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The UK Climate Change Risk Assessment 2012: Assessing the Impacts on Water Resources to Inform Policy Makers

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Abstract The Climate Change Act 2008 requires a series of assessments of the risks of climate for the UK, under both current conditions and over the long term, to 2100. This paper describes the research completed on the impacts of climate change on the UK water sector, involving stakeholder engagement and a mix of literature review, expert elicitation and broad-scale quantitative analysis to develop ten climate change risk metrics. These include measures of the demand for water, impacts on supply, water quality and asset performance using future scenarios based on the UK Climate Projections 2009 and future population projections from the Office for National Statistics. The analysis has resulted in a number of key findings that can help to inform policy in different parts of the UK. Overall the assessment showed that there is likely to be increased pressure on water resources in the UK. These pressures need to be considered in long term plans so that the needs of different users are met without impacting on the environment.

Keywords Climate change risk assessment · UK water resources · Science-policy interface · Stakeholder engagement · UKCP09

1 Introduction

It is widely accepted that the world's climate is being affected by the increasing anthropogenic emissions of greenhouse gases into the atmosphere. Even if efforts to mitigate these emissions are successful, the Earth is already committed to significant climatic change

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(IPCC 2007). Translating global changes in climate to changes in key hydrological and water resources variables, such as seasonal precipitation, river flows and groundwater recharge, over relatively small areas such as the UK, is subject to considerable uncertainty (e.g. New et al. 2007; Vidal and Wade 2007, 2008; Watts 2010). These 'deep uncertainties' make decision-making more difficult and highlight the needs to test the robustness of long term plans and promote an adaptive and flexible approach to managing water resources (Dessai et al. 2009).

National policy makers and regional planners are faced with the need to make important choices about investment in economic and social development, including major infrastructure projects that may be affected by climate change. Decisions require the collation of the best available scientific evidence on potential risks, clear communication of the uncertainties and practical decision-making approaches, incorporating uncertainties to promote 'low regrets' decisions and, most importantly, avoid maladaptation. For governments, broad-scale climate change impacts, adaptation and vulnerability assessments (CCIAV) (Lu 2009) and, more recently, risk assessments (CCRA 2012) can provide evidence to support the development of adaptation programmes.

The UK and devolved Governments (Wales, Scotland and Northern Ireland) are committed to action on both mitigation and adaptation to climate change.[1]

The purpose of the first Climate Change Risk Assessment (CCRA) was to provide underpinning evidence, assessing the key risks and opportunities and to enable Government to prioritise climate adaptation policies for current and future policy development as part of the statutory National Adaptation Programme (NAP) which will begin from 2012. The CCRA will also inform devolved Governments' policy on climate change mitigation and adaptation.

The Water sector study was one of 11 sector-based studies commissioned by Defra as part of the CCRA. The sector was defined fairly broadly to cover water demand, supply and quality issues and the UK's requirements for high quality drinking water for households, water abstraction for agriculture, industry and to enhance the environment to meet European Commission and national legislation.

'Water' is a greatly researched sector where many impacts are well known. Assessments of the potential impacts of climate on the Water sector have been completed by water companies (MWH 2007; SNIFFER 2005), the regulators (e.g. Ofwat 2008) and regional climate change groups (West and Gawith 2005). The UKCP09 climate change projections indicate that there could be significant decreases in average summer rainfall and increases in winter rainfall in the UK during the 21st century (Murphy et al. 2009), although wetter summers cannot be ruled out (Met Office 2012). Projected increases in temperature are expected to increase potential evapotranspiration (Arnell 2004; Watts 2010; Vidal et al. 2011). However, considerable uncertainty remains with regards to how plants may respond to elevated CO2 levels and what the net effects on actual evapotranspiration could be at the basin scale (e.g. Betts et al. 2007). Any future changes in drought magnitude and frequency are likely to have the greatest impact on water resources but this is an area where different views exist and more research is required (Vidal and Wade 2009; Burke et al. 2010).

The majority of the water sector assessment was focused on water availability, and this is the main emphasis of this paper. Firstly the overall methodology for the CCRA is outlined, before projections from UKCP09 are summarised and the detailed approaches in the water sector analysis and associated outputs are presented. The paper goes on to discuss what these findings mean for policy and how they could be used by decision-makers.

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[1] http://www.defra.gov.uk/environment/climate/government/

2 Approach

2.1 Overall Methodology

The overall methodology for the CCRA was developed in early 2010 to meet the specific requirements within the timescales available for the first assessment. The proposed methodology was reviewed by the UK Government's Adaptation Sub-Committee and was published on Defra's website in July 2010 (Defra 2010).

A simplified overview of the approach is shown in Fig. 1. The figure also shows links with the Economics of Climate Resilience (ECR) project, which is a separate and ongoing research study to inform the NAP.

Risk screening involved literature reviews and consultation. The preliminary overview of the potential risks in the water sector (Reynard 2010) was based on a review of research literature and grey literature such as Government reports. This early scoping work recognised the often conflicting pressures on the management of the water resources system, for example to meet water supply, agricultural and environmental objectives, and the additional stress that climate change could place on these pressures. This work was followed by consultation with policy makers and scientists in relevant Government departments and UK universities. Additions to the list of impacts were also made following the Water sector workshop and through an online consultation process. A systematic mapping methodology provided a simple form of systems analysis which helped to identify additional risks across sectors.

Overall, more than 50 'Tier 1' impacts were identified for the Water sector from the Water sector scoping report (Reynard 2010), other relevant literature (MWH 2007; Watkiss et al. 2009) and the consultation exercises. Some rationalisation of the list of impacts and consequences was possible by removing duplicates, clustering some impacts and organising them into themes to produce a list of 34 potential impacts of climate change on the UK water sector. Table 1 shows these rationalised impacts together with the climate effect and possible consequences.

Risk selection involved a simple scoring exercise that considered the perceived magnitude and likelihood of risks and also the perceived urgency of adaptation action (the final column in Table 1). This process, which involved gathering feedback from a wide range of stakeholders, decision-makers and academics, including from the Water Experts and Water Sector workshops and online process, selected a total of ten climate risks for more detailed

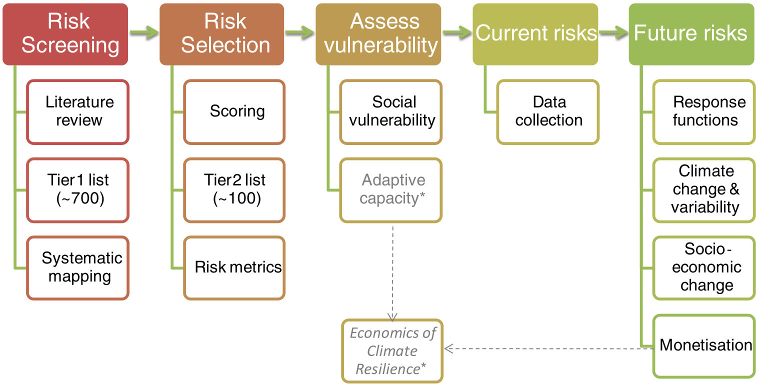

Fig. 1 Simplified summary of the CCRA methodology and links with the economics of climate resilience project. * ongoing studies to inform the NAP

Table 1 List of Tier 1 rationalised impacts and consequences

Climate effect	Impact	Consequence	Score
Increased aridity (decrease in rainfall and increase in temperature)	Supply-demand deficit	Less water available and increased competition for water	Score >30 (selected)
Intense rainfall events	Sewer flooding and Combined Sewer Overflow (CSO) spills (asset performance)	Pollution incidents and deterioration in water quality	Score >30 (selected)
Periods of extremely low rainfall	Major drought	Less water available for users including the environment	Score >30 (selected)
Increased rainfall (either long-term average or intense rainfall)	Flooding of critical infrastructure	Pollution incidents and deterioration in water quality; water supply affected	Score >30 (selected)
Decreased summer rainfall and temperature changes	Habitat change due to reduced water availability	Ecological impacts	Score >30 (selected)
Long periods (multi-season) of lower than average rainfall	Changed recharge and low groundwater levels	Change in availability of water	Score >30 (selected)
Increased summer temperatures	Increased demand for water	Increased competition for water	Score >30 (selected)
Increased summer temperatures	Increases in water temperature	In-stream habitats and species affected; may be detrimental or beneficial	Score >17 (marginal)
Long periods (multi-season) of lower than average rainfall	Change in reservoir yields for public water supply	Change in water available; change in habitats	Score >17 (marginal)
Increased summer temperatures; decreased summer rainfall	Lack of cooling water	Risk of disruption to industrial processes including power generation, potentially affecting energy supply	Score >17 (marginal)
Decreased summer rainfall; increased winter rainfall	Impacts on hydropower potential	Changes to power generation affecting energy supply	Score >17 (marginal)
Decreased summer rainfall	Low flows	Less water available; deterioration in water quality	Score >17 (marginal)
Increased summer temperatures	Increased evaporation from open water (reservoirs and wetlands)	Less water available; habitat change	Score >17 (marginal)
Sea-level rise	Saline intrusion and incursion	Freshwater supplies potentially affected meaning less water available	Score >17 (marginal)
Decreased summer rainfall; increased summer temperatures	Changes to water quality	Additional water treatment required increasing energy use; public health issues; impacts on habitats and species	Score >17 (marginal)

Table 1 (continued)

Climate effect	Impact	Consequence	Score
Increased summer temperatures; decreased summer rainfall	Algal growth	Additional water treatment required increasing energy use; public health issues; local ecological impacts	Score <17 (excluded)
Extreme rainfall events	Dam failure	Loss of life and loss of water supply; potential damage and disruption	Score <17 (excluded)
Increased summer temperatures	Water-borne diseases	Public health risk; ecological implications	Score <17 (excluded)
Increased summer temperatures	Chlorine depletion	Reduction in drinking water quality	Score <17 (excluded)
Changes to summer and winter rainfall	River/canal navigation affected	Disruption to navigational activities; economic implications	Score <17 (excluded)
Increased summer temperatures	Discolouration of water	Reduction in drinking water quality and increased costs	Score <17 (excluded)
Increased summer temperatures	Improvements in treatment process	Opportunity to save money and carbon on water treatment	Score <17 (excluded)
Decrease in summer rainfall	Low sewer baseflows	Increased risk of sewer blockages	Score <17 (excluded)
Changes in temperature and rainfall	Pipe bursts/leakage	Loss of water for supply; increased costs	Score <17 (excluded)
Increased temperatures	Deterioration of MEICA (Mechanical, Electrical, Instrumentation, Control and Automation) and other assets	Economic implications	Score <17 (excluded)
Changes in temperature and rainfall	Water supply quality	Public health risks; increased costs	Score <17 (excluded)
Changes in rainfall	Erosion and sedimentation	Reduction in water storage and yield; deterioration of water company assets	Score <17 (excluded)
Increased summer temperatures	Pollution incidents caused by increase in water use, e.g. boats	Deterioration in water quality; ecological implications	Score <17 (excluded)
Increased temperatures	Odour at works	Disruption to local residents	Score <17 (excluded)
Increased aridity (decrease in rainfall and increase in temperature)	Reduced financial rating of water companies	Increase in the cost of capital	Score <17 (excluded)
Intense rainfall events followed by high temperatures	*Cryptosporidium*	Public health risks; may lead to need for more intense or complex water treatment processes increasing costs	Score <17 (excluded)

Table 1 (continued)

Climate effect	Impact	Consequence	Score
Increased temperatures	Increase in pests at works	Environmental health incidents; potential increased use of pesticides leading to diffuse pollution	Score <17 (excluded)
Increased summer temperatures	Increase in water-based recreation	Deterioration in raw water quality and ecological implications. Opportunities for manufacturers and improvements in public health and wellbeing	Score <17 (excluded)
Increased temperatures	Sludge-related disease	Environmental health problems	Score <17 (excluded)

analysis. These impacts were considered in more detail with stakeholders and developed into risk metrics to describe risk magnitude under a range of future scenarios. The pros and cons of different metrics were considered by the project team, including the various characteristics of ‘good’ metrics. For example, one characteristic is that they would need to be sensitive to climate but allow the disaggregation of climate and socio-economic effects. Most metrics could be defined using a classic impacts assessment framework as either direct ‘biophysical impacts’ (i.e. impacts on biological and physical processes in the natural environment) or consequences as a result of these direct biophysical impacts, such as those on public water supply, the natural environment or water company assets (Parry and Carter 1998).

Metrics identified in the direct **biophysical effects** group were simply derived climate change variables relevant to the water cycle. Metrics in the consequences (social-environmental-economic effects) group were categorised into three further sub-groups—water availability; water quality and environment; and assets. In the **water availability** group, metrics considered the amount of water available for public supply, industry and agriculture. They were primarily based on water service provider assessments of the amount of water available, the rising demand for water and the balance between these two measures. Metrics in the **water quality and environment** group deal with the changes that could occur in the quality of the water environment as a result of changes in climate, looking mainly at the potential impacts of low summer flows. The **assets** group is concerned with the potential impacts of climate change on physical assets, which are vital for delivering water supply and sewerage services to customers.

While these impacts illustrated some of the biggest challenges in the Water sector they should not be regarded as the ‘top ten’ or the only important risks. As such the analysis covered should not be considered representative of the potential distribution of risks facing the sector. In addition, the Water sector review did not include flood risk and coastal erosion risks as these were assessed as part of another study, prior to integration of findings in a UK Evidence Report (CCRA 2012). The ten metrics assessed as part of the Water sector analysis are given in Table 2.

The starting point for the assessment was to understand the current risks. This involved collecting the best information available from Government departments and the regulated industries. The work also recorded the main evidence gaps in the Water sector. Future risks were then assessed using a staged approach that involved understanding the sensitivity to climate variables using ‘response functions’, considering the effect of future climate change and variability on the current population, and then considering population changes to estimate the total climate risk for future time periods. This step used the response functions to provide estimates of future risk under three different emissions scenarios (high, medium and low emissions) three future 30-year time periods (centred on the 2020s, 2050s and 2080s) and for three probability levels (10, 50 and 90 %). All hydrological analysis was completed at the river basin region scale.

In addition to this, an assessment of vulnerability was completed, collecting further evidence on other non-climate factors that influence future risks, such as the social vulnerability of different groups of people in the UK, the capacity of organisations to respond to information about future climate change and information about existing Government policy on adaptation. A qualitative assessment of the main drivers of potential risks with respect to long-term socio-economic changes was also completed as was the monetisation of some potential risks.

This paper focuses on four of the Water sector metrics: WA1, WA2, WA5 and WA7.

Table 2 Risk metrics in the water sector

Group	Metric	Description	Approach
Direct biophysical effects	WA1 - Relative aridity	Aridity describes how dry a climate is. This quantitative metric is a basic hydrological measure of how warm and dry the climate is relative to 1961–1990 (normalised value).	Development of a Relative Aridity Score (RAS) based on the Marsh Aridity Index (AI) (adapted from Marsh 2004)
	WA2 - Change in Q95 (low flows)	This is the flow exceeded 95 % of the time (or 347 days a year on average).	Further work using existing evidence from two main sources (1) (1) Hydrological modelling completed by the Centre for Ecology and Hydrology (CEH) for the Environment Agency; and (2) Similar work completed for the UK Water Industry that was based on modelling 70 UK catchments using a sub-sample of UKCP09 (UKWIR 2009).
Water availability	WA3 - Change in Deployable Outputs	Deployable Output (DO) is the amount of water that can be pumped from a water company's sources (surface and groundwater), constrained by licence, hydrology or hydrogeological factors and works capacity.	The reported impacts of climate change on DO were collected from water companies and the latest Water Resources Management Plans (WRMPs) available (2009–10), expressed as percentage change in DO compared to the baseline data and characterised by different RAS.
	WA4 - Change in the demand for water	The domestic demand for water in litres per head per day (l/h/d)	Demand was linked to climate based on the results of the CCDeW study (Downing et al. 2003). The Water sector analysis looked at domestic demand only, so the work cannot comment in detail on how demand for water for the public sector, industry and agriculture might change.
	WA5 - Supply-demand deficits (Dry Year Annual Average design condition)	Supply-demand deficits occur when resources zones fall into deficit and require demand or supply-side measures	The supply-demand balance was calculated through the use of simple models based on the water available from surface water and groundwater sources (WA3) and the demand for water (WA4).

Table 2 (continued)

Group	Metric	Description	Approach
	WA6 - Population affected by a supply-demand deficit	See above	Calculated from the same models used for WA5 as the entire population in zones with deficits
Water quality and environment	WA7 - Number of sites meeting Water Framework Directive (WFD) Environmental Flow Indicators	Environmental Flow Indicators (EFIs) were developed by the Environment Agency for WFD implementation, and they relate flow to the ecological quality of water bodies, providing a good estimate of the physical habitat required to meet good ecological status.	Decreases in Q95 are linked with environmental flows for river water bodies, using existing data which established the number of water bodies complying with their current EFIs for 10, 15 and 20 % reductions in Q95 flow.
	WA8 - Number of sites with unsustainable abstraction (CAMS water availability for UKCP09 river basin regions)	Sustainable abstraction calculations make use of EFIs, as defined above. In England and Wales, abstraction licensing is assessed at a catchment scale through the Catchment Abstraction Management Strategies (CAMS) system.	Based on percentage change in the number of CAMS water bodies being sustainably abstracted from against change in Q95, using existing data.
	WA8 (a) to (b) - As above for agriculture and industrial abstractions	Provide an insight into how the amount of water available for agricultural and industrial uses might vary with climate change, through consideration of abstractions from sustainable sources.	Reductions in Q95 flows are correlated with the percentage change in abstractions from sustainable sources, based on CAMS abstraction figures (Ml/day) (using existing data).
	WA9 (a) The percentage of rivers with a net decline in ecological status—sanitary determinands	This metric is an assessment of the impacts of climate change on one aspect of water quality as a result of the potential change in low flows.	Quantitative response function based on the outcomes of the Environment Agency's SIMCAT water quality modelling that was developed to assess the discharge consenting policies
	WA9 (b) Diffuse pollution	This metric looks at the potential impacts of climate change on one aspect of water quality, diffuse pollution	Literature review
Assets	WA10 - Change in Combined Sewer Overflow (CSO) spill frequency	This metric looks specifically at the changing frequency of heavy rainfall events and linking this to potential changes in CSO spill frequency	Based on application of the UKCP09 Weather Generator for London, Glasgow, Cardiff and Belfast.

2.2 WA1 - Relative Aridity

Aridity describes how dry a climate is and is typically characterised by annual precipitation and temperatures. In a changing climate, warmer conditions combined with reductions in annual precipitation and changes in seasonal precipitation (Murphy et al. 2009) may shift parts of the UK towards relatively arid conditions.

This quantitative metric is a basic hydrological measure of how warm and dry the climate is relative to 1961–1990. The analysis was based on an existing aridity index which combines rainfall and temperature data to define drought periods, using the equation below (Marsh 2004), where 'Rain' is the April to September total (mm) and 'Temp' is the April to September Central England Temperature (CET) (°C). Av and SD are the full record average and standard deviation respectively, in both cases. In this 'drought'[2] indicator, rainfall deficiency is given twice the importance weighting of temperature increases. Dividing by the standard deviation normalises the data with respect to the long term climate for the area considered. This means that the AI is relative rather than an absolute measure and AIs cannot be compared between areas.

$$Aridity\,Index(AI) = 0.5 \times \frac{Temp - Av\,Temp}{SD\,Temp} - \frac{Rain - Av\,Rain}{SD\,Rain}$$

This analysis considered the annual water balance and made use of a weighted measure that normalises data (so that scores above zero are more arid). In addition temperature, through its effect on evapotranspiration, was considered to be of greater importance in the water balance in the context of future climate change (it is given a weight equivalent to two thirds rather than half of mean rainfall in the Marsh formula). A Relative Aridity Score (RAS) approach was therefore developed using the equation:

$$Relative\,Aridity\,Score = 0.4 \times \frac{T_{future} - T_{61-90}}{SDT_{61-90}} - 0.6 \times \frac{Rain_{future} - Rain_{61-90}}{SD\,Rain_{61-90}}$$

Where T_{future} is the average of annual temperatures over a given period in the future, T_{61-90} and SDT_{61-90} are the average and standard deviation over the 30-year period, $Rain_{future}$ is the average of annual totals over a given period in the future, $Rain_{61-90}$ and SD Rain_{61-90} are the average and standard deviation over the 30-year period. This approach provides a useful and simple indicator that describes the average relative aridity score for future 30 year periods with respect to the observed baseline. It does not consider future year to year variability and has limitations; the use of more advanced hydrological indicators would be more appropriate for detailed catchment studies (e.g. Tallaksen and Van Lanen 2004).

For each major river basin region in the UK, each future time period and each emissions scenario, 10,000 aridity scores were calculated using the probabilistic UKCP09 data (Murphy et al. 2009) to include all the possible combinations of changes in precipitation and temperature in the UKCP09 data set. Then, the 10th, 50th and 90th percentile scores (i.e. p10, p50 and p90) were calculated. These were referred to as 'wet', 'mid' and 'dry' scenarios respectively.

This assessment was able to link future changes in 'relative aridity' (WA1 in Table 2) to other metrics including those on low river flows, water available for abstraction and the demand for water (WA2, WA3 and WA4). While it is convenient to use relative aridity in this

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[2] The indicator is referred to as a drought indicator when used with annual time series to define particularly dry calendar or hydrological years; here it is also used to estimate the average relative aridity over longer time periods.

way it has some limitations, notably that hydrological responses depend on catchment characteristics and have a much more non-linear response to changes than relative aridity.

2.3 WA2 - Q95 Low Flows

Over the last two decades, the potential impacts of climate change on river flows in the UK have been studied in some detail (CCIRG 1996; Arnell 2004; Wilby et al. 2006; New et al. 2007; UKWIR 2007; Lopez et al. 2009; von Christierson et al. 2009, 2012; Watts 2010; Vidal et al. 2011). In general, these studies indicate a more intense hydrological cycle characterised by higher winter flows and lower summer flows in the UK.

In order to consider the effects of generally more arid conditions on river flows in this study, two main sources of evidence were used: (1) hydrological modelling completed by the Centre for Ecology and Hydrology (CEH) for the Environment Agency (Environment Agency 2008c); and (2) Similar work completed for the UK Water Industry that was based on modelling 70 UK catchments using a sub-sample of UKCP09 (UKWIR 2009). These studies had developed national modelling capabilities to convert future climate change scenarios to changes in flow using the 'delta change' method for perturbing climate data (Hay et al. 2000) and then running these data through gridded or lumped catchment hydrological models.

The results from these studies were used to produce a response function for regional average percentage change in the low flow statistic, Q95, in relation to relative aridity of the climate series used to run the models. This was achieved by comparing the change in Q95 with the change in relative aridity for each UKCP09 region, for the 2020s.[3] This resulted in a series of regional relationships for all UKCP09 river basin regions in the UK.

The relationships developed are based on the average hydrological response of different catchments within each UKCP09 region. While the premise that low flows are reduced in warmer and drier annual conditions is based on strong evidence, the response of individual catchments will vary considerably and this simplified relationship is subject to a number of assumptions and caveats. Firstly, it only considers changes in annual average climate and changes in precipitation and temperature; it does not consider changing seasonal effects of patterns of rainfall that are important and may have equal significance to changes in annual average conditions. Secondly, the response function does not consider other important climatological variables such as relative humidity or wind speed that influence evapotranspiration (Brutsaert and Stricker 1979) and therefore the catchment water balance. The next assumption is that there are no changes in catchment characteristics, for example, land use changes or major artificial influences which would affect flow regimes. Moreover, being at the scale of UKCP09 river basin regions, the response function does not reflect the characteristics of individual basins. This is an important consideration as changes may therefore be different, for example they may be greater in catchments with little or no groundwater storage and smaller in those dominated by groundwater. This means that the analysis is relevant only for assessing average regional changes rather than any catchment scale or local changes.

All of these assumptions add uncertainty to the analysis and outputs. Since estimates of changes in Q95 were also linked to subsequent metrics, including both WA5 (supply-demand deficits) and WA7 (number of sites meeting WFD Environmental Flow Indicators) as well as WA8, WA8 (a) to (b) and WA9 (metrics in the water quality and environment group), these assumptions apply to these analyses too.

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[3] The response function is for the 2020s as it uses the data available from the UKWIR work

2.4 WA5 - Supply-Demand Deficits

Although public water supplies have proven to be reasonably resilient to variations in climate, in the past major droughts including those in 1921/22, 1975/76 and1995/96 (Marsh 2004; Cole and Marsh 2005; Marsh et al. 2007) have led to shortages of water in some parts of the UK, as well as environmental problems.

A number of catchment-scale research studies have highlighted the consequences of climate change for public water supply (e.g. New et al. 2007, 2009). Evidence from UKWIR and Environment Agency funded research has been translated into practical methods for including consideration of climate change in water resources planning, used by all water service providers in the UK (Arnell 2003; UKWIR 2006; Arnell and Reynard 2007). In these studies, available climate change projections or General Circulation Models (GCMs), downscaled to UK catchments, have been used (UKWIR 2007; Vidal and Wade 2007, 2008) to provide projected changes in monthly river flows and annual average recharge for catchments in the UK. The national-scale assessment from 2008 (Vidal and Wade 2007) was used as the basis for the latest WRMPs, submitted in autumn 2009 for the last Periodic Review (PR09). Estimates of the impacts of climate change on DO were shown to be greatest in South East England, with the largest percentage changes mostly within the smaller resource zones (Charlton and Arnell 2011). Recent work by the Environment Agency suggests that maintaining water supplies in the 2050s may be particularly challenging in the south-east of England and the Midlands, where water availability is most limited (Environment Agency 2011b).

In this assessment, supply-demand balance results were calculated firstly based on climate change only, then to include consideration of socio-economic changes by combining the results on changes in Deployable Outputs (WA3) and the household demand for water (WA4)[4] with additional information on future population projections. The water balance models were developed at the UKCP09 river basin region scale. They made use of the following:

- Water company data submitted to Government regulators each year (e.g. the Ofwat June Return data)
- Water company estimates of DO from water resources management plans produced in 2009/10
- Water company estimates of the demand for water—per capita consumption and baseline population in each river basin region
- UK Government estimates of future changes in population from the Office for National Statistics (ONS), based on the 2008 census.

The two parameters used to define the socio-economic scenarios were the change in population and change in the demand for water (per capita consumption). The population change is based on different ONS forecasts for population growth, with ‘low’, ‘principal’ and ‘high’ following the naming convention of these forecasts. The baseline per capita consumption was assumed to be 150 l/h/d, which is the current estimate for England and Wales (Defra 2008; Ofwat 2010). The scenarios considered are given in Table 3.

The water balances make assumptions about the level of headroom (the margin between supply and demand) needed to create an allowance for uncertainties between projected demand and supply. This assessment considers the same percentage headroom in the future

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[4] Looking only at the domestic demand for water is a limitation of the work

Table 3 Socio-economic scenarios considered for metric WA5

Scenario	Description
Baseline	Principal projection population figures and assuming no change in the baseline per capita consumption
High population	High population figures and assuming no change in the baseline per capita consumption
Principal projection	Principal projection population figures and assuming reductions in the baseline per capita consumption[a]
Low population	Low population figures and assuming larger reductions in the baseline per capita consumption (than in the principal projection scenario).[b]

[a] Based on the ambition for water consumption in the Future Water strategy, which is to reduce water consumption in England by 13 % to 130 l/h/d (this is now being reviewed)

[b] 126.4 l/h/d by the 2020s, 101 l/h/d by the 2050s, 83.7 l/h/d by the 2080s

as in the base year, which ensures a consistent approach across the UK but underestimates this component compared to what is reported in water company plans. This is because headroom generally increases through time as the future is more uncertain than the present. Leakage from supply pipes was not considered in detail although this may be sensitive to climate, for example cold winters may increase the frequency of pipe bursts, while warmer winters may lead to fewer pipe bursts.

2.5 WA7 - Number of Sites Meeting WFD Environmental Flow Indicators

Another major consideration for the water balance is the resources required to maintain and enhance the quality of UK rivers. Changing flow patterns can affect the natural world in a number of ways, determining how much water is available for different ecosystems as well as having implications for water quality (Conlan et al. 2007; Hammond and Pryce 2007; Environment Agency 2008a; Whitehead et al. 2009a, b). Meeting environmental requirements may mean less water is available for public supply and some trade-off between these two demands is likely in the medium term. In particular, implementation of the Water Framework Directive (WFD) may require substantial reductions in abstraction in some river basins to meet environmental flow objectives and avoid a potential lack of compliance. Processes such as those involved in energy production which discharge cooling water to the environment could also be affected.

This metric links decreases in Q95 with environmental flows for river water bodies. Although Q95 is regularly used as a key indicator it is known to be a poor marker of ecological stress on river ecosystems on its own. Hydro-ecological understanding of stress from flow modifications is based on the importance of the flow regime as a whole, including low flows, mid-range flows and high flows. Therefore the following analysis only provides a partial view and more work is needed on this risk in future.

A sensitivity analysis was carried out using existing data which established the number of river water bodies in England and Wales complying with their current Environmental Flow Indicators (EFIs) for 10, 15 and 20 % reductions in Q95 flow (Entec 2010). EFIs have been developed by the Environment Agency for WFD implementation, and they relate flow to the ecological quality of water bodies, providing a good estimate of the physical habitat required to meet good ecological status.

One of the main assumptions associated with the analysis for this metric is that it is based on current EFIs, which means that they are fixed based on the historic natural flow regime estimated from current data (i.e. no further abstraction licences are granted and current licences are used at a similar level). The application of EFIs in a non-stationary climate is the key challenge in their use. Over the longer term it may be that the level of environmental flows required to protect water ecosystems is changed. This is something which is a matter for future policy at the European and national level.

3 Results

3.1 WA1 - Relative Aridity

Table 4 presents the indicative aridity for the UK from the "wet" end of the Low emissions scenario, to the "mid" estimate from the Medium emissions scenario and the "dry" end of the High emissions scenario. It presents average results from individual regions to provide an overview of the range of possible changes. The probability levels are cumulative and denote the degree of confidence in the change given; for example 90 % suggests that it is thought very unlikely that the change will be higher than this; 50 % suggests that it is thought equally likely that the change will be higher or lower than this; and 10 % suggests that it is thought very unlikely that the change will be lower than this.

As the RAS is a normalised score values of between plus and minus one are regarded here as 'normal' with respect to the 1961–1990 climate; values greater than one as relatively 'more arid' than normal and values greater than two as 'extremely arid' compared to 1961–1990. For a climate change assessment, these average scores provide information on future long-term (30-year periods) average climate conditions, not the changing frequency and magnitude of major drought events. However, the results do indicate a generally drier situation by the 2050s, with only the wettest end of the Low emissions scenario within the normal range in this period. More arid conditions would affect river flows, soil moisture content, groundwater recharge and reservoir yields.

3.2 WA2 - Q95 Low Flows

Of all the regional relationships developed for this metric, the response functions for the UKCP09 river basin regions which showed the most extreme changes in Q95, are

Table 4 Projected relative aridity scores, averaged for river basin regions across the UK and showing a range of results from the UKCP09 low, medium and high emissions scenarios for the 2020s, 2050s and 2080s

	Projected relative aridity (national average)								
	Low emissions			Medium emissions			High emissions		
	p10 (wet)	p50 (mid)	p90 (dry)	p10 (wet)	p50 (mid)	p90 (dry)	p10 (wet)	p50 (mid)	p90 (dry)
2020s	0.53	1.07	1.65	0.53	1.08	1.68	0.55	1.08	1.65
2050s	0.92	1.68	2.55	1.08	1.87	2.79	1.23	2.08	3.07
2080s	1.17	2.06	3.13	1.55	2.60	3.85	1.96	3.19	4.70

Key	
	New baseline condition is a 'normal dry year'
	New baseline condition is more arid
	New baseline condition is 'extremely arid' compared to historic climate

Anglian (largest decreases in Q95) and Orkney and Shetland (smallest decreases in Q95). These are given in Fig. 2.

The response functions indicate that average changes in flow are strongly linked to average annual precipitation and temperature. Considering the range across all river basin regions, as the average climate becomes drier Q95 flows will decline by up to 20 % for an RAS of one and by up to 35 % for the levels of relative aridity projected for the 2020s (around 1.6). Any changes to river flows and groundwater recharge are likely to alter the amounts of water available for abstraction for public water supply.

Considering the effects of future climate change, it is not possible to estimate average changes for the UK so these results need to be considered at the river basin region scale only. To demonstrate the full range of possible regional changes in Q95, the regions with the highest and lowest sensitivities are compared in Tables 5 and 6. The colour shading indicates the magnitude of the changes with respect to historical data.

The percentage change in Q95 figures for both regions cover a reasonably wide range from increases for the 2020s 'wetter' scenario to reductions for the 2080s 'more arid' scenario. Changes of plus or minus 15 % for long-term (30 year) averages are not unusual and may be within the range of 'natural variability'; research on severe droughts in the east of England and north-west has shown that average flows over 30-year time periods may vary by this amount in records back to the early 19th century (Wade et al. 2006).

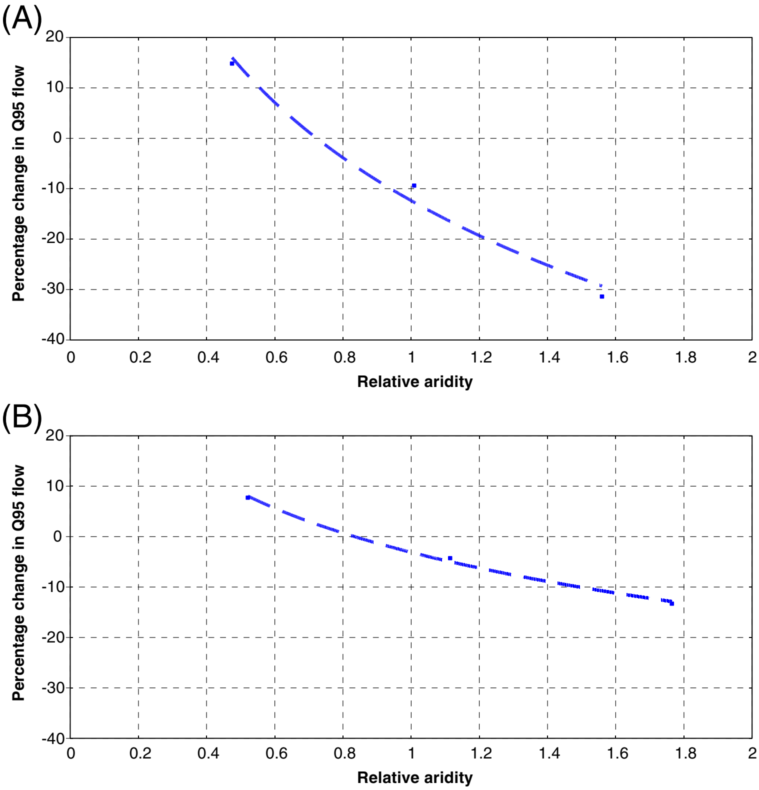

Fig. 2 Percentage change in Q95 from the baseline against relative aridity, 2020s Medium emissions scenario for **a** Anglian river basin region and **b** Orkney and Shetland river basin region

Table 5 Percentage change in Q95—Anglian UKCP09 river basin region

	Low emissions			Medium emissions			High emissions		
	p10 (wet)	p50 (mid)	p90 (dry)	p10 (wet)	p50 (mid)	p90 (dry)	p10 (wet)	p50 (mid)	p90 (dry)
2020s	15	−12	−29	15	−13	−31	13	−13	−30
2050s	−7	−30	−46	−14	−35	−50	−19	−39	−54
2080s	−16	−38	−54	−29	−48	−63	−38	−56	−70

Any changes to river flows are likely to alter the amounts of water available for abstraction for public water supply, as well as for other users (e.g. agriculture and industry). The Anglian river basin region is located in one of the driest parts of England so large reductions in flow could exacerbate existing pressures. Overall the results indicate reductions in Q95 and by implication, summer flows, across all river basin regions in England and Wales by the 2050s for around two thirds of all scenarios considered. However, smaller changes within the range of natural variability cannot be ruled out for the 2050s and the majority of scenarios indicate significant reductions only by the 2080s.

3.3 WA5 - Supply-Demand Deficits

If supply versus demand is considered as a simple balance of water available for use, i.e. imports and exports and 'distribution input', the total amount of water put into supply, (without maintaining any additional headroom for uncertainties) most parts of the UK currently have sufficient public water supplies and some river basin regions, such as North East Scotland, have large surpluses of available water. This is reflected in assessments in England and Wales that show a high 'security of supply' in most water resources zones with some risks highlighted for zones in the south-east, south-west, Midlands and north Wales (Environment Agency 2008b, based on Ofwat data). If the UK is considered as a whole and it is assumed that water is transferred between companies then the current balance is very healthy and the short range impacts of climate change appear insignificant with a surplus of around 253 Ml/d for the 'mid' Medium emissions scenario by the 2020s.

However, major water transfers are very expensive (Environment Agency 2006), have high energy costs for pumping water and could potentially impact on the environment (Furse et al. 1997). Companies also need to retain some additional resources (typically 5 to 10 %) in order to deal with uncertainties in their supply-demand calculations. If it is assumed that companies are unable to share resources then the potential impacts of future climate change could be much higher (a deficit of around 361 Ml/d for the 'mid' Medium emissions scenario by the 2020s). Currently the

Table 6 Percentage change in Q95—Orkney and Shetland UKCP09 river basin region

	Low emissions			Medium emissions			High emissions		
	p10 (wet)	p50 (mid)	p90 (dry)	p10 (wet)	p50 (mid)	p90 (dry)	p10 (wet)	p50 (mid)	p90 (dry)
2020s	7	−5	−14	7	−5	−14	7	−5	−14
2050s	−2	−13	−21	−4	−15	−22	−6	−17	−25
2080s	−5	−16	−24	−9	−20	−28	−13	−25	−33

situation is closer to the latter case as the costs of major transfers are far greater than measures already in water companies' WRMPs (Environment Agency 2006).

In the longer term (assuming no sharing of water), the largest deficits are projected to occur in the Thames region, with a deficit of around 955 Ml/d (−47 to −1,780 Ml/d) by the 2050s that increases to 1,340 Ml/d (−277 to −1,840 Ml/d) by the 2080s. Conversely, a number of regions are projected to experience no deficit in supplies for some scenarios, including Neagh Bann, Tweed and Forth. One region, North East Scotland, is projected to experience no deficit in supplies for all scenarios.

The combined impacts of climate and socio-economic change on the water supply-demand deficit are summarised by UKCP09 river basin region in Fig. 3. The maps show the estimated impacts of climate change only, climate change and population

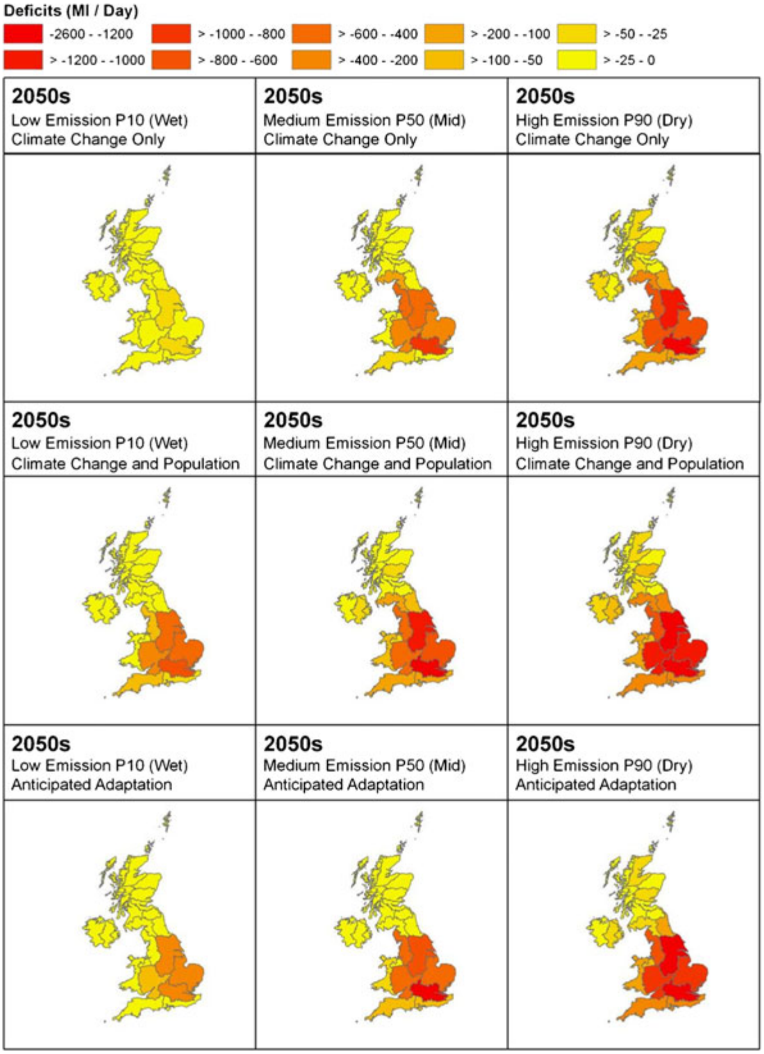

Fig. 3 Water supply-demand deficit (Ml/day) (assuming no sharing of water) by UKCP09 river basin region considering climate change scenarios and socio-economic change

growth (baseline scenario) and the results of some anticipated demand measures (principal projection scenario) to promote water efficiency.

While the results show that climate change alone is projected to have a large influence on the supply-demand deficit, Fig. 3 shows it is also likely to be heavily influenced by population growth. This is because population changes are the main driver in determining the future demand for water. The deficit is consistently higher in the Climate Change and Population maps, than in the Climate Change only maps. At the UKCP09 river basin region scale the supply-demand deficit could also be affected by population movements within the country. Probably to a lesser extent, the figure shows that technological changes such as improved water efficiency measures could also affect the results for this metric, as the deficits are smaller in the maps on the bottom row of Fig. 3, compared with those in the middle row.

3.4 WA7 - Number of Sites Meeting WFD Environmental Flow Indicators

The sensitivity analysis for this metric provided a response relationship for UKCP09 river basin regions in England and Wales[5] (Fig. 4) which could be applied to UKCP09 estimates of changes in Q95, i.e. as Q95 is reduced then more rivers would fail their current environmental flow targets. The consequences of this are unclear but current legislation means that it could lead to water companies and others losing their rights to abstract water.

Figure 5 shows percentage changes in the number of rivers complying with their current EFI for future projections of Q95 by UKCP09 river basin region. As flows reduce the number of sites that can support good ecological status is significantly reduced.

The results indicate a general increase in pressure on environmental flows that may be experienced first in the South West and Severn regions but could affect all regions in England as Q95 changes. The spread of results is from positive to negative in the 2020s but almost entirely negative for the 2050s. While there are quite large percentage reductions in the number of water bodies complying with their EFI for a number of river basin regions, the largest projected decreases in compliance overall for all time periods are for Solway. By the 2020s there is projected to be a 17 % reduction (4 to −89 %) in the number of compliant water bodies which then further decreases to 95 % (4 to −96 %) from the baseline for the 2050s, and 96 % (−28 to −96 %) by the 2080s. Contrastingly, in other regions there appears to be a larger reduction in compliance by the 2020s. In South West England, for example, there is a projected reduction of 71 % (8 to −84 %) by the 2020s, 84 % (−40 to −86 %) by the 2050s and 85 % (−74 to −88 %) by the 2080s. These changes would have the potential to impact on many different habitats and species.

4 Discussion

4.1 Impacts of Climate Change and Socio-economic Drivers

This study has provided a broad-scale assessment of some of the key potential impacts of climate change on the water sector in the UK that can help to inform policy in different parts of the UK. Large reductions in summer flows could have significant consequences for different users including public water supply, agriculture, industry and the environment. In

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[5] Similar data showing a possible change in rivers or water bodies complying with WFD objectives due to variations in flow were not available for Scotland or Northern Ireland

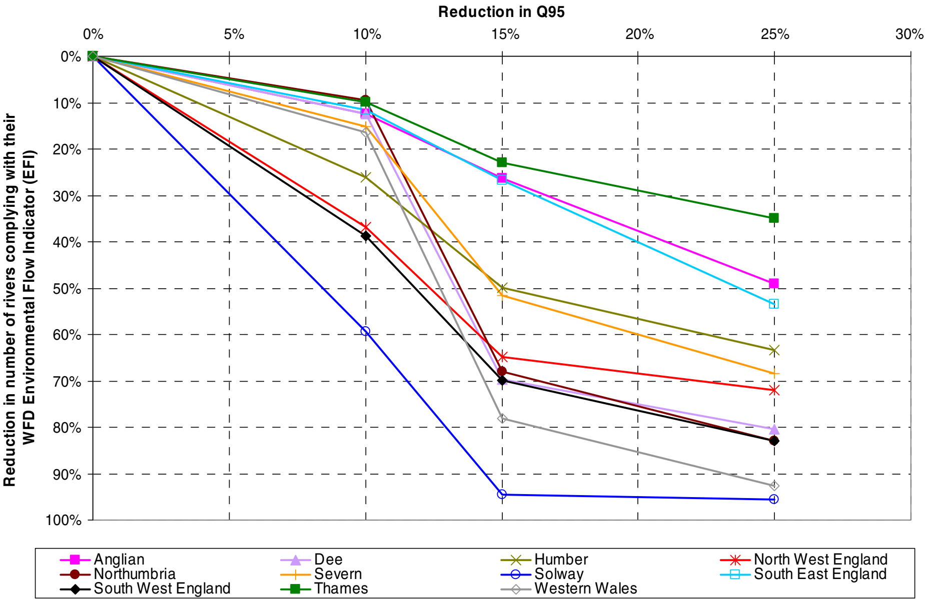

Fig. 4 Reduction in compliance with EFI against reduction in Q95 (historic) by UKCP09 river basin region (where data were available)

the near term, the impacts on low flows are projected to be the greatest in the east of England. In the north and west changes are smaller and not dissimilar from conditions experienced in the past, but these changes could still be significant in some sensitive catchments. However, some of the consequences for water supplies may be offset by making use of surplus winter flows that are expected to increase under most scenarios. The new assessment of 'Future Flows' (Haxton et al. 2012; Prudhomme et al. 2012) could improve the assessment of changes in flows in future iterations of the CCRA. Increasing pressures on water resources could mean changes to planning and management are required. In the near term (2020s), the majority of the UK population will be living in areas with increased pressure on water resources. The main risk to the UK is if warming is at a much greater rate than is accounted for in the plans. In the longer term (2080s), projections of the supply-demand deficit are very large (several times the total supply of the UK's largest water company), indicating that major supply and demand-side measures could be required to maintain supplies at today's level of risk (in terms of restrictions on non-essential use, for example the implementation of hosepipe bans) to millions of people located in the south-east (South East England and Thames river basin regions) Midlands (Severn region), north-west and east of England (Humber and Anglian regions). Water resources planning may benefit from taking a longer-term view of the potential impacts to support the development of flexible and robust investment plans. Changes in population and the demand for water play a major role too and along with other socio-economic drivers are key considerations for future adaptation planning. By including broader consideration of the factors influencing the supply-demand balance, such as the potential withdrawal of abstraction licences due to environmental pressures, the outputs from this analysis could be greatly improved.

Summer abstraction may become unsustainable, i.e. environmental flow targets are not met, in a large proportion of rivers in England and Wales due to low summer flows. In the

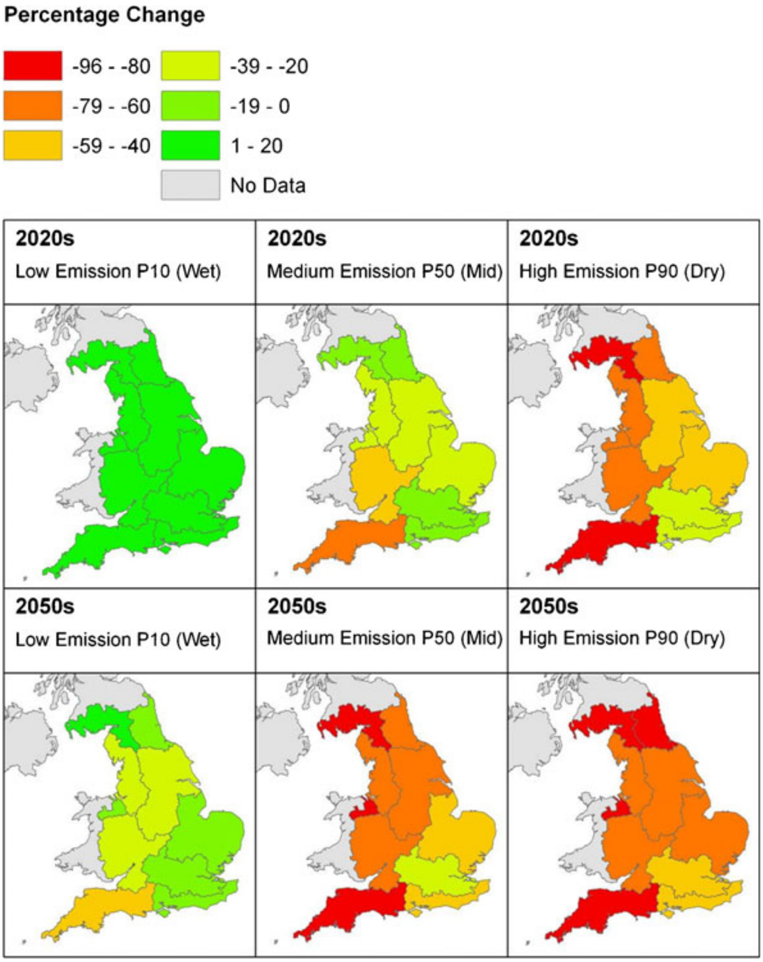

Fig. 5 Percentage change from the baseline (2009) in the total number of water bodies complying with their current EFI, by UKCP09 river basin region

near term (2020s), the assessment indicates that a number of rivers could fail environmental flow targets if we continue to use the historic climate to guide our regulatory framework. This also appears to be the case in the longer term (2050s, 2080s). This may have serious consequences for public water supply as licences for abstraction could be limited by regulators, something of which planners will need to take into consideration. Agricultural, industrial and energy production abstractions could also be affected. Farmers abstract water for irrigating horticultural crops during the summer, particularly in the east and south of England. With drier summer conditions their needs are expected to increase significantly. Although industrial abstraction has declined over the last decade (Environment Agency 2008b) reliable supplies need to be maintained. During the 2003 heatwave, for example, there was disruption to energy supplies in the Netherlands and France because of extremely low discharge levels in rivers, affecting the availability of cooling water (Fink et al. 2004; Eisenreich 2005).

However, the situation is complex since it may be necessary to regularly review conservation targets as habitats themselves change in character in response to climate change, something which is a matter for future policy at the national and European level. Consequently further work is needed to monitor and possibly re-evaluate these environmental flows in rivers under a changing climate, while reductions in water availability coupled with increased demands and the requirement to maintain 'good ecological status' in rivers and lakes all need to be considered in long-term water resource planning (Environment Agency 2011a, see relevant papers in this journal issue).

4.2 Indirectly Informing Policy

While the key findings can help to inform policy directly, they can also help to address a number of indirect impacts and issues that policy makers may be presented with. For instance, potential supply-demand pressures could have implications for the amount of water that can be abstracted for new housing, or for industrial processes and may affect the location of businesses. A similar situation could be faced by the agricultural sector. To what extent would future adaptation measures, such as supply and demand-side measures proposed by water companies influence the availability of water, and how might these measures be affected by conflicting interests over their implementation? If there are water supply or quality pressures, developments for housing could potentially be turned down for environmental reasons and the requirement to comply with the objectives of the WFD and Habitats Directive. Local authorities will need to consider the potential long-term costs of climate change against the more immediate social and economic benefits from development when planning land use (ASC 2011).

Issues surrounding water quality and the WFD could also affect the discharge of wastewaters to the environment, potentially requiring improvements in quality, increasing the need for water treatment processes and therefore energy requirements with implications for climate change mitigation. There are public health and social vulnerability issues to consider too, for example if vulnerable groups reduce their water use should water bills rise as water becomes scarcer. Vulnerable groups might include those that have a low income; large households; the elderly or the very young; or those with any medical condition that requires large amounts of water (Benzie et al. 2011). Measures which enable water companies to take action to reduce the affordability problems currently faced by households are set out in the Government's Water White Paper (Defra 2011).

Such issues require consideration as part of adaptation planning. They also further highlight the conflicting pressures that are present in the water sector, with many different users competing for resources. To a certain extent this is currently addressed by existing plans and policies. For example, water cycle studies identify potential solutions to tensions between growth proposals and environmental requirements and the studies may therefore help to plan for sustainable housing growth (Environment Agency 2008c). A number of different organisations and stakeholders are involved in the consultation procedures during the preparation and development of water companies' WRMPs. The WFD river basin management planning process requires extensive consultation and input from stakeholders from a wide range of different backgrounds and at different scales.

4.3 Limitations of the Methods Used

The limitations in the current methodology must be considered when looking at the outputs of the analysis. Firstly, not all metrics cover the whole of the UK, with several (including WA4, WA7, WA8, WA8 (a) to (b) and WA9 (a)) covering England and Wales only. This is partly due to the information that was available at the time of the analysis. Conversely, the other metrics do cover the whole of the UK with a consistent level of detail. Scale is an important consideration in studies of this type, and the use of the river basin region scale here could potentially mask some of the detail, for example of individual basin responses to changes in precipitation and temperature. This is a particularly important issue for adaptation planning, which will need to consider local factors which are not apparent in this analysis.

It must also be highlighted that the development of some of the metrics within this analysis is based on pragmatic solutions given the timescale of the project and the data available at the time. This serves to add further uncertainties to the outputs which must be considered in the interpretation of these metrics. However, it should also be mentioned that other aspects of the analysis rely on previously undertaken research for the regulators and water industry, the data and modelling of which has in general undergone peer review, either through specific review during the project phase, or through peer-reviewed publications. Overall, there is a great deal of evidence supporting the findings from this sector.

One area which could be afforded improvement is the consideration of socio-economic drivers in the analysis. While aspects of socio-economic drivers are included in the analysis for metrics WA5 and WA6, this is only to a certain extent, looking at two of many possible drivers. Numerous other socio-economic influences exist which would affect both the supply-demand deficit and the population affected. Such drivers include the demand and supply-side measures that will potentially be implemented by water companies over the course of the planning period; this specifically ties in with the assumptions regarding autonomous and planned adaptation within the analysis. While some of these adaptations were considered in the form of the reduced demand for water, there are other important anticipated adaptations that were not explicitly included, mainly because the analysis was prepared before final water company Business Plans were agreed between water companies and the regulators. These include leakage rates, and the plans for large-scale leakage reduction potentially beyond the ‘economic level’; the implementation of supply-side measures such as the construction of new reservoirs, the re-use of effluent, or the use of desalination plants; and the influence of regulation such as the EU WFD and Habitats Directive, which could result in the loss or modification of some water company abstraction licences. For other metrics including WA2, WA3 and WA9 (a), important drivers such as land use change have not been considered; a factor which could, for example, affect flow regimes and may also prove to be of greater significance than climate change in determining water quality (Dunn and Brown 2010).

It is clear that the majority of the analysis completed for the water sector focused on water availability. This can in part be attributed to the constraints set by the CCRA timescale. It would have been desirable to have more metrics on water quality and asset vulnerability, and this is one of the main areas in which this analysis could be greatly improved for the next CCRA. Issues that were identified as important to consider for future analysis include the impacts of higher water temperatures on quality; the influence of soil erosion on in-stream sediment loads; the trophic status of water bodies; the influence of sewer flooding on water quality; potential hydromorphology pressures; and the possible impacts of climate change on groundwater dependent wetlands.

4.4 Conclusions

As water could potentially become scarcer due to climate change, and the needs of the many diverse users may also increase (e.g. due to increasing population, or the demand for irrigated crops) the UK Government will also be required to protect environmental flows under the WFD. As a result there is an urgent need to consider how to balance environmental water requirements with demands for water in a changing climate. Abstractors may need to consider new ways of securing water supplies, for example through options for sharing resources (both within and across sectors), forming abstractor groups or developing sites in areas with water available. The Water sector cannot be considered in isolation and policy decisions/adaptation measures need to reflect the complex linkages with other sectors.

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