E-WAter
Official Publication of the European Water Association (EWA)

Robert Keirle BSc (Hons) MSc CEnv CSci MCIWEM[1]
& Colin Hayes BSc MSc PhD CBiol FCIWEM[2]

A Review of Climate Change and its Potential Impacts on Water Resources in the UK

ABSTRACT

Climate change induced by human activities is the most severe problem we are facing today. Over the last century, the average global surface temperature rose by 0.74°C and the global mean sea level has risen 12-22cm. The rate and magnitude of these changes over the past century appears to be increasing, and it is predicted they will have significant, long-term implications for the UK's climate, and for the way the country's water resources (both in terms of quantity and quality) are managed. An overview of modelling climate change and hydrological modelling is given, along with their inherent difficulties and limitations. Finally, a review of selected recent research into the impacts of climate change on surface waters and groundwaters is given.

KEYWORDS

Climate change; global circulation models; groundwaters; hydrological modelling; IPCC, surface waters; water resources.

[1] The author to whom any correspondance should be sent. Robert Keirle's email address is 436290@swansea.ac.uk
[2] Both authors are of:
Centre for Water and Environmental Management; School of Engineering; Swansea University; Singleton Park Swansea; SA2 8PP; United Kingdom
Tel: +44 (0) 1792 602257; Fax: +44 (0) 1792 295676

OVERVIEW OF CLIMATE CHANGE

According to Sir David King, the UK Government's Chief Scientific Advisor, "Climate change is the most severe problem that we are facing today – more serious even than the threat of terrorism" [1].

It is now widely accepted that climate change is already happening and further change is inevitable; over the last century (between 1906 and 2005), the average global surface temperature rose by about 0.74°C. This has occurred in two phases, from the 1910s to the 1940s and more strongly from the 1970s to the present [2].

The 1990s were the warmest decade on record, and nine of the ten warmest years in a dataset jointly compiled by the Hadley Centre and the University of East Anglia's Climate Research Unit have occurred in the period 1995-2004 [4]. In its recently released Fourth Assessment Report the **I**ntergovernmental **P**anel on **C**limate **C**hange (IPCC) has updated these statistics slightly by stating 11 of the 12 warmest years on record have occurred in the past 12 years [2].

Many studies into the detection and attribution of climate change have found that most of the increase in average global surface temperature over the last 50 years is attributable to human activities [3].

It is estimated that, for the 20th Century, the total global mean sea level has risen 12-22cm [2; 5]. This rise has been caused by the melting of snow cover and mountain glaciers (both of which have declined on average in both hemispheres) [2], and the thermal expansion of sea water. Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3,000m and that the ocean has been absorbing more than 80% of the heat added to the climate system [2].

The IPCC also notes that observations over the past century show that changes are occurring in the amount, intensity, frequency and type of precipitation globally [2]. Closer to home, changes in precipitation over the UK have also been detected from actual measurements of rainfall dating back to 1766 in the England and Wales Precipitation Record, which shows an increase in winter rainfall and a decrease in summer rainfall [6]. Considering data gathered since 1914 to 2006, three of the five worst rainfall droughts have occurred since 1990 [7].

Here in the UK we have also experienced changes in the character of our rainfall, which is evident in the extreme weather events we have experienced over the past few years – localised, yet devastating flash floods in Cornwall and Yorkshire, widespread flooding during Autumn 2000 and a series of regional droughts – and these events have been popularly and quickly ascribed to climate change. However, making this connection is not always supported by actual measurements. For example, when flood data over the past 80-120 years was analysed statistically, no proof of a consistent trend or links to climate change was provided, as such events could be explained by natural variations in our climate rather than climate change [4].

THE INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

At this point it is worth mentioning the role and remit of the IPCC. The IPCC was established in 1988 by the World Meteorological Organisation and the United Nations Environment Programme, and its role is to "assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation" [8].

The IPCC does not carry out research nor does it monitor climate related data or other relevant parameters. Since 1998 it has produced four Assessment Reports (the most recent of which was published earlier this year), which are based mainly on peer reviewed and published scientific/technical literature [8]. Based on six emissions scenarios the IPCC has stated that, for 2090-2099 relative to 1980-1999, the best estimate for projected global average surface warming lies within the range 0.6 to 4.0^{o}C, whilst the projected sea level rise lies within the range 0.18 to 0.59m [2].

MODELLING CLIMATE CHANGE

In order to estimate the impacts of anthropogenic emissions on climate, a mathematical model called a Global Circulation Model (GCM) has to be constructed of the complete climate system, which must include the atmosphere, oceans, land and cryosphere (glaciers and ice sheets). This model is a mathematical description of the Earth's climate system, firstly broken down into layers (both above and below sea level) and then each grid is broken down into boxes or 'cells' [6].

A number of research centres around the world have developed their own versions of GCMs; the Hadley Centre's latest model is known as the Hadley Centre Global Environmental Model version 1 (HadGEM1) [6; 9].

All predictions contain uncertainties. For example, because future emissions of greenhouse gases are unknown, numerous emissions scenarios have been developed; therefore, different scenarios will obviously produce different results. However, the largest uncertainty arises from the models themselves. Even if each of the different GCMs use the same emissions scenario, they will give quite different predictions due to the different ways they represent aspects of the climate system [10; 11]. The ability of these models to accurately represent cloud-related water processes and radiative transfers is also an area of major uncertainty [2; 12]. In fact, the IPCC notes that "models continue to have significant limitations" in certain areas, although in its opinion, models "have consistently provided a robust and unambiguous picture of significant climate warming in response to increasing greenhouse gases" [2].

MODELLING HYDROLOGICAL RESPONSES TO CLIMATE CHANGE

When it comes to quantifying the potential impacts of climate change on water resources, even more problems arise. GCMs generally operate at a seasonal or annual timescale across continents, but much smaller scales (in both time and space) are required for catchment hydrological modelling [13]. For example, the spatial resolution of the Hadley Centre's HadGEM1 model is 135km x 135km, which means that for a very large river such as the Danube its catchment is only represented by 45 grid squares (as the area of its catchment is about 817,000 km^2), whilst a number of rivers in Cornwall are only a few kilometres from source to sea, so the spatial resolution offered by HadGEM1 is wholly inadequate [14].

The generally coarse spatial resolution of GCMs also presents a significant problem when rainfall is being considered. GCMs usually generate an estimate of the average rainfall over a large grid square for the GCM time step, but they fail to take into account localised temporal and spatial variations in rainfall which, on a smaller scale, can produce highly significant results [15]. The climate across the British Isles is extremely variable at all scales, "with inter-annual climatic variability particularly significant". Unfortunately though, this natural variability is often overlooked in climate impact studies [11].

The situation is further complicated because of the exceptional diversity demonstrated across the UK in terms of its geology, land use and patterns of water use, all of which directly influence regional and more local hydrological responses to climatic variability; for example, rivers draining a chalk catchment may be expected to respond very differently from nearby urban watercourses [16].

The Hadley Centre has used its HadGEM1 model to predict likely changes in the global water cycle (which is likely to get more intense), but has not yet focussed its research on the catchment level, which perhaps is understandable taking the above points into account [17]. Consequently, it is therefore "extremely difficult for water resource planners to rigorously account for uncertainty in climate change" [11].

UK Water **I**ndustry **R**esearch (UKWIR) is currently attempting to generalise the three main sources of uncertainty (climate variability, hydrological uncertainty and uncertainty in future projections) and is aiming to complete this work by March 2008 [11].

DATA REQUIRED FOR HYDROLOGICAL MODELLING

In theory, based upon the issues identified above, a separate hydrological model should therefore be built for each catchment and significant sub-catchment, and a huge volume of data (vastly in excess of the current amount being acquired) would be essential for calibration of the models. A similarly significant volume of data would be required for subsequent verification of the models; this data is used for 'backcasting', in which the models are used to reconstruct historic climates and the results compared against actual events to determine their accuracy, before they are used for forecasting purposes. It is therefore useful to consider the data we have acquired to date within the UK.

The majority of the hydrological data contained in the National River Flow Archive and the National Groundwater Level Archive is collated and validated by Government bodies from hydrometric networks generally owned and maintained by them – the Environment Agency (for England and Wales), the Scottish Environment Protection Agency (for Scotland), and the Rivers Agency (for Northern Ireland). These networks have expanded and contracted over time, in accordance with changing operational requirements and funding regimes.

Unfortunately, relatively few small, undisturbed catchments (or aquifer units), of the type best suited to establish benchmark conditions and identify climate change signals, are currently being monitored. Moreover, catchments of this type with an appropriate length of hydrological record suitable for this type of research are rare; the average record length in the National River Flow Archive is less than 23 years, and fewer than 15 sites offer "sensibly continuous" records of more than 50 years. The **C**entre for **E**cology and **H**ydrology (CEH) therefore states that any apparent trends detected in a flow or level hydrograph need to be treated with caution; an apparently compelling trend over, say, a 20-year period, may be seen to be a mere perturbation when viewed in the context of a 100-year timespan, as such short records "do not always capture the full range of variability in our current climate" [11; 16; 18].

Although the CEH states that the few very lengthy hydrometric records currently available in the UK are of immense value, the ability to distinguish any climate change-induced perturbation or trend amongst the background anthropomorphic 'noise' is a "considerable scientific challenge". The ability to undertake this task is further complicated when changes in measurement technologies and data processing procedures are factored into the equation, with the unfortunate implication that few hydrometric time series can be considered truly homogeneous [16].

Consequently, taking all the above points and limitations into consideration, catchment and aquifer models only exist for a small proportion of the supply sources in the UK [19].

It is therefore timely that a review of the quality and quantity of data (both hydrological and relating to water quality) collected across the European Union has been proposed by the Water Supply and Sanitation Technology Platform's Water Management Thematic Working Group, as part of the EU's Seventh Environment Action Plan (which runs from 2007-2013). The proposal includes research into:

- Development of more comprehensive and effective integrated monitoring networks; and
- Standards for responsible authorities carrying out monitoring and reporting in Member States (including identifying the minimum staffing and financial resources requirements needed to do the job properly).

IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

The following effects on water resources in the UK – and, by extension, the country's water industry – have been predicted as a result of climate change [7; 20-22]:

- Deterioration in summer surface water quality, due to increased evapo-transpiration, lower flows and rivers becoming warmer, making the management of water treatment works (and subsequent compliance with the drinking water quality regulations) more challenging;
- Large decreases in average summer river flows and small increases in average winter flows throughout the UK;
- Water supply pipes and sewerage pipes damaged by subsidence caused by shrinkage and settling of ground during droughts;
- An increase of between 1% and 2% in the demand for water for domestic water supply by the 2020s (although the impacts on peak demand, particularly during the summer months, are likely to be more significant);
- Water shortages and rationing during the hotter, drier summers;

- A resource loss of between 25% and 77% of water companies' target headroom in 2030;
- Sewage and water treatment works on floodplains and in coastal areas at increased risk of flooding due to rising sea levels and increased and more intense rainfall;
- Increase of the risk of saline intrusion in coastal aquifers because of rising sea levels;
- Sewage discharges and combined sewer overflows in coastal areas may have to be re-located due to rising sea levels; and
- Back-up occurring with greater frequency in the sewerage network leading to flooding and cross-contamination due to increased and more intense rainfall.

IMPACT OF CLIMATE CHANGE ON HYDROMETRIC DATA

Accurate return periods of floods and droughts are essential to many people such as civil engineers, water resources planners and town planners. However, according to the **I**nternational **U**nion for **C**onservation of **N**ature and **N**atural **R**esources (IUCNNR), "extrapolations from observed data are becoming increasingly unreliable", which "suggests that the data and assumptions used in the past can no longer be regarded as valid for the future" [13].

SELECTED REVIEW OF RESEARCH INTO THE POTENTIAL IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

Because of the problems associated with climate change modelling and hydrological modelling, limited research into the effects of climate change on surface water resources has been undertaken; an overview of some of this research is presented in the following sub-sections. Unfortunately, even when research has been undertaken it can be inconclusive. For example, UK temperatures over the last 150 years have demonstrated significant season warming, but researchers' ability to detect seasonal trends in regional rainfall has been less successful; some studies have reported no trends in annual rainfall and few significant seasonal trends, whilst others have stated that trends due exist [4].

There may be other reasons why limited research has been undertaken. According to the IUCNNR, "the water sector has paid little attention to, and is often unaware of, the expected impacts of climate change on future water resources", which it feels is probably due to there having been "few serious attempts to inform water experts about the links between climate change and the water sector". It therefore urges for more attention to be paid to incorporating climate change considerations into water resources planning, as development of new resources can "often take decades to materialise" [13].

HR Wallingford has attempted to demonstrate whether or not climate change has already had an impact on river flows [23]. Although they have found a small number of upward trends in autumn/winter runoff, they feel it is too early to attribute them to climate change over and above natural variability.

When it comes to groundwater, even less research has been carried out, despite it being a major source of drinking water in Europe (and indeed, throughout the rest of the world) – for example, 28% of the UK's drinking water is derived from groundwater, whilst in Austria this figure is 99% [14]. Consequently, when the IPCC produced its Third Assessment Report in 2001, it could only include a series of hypotheses relating to the impacts of climate change on groundwater, and these are reproduced below [24][3].

The same report states that the direct impact of climate change on water quality in surface waters and in groundwater "may be very small in relative terms", as it is "heavily dependent on direct and indirect human activities" such as land-use and agricultural practices, and water management and land management policies and strategies [24]. However, climate change may well have fundamental implications for how we use the land in the future, which in turn is likely to have a significant influence on river water quality [25].

[3] *At the time of writing (May 2007), Working Group II (relating to Climate Change Impacts, Adaptation and Vulnerability) of the IPCC had only published its Summary for Policymakers, which does not consider in any great detail the potential impact of climate change on water resources. Reference is therefore made in this paper to Chapter 4 (Hydrology and Water Resources) of Working Group II's contribution to the Third Assessment Report, produced in 2001.*

The IPCC's statement that climate change will probably only have a minimal direct impact on environmental water quality appears to be supported by research undertaken by **UK W**ater **I**ndustry **R**esearch (UKWIR), which assessed whether available, calibrated water quality models for five UK rivers and one reservoir were capable of assessing changes in water quality under likely climate change scenarios; it concluded that no significant effects on water quality would result, though it qualified this by stating that it was not valid to conclude that significant effects will not occur, because of the nature of the models used, the way changes were assumed to happen, and the nature of the climate change scenarios themselves. One of the recommendations of this report was that it was important for water quality models to allow for the effects of diffuse sources of pollution, which UKWIR felt meant that effective land-use models should be developed, and linked to appropriate water quality models [26].

There are a number of plans relating to the management of water resources within England and Wales, ranging in scale from the short term (such as the Environment Agency's Catchment Abstraction Management Strategies) through to its longer-term Water Resources Strategy. However, as HR Wallingford identified in a recent report produced for the UK Government's Department for Environment Food and Rural Affairs (DEFRA) relating to the development of practical guidance on how to manage water resources in a changing climate, many of these plans "either do not consider climate change or are poorly integrated with water resources plans so the impacts of climate change on water are not fully considered in many land use planning activities" [7]. This is undoubtedly due to the difficulties and issues highlighted above. Indeed, even the Water Framework Directive itself is based upon the assumption that today's climate will not change [27].

In the same report, and again probably for the same reasons, it is stated that "it is not possible at this stage to determine the adequacy of the river basin management planning process for helping to adapt to climate change", so the report's authors could not, at the time of writing, make detailed recommendations on potential improvements to the process. However, as the production of River Basin Management Plans is a cyclical process, there will be opportunities to update them in the future as our understanding of the detailed impacts of climate change on water resources improves [7].

UK Climate Impacts Programme's 'RegIS' Report

DEFRA funds the UK Climate Impacts Programme which coordinates research to help organisations in all four devolved parts of the UK assess how they might be affected by climate change, so they can prepare for its impact [28]. In May 2001 it published a report on its first attempt to quantitatively model the cross-sectoral impacts of climate change within an integrated framework at a regional scale within the UK. The project was called RegIS (from "**Reg**ional Climate Change **I**mpact and Response **S**tudies in East Anglia and North West England") and it considered the impacts of climate change on various sectors, including water [29].

RegIS is the first project to incorporate the following two important aspects of climate change impact studies within a regional context:

- The simulation of the likely changes in land use distribution and the consequent impacts of these changes on the water system; and
- The simulation of entire regions at the sub-regional or catchment scale [29].

However, because such models require catchment- by-catchment calibration and verification, the data required for this limits the number of catchments that can be modelled. Accordingly, only five out of 88 catchments in East Anglia were modelled, and four out of 95 catchments in the North West. According to the authors of the water section of the report, this number "is insufficient to incorporate the great variability in catchment hydrology and response caused by land use, climate, soils and geology" [29].

Such statements from the report's own authors, and the continued dearth of small-scale models developed for UK catchments may have been the basis for comments in a recent House of Lords Select Committee report which stated that it will be "important to make progress in producing smaller-scale, catchment-specific models that will allow a better understanding of climate change impacts at the local level, thus allowing water companies and others to plan with more confidence" [30].

The same House of Lords report goes on to say that the Select Committee "saw insufficient evidence to convince [them] that the potential consequences of climate change are being adequately factored into long-term planning for water management", which would be rooted in accurate models. It therefore recommended that both Ofwat and the Environment Agency "take steps to make the process whereby such issues are addressed within long-term planning more transparent and open to scrutiny" [30].

In fact, it is the opinion of Water UK (the industry association that represents all UK water and wastewater service suppliers at national and European level [31]) that insufficient attention was given to impacts of climate change within the recent Periodic Review (PR04). They even call for a European Directive on responding to climate change with a focus on the protection of water resources [32].

Stockholm Environment Institute's Report

Almost two years after the publication of the RegIS report, the Stockholm Environment Institute published a DEFRA-funded extensive research programme into demand management, demand forecasting, sensitivity of demand to climatic variations, and sources of risk and uncertainty. This research built upon the work of the RegIS project and others, but its remit was broader in one key area – it also considered the impact of climate change on demand for water [33].

The study did consider the impacts of climate change on the demand for water within the leisure sector, but the report noted that no specific methodology has been developed for this purpose. It therefore noted that such impacts are likely to be very location specific, and therefore would not be detected in a region by region analysis, such as presented in the report [33].

Environment Agency's National Report on Climate Change

The Environment Agency's first national report on climate change was launched in Spring 2005 [34]. Within the report it mentions a number of case studies and statistics relating to water resources and water quality that can be attributed to climate change, but does not mention how it proposes to tackle the impacts of climate change, possibly because its research is still in its early stages [35].

Intergovernmental Panel on Climate Change's Third Assessment Report
As previously mentioned, in its Third Assessment Report published in 2001 the IPCC could only present a series of hypotheses relating to the impacts of climate change on groundwater, in lieu of a robust body of research.

Aquifers are generally recharged directly by local rainfall, rivers and lakes, so their rate of recharge will be directly affected by changes in precipitation, as well as changes in the duration of the recharge season. The increase in winter precipitation that has been forecasted for the UK will generally result in increased groundwater recharge. This may well be offset though by increased rates of evaporation during summer months, which may give rise to soil deficits persisting for longer and commencing earlier [24].

In the case of shallow unconfined aquifers in floodplains, these are recharged by seasonal streamflow and can be depleted directly by evaporation. Climate change may have variable impacts on streamflow so a net change to groundwater storage in these situations is difficult to forecast; what is more certain is that climate change-induced increases in evaporative demand would tend to lead to lower groundwater storage [24].

Sea level rise over the next 100 years will give rise to increased instances of saline intrusion in coastal aquifers, with shallow aquifers most at risk, so communities reliant on these aquifers will find their drinking water supplies increasingly under threat. This problem can only be exacerbated if groundwater overpumping is a factor as well [24].

Turning now to confined aquifers, these are far less sensitive to localised precipitation, as their recharge zones may be anywhere up to several thousand miles away (and therefore may not be adversely influenced by seasonal or interannual variations in precipitation or temperature); recharge rates of confined aquifers can also vary from a few days to decades. These factors consequently make it difficult to estimate the impacts of climate change [24].

Taking the above into consideration, it is therefore easy to accept the report's general conclusion that groundwater modelling efforts need to be intensified [24].

UKWIR Report on the 'Effect of Climate Change on River Flows and Groundwater Recharge'
In 2005 UKWIR published a report describing an analysis of 10 groundwater observation wells and 47 river flow records for the period 1970 to 2002, the main objective of which was to detect trends in river flows and their possible attribution to climate change [4].

The report found that there were a small number of short- to medium-term trends in winter and autumn runoff (but none in spring and summer runoff), but that these changes could not be attributed to climate change over and above natural variability. No trends were found in groundwater annual minimum or seasonal average groundwater levels, but this may be due to the small number of sites included in the study [4].

In mitigation though, it is pointed out that attempting to detect a link between climate change and changes in river flows is challenging for a number of reasons, including the following:

- The high variability of river flows and groundwater levels generally masks any underlying trend;
- Rivers respond to changing land use and other human influences as well as changes in rainfall and evaporation patterns;
- Rainfall (and by supposition runoff) in some parts of the UK is strongly influenced by the North Atlantic Oscillation;
- There is inherent uncertainty in climate change scenarios so it is unclear how fast the climate will change due to rising greenhouse gas emissions [4].

It is also stated that it may take a period of decades before any clear patterns of changing rainfall and catchment water balance can be detected across the UK, so the report recommends that the study is repeated regularly, possibly with more sites [4].

CONCLUSIONS

1) This review has highlighted some of the difficulties associated with modelling climate on both a global and a regional scale. Efforts must be intensified in order to overcome these difficulties, to ensure that the most accurate outputs possible are practicably obtained.

2) Although it is now almost universally accepted that climate change will have significant impacts on water resources, greater attempts must be made in order to quantify these predicted impacts so that mitigation effects can start to be put in place.

3) There is currently a dearth of research being undertaken into the impacts of climate change on water resources, which is in part due to the lack of sufficient data and hydrological models being available. Urgent action must be taken in order in order to redress this.

4) In order for the quantification of the impacts on water resources to be undertaken, robust hydrometric data of sufficient volume are required. It would appear that a review of the national dataset is urgently required, so that measures can be put into place to plug any gaps in the national hydrometric network and to ensure data of consistently high quality is captured.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the European Social Fund Objective 1 funding, without which this review would not have been possible.

The views presented in this review are those of the authors and not necessarily of Swansea University.

REFERENCES

1 House of Lords. (2005) *The Economics of Climate Change. HL Paper 12-I*, UK Parliament, London.

2 Intergovernmental Panel on Climate Change. (2007a) *Working Group I: The Physical Basis of Climate Change*. Accessed on 8 May 2007 from http://ipcc-wg1.ucar.edu/wg1/wg1-report.html.

3 Intergovernmental Panel on Climate Change. (2001a) *Climate Change 2001: The Scientific Basis*. Intergovernmental Panel on Climate Change.

4 Dabrowski, C., Romanowicz, R., Vidal, J.-P., Wade, S., and Young, P. (2005) *Effect of Climate Change on River Flows and Groundwater Recharge, a Practical Methodology: Trends in UK River Flows 1970-2002*. UK Water Industry Research, London.

5 Three Regions Climate Change Group. (2005) *Adapting to Climate Change: A Checklist for Development*. Greater London Authority.

6 Hadley Centre for Climate Change and Prediction. (2005a) *Climate Change and the Greenhouse Effect: A Briefing from the Hadley Centre*. Hadley Centre for Climate Change and Prediction, Exeter.

7 Wade, S., Fenn, T., and Barnett, C. (2006) *Defra Research Contract: Climate Change Impacts and Adaptation - Cross-regional Research Programme (Project C - Water) Draft Final Report*. HR Wallingford, Wallingford.

8 Intergovernmental Panel on Climate Change. (2007b) *About IPCC*. Accessed on 8 May 2007 from http://www.ipcc.ch/about/about.htm.

9 Hadley Centre for Climate Change and Prediction. (2004b) *HadGEM1 - Model Description and Analysis of Preliminary Experiments for the IPCC Fourth Assessment Report*. Hadley Centre for Climate Change and Prediction, Exeter.

10 Hadley Centre for Climate Change and Prediction. (2004a) *Uncertainty, Risk and Dangerous Climate Change*. Hadley Centre for Climate Change and Prediction, Exeter.

11 Davies, H., Osborn, T., Piper, B., and Prudhomme, C. (2005) *Climate Change Uncertainty in Water Resource Planning*. UK Water Industry Research, London.

12 Garbrecht, J. D., and Piechota, T. C. (2006) *Climate Variations, Climate Change and Water Resources Engineering*. American Society of Civil Engineers, Reston.

13 Bergkamp, G., Orlando, B., and Burton, I. (2003) *Change: Adaptation of Water Management to Climate Change*. International Union for Conservation of Nature and Natural Resources, Gland & Cambridge.

14 Chave, P. (2001) *The EU Water Framework Directive: An Introduction*, IWA Publishing, London.

15 Calder, I. R. (2005) *Blue Revolution: Integrated Land and Water Resource Management*, Earthscan, London.

16 Centre for Ecology & Hydrology. (2006a) *Hydrological Trends - Background*. Accessed on 9 October 2006 from http://www.nerc-wallingford.ac.uk/ih/nrfa/hydrological_trends/hydrological_trends.htm.

17 Hadley Centre for Climate Change and Prediction. (2005b) *Climate Change, Rivers and Rainfall*. Hadley Centre for Climate Change and Prediction, Exeter.

18 Centre for Ecology & Hydrology. (2006b) *Long Hydrometric Records*. Accessed on 9 October 2006 from http://www.nerc-wallingford.ac.uk/ih/nrfa/hydrological_trends/long_records.htm.

19 Arnell, N. W. (2003) *Effect of Climate Change on River Flows and Groundwater Recharge: UKCIP02 Scenarios*. UK Water Industry Research, London.

20 CAG Consultants, and Oxford Brookes University. (2004) *The Planning Response to Climate Change: Advice on Better Practice*. Office of the Deputy Prime Minister, London.

21 National Farmers' Union. (2005) *Agriculture and Climate Change*. National Farmers' Union, Stoneleigh.

22 Fenn, C. (2006) *Like a Good Wine*. Water & Environment Magazine. Vol 11:5, May 2006.

23 HR Wallingford Ltd. (2005) *Effect of Climate Change on Rivers and Groundwater*. Edge. Vol September 2005.

24 Intergovernmental Panel on Climate Change. (2001c) *Climate Change 2001: Impacts, Adaptation and Vulnerability - Hydrology and Water Resources*. Intergovernmental Panel on Climate Change.

25 Conlan, K. (2003) *Effects of Climate Change on River Water Quality, Phase 3: Scoping Study*. UK Water Industry Research, London.

26 Humphrey, N. (2001) *Modelling the Effects of Climate Change on Water Quality in Rivers and Reservoirs*. UK Water Industry Research, London.

27 ADAS. (2006) *Climate Change*. Accessed on 9 October 2006 from http://www.adas.co.uk/water/climate.html.

28 UK Climate Impacts Programme. (2006) *About UKCIP*. Accessed on 30 September 2006 from http://www.ukcip.org.uk/about/.

29 UK Climate Impacts Programme. (2001) *REGIS: Regional Climate Change Impact and Response Studies in East Anglia and North West England*. UK Climate Impacts Programme, Oxford.

30 House of Lords. (2006a) *Water Management, Volume I: Report*. *HL Paper 191-I*, UK Parliament, London.

31 Water UK. (2006) *About Water UK*. Accessed on 18 August 2006 from http://www.water.org.uk/home/about.

32 House of Lords. (2006b) *Minutes of Evidence taken before the Science and Technology Committee (Sub-Committee I)*. UK Parliament, London.

33 Downing, T. E., Butterfield, R. E., Edmonds, B., Knox, J., Moss, S., Piper, B., and Weatherhead, E. (2003) *Climate Change and the Demand for Water: Final Report*. Stockholm Environment Institute, Oxford.

34 Environment Agency. (2006q) *The Climate is Changing: Time to Get Ready*. Accessed on 2 October 2006 from http://www.environment-agency.gov.uk/yourenv/639312/641094/642206/642375/100..

35 Environment Agency. (2005) *The Climate is Changing: Time to Get Ready*. Environment Agency, Bristol & London.