## Chapter 1 - Water Resources

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## Recommendations

- Research councils, particularly the Natural Environment Research Council (NERC), should ensure adequate support for scientists to further the understanding of the global, national and regional effects of climate change upon precipitation, with particular emphasis on drought and flooding.
- Research councils, particularly NERC, should as a priority, fund studies into the effect of climate change on groundwater resources.
- Government, regulators and water companies should ensure that water management strategy and policy incorporates climate change predictions.

## Executive Summary

The majority (97%) of water on Earth is saline and, without energy intensive desalination technology, is non-potable. The remaining 3% is freshwater of which two thirds are locked away in glaciers and the polar ice caps. Humanity's needs therefore must be met with only 1% of the Earth's total water. Of this, the majority is groundwater, with 0.3% as surface water and only 0.04% present in the atmosphere.

It is clear that weather patterns are changing and will continue to do so over the coming decades as a result of global warming. Globally, there is expected to be marked effects on precipitation leading to an increase in both droughts and floods. These changes are critical for the management of water resource systems.

Drought and floods have significant impacts upon pollution. Lower summer water flows will mean less dilution of point sources of contaminants, whilst summer storms and wetter winters will result in increasing frequency and severity of diffuse pollution events. Increases in flooding will activate and redistribute contaminants around the landscape.

Over eastern parts of North and South America, northern Europe and northern and central Asia, climate models predict significant increases in precipitation with climate change. However, reductions are predicted in the Sahel, the Mediterranean, southern Africa and parts of southern Asia. More intense and longer droughts are predicted over wider areas of the tropics and subtropics and heavy rainfall events are expected to increase in frequency over most land areas. Droughts and increasing imbalances between demand and available resource will force use of more contaminated (including saline) water sources.

UK water resources can be characterised as follows: in the populous south east where there is low precipitation, demand is met primarily by groundwater abstraction; where there is lower population density in the north and west there is high precipitation and demand is met mainly through surface water resources. Drought in the UK has been classified into two main types: firstly the precipitation gradient is steepened between the north and south; secondly the total precipitation is reduced across the whole of the UK.

For the UK, recent climate models predict that by 2080 changes in precipitation will be greatest in the south and east of England where summer precipitation may decrease by 50% and winter precipitation may increase by up to 30%. This has significant implications for the water supply system including managing different flows and flooding, reduced reliability of supply infrastructure, changing water quality and changing water demand.

By 2080 the UK will most likely experience greater instances of flooding and drought. Risk of flooding is expected to increase because the rainfall intensity is predicted to rise; by 2080 the increase in frequency of heavy rainfall events could be as high as 60% (the most probable range is 10 to 30% with larger increases possible in Scotland). This has massive economic implications for flood defence infrastructure and engineering. More intense short-term droughts are expected in

England and Wales but fewer long-term droughts. This will be a planning challenge for UK water companies.

Changes in precipitation have important knock-on effects on river flows and groundwater recharge. For example, in 2020, summer river flows in the south east of England could be reduced by up to 30%. The effect of climate change on groundwater recharge is much less well understood and should be addressed as priority, particularly in the south east of England.

**Introduction**

Water is the second largest mover of mass after the geological cycle. Material moved can be in particulate or soluble form and can come from any one of, or a complex combination of, spatially distributed sources. These sources can also change over time, either as the sources themselves become active or inactive, or as water becomes available at the right time, in the right location and in the right quantity to transfer them. Water is continuously in motion around the planet in liquid or vapour form and material moved by water in one of its forms can travel around the globe, or may move more locally, this can happen over periods of hours or millennia. Such transferred materials are referred to as contaminants and can be simple or complex chemical substances. Clearly a large control on the concentration, mix and load of contaminants is the pathways followed by water as it moves from stage to stage of the hydrological cycle, which describes the continuous circulation of water within the Earth's hydrosphere, driven by solar radiation (see Figure 1).

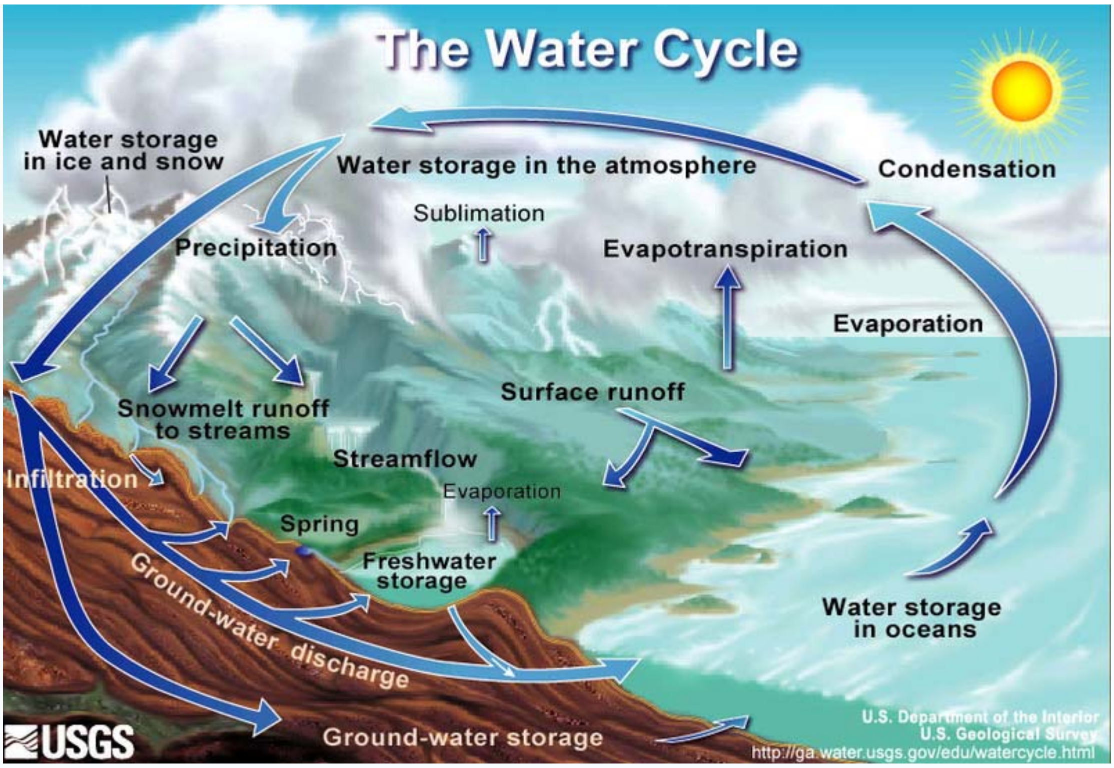


*Figure 1: The Hydrological Cycle (from the US Geologic Survey*[1]

**Water Resources**

Water resources are sources of water that are useful or potentially useful to humans. Only 2.5% of water on the Earth is freshwater, and over two thirds of this is frozen in glacier or polar ice. Water demand already exceeds supply in many parts of the world, with many more areas expected to experience this imbalance in the near future.

Water resources have three main uses: agriculture, industry, and household. It is estimated that 70% of world-wide water use is for agricultural irrigation, 15% is used in industrial processes and 15% is for household purposes. Basic household water requirements have been estimated at around 50 litres per person per day, excluding water for gardens, although 9 litres per day is considered the minimum acceptable (Millennium Development Goals).

[1] http://ga.water.usgs.gov/edu/watercycleprint.html

In 2004 ~3.5 billion people worldwide (54% of the global population) had access to a piped household water supply. Another 1.3 billion (20%) had access to safe water through other means, e.g. standpipes, protected springs and wells. However, > 1 billion people (16%) did not have access to a safe water supply. Looking more broadly at demands for water, Alcamo et al. (2000) estimated that 25% of the earth's terrestrial surface, containing a population of 2.1 billion was under severe water stress (defined as : (average annual water withdrawals / average annual water available) > 0.8). The Earth Summit or The United Nations Conference on Environment and Development held in Rio de Janeiro from June 3$^{rd}$-14$^{th}$ 1992, addressed, among many concerns, the issue of the growing scarcity of water.

Sources of freshwater for water supply can be split into two main types: surface water and groundwater. Surface water resources include abstractions from rivers, lakes or reservoirs and these tend to be dependent on short-term precipitation inputs, mitigated to some extent by reservoir storage. Groundwater is fresh water located in the pore space of soil and rocks or water stored within aquifers below the water table. For groundwater, storage is generally much larger compared to recurrent inputs than it is for surface water. This difference makes it easy for humans to use sub-surface water unsustainably for a long time without severe consequences.

In the developed world, abstracted water should at a minimum, be filtered and disinfected through chlorination. Treated water then either flows by gravity or is pumped to storage reservoirs. In less developed countries treatment of abstracted water may be rudimentary or non-existent.

**Water resources in the UK**

Since 1989 public water supplies in the UK have been provided by private-sector water companies under long-term licence agreements (Arnell and Delaney, 2006). Water supply and sewerage services in England and Wales are provided by 10 major private companies, although a number of smaller companies (15 in 2004) providing water supply-only services operate within a number of regions. The total amount abstracted by the water companies for public water supply in England and Wales in 2002/3 was 15400 Ml/d[2]: 56% of this was supplied to households, 25% was supplied to industrial, commercial and agricultural customers, and 18% was lost as leakage through the distribution network (Arnell and Delaney, 2006). Water-supply in Scotland is provided by one state-owned company and in Northern Ireland by a state run executive agency. In contrast, the Environment Agency (EA) is the main body responsible for creating and maintaining flood defences and providing flood warning systems. The EA are also the responsible agency for delivery of the European Water Framework Directive (WFD), a far reaching water related environmental legislation, requiring that all water bodies (surface and sub-surface) meet ecological and chemical quality standards by 2015.

Three government departments regulate water supply companies. The Drinking Water Inspectorate (DWI) regulates the quality of water delivered to customers. The Environment Agency has a duty to conserve, augment, redistribute and secure the proper use of water resources in England and Wales through issuing licences to abstractors and approving water company water resources plans, under the guidance of the Department for the Environment, Food and Rural Affairs (Defra) for England and the Welsh Assembly for Wales, and directives from the European Union. Economic regulation of the water companies is by the Office of Water Services (Ofwat), largely through determining prices charged to customers (Arnell and Delaney, 2006).

Within the UK to assess the water resource situation in terms of demand and the effects of drought it is appropriate to draw a line from Teeside, down the east of the Pennines, south to Dorset. The area to the southeast is densely populated with low effective precipitation but a high demand for water met mainly through groundwater abstraction. The area to the northwest is characterised by lower population densities and higher effective precipitation, but is mainly reliant on surface water resources. In much of the north of England, short-term summer drought can have an extremely detrimental effect on water supplies (Marsh, 1996). The geology of many areas results in little, if any, groundwater storage potential, with a resulting reliance upon surface water resources. These resources can be depleted rapidly during a dry period, initiating a water resource 'drought' during which restrictions might have to be applied (Fowler et al., 2003).

Historical water resources drought events in the UK have been much studied (e.g. Bryant et al., 1992, 1994; Mawdsley et al., 1994; Jones et al., 1997; Goldsmith et al., 1997; Phillips and MacGregor, 1998; Fowler and Kilsby, 2002). Hisdal et al. (2001) indicated that over the UK there has been a mixed pattern of change in low river flows since the 1960s. A decrease in non-winter precipitation has resulted in an increase in drought severity in areas with limited groundwater storage capacity such as Wales, Scotland and southwest England. Hannaford and Marsh (2006) detected some spatial consistency in recent low-flow trends, with catchments in Wales and western England showing a decreasing frequency but increasing magnitude of low-flows. However, Jones and Lister (1998) indicated that low flows in the 1990s were not historically unusual as more severe events could be identified in the early 20$^{th}$ century.

Over the last two decades, water resource droughts have occurred frequently in the UK. During the late 1980s and early 1990s, numerous water resource drought events (e.g. Bryant et al., 1994; Marsh and Turton, 1996) were a recurrent outcome of increased hydrologic seasonality (Marsh and Monkhouse, 1993). This culminated in the severe drought of 1995-96 which affected mainly the north and west of the country (Marsh, 1996). The recent pan-European drought of 2003 has increased the concerns that our climate is changing, and it has been suggested that there will be large increases in temperature variability during summer months under global warming (Schär et al., 2004). Additionally, current trends in UK rainfall and future projections from climate models suggest that winters will become wetter and summers drier on average (Hulme et al., 2002). The exacerbation of seasonal rainfall contrasts and an increase in extreme events, such as recently experienced in the droughts of the 1990s (e.g. Marsh, 1996) and floods of 2000/01 (Marsh, 2001) and 2007, will severely affect the water balance of river basins. This will influence the available water resources, as well as the frequency of flooding and ecologically damaging low-flows.

Largely as a result of the 1995 drought, water resources management in the UK has received considerable attention. In 1996, the Department of the Environment published an Agenda for Action (DoE, 1996) and the House of Commons Environment Select Committee conducted hearings and published recommendations (Environment Select Committee, 1996). Both reports acknowledged climate change as high on the agenda and recommended that the potential implications of climate change for water resources in the UK should be examined. The Director General of OFWAT announced in 1997 that in 1999 there would be a periodic review of water company investment proposals. For these, companies would be required to consider the effects of climate change in the assessment of future resources, demands and investments. Although at the time there had been several studies into the possible effects of climate change on hydrological regimes in the UK, few had considered the implications for water resources. Therefore, a project was commissioned jointly by UKWIR (UK Water Industry Research Limited) and the EA (Environment Agency) to examine the effects of climate change on river flows and groundwater recharge and produce guidelines for resource assessment.

The results were presented in 1997 (UKWIR/EA, 1997) and consisted of a series of regional factors that could be applied to observed monthly streamflow or annual groundwater recharge data to represent the consequences, by 2020, of four of the Hadley Centre's future climate change scenarios. The effects of climate change on yields could then be examined by comparing yields determined using the original data and the perturbed data. This approach was applied by the UK water companies to investigate the likely effect of future climate change upon long-term yields, and results were included in the 1999 OFWAT assessment. Since this time water companies within the UK have been tasked with assessments of the impacts of climate change upon the operation of their water supply systems using updated UKWIR factors. Additionally, water supply companies are required by the

Environment Agency to prepare 25-year water resources plans and drought plans including the impacts of climate change, which need to be approved by the Agency.

**Surface water and groundwater quality**

Surface and groundwater bodies, as well as providing our freshwater resources have historically also been used for disposal of waste, and can be subject to accidental contamination though leaks or spills. Liquid waste, e.g. from wastewater treatment or industrial plants, is often returned to a water body (under licence from the EA in England and Wales) at a fairly constant flow and concentration. Accidental spills and leaks can add intermittently to these loads. In periods of lower river flow, dilution of these discharges is less (indeed in some rivers in the UK licensed discharges provide almost the entire summer baseflow) and concentrations may be high, whilst the converse is true during high flow periods. However, the patterns are complicated by the relative importance of sources of water during high and low flows, which may carry with them high concentrations of contaminants in their own right.

Easily identifiable and locatable discharges are often referred to as point discharges, whilst those whose sources are more disperse are referred to as non-point, or diffuse. Diffuse contaminants can come from industry (including from currently non-active sites and old deposits), agriculture, where most research effort has been focussed, or from urban or atmospheric sources. As this suggests the contaminants can range from heavy metals, though sediments to nutrients and pesticides and sheep dip. Because wastewater and industrial point sources are easy to locate and regulate they have been the focus of much improvement in water quality over recent years. However, we are now at a point of diminishing return in terms of costs of further improvement versus reduction in contaminants. Scope may exist for novel treatment processes at such sites.

The pathways taken by water determine the forms and concentrations of contaminants transferred to surface or groundwater resources. For recharge of groundwater, the pathway is via the soil profile through a series of interconnected soil pores and cracks to the saturated zone below the water table. This transfer from soil surface to water table can take many years, dependent on soil and geology in a locale, and tends to be initiated at times when the soil profile is saturated, i.e. during autumn and winter in the UK. Contaminants moved are mainly those which dissolve in water and can thus move through the soil pore system. As groundwater bodies are often very large compared with annual water recharge, upward trends in contaminant concentrations can be slow. The time delays in the groundwater recharge and transfer system mean that contaminant issues can develop over decades and can therefore take long periods to resolve (e.g. the problems of increasing nitrogen in groundwater over recent decades as a result of intensification of farming after World War II).

In contrast, transfer of water across the land surface or through field drains, can move both soluble and particulate matter. These transfers occur over much shorter time spans, and potentially much more focussed spaces, than those to groundwater, with consequent implications for contaminant monitoring in water bodies, and for short-term but high contaminant concentrations locally or at river basin scale.

For both surface and groundwater, contaminants do not have to originate from the same location as the water, but can be acquired by the water in transit, from e.g. landfill sites, old mine workings, previously deposited contaminated sediments etc. The complexity of hydrological pathways over space and time in combination with the strength and location of contaminant sources make water quality monitoring complex. However, the EA do have a routine monitoring programme for a wide range of contaminants and in 2004 used information from this network, together with process understanding and models to make a first assessment of the risk of water bodies in England and Wales failing to meet the WFD requirements. These requirements are to achieve, or be heading towards, good ecological, chemical and morphological status of water bodies by 2015. In the UK the risk has been evaluated for Priority Hazardous Substances[2], nitrate, phosphate and sediment. High proportions of water bodies were at risk of failing WFD for one or multiple reasons. There is now a period of improved monitoring alongside design of mitigation methods to reduce contaminant loading of water bodies. Further risk assessments will be carried out through to 2015, to improve the processes used and, it is hoped, to distinguish reducing risk. There is a challenge here for chemists and eco-toxicologists to work alongside ecologists and river basin managers to define more precisely the ecological danger levels of chemicals in the water environment and how they can be managed into the future.

**Climate change projections from the IPCC AR4**

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) Summary for Policymakers published in February 2007 states that "*warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level*" (IPCC, 2007, p5). Indeed, eleven of the last twelve years (1995-2006) rank among the 12 warmest years in the instrumental record of global surface temperature from 1850, and the 100-year linear trend in warming is 0.74°C (IPCC, 2007). The warming trend over the last 50 years is nearly twice this (IPCC, 2007). Most of this warming is "*very likely due to the observed increase in anthropogenic greenhouse gas concentrations*" (IPCC, 2007, p10).

They also state that "*at continental, regional and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation and the intensity of tropical cyclones*" (IPCC, 2007, p8). Long-term trends (>100 years) have been noted in precipitation over some regions. Over eastern parts of North and South America, northern Europe and northern and central Asia significant increases in precipitation have been observed (IPCC, 2007). However, reductions have been observed in the Sahel, the Mediterranean, southern Africa and parts of

[2] http://ec.europa.eu/environment/water/water-framework/priority_substances.htm

southern Asia (IPCC, 2007). In terms of extreme events, since the 1970s, more intense and longer droughts have been observed over wider areas of the tropics and subtropics – linked to increases in temperature and reductions in precipitation – and heavy rainfall events have increased in frequency over most land areas (IPCC, 2007).

In terms of projections of future change in climate, for the next two decades a warming of about 0.2°C per decade is projected. "*Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century*" (IPCC, 2007, p13). For 2090-2099, under six SRES emissions marker scenarios, estimates of warming range from 1.1-6.4°C, with warming expected to be greatest over land and at high northern latitudes (IPCC, 2007). "*It is very likely that hot extremes, heat waves and heavy precipitation events will continue to become more frequent*" and "*increases in precipitation are very likely in high latitudes*" (IPCC, 2007, p16).

**Climate change projections for the UK and Europe**

Europe is likely to experience a diverse range of impacts in response to climate change, with temperature increases accompanied by a perturbed hydrological cycle. Changes in the distribution of daily precipitation totals and in the persistence of dry days may lead to an increased frequency of droughts in some areas and increased flooding in others (Watson et al., 1997) – changes to the intensity and frequency of flood and drought events being the main impacts on water resources from climate change. The ARIDE project (Assessment of the Regional Impact of Droughts in Europe) noted that increasing drought deficits have already been observed in Spain, eastern Europe and large parts of central Europe, with changes in precipitation cited as a major explanatory factor (Demuth and Stahl, 2001). The impact of such events may be felt in a wide range of sectors either directly e.g. food supply, energy use, natural fires, or indirectly e.g. recreation and insurance (Lehner et al., 2006).

Assessments of future impacts on water resources and particularly floods and droughts have traditionally used only one climate model to assess possible impacts. However, climate models project diverse patterns of change in climatic variables across Europe. These vary depending on which climate model is used, with some areas showing opposite developments and different magnitudes of change (Lehner et al., 2006).

Within the UK, climate change scenarios are provided by the UK Climate Impacts Programme (UKCIP). The most recent of these were released in 2002 and called the UKCIP02 Scenarios (Hulme et al., 2002). These will be updated by UKCIP in 2008: UKCIP08. The UKCIP02 projections were taken from the Hadley Centre's Regional Climate Model, HadRM3H, for four emissions scenarios: High, Medium-high, Medium-low and Low, which roughly correspond to the IPCC SRES A1, A2, B2 and B1 emissions scenarios respectively, and three time-slices: 2020s, 2050s and 2080s. By 2080 they suggest that the UK climate will become warmer, with an average annual temperature increase of 2°C – 3.5°C. There will be greater warming in the south and east and there may be greater warming in summer and autumn months than during winter and spring. High summer temperatures will become more frequent, whilst very cold winters will become increasingly rare. The temperature of UK coastal waters will also increase, although not as rapidly as over land. In terms of changes in precipitation, seasonal contrasts are expected to increase over the UK. Changes will be largest in the south and east of the UK where summer precipitation may decrease by 50% or more and winter precipitation may increase by up to 30%. Summer soil moisture may be reduced by 40% or more. Snowfall amounts will decrease throughout the UK, with reductions in average snowfall over Scotland of 60% to 90%. However, heavy winter precipitation will become more frequent.

**Climate change impacts in the UK: floods, droughts and water resources**

Arnell and Delaney (2006) suggest that climate change may have the following potential impacts on the water supply system:

- *it may alter the reliability of raw water sources by changing the frequency of low flows and recharge, increasing the frequency of floods which may inundate bankside facilities, increasing the frequency of highly turbid flows and threatening abstraction points with saline intrusion;*
- *it may alter the reliability of the supply infrastructure, by for example altering reservoir safety;*
- *it may alter the ability to treat raw water to potable standards by changing the frequency of inundation of treatment works and by changing the quality of the abstracted water;*
- *it may alter the demand for water and the ability to distribute water to meet customers' needs, particularly at times of peak demand.*

**(a) Floods**

The UK Government's strategy *Making Space for Water* (MSfW) states that: "*We need to consider how we adapt to climate change, incorporating allowances into our consideration of flooding and erosion risks, ensuring our measures are reversible and adaptable, and that we review our approach on a regular basis using the foundation of best available science"* (Defra, 2005a:7). In the UK, flood management has traditionally favoured hard-engineered defences (Brown and Damery, 2002) but MSfW advocates a shift in thinking towards a more holistic approach involving *whole catchment* and *risk-driven* adaptability to climate change (Wilby et al., in review).

There are some suggestions that heavy rainfall is increasing. Fowler and Kilsby (2003a, b) found evidence that heavy rainfall intensities, particularly over 5 or 10 days, had more than doubled in northern regions of the UK in the last ten years. Ekström et al. (2005) then estimated the likely change in occurrence and intensity of heavy rainfall events under climate change using the same regional climate model as UKCIP02. By 2080, the intensities of short events (1 to 2 days) are expected to increase by 10% across the UK. For longer events (5 to 10 days), intensities show large increases in Scotland (up to +30%) but smaller increases elsewhere. These figures were corroborated in a study by Buonomo et al. (2007).

Recent work using results from six different regional climate models suggests a median increase of 10-20% in heavy rainfall intensities across the UK by the 2080s (Fowler et al., submitted). Although there are large uncertainties in the range of estimated change, all models project increases in heavy rainfall of up to +60% for the UK under climate change (Fowler et al., in press).

Although there is some evidence in the UK for an increase in high flow episodes, such as the 30-day maximum flow (Hannaford and Marsh, 2006), studies seldom find trends in flood peaks or volumes over the past 100-years (e.g. Robson et al., 2002). However, this is because expected trends in UK summer river flows will rarely be detectable within typical planning horizons such as the 2020s (Wilby, 2006). In contrast, most studies assessing the impacts of future climate change show an increased risk of flooding in the UK (e.g. Reynard et al. 2004). This endorses the +20% climate sensitivity allowance now applied to peak flows by flood engineers (Defra, 2006). Planning Policy Statement 25 (PPS25) and Defra's (2006) Supplementary Note (FCDPAG3) provide guidance and updated tables of sensitivity allowances for testing flood designs against projected changes in extreme rainfall, peak flows, wind and waves out to 2115. These recommended national precautionary allowances are based on available evidence at the time of publication and are deliberately rounded to the nearest 5% to reflect the large degree of uncertainty in each case (Wilby et al., in review).

**(b) Droughts**

Many studies have used simple measures based on precipitation deficits to examine likely changes in drought under climate change. The most commonly used of these are the Standardised Precipitation Index (SPI) (McKee et al., 1993) which transforms monthly precipitation time series into a standardized normal distribution, and the Drought Severity Index (DSI) which uses accumulated monthly precipitation anomalies (e.g. Phillips & McGregor, 1998). Using the same regional climate model as UKCIP02, Fowler and Kilsby (2004) estimated changes in the future occurrence, severity and duration of UK water resource droughts using DSI. They suggested that drought frequency and severity will increase in most UK regions by the 2080s, but particularly in the south and east of the UK and for both 3-6 month duration and longer drought events.

However, more recent studies suggest that using the results from only one climate model does not provide an adequate estimate of uncertainty in possible impacts under climate change. A study by Blenkinsop and Fowler (2007) examined the projections from 6 regional climate models over the UK for the 2080s Future projections suggest an increase in mean precipitation in winter and decrease in summer months. Short-term summer drought is projected to increase except in Scotland and Northern Ireland, although the uncertainty associated with such changes is large. Short-term droughts may decrease in duration but drought severity may increase for some regions. Projected changes in longer droughts are highly uncertain, particularly for the south of England, although the longest droughts are projected to become shorter and less severe by most models. This suggests that many UK water supply companies may need to plan for more intense short-term droughts but may experience fewer longer duration events under future climate change.

However, precipitation-only drought indices do not take into account other features of a changed climate which may impact on drought occurrence. In particular, the indices do not reflect changes in evapotranspiration which will arise with temperature change. Such changes and their associated uncertainties will have an effect on evapotranspiration rates and thus effective precipitation, which are implicitly assumed to be stationary by precipitation-only indices. These indices also make no account for potential changes in the temporal distribution of precipitation events. Under enhanced greenhouse conditions it is predicted that the frequency and magnitude of extreme precipitation events will increase (Ekstrom et al., 2005) and climate model integrations have indicated that the convective/frontal precipitation ratios will increase (Hennessy et al., 1997). It is feasible therefore that some of the increase in precipitation or even an increased proportion of existing precipitation may be provided by events which result in overland flow of surface water and will not be effective in the recharge of groundwater aquifers.

**(c) Hydrology and water resources**

There have been many studies on the effects of climate change on hydrological regimes in England and Wales. However, most have been concerned only with changes in mean climate, using the 'perturbation method' (Prudhomme et al., 2002) to alter the observed input data to a hydrological model on a monthly, seasonal or annual basis according to the future changes projected by climate models (e.g. Arnell, 1992; Arnell and Reynard, 1996; Sefton and Boorman, 1997; Pilling and Jones, 1999, 2002; Limbrick et al., 2000). This allows examination of changes to mean flows within the historic record only, without separate consideration of change in variability (extremes) or sequences of storms and dry periods. However, it is precisely these that will have the most effect on hydrological processes.. Under UKCIP02, winter river flows are projected to increase slightly by the 2020s, but summer flows are reduced by up to 30% in the south and east of England (Arnell, 2004). There have been fewer studies of potential changes in groundwater recharge. However, there are indications that under the UKCIP02 scenarios recharge will decrease (UKWIR, 2003).

The effect of such changes in river flows and recharge on water supply reliability, however, depends on how water resources are managed (Arnell and Delaney, 2006). Water resource companies have used the UKCIP/EA flow factors to assess impacts on their water supply systems, for example the UKCIP02 climate changes would reduce Severn Trent's deployable output by around 6.5% by 2025 (Crookall and Bradford, 2000). However, there have been few climate change impact studies which examine the impacts of change in both mean climate and variability on water resource systems in the UK. One example is Fowler et al. (2003) who presented an integrated methodology for modelling the impacts of both natural climatic variability and climate change on the complex Yorkshire water resource system using Reliability, Resilience and Vulnerability analysis. They achieved this by modelling changes to weather type frequency, mean rainfall statistics and potential evapotranspiration using a stochastic weather generator approach (Fowler et al., 2005). Results indicated that there would be future improvements in water resource reliability in this region due to increased winter rainfall, but reductions in resource resilience and an increased vulnerability to drought. Severe droughts comparable to that of 1995 showed only a slight increase in frequency by 2080. However, significant increases in both the magnitude and duration of severe water resource drought were indicated, as a consequence of summer rainfall reductions and increased climatic variability.

In a similar study, Fowler et al. (2007) investigated the impact of climate change on the operation of the Integrated Resource Zone (IRZ), a complex conjunctive-use water supply system in the northwest of England. Climate change impacts were examined using the UKCIP02 Medium-High (SRES A2) scenario for 2070-2100. Results indicated that the contribution of individual sources to overall yield may change substantially under climate change, but that overall yield is reduced by only 18%. This was found to have a significant impact on water supply but the flexibility of the system meant that it was still able to meet modelled demand for the majority of the time under future climate, even without a change in system management. However, increased abstraction from lake and borehole sources and the associated pumping costs mean that meeting the demand may be increasingly expensive.

**(d) Hydrology and water quality**

The predicted changes in flow regime, with generally lower flows in summer, but with the potential for high intensity rainstorms causing summer flash floods, and higher winter flows and increased flooding will have many implications for water quality (Whitehead, J., 2006). Lower summer flows mean that there will be less dilution for point source pollutants, providing a challenge to further reduce the concentrations of chemicals in such discharges through recycling, more efficient chemical use and more effective treatment. Flash summer flooding, relating to high intensity rainfall and surface runoff, will cause increased erosion and transfer of soluble and sediment bound pollutants to water bodies. Wetter winters will result in potentially more transfer of soluble pollutants to groundwater and increased transfer of soluble and sediment bound pollutants via surface routes. Increased flood frequency and extent will result in redistribution of contaminants around the environment, potentially including a range of contaminants from inundated industrial sites. Finally changing flow patterns, with the predicted increase in the size of the 2-year return period flood, traditionally seen as the channel forming event, will cause remobilisation or river banks and the release of a range of historic contaminants from river floodplain deposits.

**Conclusions and challenges**

1. It is clear that weather patterns are changing and will continue to do so over the coming decades with global warming
2. There is some evidence that heavy rainfall is increasing and climate models suggest that this is very likely for future decades
3. Changes to the extremes are important for management of water resource systems: both droughts and floods are expected to increase,
4. In the UK, and much of Europe, lower summer flows will mean less dilution of point sources, whilst summer storms and higher winter flows will result in increasing frequency and severity of diffuse pollution events
5. Increasing flooding will also activate and redistribute contaminants around the landscape as has been seen in the summer 2007 floods in the UK
6. Droughts and increasing imbalances between demand and available resource will force use of more contaminated (including saline) water sources
7. Environmental legislation and a move towards more energy efficient and less waste producing processes mean that both waste and water treatment will become more challenging
8. One approach to reducing the water pollution load would be the development of more biodegradable and less toxic chemicals for use in households, agriculture and industry

9. The Water Framework Directive provides a new set of challenges to chemistry. What is the ecological significance of any given chemical? How do multiple chemical stressors affect the water ecosystem?
10. Internationally there is still a need for low-cost, reliable small scale water treatment to combat avoidable disease and improve quality of life.

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