little work on the impact of climate change on groundwater levels, though reductions in recharge would be expected to lead to lower groundwater levels.

3.3 River and groundwater temperature, quality and freshwater ecosystems

River water temperature is expected to change with climate change, but there has been little work to examine this in the UK. Worldwide, most projections are based on statistical relationships between air temperature and water temperature: these relationships are stronger at monthly resolution than daily, and weaker again at the annual resolution because water temperature varies much less than air temperature (Webb et al. 2008). Webb and Walling (1992) look at 36 river sites in the UK, projecting an increase in monthly mean water temperature of +1 to +3.6 °C with an air temperature increase of 2 °C; the response was modified by river basin characteristics, with groundwater and shading from trees controlling response. Van Vliet et al. (2011) demonstrate that, globally, changes in flow can be an important control on changes in water temperature, with reductions in flow leading to greater increases in river temperature; projections of predominantly reduced summer flow (Christiersen et al. 2012, Prudhomme et al. 2012) may imply enhanced increases in summer UK water temperature through the 21st century. Future changes in groundwater temperature remain unclear.

Most chemical reactions and bacteriological processes are faster at higher temperatures, and temperature controls the growth rate of many aquatic plants

(Wade et al. 2002, Whitehead and Hornberger 1984, Whitehead et al. 2009) as well as behaviour of aquatic organisms including fish and insects (Durance and Ormerod 2007). More intense rainfall could result in increased suspended solids (Lane et al. 2007) and increased sediment yields (Wilby et al. 1997). Higher water temperatures may lead to increased growth of algae (Whitehead and Hornberger 1984) and reduced flows may increase the impact of nutrients from agriculture (Whitehead et al. 2006). In the uplands, increased summer drought could enhance the acidification of streams and lakes (Wilby 1994, Whitehead et al. 2009). In urban environments, poorer water quality may be driven by short duration high intensity rainfall events (Whitehead et al. 2009). Groundwater quality will be affected by changes in the rate of recharge, as well as the availability of pollutants and nutrients.

What does this mean for UK freshwater ecosystems? Cold water fish species may be threatened by increases in water temperature, with invasive non-native fish species such as common carp *Cyprinus carpio* and European catfish *Silurus glanis* being more successful (Britton et al. 2010). Similar changes already seem to be apparent in the upper Rhone (Daufresne et al. 2004). Other changes may be complex, and it is important to understand how other factors interact with changes in water temperature before making speculative assessments of possible change (Durance and Ormerod 2009).

Few studies have tried to draw all these possible impacts together to understand their combined effects. Whitehead et al. (2006) use a coupled hydrological and nitrate model to investigate flow, nitrate and ammonia changes in a groundwater-fed river in southeast England, finding increases in nitrate and ammonia over the 21st century, mainly driven by higher temperatures and enhanced microbial activity. Johnson et al. (2009) bring together climate models, hydrological models and expert opinion to draw a picture of the British river of the future, concentrating on contrasting river systems in southeast and northeast England. They conclude that, with lower flows and higher temperatures, there may be more algal blooms and that ecosystems may change, with wetlands particularly vulnerable, especially in southeast England.

3.4 Water use

Climate change may alter both the demand for water and the volume available (Watts 2010, Hall et al. 2012). Demand for public water supply is expected to respond to increased temperatures, the main changes thought to be in outdoor water use and showering and bathing (Herrington 1996, Downing et al. 2003); Herrington (1996) estimates an increase of 3% in southeast England between 1991 and 2021 in response to a projected 1 °C temperature increase over the same period. Downing et al. (2003) project a range of increases depending on global emissions scenario; 1 to 6% by the 2020s, and 2 to 13% by the 2050s. The higher end of this range is not insignificant, but other components of demand may lead to bigger changes over shorter timescales (Wade et al. 2013).

Water companies in England and Wales assess the impact of climate change on water availability in plans produced every five years (Charlton and Arnell 2011). In their 2008 draft plans, water companies estimated a loss from climate change by 2035 of around 500 Ml d^{-1} of a total of around 17,000 Ml d^{-1} (Charlton and Arnell 2011). However, different companies make different assumptions in coming to this value, and it is not at all certain that this represents a consistent assessment. A consistent assessment using UKCP09 (but also considering the additional pressure of population growth) gives a central estimate of a supply-demand deficit of 1000 Ml d^{-1} by 2050 in the Thames basin alone with an upper bound of 1800 Ml d^{-1} (Wade et al. 2013). Smaller deficits are found by the same date across England and Wales, though this analysis suggests few problems in Scotland or Northern Ireland.

Water demand for agriculture is also expected to increase with increasing temperatures (Wade et al. 2013) as crops require more irrigation in warmer, drier periods. However, irrigation demand is constrained by the availability of suitable soils and affected by a range of non-climate risks which may present a greater impact than climate change (Knox et al. 2010).

UK agriculture accounts for around 75% of the total land area (Angus et al. 2009). Although most crops are fed by rainfall, supplemental irrigation could become significant if adequate water were available, not only for high-value vegetable cropping but also for cereals. A changing climate may also increase production risks (Knox et al. 2012) and affect the viability of rainfed cropping through changes in land suitability (Daccache et al. 2012). With over half of all irrigated production located in water stressed catchments (Hess et al. 2010) there are concerns regarding the environmental impact that any future increases in demand for agriculture might have on water resources.

In the UK, irrigation is a supplement to rainfall. Many farmers apply less irrigation water than the calculated crop demand because of equipment or water resource constraints, or as a deliberate policy to maximise profit. Various approaches have been developed to simulate future irrigation demand (e.g. Weatherhead and Knox 1999, Downing et al. 2003), and as with other sectors, irrigation forecasts are highly sensitive to the prevailing socio-economic conditions.

3.5 Summary of future impacts

It is clear that the impact of climate change on the water sector in the UK could be significant; changes in rainfall, evapotranspiration, flows and water temperature all affect water quality, ecosystem form and function, water availability and flood impact. Approaches to understanding these effects vary greatly; rainfall, evapotranspiration and river flow have been the subject of detailed numerical assessment, but further impact studies tend to be either site specific or more conjectural. This affects confidence in the assessments. There is greatest confidence in the assessment of changes in temperature and rainfall, though the range of possible changes is great. Confidence in the impact on aquatic ecosystems is lowest, because of the multiple interacting drivers of change and poor understanding of the responses of and interactions between species.

4 Discussion and conclusions

This work started from the premise that summarising and synthesising research on the impact of climate change on the UK water environment would help decision-makers with effective adaptation. It would be valuable to expand this review to cover other areas that have not been considered in detail here. Examples of omissions include consideration of changes in snowfall and snow cover, the impact of changes on lake quality and lake ecosystems, estuaries, and some aspects of water use, such as demand for power station cooling, and navigation and recreation. More detail would be valuable for climate change impacts on mammals and fish, and it would be useful to consider the specific problems of different geographical areas, such as the uplands and wetlands.

In all the subject areas considered there is a wide range of possible outcomes, reflecting a chain of uncertainty that includes natural climate variability, climate modelling uncertainty, and further uncertainty in the response of the water environment to changing climate variables. It is also important to set climate change in its wider context; where the planning horizon is short – perhaps 20 years or less – climate variability will dominate (Hawkins and Sutton 2011) and for all time horizons other social and economic changes will always be of importance (Wade et al. 2013).

Despite the growing body of literature on the impact of climate change on the UK water environment, there are several areas where more research would be of value. Changes in evapotranspiration are still poorly understood (Kay et al. 2013), even though evapotranspiration forms one of the main cornerstones of hydrological modelling. Droughts also need more work; as there are relatively few droughts in the historic record, we have little understanding of plausible extremes now, and future projections are limited by the poor understanding of the drivers of long drought and the apparent inability of climate models to reproduce persistent periods of low rainfall. Future flooding also remains a difficult area; intense rainfall (particularly summer convective storms) occurs at scales that cannot readily be resolved by climate models, which is particularly problematical for small catchments. Baseline groundwater temperatures are poorly understood but groundwater contributes much of the summer flow in some rivers and streams, directly influencing water temperature. The way that aquatic ecosystems respond to climate change remains a difficult area, both because many ecosystems are robust to considerable climate variability and because of the complex relationships between flow, water temperature, water quality and ecosystem response. More generally, there are few studies at a scale that helps policy-makers and decision-makers understand the problems that they face; catchment-specific studies are valuable scientifically but often provide little on which decisions can be made. Large-scale, country-wide assessments are inevitably compromised by their general nature, but these are the studies that provide the picture of change that decision-makers find most useful.

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