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Groundwater and climate change research scoping study

Groundwater Management Programme

Internal Report IR/06/033

BRITISH GEOLOGICAL SURVEY

GROUNDWATER MANAGEMENT PROGRAMME

INTERNAL REPORT IR/06/033

Groundwater and climate change research scoping study

C.R. Jackson, M. Cheetham, P. Guha

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Groundwater flooding at Compton, Berkshire during February 2001.

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British Geological Survey offices

Keyworth, Nottingham NG12 5GG

☎ 0115-936 3241 Fax 0115-936 3488
e-mail: sales@bgs.ac.uk
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Geological Survey of Northern Ireland, Colby House, Stranmillis Court, Belfast BT9 5BF

☎ 028-9038 8462 Fax 028-9066 2835
e-mail: gsni@detini.gov.uk

Maclean Building, Crowmarsh Gifford, Wallingford, Oxfordshire OX10 8BB

☎ 01491-838800 Fax 01491-692345
e-mail: hydro@bgs.ac.uk

Sophia House, 28 Cathedral Road, Cardiff, CF11 9LJ

☎ 029–2066 0147 Fax 029–2066 0159

Parent Body

Natural Environment Research Council, Polaris House, North Star Avenue, Swindon, Wiltshire SN2 1EU

☎ 01793-411500 Fax 01793-411501
www.nerc.ac.uk

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Summary

This scoping study has reviewed much of the published literature in the field of climate change and groundwater research. Whilst it is not exhaustive with regard to groundwater quality issues, most of the published literature relating to climate change and groundwater resources, particularly in the UK, is covered. Further work is required to identify current research needs relating to the effects of climate change on groundwater quality.

The study of the effects of climate change on water resources is a relatively immature area of scientific research. Consequently, there are relatively few studies relating to possible future effects of climate change on groundwater.

A large number of the studies that have been undertaken use perturbed historic climate data to examine the possible effects of climate change. This is not a good approach and more recent work applies data from global climate models in impact assessment. The different approaches of generating climate change scenarios and assessing their impacts is shown in Figure 1.

In addition to presenting a review of the published groundwater and climate change research this document provides an overview of (i) the scientific basis for climate change, both globally and within the UK, (ii) the UK Climate Impacts Programme, (iii) UK stakeholders in climate change research and (iv) groundwater-related socio-economic impacts of climate change. Finally recommendations are made for future BGS groundwater and climate change research.

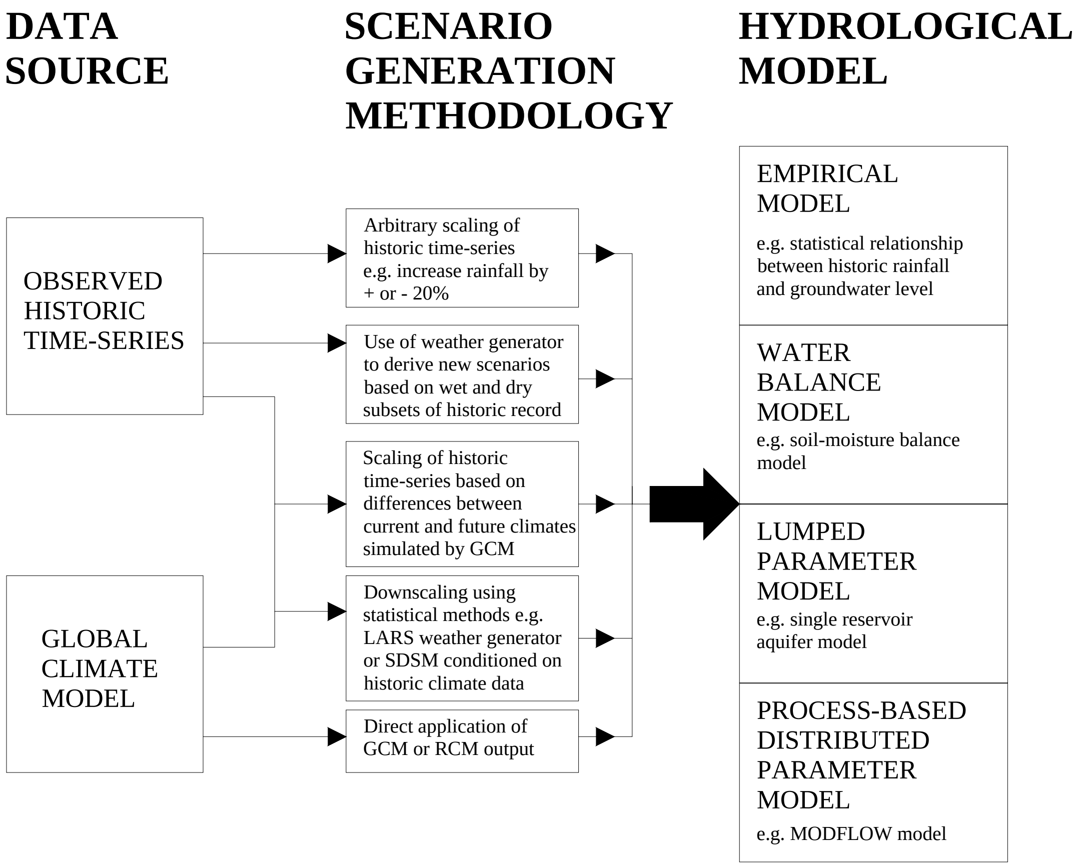

Figure 1 Summary of modelling approaches used in climate change impact studies

1 Introduction

Despite the importance of groundwater in the UK and the increasing recognition that the climate is changing, there has been limited assessment of the potential impacts of climate change on groundwater resources, and particularly of the potential effects of more frequent extreme events.

The link between climate change and increased greenhouse gas emissions is now well-established. In 1996, when the Intergovernmental Panel on Climate Change published their Second Assessment Report (IPCC, 1996) the effects of anthropogenic activity were not clearly distinguishable from natural climate variability (IPCC, 2001). However, subsequent research has indicated that it is very unlikely that the warming over the past 100 years has been due to natural climate variability alone and there is strong evidence that most of the warming observed over the last fifty years is attributable to human activities (IPCC, 2001).

In line with the warming of the global climate over the past 100 years, the climate of the UK has changed and average temperatures have risen. The instrumental record of temperature for Central England provides evidence for this and shows that twelve of the twenty-two warmest years between 1659 and 2005 have occurred after 1989. UK temperatures are predicted to increase by approximately 2 to 3.9°C by the 2080s with respect to the 1961-1990 average (Hulme et al., 2002) and winters will probably become wetter and summers drier. It is likely that there will be greater variability in climatic conditions, with extremes - flooding and drought - becoming more common.

Such predictions place a responsibility on water professionals to assess the impacts of climate change on water resources, which in much of the UK involves forecasting the impacts on groundwater resources; in the south-east of England groundwater sources provide up to 70% of the water used for public supply. Overall, groundwater resources are likely to be relatively robust in the face of climate change compared with surface water, due to the buffering effect of groundwater storage. Consequently, groundwater may have an important role to play in ameliorating the worst effects of climate change on the water environment, if managed appropriately. Management options may include schemes that use aquifers for short-term storage of water where no suitable sites exist for surface water reservoirs.

In recent years a significant amount of research has been undertaken to examine the possible impacts of climate change on surface-water, however, research examining the effects on groundwater is limited. The Groundwater Management Programme of the British Geological Survey is addressing this need and undertaking research into the impacts of climate change, as well as extreme events such as groundwater induced flooding and droughts.

Stakeholders in groundwater management have identified the need to provide tools to assess the impact of climate change on groundwater levels and the yields of pumping wells used for public supply and to address the effects of changes in climate variability rather than just average changes. However, in addition to addressing the needs of stakeholders such as water companies, there is a need for more scientific research.

This document summarises the findings of a scoping study to identify such research needs and proposes possible areas for BGS research. The scoping study is based on a review of the groundwater and climate change research, undertaken both in the UK and internationally, which has been published in peer reviewed literature and elsewhere e.g. the web.

2 Summary of the scientific basis for climate change

2.1 GLOBAL PERSPECTIVE

The Intergovernmental Panel on Climate Change (IPCC) was formed in 1988 by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP). Working Group 1 of the IPCC addressed the science of the climate system and climate change. Their First Assessment Report, published in 1990 (IPCC, 1990), described the status of global climate research and the understanding of climate change. The working group produced its Second Assessment Report in 1996 (IPCC, 1996) and this re-emphasised the phenomenon of increasing greenhouse gas concentrations in the atmosphere and the need to cut emissions. The Third Assessment Report (IPCC, 2001) incorporated an assessment of the most recent climate research and built upon the previous assessments. It is from this report that the following summary of the scientific evidence for climate change and, the role of natural and human agents in climate change is based.

2.1.1 The evidence for climate change

The scientific evidence that the global climate is changing is “unequivocal” (IPCC, 1990) and based on a suite of observational data. The following points are reproduced from the IPCC (2001) assessment report and represent a number of pieces of such evidence.

- The global average surface temperature has increased by 0.6 ± 0.2 °C since the late 19th century. It is very likely that the 1990s were the warmest decade and that 1998 was the warmest year on instrumental record since 1861.
- Weather balloon records indicate that, since the late 1950s, the overall global temperature in the lowest 8 km of the atmosphere has increased by 0.1 °C per decade.
- Satellite data show that that there are very likely to have been decreases of about 10% in the extent of snow and ice cover since the late 1960s.
- Tide gauge data show that global average sea-level rose between 0.1 and 0.2 metres during the 20th century.
- It is very likely that precipitation has increased by 0.5 to 1% per decade in the 20th century over most mid and high latitudes of the Northern Hemisphere continents and it is likely that there has been a 2 to 4% increase in the frequency of heavy precipitation events.

Changes in global climate are due to internal variability in the climate system and external factors, which can be both natural or anthropogenic. Evidence for anthropogenic causes of climate change are provided by the record of the three greenhouse gases, carbon dioxide, methane and nitrous oxide:

- Atmospheric concentrations of carbon dioxide, methane and nitrous oxide were relatively constant between the years of 1000 and 1750 at 280 ppm, 750 ppb and 270 ppb, respectively. However, since 1750, levels of these three gases have risen by 31%, 151% and 17%, respectively and continue to rise.
- The present carbon dioxide concentration has not been exceeded during the past 420,000 years and likely not during the last 20 million years (IPCC, 2001). About three-quarters of the anthropogenic emissions of CO_2 have been due to fossil fuel burning.

The IPCC (2001) state that there is strong evidence that most of the warming observed over the last fifty years is attributable to human activities. At the time of the IPCC's Second Assessment Report "the anthropogenic signal was still emerging from the background of natural climate variability" (IPCC, 2001). However, later research indicates that it is very unlikely that the warming over the past 100 years is due to internal variability alone. The following points are made by IPCC (2001) regarding the evidence for the impact of human activities on climate:

- Assessments based on physical principles and model simulations indicate that natural forcing alone is unlikely to explain the recent observed global warming or the observed changes in vertical temperature structure of the atmosphere.
- There is a wide range of evidence of qualitative consistencies between observed climate changes and model responses to anthropogenic forcing. Models and observation show increasing global temperature, increasing land-ocean temperature contrast, diminishing sea-ice extent, glacial retreat, and increases in precipitation in high latitudes in the Northern Hemisphere.
- Detection and attribution studies comparing model simulated changes with the observed record can now take into account uncertainty in the magnitude of modelled response to external forcing, in particular that due to uncertainty in climate sensitivity.
- Most of these studies find that, over the last 50 years, the estimated rate and magnitude of warming due to increasing concentrations of greenhouse gases alone are comparable with, or larger than, the observed warming.
- The best agreement between model simulations and observations over the last 140 years has been found when anthropogenic and natural forcing factors are combined (Figure 2).

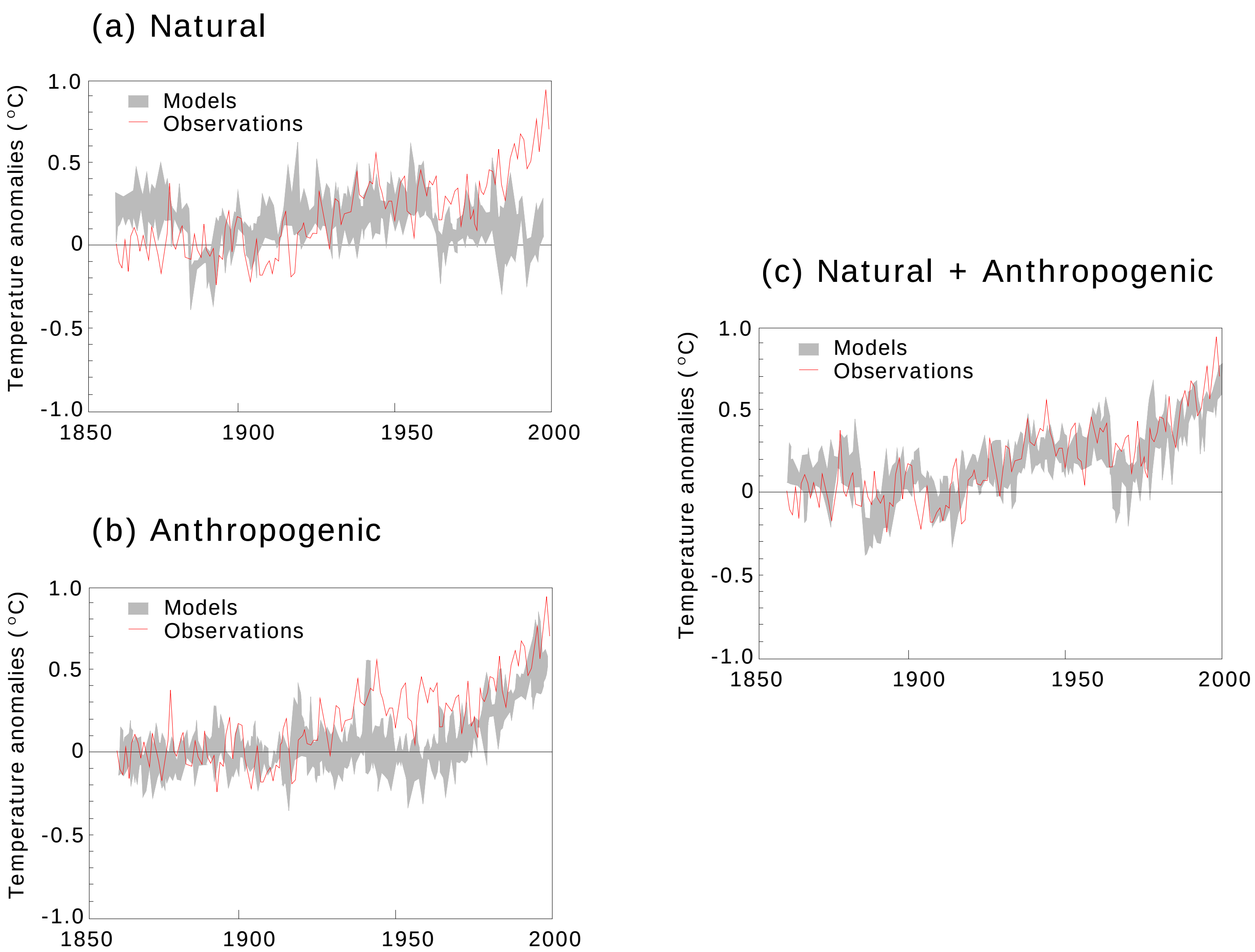

Figure 2 Comparison between observed and modelled temperature anomalies when (a) only natural forcing factors are simulated and (b) when anthropogenic forces are incorporated and (c) when all forcings are represented (after IPCC, 2001)

2.1.2 Global climate change in the 21st century

Scenarios describing the emission of greenhouse gases in to the atmosphere in the future have been developed by the IPCC (IPCC, 2000). These are referred to as the SRES scenarios (Special Report on the Emission Scenarios). Based on these scenarios, models have been used to make predictions about future atmospheric greenhouse gas concentrations and consequently, climatic conditions. With regard to the anthropogenic forces in the 21st century and the resulting climate impacts, IPCC (2001) summarise the finding of the current research:

- Emissions of carbon dioxide due the burning of fossil fuels are virtually certain to be the dominant influence on the trends in atmospheric CO_2 concentration during the 21st century.
- The globally averaged surface temperature is projected to increase by 1.4 to 5.8 °C over the period 1990 to 2100. These results are based on the full range of 35 SRES scenarios, based on a number of climate models.
- The projected rate of warming is much larger than the observed changes during the 20th century and is very likely to be without precedent during at least the last 10,000 years based on palaeoclimate data.
- Based on recent global model simulations, it is very likely that nearly all land areas will warm more rapidly than the global average, particularly those at northern high latitudes in the cold season.
- By the second half of the 21st century it is likely that precipitation will have increased over mid to high latitudes in winter. Larger year-to-year variations in precipitation are very likely over most areas where an increase in mean precipitation is projected.
- Global mean sea level is predicted to rise by 0.09 to 0.88 metres between 1990 and 2100, for the full range of SRES scenarios. This is primarily due to thermal expansion and loss of mass from glaciers and ice caps.

2.2 CHANGES IN THE CLIMATE OF THE UK

In line with the warming of the global climate over the past 150 years, the climate of the UK has changed and average temperatures have risen. Evidence for this is provided by the instrumental record of temperature for Central England: twelve of the twenty-two warmest years since 1659 have occurred after 1989. The thermal growing season for Central England, as identified from the daily temperature series, is now longer than at any time during its 229-year record period.

Hulme et al. (2002), summarise additional data that show the change in the UK's climate during the past 200 years. The following pieces of evidence are presented:

- There has been an increase in the frequency of "very hot" days in Central England since the 1960s with particularly extreme summers experienced during 1976, 1983, 1990, and 1995.
- The decade 1991 to 2000 was 0.5 °C warmer than the 1961-1990 average. The years 1990 and 1999 were the two warmest on record in Central England.
- Although there is no long-term trend in annual precipitation there is considerable variability in the annual precipitation the UK receives between individual years and decades. The year 2000 was the wettest in England and Wales in the twentieth century and the third wettest since records began in 1766.

- There is a trend in the seasonality of UK precipitation. The proportion of precipitation received in winter relative to summer has changed over time, so that winters have never been as wet relative to summers in about 240 years of measurement as they have been over about the last 30 years. Between the period 1770 to 1800 and the period 1970 to 2000, annual precipitation in England and Wales increased by only 24 mm yet winters became 55 mm wetter and summers 45 mm drier.
- After adjustment for natural land movements, the average rate of sea-level rise during the last century around the UK coastline was approximately 1 mm per year.

3 UK social and economic setting

3.1 BACKGROUND INFORMATION

Over 60 million people live in the UK. Average population growth is currently about 0.3% per annum. The 2001 census estimated that there were 21,660,475 households in England and Wales. The proportion of single-person households rose from 26.3% in 1991 to 30% (6.5 million) in 2001, and is projected to rise further in the future. Increase in the number of single-person households is likely to contribute to higher rates of domestic water use.

The UK is the fourth largest economy in the world, after USA, Japan and Germany, with a GDP of $1.87 trillion in 2005. Per capita GDP in the same year was $30,900. The UK is ranked 12th in the world in terms of per capita GDP.

The average growth rate of the UK economy is about 2% per annum. The services sector (banking, insurance, business services, etc.) is the largest and fastest-growing sector of the economy, accounting for about 73% of GDP. It is followed by the industrial sector, the share of which has been declining over time. Primary energy production (coal, oil, natural gas) is an important industry, accounting for 10% of GDP. The agricultural sector accounts for 1% of GDP and 1.5% of the labour force. Agriculture is intensive and highly mechanized.

Environmental taxes currently yield about £35 billion in revenue to the government. Two-thirds of this is made up of duty on hydrocarbon oils such as petrol and diesel.

Government spending on measures to protect the atmosphere and to prevent climate change fell from £313 million in 2003 to £250 million in 2004.

3.2 GOVERNMENT POLICY / UK LEGISLATION

The UK Government sees itself as a leader in the field of climate change, particularly in emission reduction. Climate change was made one of the major themes of the UK presidency of both the G8 and the EU in 2005.

The UK Government’s document *Climate Change – the UK Programme* (DETR, 2000) was published in 2000 and is currently under review. In this document it is stated that “the Government and the devolved administrations believe that the UK will benefit from strong action to tackle climate change”. The aims of the climate change programme include: safeguarding the UK’s competitiveness, tackling social exclusion, reducing harm to health, focusing on cost effective policy options and looking at targets beyond the Kyoto period (2010). Policy can be divided into two main strands: reducing the severity of climate change through greenhouse gas emission reduction, or *mitigation*, and forming policies and guidance on how to adapt to climate change, or *adaptation*.

The core of the programme is mitigation of climate change through a reduction in greenhouse gas emissions. The commitment given in the DETR (2000) report was to reduce emissions of carbon dioxide by 20% below 1990 levels by 2010. The Kyoto Protocol, which came into force in February 2005, commits the Government to reducing emissions of six greenhouse gases by 12.5% below 1990 levels by the period 2008-2012. By 2004 greenhouse gas emissions were 12.5% below 1990 levels and projected to fall to 20% below the same levels by 2010 (DTI, 2005). Emissions of carbon dioxide however were only 4.5% below 1990 levels. A longer-term goal is to reduce carbon dioxide emissions by 60% by 2050. Emission reduction policies include regulatory instruments for encouraging energy efficiency (the climate change levy), an emissions trading scheme and increasing the supply of renewable energy to 10% by 2010.

DETR (2000) states that "adaptation to the impacts of climate change will require substantial investment. Uncertainties about the extent and magnitude of these impacts will remain, but action cannot be deferred until all the questions are answered. Decision making will need to accommodate the uncertainties."

Adaptation and impact studies are currently being undertaken by a number of public and private sector organisations using tools generated by the UKCIP. Regional climate change partnerships form a crucial focus of adaptation activity. Strategies to adapt to climate change, such as the 25-year plans required from water companies, are beginning to be developed but as yet little practical activity has occurred. Future flood defence planning (Evans et al., 2004a, 2004b) and implementation of EU legislation (such as the Water Framework Directive) also need to account for predicted trends in climate.

4 UK Climate Impacts Programme (UKCIP)

4.1 BACKGROUND

UKCIP was established in 1997 by the Government to generate the data and information necessary to allow decision makers, not limited to the public sector, to carry out long-term planning and adaptation studies for climate change. UKCIP has also provided a number of tools to help stakeholders carry out adaptation studies, the most important of which is a set of common climate change scenarios. These tools are freely available to those carrying out adaptation studies.

4.2 UKCIP CLIMATE CHANGE SCENARIOS

The flagship output from the UKCIP studies is climate change scenarios for the UK. These scenarios describe the change in temperature, rainfall, sea level and a range of other climate variables for the remainder of the century. To date, two sets of scenarios have been produced: the first in 1998 (Hulme and Jenkins, 1998) and the second in 2002 (Hulme et al., 2002). The 2002 scenarios are generally more detailed than the 1998 scenarios, especially with respect to spatial resolution across the UK, and are described here. The 2002 scenarios also incorporate a number of improvements in climate modelling which are (at least implicitly) assumed to lead to improved ability to predict future climate based on a given emission scenario when the outputs of the climate change scenarios are being used in impact studies.

4.2.1 Emissions Scenarios

The climate change scenarios are the result of running a climate model based on a selection of the greenhouse gas emission scenarios developed by the IPCC (2000). The emissions scenarios predict the growth of greenhouse gas emissions based on “storylines” describing a future world. UKCIP has picked out four scenarios to represent the range of growth of greenhouse gases envisaged. The scenarios do not account for any interventionist policy to reduce or restrict the growth of greenhouse gases. Neither do they make any predictions about land use change driven by socio-economic factors, which are therefore not accounted for in the UKCIP02 scenarios. The scenarios are termed Low, Medium-Low, Medium-High and High. The estimated concentrations of CO_2 in the atmosphere range from 540 ppm for the Low scenario to 920 ppm for the High scenario compared with a pre-industrial value of 280 ppm.

4.2.2 Climate change scenarios

The emissions scenarios are used in a coupled ocean-atmosphere global model to generate climate change scenarios. This is used to drive an atmospheric model at higher spatial resolution, which in turn is used to drive a regional climate model for Europe at a yet higher resolution. The final output of the modelling process is on 50 km grid squares. This is one of the major advantages of UKCIP02 over the 300 km resolution UKCIP98. However, the “double nesting” of the models has a high computational cost, meaning that only a limited number of regional experiments can be carried out. The Medium-High emissions scenario was directly simulated using the regional model for the thirty-year period 2071 to 2100 (referred to as the 2080s). Climate variables were then created for other time periods (the 2020s representing 2011 to 2040 and the 2050s representing 2041 to 2070) and the remaining emissions scenarios by using scaling factors. Scaling factors for the other scenarios were derived by comparing the global-average temperature change for the four emissions scenarios for the 2080s. The respective global-average temperature changes for the earlier periods were then used to scale the results from the 2080s.

4.2.3 Data generated by the climate models

The data available as the outputs of these experiments are shown in Table 1, which has been taken from the UKCIP website (www.ukcip.org). The 5 km gridded data are based on a simple interpolation between the 50 km grid and 5 km grid, except for rainfall, which is distributed to account for topographic variations.

The data represent the simulated daily weather over a 50 km grid square rather than from a single meteorological station. Daily time-series of the weather "observed" in the scenarios will differ statistically from the 50 km grid square output. There are two tools recommended in the UKCIP02 Scientific Report (Hulme et al., 2002) for distributing the 50 km data and generating surrogate daily weather sequences. These are the LARS Weather Generator and the Statistical Down Scaling Model.

4.2.4 Predictions

Based on the UKCIP02 model, the 2080s the total range of temperature variation for all parts of the UK and all scenarios is 1 to 5 ºC warming, with greater summer warming in the south and east than the north and west and greater warming in the summer and autumn than in the winter and spring. Average annual precipitation is predicted to remain about the same, but winters will be wetter by up to 30% and summers drier by up to 50% depending on the scenario and region. Other variables such as soil moisture, humidity and wind speed are also predicted with varying degrees of confidence.

Sea level rise is predicted to be (uncorrected for changes in land height) between 23 and 36 cm. However the IPCC predictions from global models are between 9 and 69 cm, which correspond roughly with the range of uncertainty (±50%) suggested for users of the UKCIP02 scenarios. Most of the rise in sea level is accounted for by thermal expansion of the ocean, with melting of the glaciers and the Greenland ice sheet being roughly offset by a slight expansion of the Antarctic ice sheet. However, due to the complexity of the processes involved considerable uncertainty is attached to these estimates.

It should be noted that for all scenarios the climate changes predicted for approximately the next 30 years are relatively similar. This is because the climate over this time period has been determined by historic emissions. However, significant divergence of the climate change scenarios occurs after this.

4.2.5 Uncertainties

There are a large number of uncertainties associated with the climate change scenarios. They may be broadly divided into emissions uncertainty or uncertainty about the rate at which future anthropogenic emissions will occur, and scientific uncertainty or uncertainty about the scientific basis of the processes which the climate models represent.

Table 1 Data available from the UKCIP02 climate change scenarios

	Model simulated baseline 50 km grid (1961-1990)	Climate change scenarios 50 km grid (2020s, 2050s, 2080s)	Climate change scenarios 5 km grid (2020s, 2050s, 2080s)	Monthly time-series 5 km grid (2011-2100)
Maximum temperature	Yes (°C)	Yes (°C)	Yes	No
Minimum temperature	Yes (°C)	Yes (°C)	Yes	No
Daily mean temperature	Yes (°C)	Yes (°C)	Yes	Yes
Total precipitation rate	Yes (mm/month)	Yes (%)	Yes	Yes
Snowfall rate	Yes (mm/day)	Yes (%)	No	No
10 m wind speed	Yes (m/s)	Yes (%)	Yes (knots)	No
Relative humidity	Yes (%)	Yes (%)	No	No
Total cloud in long wave radiation (fraction)	Yes (%)	Yes (%)	Yes	No
Net surface long wave flux	Yes (W/m^2)	Yes (W/m^2)	No	No
Net surface shortwave flux	Yes (W/m^2)	Yes (W/m^2)	No	No
Total downward surface shortwave flux	Yes (W/m^2)	Yes (W/m^2)	No	No
Soil moisture content	Yes (mm)	Yes (%)	No	No
Mean sea level pressure	Yes (hpa)	Yes (hpa)	No	No
Surface latent heat flux	Yes (W/m^2)	Yes (W/m^2)	No	No
Specific humidity	Yes (g/kg)	Yes (%)	No	No

Emissions uncertainty is not quantitatively dealt with by UKCIP02. No probability has been attached to any emissions scenario by the IPCC and it is unlikely that this will be done in the future. Future emissions of anthropogenic greenhouse gases will depend on a number of factors not accounted for in the IPCC (2000) emissions scenarios including future policies, technologies and political circumstances. The emissions scenarios therefore represent a seemingly reasonable "bracketing" of potential future emissions, but not all possible future paths.

Scientific uncertainty exists about a number of processes in the climate models including the following that are highlighted in the UKCIP report:

- Calculations about how greenhouse gas emissions will affect atmospheric concentrations, e.g. in a warmer world microbes emit more CO_2 and might switch from being a net sink (as they are at the moment) to a net source.
- Calculations about the radiative forcing arising from this change in the atmospheric level, although this is well understood for greenhouse gases the role of sulphate aerosols in cooling is uncertain.
- Calculations about the response of large-scale climate to radiative forcing. Uncertainty on this is only currently dealt with by inter-model comparisons, and cannot be dealt with probabilistically.
- The natural variability of climate, which on a scale of years or longer might exceed the scale of climate change.
- Uncertainty arises from downscaling to finer resolutions using the nested model approach. At present no estimate of the scale of this problem exists.
- The method of pattern scaling used to generate additional regional scenarios from one regional and a number of global scenarios makes the assumption that the distribution of weather patterns will remain approximately constant.

Currently the magnitude of these uncertainties can only be dealt with by inter model comparison. These inter model comparisons have been used to assign high, medium or low confidence to the predictions made by UKCIP, and to highlight variables such as wind speed for which no confidence level can be assigned. Future work is planned to quantify these uncertainties, and work is being carried out currently to allow global models to predict future climates probabilistically. The natural evolution of this work is to progress towards probabilistic regional scale models, but this outcome is currently some years in the future.

Uncertainty of the climate change scenarios using inter model comparisons is summarised as follows. Confidence in annual average changes of temperature and precipitation is high, as is the prediction of wetter winters. The prediction of drier summers is of medium confidence. Predictions of wind speeds are not able to be assigned any relative confidence level.

4.3 UKCIP SOCIO-ECONOMIC SCENARIOS

The UKCIP recognises that it is not possible to predict the impacts of climate change without taking into account future social and economic changes:

> *"Whilst the use of climate scenarios as inputs into vulnerability, impact or adaptation assessments is well established, there is far less experience of using socio-economic scenarios. However, studies to assess climate change impacts suffer from serious weakness if by default they merely assume that the projected future climates will take place in a world with a society and economy similar to today" (UKCIP, 2001)*

The way in which the economy and society evolve in the future will determine the response and degree of adaptation to climate change, which in turn will influence the nature and scale of climate change impacts.

As a result, four socio-economic scenarios – *National Enterprise*, *Local Stewardship*, *World Markets* and *Global Sustainability* – have been developed by the UKCIP, to be used in conjunction with the emissions and climate change scenarios. The scenarios are illustrated in Figure 3. They have been constructed around two broad qualitative dimensions:

- **Governance, and the capacity of institutions at different levels to manage change**. For the UK, this will be greatly influenced by global and EU-level developments, as well as developments within the nation's political and administrative system. On the one hand, individual nations (and regions within nations) may become more autonomous. On the other hand, globalised economic and political systems may become the norm, with relatively limited regional autonomy.

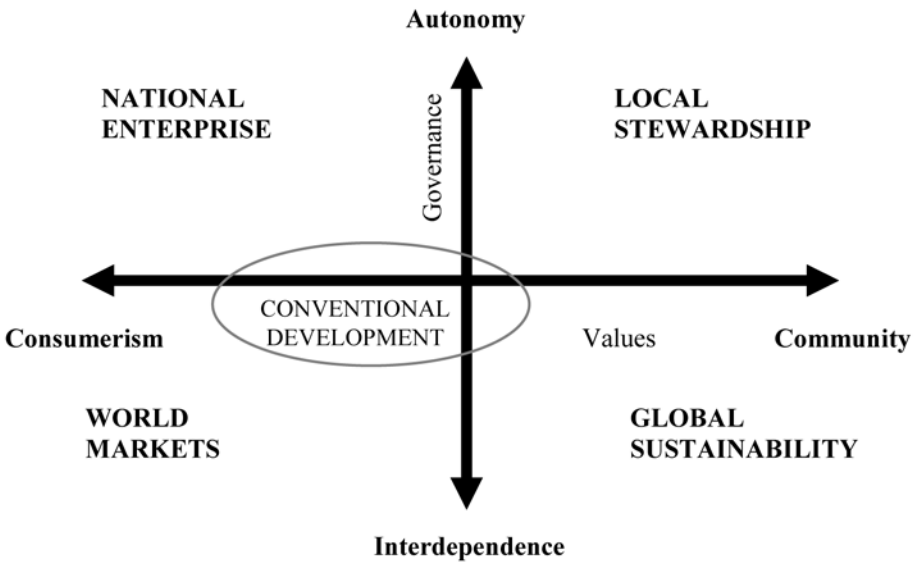

Figure 3 UKCIP socio-economic scenarios for the UK

- **Orientation of social and political values**. Societal values may swing towards greater consumerism in the future, implying a strong and sustained interest in maximising economic growth. Alternatively, concern for the common good or community welfare may predominate.

Other dimensions of socio-economic change – such as demography and settlement patterns, the composition and rate of economic growth, and the rate and direction of technological change – are also important, but are considered to be associated to a greater or lesser extent with governance and values.

The scenarios have been developed for two time periods: the 2020s and the 2050s.

The four scenarios present very different visions of the future, which in turn lead to different predictions about water demand and use. A greater interest in community welfare (*Local Stewardship* and *Global Sustainability*) appears to be linked with greater concern for environmental issues and an interest in sustainable development. Therefore, if UK society moved in this direction in the future, it is expected that water demand would not increase (and would actually decrease in the *Local Stewardship* scenario) due to the adoption of demand management measures. Water quality would improve due to the reduced use of chemical fertilisers and pesticides in agriculture.

On the other hand, if social and political values are motivated by consumerism in the future (*National Enterprise* and *World Markets*), it is likely that the demand for water would increase substantially, due to economic growth combined with minimal concern for environmental issues. Water quality would be expected to decline, due to increased use of chemicals in agriculture. In the *National Enterprise* scenario, supply difficulties could emerge in areas where urban and population pressures are at their peak, such as the south and south east of England.

Although the UKCIP lays stress on integrating climate change and socio-economic scenarios in climate impacts studies, most studies tend to assume a ‘business as usual’ approach or make only limited adjustments, in order to avoid dealing with the complexities involved in the use of socio-economic scenarios. A notable exception is the RegIS study (Holman et al., 2002), which is described in a subsequent section.

5 Stakeholders in groundwater & climate change impact assessment / research

5.1 INTERNATIONAL GOVERNMENT

The premier international organisation supplying data on climate change is the IPCC, whose role is to assess the best available scientific, technical and socio-economic information on climate change from around the world. The IPCC publishes Assessment Reports (consisting of comprehensive scientific, technical and socio-economic information on climate change, its causes, possible impacts and related response measures), Special Reports (on particular topics), Methodology Reports, and Technical Papers. A technical paper on Climate Change and Water Resources is due to be published in 2007. The IPCC also organises workshops and conferences, and disseminates observed and modelled climate data. These data are publicly available through the IPCC website. No water resources related workshops are due to be held in 2006.

One source of EU funding on climate change has been through the Interreg programme (e.g. Adaptation and Mitigation - an Integrated Climate Policy Approach, a project undertaken by a number of German, Austrian and Italian authorities or Water Management in the 21st Century suggested as a project by a Dutch consortium). However Interreg III is due to finish in 2006 and there is no indication as to what will replace it.

The principal EU organisation with an interest in climate change is the European Environment Agency (EEA). The EEA has the twin aims of supporting sustainable development and achieving measurable improvement in Europe's environment by providing relevant information to policy makers and members of the public. One of the instruments for the EEA to generate information is through the European Topic Centres (ETC). Currently there are ETC on air and climate change and also on water. The water consortium is lead by WRC. UK interest in the climate change consortium is from the University of East Anglia (UEA). Proposals for ETC for the period 2007 to 2010 are currently requested by the EEA.

5.2 NATIONAL GOVERNMENT

In the UK the Government funds a large part of work on the impacts of climate change either directly or indirectly through the Department for the Environment, Food and Rural Affairs (DEFRA). Not only do DEFRA fund the Hadley Centre, UKCIP the Environment Agency (EA) and English Nature (EN), but also directly commission research. Relevant agencies sponsored by DEFRA are considered under their own headings. One example of a directly funded project was entitled *Scoping study of potential impacts of climate change on nutrient pollution (of water) from agriculture* undertaken by ADAS (2004). No climate change or groundwater related proposals are currently given on the DEFRA website.

UKCIP is not a funding body, but coordinates research between different stakeholders by activities such as establishing climate change partnerships in six of the nine English regions.

The EA is involved in climate change both in mitigation and adaptation. In mitigation the EA regulates certain industrial emissions and is likely to be involved in emissions trading in some capacity. In adaptation the EA has particular interests in water resources and flood defence. The EA published a 25-year strategy for water resources in 2001 (Environment Agency, 2001) that considered climate change. This strategy has undergone annual updates, and predicted increased pressure on water resources due to both increased usage and climate change. The strategy recommended both increased water efficiency measures and building of new reservoirs. The EA also has a research programme into climate change, including (but not limited to) an entire "thematic programme" identified in its science strategy. Currently there are no proposed research projects on groundwater and climate change identified on the EA website.

5.3 REGIONAL AND LOCAL GOVERNMENT

Presently there is no known large-scale investment in climate change mitigation or adaptation and no known central government requirements on local government for action on climate change. However a number of local councils are producing strategies and scoping studies (e.g. Devon County Council, 2005) outlining their initial response to climate change. The voluntary *Nottingham Declaration on Climate Change* sets out a number of actions for local government and to the middle of 2005 had been signed by 86 members of the Local Government Association. It should be noted that the actions and duties relating to the water environment are minimal compared to some of the other stakeholders.

Southern Region (EA) has obtained UKCIP02 data to use in a rainfall-runoff model.

5.4 PRIVATE SECTOR

In 1993 the UK water companies set up UK Water Industry Research (UKWIR) to provide a common research body for issues relating to the water industry. The majority of work is put out to competitive tender, but UKWIR also collaborates with various research institutes to produce reports. The research is split into a number of topic areas the most relevant of which is the *Climate Change and Water Resources* topic area. Current and future projects are listed on the UKWIR website. Next year two projects are proposed in the Climate Change topic area one of which aims to provide an assessment of the impact of climate change on aquifer storage and the yield of groundwater sources. Currently, there appears to be no regulatory requirements on water companies to plan for extreme events over the *long-term* in the contaxt of climate change.

The Mining Industry Research Organisation (MIRO) is a not for profit company managing research on behalf of the mining industry. MIRO intermittently funds water resource or quality related projects, although none of the recent projects managed by the company has related to climate change.

The Association of British Insurers and the insurance industry have a strong interest in the impacts of climate change on their business. Of particular relevance is the risk of flooding. Although groundwater flooding is of less concern than fluvial or coastal flooding it is still of concern. There seems to be little science research conducted by the ABI or its members, although there is plenty of research translating scientific reports (such as the Office of Science and Technology, 2004) into the risks applicable to ABI members.

There is clearly a major potential challenge for farming in climate change. The impacts and possible mitigation measures are listed in NFU (2005). Most of the science research relating to farming is sponsored by government in one form or another. NFU (2005) considers potential requirements to increase irrigation, along with the effects of increased winter rainfall such as water-logging of soil.

A number of consultants have undertaken work for a variety of clients using the UKCIP02 data. Atkins and Entec are major users of UKCIP02 data, and both of these consultants have made predictions about groundwater recharge or potential evapotranspiration.

5.5 RESEARCH BODIES AND UNIVERSITIES

One of the major centres of climate change research in the UK is the Tyndall Centre. This centre is a consortium of a number of universities together with CEH and is funded through a five year grant from three of the UK research councils (NERC, ESRC and EPSRC). The Tyndall Centre currently divides its research programme into 4 themes: integrating frameworks; decarbonising modern societies; adapting to climate change; and sustaining the coastal zone. Together with the Hadley Centre it is responsible for generating the UKCIP02 climate change scenarios. A full list of their current and completed projects can be found on their website (www.tyndall.ac.uk). At present few projects directly relevant to the impacts on groundwater are being carried out by the Tyndall Centre, although one project has developed a hydrological impacts model which generates data on river flows. The Tyndall Centre encourages other researchers to contact it with ideas for collaboration and also offers funding.

The Hadley Centre, which is a part of the Met Office, aims to monitor climate change, understand the mechanisms which cause climate change and model past, present and future climates. The principle relevant output from the Hadley Centre is UKCIP02, although their researchers collaborate with other institutions, and have produced a number of papers and reports which may be of use to a groundwater impact assessment.

The following universities have obtained UKCIP02 data and are therefore active in climate change impact research in some way:

- Birmingham.
- Bristol.
- Cambourne School of Mines.
- Cambridge.
- Cranfield.
- Durham.
- Edinburgh.
- Heriot Watt.
- Leeds.
- Loughborough.
- Newcastle.
- Nottingham Trent.
- Oxford.
- Reading.
- Sheffield.
- Southampton.
- University of East Anglia.
- University College London.

Many of these uses are for MSc or BSc projects. However a number of projects of longer duration have been undertaken including assessment of the water resources of the North Kent Marshes (UCL), a PhD on groundwater and climate change at Southampton, and another on long-term hydrogeochemistry in the Chalk at Reading.

6 Current and previous research

This section summarises the current and previous research related to groundwater and climate change research. For clarity the review is split into subsections, which predominantly relate to different components of hydrogeology e.g. climate change and *groundwater recharge*, or climate change and *coastal aquifers*. For most of these themes it has been possible to review much of the relevant literature. However, due to time constraints it has not been possible to review so much of the research relating to climate change and water quality. This is partly because this is a very broad topic area, but also because the scoping study has focussed on resource issues. Whilst there are significant research needs relating to the effects of climate change on groundwater quality, the associated uncertainties are generally more difficult to quantify than for groundwater resource and the impacts more greatly affected by management practice. It is for these reasons that the review has focused more heavily on groundwater *resources*.

6.1 CLIMATE CHANGE AND WATER RESOURCES

Arnell (1998) provides and overview of the potential impacts of climate change on water resources in Britain. Arnell highlights the important difference between the *effect* that climate change will have on water quantity and quality and the resulting *impact*. Impacts depend on a number of factors, but will be related to the current stress on the water supply system. Obviously a system currently under significant pressure is likely to experience a larger impact due to climate change.

Arnell (1998) reviews issues relating to climate change in the UK in relation to changes in the resource base, impacts on resources and changing management practises. Previous work by the same author is cited (Arnell and Reynard, 1996; Arnell et al., 1997), which examines impacts on UK river flows. These studies involved perturbing the inputs to “calibrated” hydrological catchment models according to climate change scenarios. The results of most of this modelling work indicate an increase in seasonality of river flow with reductions during summer. For example, the predictions indicate that river flows may decrease by up to 50% during summer months in the south-east of the UK. As Arnell discusses though, these types of models represent a worst-case approach to climate impact assessment because they are based on *current* catchment management practice.

Price (1998) noted that the south and east of the UK have more storage capacity than the north and west due to heavier reliance on groundwater over surface water reservoirs. This tends to mean that it is easier to manage water resources in the south and east to avoid supply problems. Under the scenario of warmer drier summers it is suggested that greater use will have to be made of groundwater storage in the north west, as well as conjunctive use schemes, an even distribution of wells to abstract groundwater uniformly, and artificial recharge schemes.

Bloomfield et al. (2003) develop a multiple-linear regression model to predict annual minimum groundwater levels using monthly rainfall data. This is then used to predict annual groundwater level trends under different future climates. Synthetic rainfall series are generated by perturbing historic rainfall data based on the UKCIP98 scenarios. The model is used to provide groundwater drought analyses for up to 1 in 200 year events for three observation boreholes with good historic records. The study suggests that “even given a small predicted increase in total annual rainfall, due to changes in seasonality and increased frequency of drought events, annual groundwater-level minima could fall in the future.

6.2 CLIMATE CHANGE AND GROUNDWATER RESOURCES / STORAGE

Cole et al. (1994) examine the potential effects of climate change on the yields of surface reservoirs and aquifers and, on the changes in saline intrusion in coastal aquifers and river estuaries. The basis of their investigation of changes in borehole yields is the development of a statistical time-series model of rainfall for the period 1931-1989. This model is used to construct 50-year precipitation sequences for "current" and "future" (2030) climatic conditions; the rainfall model of current conditions is adjusted to the year 2030 using predictions of the increase in precipitation from GCMs. Future recharge rates are then calculated using a rainfall-runoff model that takes the synthesised rainfall sequences and predicted actual evaporation rates as input. Using the resulting recharge sequences a yield/storage/reliability relationship is developed for a simplistic gravel aquifer. This is based on the application of a model that balances changes in storage with recharge, groundwater abstraction and spring flow, however, little information is provided regarding the formulation of this model.

Two of the earliest studies examining the impact of climate change on groundwater in the UK are presented by Wilkinson and Cooper (1993) and Cooper et al. (1995). Wilkinson and Cooper (1993) examine changes in aquifer storage and baseflow in three types of aquifer due to changes in the amount and seasonality of rainfall and evaporation. It is demonstrated that different aquifers show variable response times to climate change and that this is related to aquifer properties. Cooper et al. (1995) examine the response of Chalk and Permo-Triassic sandstone aquifers to warmer, wetter winters and drier summers.

Querner et al. (1997) use a MODFLOW model in the Noor Basin, a strongly groundwater dominated catchment, in the Netherlands and assumed 20% increases and decreases in recharge due to factors that could include climate change. It was found that the reduction in drought due to a 20% increase in recharge was less than the increase in drought due to a 20% decrease in recharge.

Neff et al. (2000) examine possible changes in groundwater level due to climate change in Pennsylvania, US, by undertaking a statistical analysis of the historic relationship between groundwater levels and precipitation. The process involves grouping the borehole groundwater level records by "precipitation-based regions" and normalising the hydrograph data to account for differences in geology. The groundwater levels are then averaged within each of the five precipitation-based regions. The resulting five time-series of normalised groundwater levels is then related to historic climate data using the following procedure:

> *"A stepwise regression suggested a relationship between groundwater levels and precipitation as far back as an 18-month lag. This presented a statistical challenge due to multicolinearity among lagged precipitation values. To alleviate this problem, a temporal principal component analysis was performed on the precipitation data to reduce the number of lagged precipitation values to a more manageable number of principal components. These components were then regressed as independent variables against the normalised regional mean groundwater levels."*

To predict future groundwater levels, this statistical model relating contemporary groundwater levels to rainfall is applied to the climate change scenarios from two GCMs.

Limbrick et al. (2000) use a semi-distributed rainfall-runoff model with inputs from three GCMs developed by the Hadley Centre in 1996 to model the River Kennet, UK. They concluded under all scenarios groundwater recharge and storage would be reduced due to a shortening of the recharge season and a reduction in total annual runoff.

Prior to describing their research in the impacts of climate on four European aquifers, Younger et al. (2002) provide a review of previous groundwater and climate change research and discuss some of the issues that are important to consider when using models in this context. They state that the few studies undertaken up to this time that examined the possible effects on aquifer of changes in climate were largely restricted to evaluations of changes in recharge and that these tended to assume that total groundwater discharge would equal total recharge under future conditions. That is, these studies did not consider the inter-annual or sub-annual variations in groundwater discharge rate and the degree to which an aquifer transforms a recharge time-series into a discharge time-series. Consequently, as the authors state, aquifer responses to climate change might show a significant lag, which may not be apparent by simply equating total recharge and total discharge.

Younger et al. (2002) also consider the applicability of models when using them to examine the effects of climate change. As they state, because it is inadvisable to apply empirical models, based on a relationship between inputs and outputs, to conditions that fall outside of the historic calibration period, the application of physically based process models is more defensible. The difficulties of linking climate change predictions to hydrological models are also discussed. Downscaling of GCM data to the catchment scale is stated to be an active area of research, which means that “specific climate change predictions tend to have an extremely short shelf life”.

Younger et al. (2002) adopt the approach of applying GCM output to physically based groundwater flow models to assess the effects of climate change in aquifers in the UK (Yorkshire Chalk) Germany, Spain and Mallorca. The link between the GCM and the UK groundwater model is made by obtaining GCM grid point estimates for mean temperature and mean precipitation from the UK Climate Impacts-Link project (www.cru.uea.ac.uk/link/). In this work ‘equilibrium’ GCM models are used which simulate the dynamics of the atmosphere with a fixed CO_2 concentration. Data from transient GCMs were not used because these models suffered from ‘cold start’ problems (i.e. problems associated with defining initial conditions) at this stage of development. Results are presented comparing the 10-year average behaviour at the end of the 50-year simulation period (2036-2045) with observed values for the period 1986-1995. For the Yorkshire Chalk aquifer, decreases in river flow were only predicted to occur under the ‘fossil-fuel free energy future’ scenario and thus groundwater resources may be expected to increase during the next forty years.

A further ten studies of the effect of climate change on a specified regional groundwater and linked surface water system are summarised (and necessarily simplified) in Table 2. All of these studies created synthesised data sets of weather for various periods in the 21st Century and used these data sets to drive various groundwater and rainfall-runoff models to draw conclusions about future climate.

The recent availability of data from GCMs and even RCMs is apparent as studies before 2000 tend to use hypothetical changes in temperature and precipitation only whereas studies after that date use outputs from climate modelling.

There are a variety of approaches in determining the sensitivity of the modelled climates, some studies use multiple climate change outputs from different models (e.g. Gellens and Roulin, 1998; Brouyère et al., 2004) whereas some only use one climate change model (e.g. Loáiciga, 2000). In examining the sensitivity of hydrological systems to climate change scenarios with differing temperature and precipitation variation Rosenberg et al. (1999) found total yield (defined as the sum of runoff and lateral flow) variations of between -57 and +30% and recharge variations of -75% to +8% with respect to the baseline period depending on scenario.

With the exception of Rosenberg et al. (1999), all of the studies summarised here that used GCMs or RCMs appear to have assumed CO_2 conditions of double the pre-industrial average and there has been no attempt to predict future emissions scenarios.

All studies use a historical weather sequence rather than stochastic weather generation, thus preserving the temporal and spatial structure of present weather patterns.

Only one of the studies (Brouyère et al., 2004) presented results applicable to the early part of the 21st Century (defined as 2010 to 2039). Curiously in this study one of the most extreme results for groundwater levels was obtained for this period. The reason given in the discussion is that this is due to the interaction between variation in temperature and precipitation. It might be expected that if there is to be a significant change in recharge (and hence groundwater levels) in the early part of this century the first signs of the trend may be apparent.

Results from the studies vary widely ranging from large increases in baseflow (Loáiciga, 2000) to large decreases in baseflow (Gellens and Roulin, 1998). Recharge also shows extreme variation, as do future potential groundwater levels.

None of the regional studies examine the historical records of recharge, precipitation, baseflow or groundwater storage in search of climate induced changes. The reasons for this are not given, but some of the difficulties of such an attempt are apparent from other studies:

- Although upward trends in temperature have been recognised in the UK, which are perhaps significant in terms of the overall anticipated climate change by 2100, no significant variation in annual total precipitation has been observed, although the seasonality of rainfall has changed (Hulme et al., 2002).

- When making predictions on runoff variation in UK catchments under climate change scenarios, Arnell and Reynard (1996) imposed trends from GCM outputs in temperature, wind speed, humidity and precipitation on existing time-series of daily weather data and modelled river flows. Examining the synthesised data from 1990 to 2050 they had difficulty detecting the trend in rainfall and runoff using either regression or Kendall’s tau statistic in the annual series of data, however the trends were apparent when decadal data were analysed.

- Reynard and Young (2002) made the observation that using an UKWIR methodology for estimating flows in the 2020s lead to significant predicted derogations of flows in the 2020s and recommended that work should be carried out to detect the beginning of a declining trend in total flows – if such a trend is not detectable then they concluded that the results of the predictions are of dubious value.

Table 2 Summary of groundwater and climate change modelling studies (GCMs listed at end of table and in Glossary)

Authors	**Catchment**	**Brief description**	**Method of creating climate change scenarios**	**Model**	**Early C21st**		**Mid C21st**		**Late C21st**		**Comments**
					Max (wet) result	**Min (dry) result**	**Max (wet) result**	**Min (dry) result**	**Max (wet) result**	**Min (dry) result**	
Allen et al., 2004	Grand Forks aquifer, British Columbia, Canada.	4 km wide valley sand and gravel aquifer.	Scaling output of CGCM2, GFDL and GISS GCMs.	Steady-state MODFLOW					GWL increases by up to 3.5 m.	GWL decreases by up to 2.1 m.	Climate change sensitivity assessed by changing recharge, derived from distributed recharge model, and river levels in groundwater model.
Brouyère et al., 2004	Geer Basin, Belgium.	Superficial and Tertiary sands and conglomerate over Chalk. Many adit well systems affect aquifer response	ECHAM4, HadCM2, CGCM1	Transient MOHISE finite element	GWL around present level.	GWL decrease by up to 7m.	GWL around present level or slightly above.	GWL decreases by up to 4 m. Decrease in baseflow - 40% of current rates in dry years.	GWL around present level or slightly above.	GWL decreases by up to 4 m.	Note ECHAM4 simulation shows early C21st as lowest GWL. Levels are taken from a single (representative?) hydrograph presented in the paper. No seasonal enhancement in any simulation.
Lewis et al., 2004	UK sandstone.	East and West Midlands Permo-Triassic sandstone aquifers	UKCIP02	Transient MODFLOW		8% reduction in annual recharge. 0.5-1.5 m reduction in GWLs.	15-20% reduction in annual recharge. 2-3 m reduction in GWLs.				Calculated reduction in recharge, of between 7 and 20% for different scenarios are stated to be large enough to warrant consideration of any potential impact on aquifer sustainability.
Croley and Luukkonen, 2003	Tri County Region, Michigan, USA.	Pennsylvanian Grand River and Saginaw bedrock aquifers, also glacial deposit aquifers.	CCCMA GCM (not specified) and Hadley GCM (not specified)	Transient MODFLOW			GWL average increase of 0.1 m, baseflow increase of up to 6%. Recharge increase of 4.1%.	GWL average decrease of 0.6 m. Baseflow decrease of up to 30%.			Scenario is 20 years centred on 2030.
Yusoff et al., 2002	Ely Ouse, West Norfolk, UK.		HadCM2 and scaling factors	Transient MODFLOW	8 mm increase in annual recharge. 60 cm increase in spring GWLs. 12% decrease in frequency of low GWLs.		13 mm decrease in annual recharge. 1 m decrease in winter GWL. 12% increase in frequency of low GWLs.				Most notable and consistent result of the simulations is the decrease in recharge expected in autumn for all scenarios as a consequence of lower summer PPTN and increased autumn PE.

Authors	Catchment	Brief description	Method of creating climate change scenarios	Model	Early C21st		Mid C21st		Late C21st		Comments
					Max (wet) result	**Min (dry) result**	**Max (wet) result**	**Min (dry) result**	**Max (wet) result**	**Min (dry) result**	
Kirshen, 2002	Charles River, Massachusetts, USA.	River deposits, sands and gravels with clay.	Estimated 2030 increase of 1°C and present precipitation and 1°C and +10% precipitation ("similar to some GCM outputs"), used CCCMA GCM for 2100.	Transient MODFLOW.			Recharge up by about 7%. Slight increase in GWL. No seasonal change.	Recharge about same. GWL about the same. No seasonal change. Slight decrease in regional groundwater levels under drought conditions.	Recharge up by about 7%. GWL increases. Drought conditions show decreased GWL by up to 0.6 m.	Recharge down by about 6%. GWL down by 0.2 m. GWL recessions continue later into the year.	
Limbrick et al., 2000	Kennet, UK.	Chalk downs.	HadCM1 and HadCM2	Semi distributed model simulating nitrogen in catchments using INCA model.			Total annual SMD increases for all years and scenarios. Higher % of effective rainfall occurs in spring and winter. Reduction in recharge period from 6 to 4 months. Groundwater storage decreases.				
Loáiciga, 2000	Edwards Aquifer, Texas, USA.	Karstic Edwards limestone formation. Recharge mainly from stream flow.	Scaling factors from VEMAP nested RCM.	Transient GWSIM finite difference.					Increase in baseflow by 17% to 162% above baseline.		Scaled using scenario based on $C0_2$ doubling.
Rosenberg et al., 1999	Ogallala Aquifer in Missouri Basin and Arkansas-White-Red Basin, USA.	Mainly winter recharge.	GISS, UKTR, BRMC	Water balance GIS based system. Note each basin has simplified land cover & soil etc.	Total yield (defined as runoff + lateral flow increases by up to 30%. Recharge remains roughly constant.	Total yield decreases by up to 57%. Recharge remains roughly constant.	Total yield increases by up to 33%. Recharge increases by 3%.	Total yield decreases by up to 56%. Recharge decreases by up to 75%.	Total yield increase by up to 38%. Recharge increases by up to 8%.	Total yield decreases by up to 54%. Recharge decreases by up to 72%.	Uses 30 scenarios, including using different models and CO_2 concentrations scaled with different mean global T changes. CO_2 concentrations of 365, 560 and 750 ppm are not given time scale but represented in this chart as early, mid and late C21st respectively. Specifically considered CO_2 effects on plants.
Gellens & Roulin, 1998	Eight different catchments, Belgium.	Low, medium and high groundwater storage catchments, all of about 100 km^2	7 scenarios based on GFDL, NCAR, Hadley, MPI results included in IPCC	Rainfall-runoff model					Increase in baseflow of 10% to 30%.	Decrease in baseflow of up to 30%	2×$C0_2$ scenario –assumed to represent the late C21st . High groundwater storage catchments are driven by yearly mean change in recharge and generally have increase in stream flow in most scenarios, low groundwater storage catchments have baseflow significantly reduced in summer under most scenarios.

Authors	**Catchment**	**Brief description**	**Method of creating climate change scenarios**	**Model**	**Early C21st**		**Mid C21st**		**Late C21st**		**Comments**
					Max (wet) result	**Min (dry) result**	**Max (wet) result**	**Min (dry) result**	**Max (wet) result**	**Min (dry) result**	
Anderson & Cheng, 1998	Trout Lake Basin, Wisconsin, USA.	Glacial sediments with a large number of groundwater fed lakes.	GCMs not used, ± 10% in recharge, rainfall, evaporation.	Steady state MODFLOW	Lakes high in the groundwater catchment are very sensitive to recharge changes and may dry up under -10% conditions. Stream flow will decrease under -10%.						
Querner et al., 1997	Noor, Netherlands & Belgium.	Chalk aquifer, small basin. 90% baseflow.	GCMs not used, recharge varied by ± 20%	MODFLOW	Low recharge increases drought duration by 70%, high recharge decreases drought duration by 30%.						
Panagoulia & Dimou, 1996	Mesochora, Greece.	Limestone catchment at high elevation with significant snowmelt contribution.	Fifteen scenarios with T increase of 1-4°C and precipitation change of between 0% and ± 20%. Also two GISS GCM scenarios for 2×C02 conditions, one scenario with temperature but no precipitation change, the other with temperature and precipitation change.	US National Weather Service Hydrologic Research Laboratory snow accumulation and ablation model and soil moisture accounting model (which includes a baseflow component).					GW storage increases by up to 15% in winter, remains the same in summer. Peak of storage shifts to earlier in the year under most scenarios.	GW storage decreases by about 5% decreases by up to 50% in summer. Peak of storage shifts to earlier in the year under most scenarios.	Ratio of baseflow to stream flow strongly affected by snow-melt, therefore not summarised here.

Summary of GCMs listed in Table 2

ECHAM4	Max Planck Institute , German Climate Research Centre.
HadCM2	Hadley Centre, UK.
UKTR	The Met Office, UK.
CGCM1	Canadian Centre for Climate Modelling and Analysis (CCCMA).
VEMAP	Climate & Global Dynamics Division, University Corporation for Atmospheric Research, USA.
GFDL	General Fluid Dynamics Laboratory, USA (see Bultot et al., 1988).
NCAR	National Centre of Atmospheric Research (USA).
GISS	Goddard Institute for Space Studies (USA).
BRMC	Australian Bureau of Meteorology Research Centre.

N.B. wet and dry corresponds to wet and dry GCM results, not wet, dry and average years in future scenarios.

6.3 CLIMATE CHANGE AND GROUNDWATER RECHARGE

Sharma (1989) presents one on the earliest studies examining the impact of climate change on groundwater recharge. In this study of the Swan Coastal Plain of Western Australia a one-dimensional unsaturated zone model based on Richard's equation is used to examine the effect of changing rainfall on recharge. The simulations show that recharge can be modified by a much larger proportion than rainfall, but that this depends significantly on the vegetation cover. The effect of changes in recharge under possible future climates on groundwater storage is examined using a one-dimensional analytical solution to flow in an unconfined aquifer.

Thomsen (1990) created an annual recharge time-series using a soil moisture balance model for the island of Samsoe (Denmark) from 1865 to 1983. This recharge time-series had a drought period in 1884-1909, and a wet period from 1964 to 1983. Thomsen concluded that recharge varied with climate, and that climate change scenarios potentially could lead to reduced recharge in a region of north-west Europe stretching from the south-west of France to southern Sweden.

Vaccaro (1992) estimate recharge for "pre-development" and 1980s land-use for the semi-arid Ellensburg Basin in Washington State, USA. An energy-soil-water balance model is used in conjunction with a synthetic daily weather generator that produces long time-series based on wet and dry period subsets of the historical record. It is found that groundwater recharge under 1980s land-use is less sensitive to variations in climate because of the effect of irrigation. Additional recharge scenarios were then developed by scaling the historic precipitation and temperature records using output from three different GCMs considering CO_2 doubling. These simulations predicted that the variability in the estimated annual recharge was less than that in the historic record and that the median annual recharge was between approximately 55 and 75% of that for the historic simulation. Vaccaro concludes by stating that the application of physically based model to semi-arid and arid regions depends on the plant community, soil properties and the availability of climate gauging stations. It is also stated that the use of recent climate information to make projections beyond about twenty years is inadvisable.

Green et al. (1997) investigate the impact of climate change on groundwater recharge in the subtropics of Queensland, Australia using the CSIRO9 GCM. This is coupled with a stochastic point weather generator (MWGEN) to produce realisations of daily climate variables with are fed into the WAVES soil moisture and unsaturated zone model (Dawes and Short, 1993). This soil-moisture balance model incorporates a representation of vegetation response and simulates the fluxes of mass and energy between the atmosphere, vegetation, and soil systems. Green et al. (1997) state that "Transpiration rates are dynamically related not only to atmospheric forcing and soil water availability but also to the state of the vegetation" and cite Dooge (1992) who states that meaningful predictions of the impact of climate change on recharge are not possible without an understanding of vegetation response. The modelling investigation indicates that in this region simulated transpiration and thus mean recharge change disproportionately with climate: for a 37% increase in mean precipitation recharge can double. This is primarily related to the increased frequency of long wet and dry periods. It is concluded that "The effects of rainfall amounts and timing of groundwater recharge can be amplified by the soil water system and dynamic response of vegetation".

Arnell (1998) briefly discusses the change in patterns of groundwater recharge, resulting from a predicted increase in winter rainfall and a shorter recharge season due to higher temperatures and, therefore increased potential evapotranspiration. The author states that the effect of the reduced recharge season is likely to outweigh the increased winter rainfall.

A number of papers on river flows make use of rainfall-runoff models to scope the possible impact on river flows. These models require estimates of potential evapotranspiration. Gellens and Roulin (1998) use temperature and precipitation from seven GCMs to estimate PE. As only temperature and precipitation were available for six models PE was estimated for one model with fuller information and then calculated for the remainder using a weighting based on temperature. No comment is made on the output from these calculations.

Arnell and Reynard (1996) estimated PE based on the Penman-Monteith equation using outputs from models produced for the UK Climate Change Impacts Review Group. In contrast to Bultot et al. (1988) humidity is assumed to decrease (see Arnell and Reynard, 1996). Net radiation is assumed to generally increase in winter and decrease in summer (reflecting the cloudiness implied by the rainfall changes). Wind speed is assumed to increase, although this has less impact on PE. One estimate of PE was made assuming only temperature changes, one assuming changes in all parameters, and the third assuming changes in the physiology of plants due to higher CO_2 concentrations. The first scenario gave a total range of increase in annual PE of 9 to 11% and the second an increase of to 29 to 36%. The third scenario was not fully developed due to uncertainties surrounding the responses of plants to climate change.

The Regional Climate Change Impact and Response Studies in East Anglia and North West England (RegIS, Holman and Loveland, 2001) used a surface water model based on empirically derived links between soil type and stream response to rainfall. Hydrologically effective rainfall (HER) is routed to a groundwater store or surface water in proportions based on the stream flow coefficient attached to the soil type (based upon the Hydrology of Soil Types or HOST data set). The rate of outflow from the groundwater store is determined by a constant based on the HOST class and the substrate hydrogeology. The model predicts (amongst other things) the baseflow component of the river, the changes in the volume of stored groundwater, long-term average groundwater recharge, and mean nitrate concentrations in groundwater. Long-term recharge is calculated as that proportion of HER routed to the groundwater store. HER was calculated using a crop model, with weather inputs based on historical data modified by outputs from the UKCIP98 report. The model was run at 5 km grid spacing. The project as a whole considered both climate change and socio-economic change. The outputs of the climate change only (for high and low emissions scenarios from the 2050's) catchment modelling are as follows. The increase in the length of the growing season leads to a reduced length of recharge season, as well as an increase in winter evapotranspiration, which are counterbalanced by increases in annual rainfall. For East Anglia under the high emissions scenario there are large reductions of up to 50% (for each 5 km grid square) in HER, with the low emissions scenario showing a lesser reduction in HER, translating into corresponding reductions in recharge. These reductions in recharge were minor under the low emissions scenario, but more serious under the high emissions scenario. For the north-west there is a general slight increase in HER under both scenarios, although localised decreases may occur, especially under the high scenario.

Eckhardt and Ulbrich (2003) investigate the impact of climate change on groundwater recharge and stream flow in the Dill catchment in Germany. They apply the eco-hydrological model, SWAT, which simulates how CO_2 concentration, rainfall, temperature and humidity affect plant growth, evapotranspiration and snow and runoff generation. Rosenberg et al. (1999) also apply the SWAT model to the Ogallala aquifer (see Table 2). Eckhardt and Ulbrich (2003) apply SWAT because they state plant stomatal conductance has been shown to decrease by up to 40% in increased CO_2 atmospheres, and this process must be represented in their study area where 70-90% of the rainfall is evapotranspired. In addition to estimates of recharge the SWAT model is used to simulate stream flows under different climate scenarios. Climate scenarios are generated by scaling historic climate time-series using differences between current and future climate as simulated by five GCMs. For a low emission scenario mean groundwater recharge and stream flow are predicted to decrease by 3% and 4%, respectively. For the high emission scenario mean groundwater recharge and stream flow are both predicted to decrease by 2.5%.

Herrera-Pantoja and Hiscock (in press) examine the impacts of climate change on recharge in East Anglia, UK by applying downscaled (5km resolution) data output from a regional climate model to soil-moisture balance models. This approach of using downscaled data, which take account of local topographic variations, differs from the method of scaling historical time-series using RCM output. Comparisons are made between recharge calculated using historic and predicted "future" climate data. Results are presented for a high emissions scenario for the 2020s (2011-2040), 2050s (2401-2070) and 2080s (2071-2100). In addition to a description of the average seasonal change in recharge, the *severity*, *persistence* and *frequency* of dry and wet periods are analysed. With regard to the change in summer recharge, the modelling predicts that summers will be 25% drier during the 2020s but that recharge will increase by 19% and 58% during the 2050s and 2080s, respectively. It is concluded that the approach of using the downscaled data needs comparison with the application of scaling factors to historical time-series based on RCM output.

6.4 CLIMATE CHANGE AND RIVER FLOWS

Arnell and Reynard (1996) examined twenty-one UK catchments with a rainfall-runoff model using scenarios from the UK Climate Change Impacts Review Group (CCIRG). Annual runoff increases by up to 20% in the wettest scenarios, but decreases by up to 20% in the driest. However all scenarios see a greater concentration of flow in winter. Scenario climate data were created by perturbing existing data for a 30-year time-series using outputs from CCIRG. When the perturbed time-series data were examined the impacts of climate change were not detectable in annual statistics, but could be seen in decadal data.

Querner et al. (1997) used a rainfall-runoff model for the Gulp and Haugland basins in Northern Europe and assumed temperature changes of 2 to 4 °C (hence affecting PE) and rainfall changes of ±10%. The number of drought events in both basins increased under higher temperature and lower rainfall scenarios, although a 10% increase in rainfall compensated for a 2 °C increase in temperature.

Gellens and Roulin (1998) used results from seven different GCMs to drive a rainfall-runoff model. Impacts on stream flow in the catchment were found to vary according to the physical properties of the catchment, but largely depended on, and followed, variations in rainfall predicted by the climate change scenario. GCM outputs with a high seasonal variation in rainfall were likely to cause a wider range of responses between catchments. Catchments with a high infiltration capacity tended to respond with smaller variations in surface water flow, corresponding to the sign of the change in rainfall. Baseflow increased in catchments with high groundwater storage for most GCM scenarios responding to the change in yearly mean rainfall. In low storage catchments GCM scenarios with drier summers tended to simulate lower baseflows. The authors noted that as the patterns of climate change vary they prefer to use a range of GCM results to drive models rather than a best guess, wettest and driest scenarios.

Neff et al. (2000) examine the possible effects of climate change on river flows in the Susquehana River Basin, US, by combining climate change scenarios from two GCMs to a water balance model of the basin. The water balance model takes mean monthly air temperature and total monthly rainfall as input. Uncertainty is incorporated into the results because of differences between the two GCMS (the Hadley Centre's HadCM2 model and the Canadian Climate Centre's, CGCMI model); the CGCMI model predicts much larger changes in temperature but smaller changes in precipitation compared to the HadCM2 model and this results in significant differences in predicted stream flows.

Hiscock et al. (2001) examine rainfall and surface water flow from the Bure, Nar and Wensum in eastern England and concluded that rainfall since 1931 has not shown any significant change that might be attributable to climate change. Similarly since 1960 there has been no change in the seasonal distribution or baseflow component of flows, which suggests that there have been no changes in the amount of groundwater recharge. It is suggested that climate change may lead to increased demand for irrigation water.

Dibike and Coulibaly (2005) investigate the differences in hydrological model output when using different downscaling methods to define sub-basin scale precipitation and temperature time-series from a GCM. Two hydrological models and two downscaling methods are applied to examine possible catchment flow regimes under climate change scenarios. The downscaling methods (one regression-based and one a stochastic weather generator) are available through the Canadian Climate and Impacts Assessment project (www.cics.uvic.ca/scenarios). The differences in the predicted trends for precipitation and river flow river flow between the models using the two downscaling methods provide a "clear indication that the outcome of a hydrologic impact study can be affected by the choice of any one particular downscaling technique and hydrological model combination over the other". However, the simulations do provide consistent predictions for some hydrological model output e.g. increase in low-flows during winter months.

6.5 CLIMATE CHANGE AND AGRICULTURE

The RegIS study carried out research into future agricultural land use under different socio-economic and climate change scenarios. The details of the models are not discussed here, but can be found in Holman & Loveland (2001). The model aims to optimise yields, and therefore changes in planting are based on the crop which will offer the best return. At the present time the East Anglian area of the study primarily consists of arable farms with some sugar beet, whereas the north-western area is primarily managed grassland or rough grazing. Climate change alone was found to be insignificant in altering crop areas.

6.6 CLIMATE CHANGE AND GROUNDWATER QUALITY

Possible changes in water quality are discussed by Arnell (1998). Much of this discussion focuses on surface water quality. However, issues relating to groundwater quality are also raised. These relate to:

- Changes in input of chemicals to catchment as a result of changing agricultural practice.
- Increases in temperature affecting the rate of de-nitrification more than that of nitrification, so nitrate concentrations should fall.
- Rises in temperature could increase the mineralisation of organic nitrogen in soil leading to increased inputs to the river channel.

Neff et al. (2000) provide a brief assessment of the possible changes in nitrate concentration at the bottom of a river catchment because of climate change. This is based on their work to predict changes in stream flow under different climate change scenarios (see Section 6.4). Projected stream flows are then used to assess future nitrate concentrations by applying these to a statistical model relating historic stream flow and nitrate time-series.

Under the RegIS project (Holman and Loveland, 2001) median groundwater nitrate concentrations in East Anglia were predicted to decrease slightly under the low emissions scenario, and decrease significantly under the high emissions scenario in some areas.

ADAS (2004) undertake a scoping study to address the scientific research required to improve the understanding of nutrient loss from agricultural soils under current and future climate and how that these processes should be modelled. The existing literature on the effect of climate on soil and vegetation processes is reviewed and this shows that very little modelling work has been undertaken in this area. It is stated that previous climate change impact studies have examined the effects on agriculture but have focused on changes in crop yields, crop types and possible farmer adaptation.

The important climate variables in the nutrient cycle/loss process are identified as rainfall volume and intensity, mean temperature, potential evapotranspiration and wind speed. In addition to representing these variables there are a number of key soil-vegetation processes that directly affect the availability and loss of N and P in the soil. This ADASs study applies two numerical models to examine the impact of climate change on nutrients in the soil. This requires the downscaling of climate data from the UKCIP02 scenarios and the LARS weather generator is used for this purpose. This provides daily data that “properly captures changes in the timing and intensity of rainfall events”.

ADAS (2004) also review the capabilities of various nutrient loss models to determine which are suitable for application in climate change impacts studies. The ANIMO model (Groenendijk and Kroes, 1999) is applied as this is capable of modelling both N and P loss. ANIMO is combined with the SWAP (Soil-Water-Atmosphere-Plant) model (van Dam, 2000) to simulate the soil-moisture water balance and crop growth. This coupled model is then validated for a site near Lowestoft, UK. The model is then applied to the climate change scenarios.

The project investigates the operation of the model under different future climates to determine its ability to simulate nitrogen and phosphorous loss under these conditions. However, the results obtained are not predictions of future behaviour because “they are based on only a limited number of weather years and do not incorporate all the changes in farm and land management that may be expected under altered climate”.

The comparison of the model results with historic observed data is reasonable, however, more detailed validation of the model over a range of site, soil and cropping conditions is stated to be required. The project concludes “that there is a range of suitable models available for modelling nutrient loss under climate conditions but that any analysis should look critically at how the timing of farm practices and crop development may interact nutrient flux processes”.

The British Geological Survey (2004) examine how climate change may impact on pesticide levels in the soil, ground and surface waters and air. In this study the question of whether the use of climate information in environmental exposure and fate modelling of pesticides will continue to be appropriate is addressed. A source-pathway-receptor approach is adopted to address how climate change will impact on pesticide fate and transport in the environment and a discussion of the main climate sensitivities of pesticide sources, pathways and receptors is presented.

It is stated that the overall effect of climate change on pesticide fate and transport is likely to be very variable and difficult to predict because of the uncertainties associated with the climate predictions, because of the complexity of the natural environment and, most importantly, because of the range of competing climate-sensitive processes that may have conflicting implications for pesticide fate and transport. For example, lower summer flows in rivers may lead to a significant reduction in dilution potential and hence to increased concentrations of pesticides in rivers, but higher temperatures during the summer will lead to increased potential for pesticide degradation and so have an opposite effect on pesticide concentrations. With regard to receptors the following points are made:

- In summer, mean river flows may decrease significantly contributing to a significant reduction in the dilution potential of surface water bodies potentially increasing pesticide concentrations if runoff or spray drift events occur.
- Reduction in annual minimum groundwater levels in the Chalk of up to about 2 m by the 2080s are possible but the implications for source yields and pesticide exposure at receptors is uncertain.
- The impact of climate change on baseflow to groundwater-dominated rivers, e.g. Chalk rivers, has not been systematically studied, and implications for changes in pesticide exposure due to changes in baseflow is very uncertain

Various mathematical models are used to predict the fate and transport of pesticide. Currently the organisation FOCUS have suggested a number of models and associated use scenarios for predicting surface and groundwater concentrations. FOCUS is a forum for the co-ordination of pesticide fate models and their use. The forum is an initiative of the European Commission to harmonise the calculation of predicted environmental concentrations of active substances of plant protection products. The British Geological Survey (2004) state that FOCUS have suggested a number of models and associated use scenarios for predicting surface and groundwater concentrations but that their applicability under future climate change needs to be assessed.

Although not a weakness of the climate change scenarios themselves, the main problem in applying the climate change scenarios in a research context is the present lack of understanding of the complex interdependencies of climate sensitive processes in the environment as a whole. In addition, the level of confidence that can be attached to any climate change impact assessment is limited by uncertainties associated with the effects of climate change on economic and social factors. Agriculture and agricultural practices are generally very responsive to social and environmental change. In the long-term, land-use change driven by changes in climate may have a more significant effect on pesticides in the environment than the direct impacts of climate change on specific pesticide fate and transport processes.

The summary of the findings and recommendations of the British Geological Survey (2004) are reproduced below.

- *The main climate drivers for changing pesticide fate and behaviour are changing rainfall patterns (changes in seasonality and intensity) and increased temperatures.*
- *The overall effect of climate change on pesticide fate and transport is likely to be very variable and difficult to predict.*
- *Some important source, pathway and receptor responses to climate change have been identified, but many of these responses have conflicting implications for*

pesticide fate and transport and the system needs to be assessed in a holistic manner if a full picture of pesticide fate is to be obtained.

- *There are probably mechanisms within the existing pesticide registration process to take account of most key climate change implications.*
- *In the long-term, land-use change driven by changes in climate may have a more significant effect on pesticides in the environment than the direct impacts of climate change on specific pesticide fate and transport processes.*

Four areas of work are identified that would enable the development of an improved understanding of the implications of climate change on the fate and transport of pesticides in the environment:

- *Climate sensitivity analysis of the FOCUS scenarios and models, particularly under extreme climate conditions.*
- *Systematic analysis of selected historic pesticide use, fate and transport and climate data.*
- *Catchment-based modelling study of pesticide behaviour under a range of climate change scenarios.*
- *A desk study to provide an overview of the relationships between climate-driven long-term land use change and the implications for pesticides use, fate and transport.*

6.7 CLIMATE CHANGE AND COASTAL AQUIFERS

Oude Essink et al. (1993a) summarise three case studies in the United States (Leatherman et al., 1984; Kana et al., 1984; Lennon et al., 1986) and one in the Netherlands (Oude Essink et al., 1993b) that examine the effect of increasing sea-level on saline intrusion into aquifers. The results of three of these studies suggest that saline intrusion resulting from sea-level rise would either probably not be significant or its impact would be outweighed by the existing contamination of the aquifers caused by historic over-abstraction. The study undertaken by Lennon et al. (1986) showed a more significant threat, however, this was due to increases in salinity in the Delaware River, New Jersey, which recharges the aquifer, and not due to direct sea-water ingress to the aquifer.

Cole et al. (1994) examine the possible effect of an increase of 0.6 m in mean sea level on the position of the saline interface in three coastal aquifers in the UK. The confined Lincolnshire Chalk, Otter Valley sandstone in Devon and, the Brighton Chalk block are chosen because “existing pumping is not itself inducing major extension inland of the natural saline wedge”. A finite element model of each aquifer is constructed and the Ghyben-Herzberg relationship is used to calculate the position of the saline-freshwater interface. By applying both current and predicted “future” recharge rates to the models and adjusting the pumping rates to avoid the abstraction of saline water, estimates of the change in safe yield due to climate change are made. This exercise predicts that safe yields only fall by approximately 1-2%, which are stated to be small compared to the reductions in abstraction that are generally required to negate the effects of historic over-exploitation.

Arnell (1998) briefly discusses the potential impacts of sea level rise on the viability of groundwater resources. The author reviews the work of Clark et al. (1992). It is stated that Clark et al. showed that the effects of sea level rise on yields would be minor and lead to a reduction of coastal borehole yields of 1-2% only and that this could easily be offset easily by moving the boreholes inland.

Sherif and Singh (1999) apply a variable density numerical groundwater model to examine the effect of sea level rise on two coastal aquifers: the Nile delta and the alluvial aquifer on the Indian coast at Channai. A numerical model of each aquifer is developed and used to simulate three possible future scenarios with higher sea levels and reduced fresh groundwater head due to additional abstraction. The effects of the changes are compared by examining the shift in the positions of concentration contours simulated using the steady-state models. The two aquifers show different responses to the scenarios, with saline intrusion increasing more significantly in the Nile delta. In the two scenarios simulated in which coastal abstraction is not adjusted, the 5 kg m^{-3} concentration contour moved inland by up to 4.5 km in the Nile delta, as measured along the bottom of the boundary. The simulations of the Channai aquifer predicted that the 1 kg m^{-3} concentration contour would move inland by less than 600 m inland. The difference is partly due to the greater thickness of the Nile Delta sediments; deeper aquifers or those with shallow hydraulic gradients are more vulnerable to conditions of sea-level rise. For comparison the UK drinking water limit for NaCl is 0.41 kg m^{-3}.

Lambrakis and Kallergis (2001) use geochemical models to examine ion exchange processes and the freshening of a saline coastal aquifer under a reduced pumping regime. These reductions in abstraction are necessary because of the over-exploitation of the aquifers under consideration and because of the anticipated effects of climate change. Changes in climate change are not, however, explicitly considered in the work. The results of the modelling give varying times for freshening under natural recharge conditions, when pumping is discontinued. For two of the three aquifers investigated freshening times are greater than 8000 years but for the third a freshening time of 15 years is predicted. These times are shown to depend mainly on cation exchange capacities and recharge rates of the aquifer.

Bobba (2002) develops a variable density numerical model of the Godavaru Delta, India using the SUTRA code to investigate the effects of different water resource management schemes on the depth of freshwater in the coastal aquifer. Whilst, effects due to sea-level rise resulting from climate change are not considered explicitly, the effects of current tidal sea-level variations are simulated to examine their effects during different seasons.

Holman (n.d.) describes the possible impact of an increase in mean sea level on the inflow of saline water to the Thurne catchment, which forms part of the Norfolk Broads. Water levels in the main drainage networks in the area are approximately two metres below mean sea level and consequently, an increase in sea level would cause an additional influx of saline water. However, it is stated that an increase in mean sea level of 20 cm by 2050 (as suggested by Hulme et al., 2002) would only lead to an increase in the hydraulic gradient of around 10%. This is not thought to represent a major threat.

6.8 UKWIR RESEARCH

In 2000 UKWIR published a report (UKWIR, 2000) presenting the findings of a scoping study to identify research requirements to assist UK water companies cope with changing patterns of drought. This focused on research to assess the effects of climate change on the management of water resources, water demand, water supply and treatment and, catchment management. At this time a number of areas of research were proposed that would benefit the UK water industry. Whilst UKWIR has commissioned a number of projects in the proposed areas of research, some of which are discussed below, some of these are still worthy of further investigation. In particular the following areas of research, which they propose, are still valid:

- Investigation of the relative impacts of anthropogenic changes and natural climate variability on water resources.
- Downscaling of results from GCMs to the catchment scale.
- Sensitivity analysis of models to identify if threshold levels of climatic changes exist, and if so, at what point water resources are affected beyond the natural climatic variation.

In the UKWIR report 03/CL/04/02 (2003) Arnell presents a procedure to assess the effects of climate change on mean monthly runoff and average annual groundwater recharge by the 2020s, which UK water companies and others can use for strategic resource assessment. This method implements three UKCIP scenarios. Four additional scenarios are also used to address uncertainty and natural climate variability.

Three methods of applying the UKCIP02 scenarios are proposed. The first and second of these approaches use output from the UKCIP02 scenarios directly and regionally average UCIP02 scenarios as inputs to hydrological models, respectively. The third method involves perturbing historic runoff and recharge time-series using a set of tabulated factors. The effects of natural variability can be superimposed on these results by adding monthly runoff change factors, which are presented. Predictions for the 2000s, 2010s and 2030s can be developed by interpolation or extrapolation of the results for the 20202s and guidelines to do this are presented.

The study updates the factors "for change in monthly runoff and annual recharge to observed naturalised runoff and recharge data to produce perturbed time-series representing conditions under a change climate in the 2020s" that were generated by a previous UKWIR study (UKWIR and Environment Agency, 1997). These new factors are generated using the low, medium and high UKCIP02 scenarios.

Three options are presented for estimating changes in runoff and recharge as part of a strategic-scale assessment. The first involves the use of a calibrated catchment or groundwater model and the use of the UKCIP02 scenarios to perturb the input data. The second is also based on the application of a catchment model but perturbs its input using regional average changes in mean monthly climate. These average changes are derived by "allocating each UKCIP02 50×50 km grid cell to one region and calculating the average". The third method time-series of naturalised monthly runoff or recharge are perturbed by a series of factors. The first set of these factors, representing regional average changes in mean monthly runoff, are "calculated by applying the UKCIP02 scenarios in a sample of 56 catchments, using a locally-calibrated catchment model to simulate river flows". The factors for change in mean annual recharge are calculated by applying a soil-moisture balance model to eleven aquifer units.

UKWIR (2005, report number 05/CL/04/3) build on the earlier study and develop an Excel spreadsheet that provides monthly temperature, rainfall and potential evapotranspiration for 190 individual or groups of UK river catchments. The spreadsheet also provides estimates of uncertainty by considering different emission scenarios, climate models and downscaling methods. The study also discusses briefly the comparison of regional climate models (RCMs) with the use of statistical downscaling to obtain catchment scale climate data from GCMs. It is stated that recent studies have indicated that the use of a RCM contributes little additional uncertainty to that associated with the GCM on which it is based. Both RCMs and downscaling methods are stated to reproduce current climate with similar degrees of accuracy but produce significantly different predictions for future climate. It is suggested that "this may be because the statistical methods are based upon the assumption that empirical relationships derived from current observed variables will remain valid as climate changes". However, it "may also because the RCM does not capture some aspect of variability within the current or future climate".

A later UKWIR study (UKWIR, 2005, report number 05/CL/04/4) addresses the sources of uncertainty when assessing the effects of climate change on water resources river flows and water supply. The sources of uncertainty are incorporated in the definition of emission scenarios, the downscaling of information from low-resolution GCMs, the use of relatively short duration historic time-series, which do not include the full range of natural variability and those sources associated with the application of hydrological or groundwater models for prediction.

The study examines thirteen catchments in order to estimate the magnitudes of the different uncertainties and the following conclusions are made:

- Uncertainty in the estimation of greenhouse gas emissions for the 2020s is small.
- Impact studies should apply a number of GCMs because the uncertainty associated with the use of a single GCM is large.
- A number of different methods of downscaling should be used because downscaling uncertainty is significant. However, it is not as large as GCM uncertainty.
- The uncertainty associated with a hydrological model can be significant but tends to be catchment dependent.

An assessment of the uncertainty in downscaling is made by comparing the UKCIP02 results from the regional HadRM3 climate model (dynamic downscaling) with those made using the SDSM (Statistical Downscaling Model; Wilby et al., 2002) of downscaling directly from the HadCM3 GCM. This comparison shows that "Projected changes from SDSM-HadCM3 scenarios can be different in magnitude, and occasionally in sign, from those projected described by UKCIP02" (UKWIR, 2005). For example, the HadRM3 model predicts decreases in summer river flows for four UKCIP02 scenarios, whilst the results of the downscaling HadCM3 output using the SDSM predict increases in flow. This is stated to be due to the bias in the HadCM3 GCM which over-estimates river flow for the historic period of 1961-1990.

6.9 CLIMATE CHANGE AND EXTREME EVENTS

Research relating to climate change and extreme events is limited, however, currently there are two projects being undertaken by parties including the UKWIR, the Environment Agency and the Climate Research Unit of the University of East Anglia that are addressing the effects of climate change on drought in the UK.

The Environment Agency and UKWIR co-funded project entitled "Effect of climate change on river flows and groundwater recharge: a practical methodology" includes a project task to examine the annual variability of climate and its effects on water resources. This task will produce tools and guidance for handling changes in the year to year variation of future climate. This project is due to report in March 2007.

The Environment Agency is also funding research by the Climate Research Unit at the University of East Anglia to examine the severe droughts. It is believed that this project is at the reporting stage.

7 Groundwater-related socio-economic impacts of climate change

The topic area of the socio-economic impacts of climate change is very large and consequently, within this scooping study it has not been possible to undertake an exhaustive review of the published research. Therefore, the following section only represents a brief review of some of the issues that are of concern within the UK.

7.1 CLIMATE CHANGE AND WATER DEMAND

Domestic water demand in the UK is projected to rise in the future, due to pressures unrelated to climate change (Arnell, 1998). Much of the increase in water use in the south-east of England will be related to the expected increase in population density. These pressures include increases in population, decreasing household size, increased use of domestic appliances such as dishwashers, and increased garden watering. The National Rivers Authority (1994) estimated that such pressures would lead to a 2-25% increase in the demand for public water supply in England and Wales by the year 2021. Considerable regional variation was expected, with the largest increases likely to occur in the south and east, and possibly small decreases in parts of the north.

The impact of climate change on water demand in the UK was first examined by Herrington (1996). This study predicted that the impact of climate change would be to raise the per capita domestic demand in southeast England by a further 5% (over and above the levels predicted by the National Rivers Authority, 1994). Garden watering, and to a lesser extent increased showering, would constitute the bulk of the extra demand.

The study by Herrington was updated and expanded by Downing et al. (2003). Their study integrated climate change and water demand scenarios in order to predict the overall impact of climate change on future water demand in the UK. The climate change scenarios used were the UKCIP02 scenarios. The water demand scenarios were based on socio-economic reference scenarios developed under the Foresight ‘Environmental Futures’ framework, which are very similar to the UKCIP socio-economic scenarios described earlier. The water demand scenarios and the socio-economic scenarios on which they are based are listed in Table 3.

Table 3 Foresight scenarios used in the Environment Agency Water Resources Strategy

	Water demand	**Environmental issues and priorities**	**Values**	**UK GDP (pa)**
Alpha (Provincial Enterprise)	Stable	Low priority placed on the environment. Low levels of investment creating significant environmental problems.	Individualist	1.5%
Beta (World Markets)	Increases	Environmental improvement not a priority. Emphasis on issues which impact on the individual or local area.	Consumerist	3%
Gamma (Global Sustainability)	Declines	Sustainable development accorded high political priority. Resource use efficiency drives policy.	Conservationist	2%
Delta (Local Stewardship)	Declines	Sustainable development closely integrated into all areas of decision making. Effective community action resolves local environmental problems.	Conservationist	1%

(Source: Downing et al., 2003)

The predicted increases in different categories of water demand due to climate change are shown in Table 4. The table shows that the largest impact occurs within the agricultural sector (more on this in the next section). In contrast, the impact of climate change on domestic water demand is modest. The increase in industrial and commercial water demand is larger. It is expected that the bulk of this demand would be accounted for by the soft drinks, brewing and leisure industries.

Table 4 Impacts of climate change by component of water demand for selected marker scenarios

Domestic demand

<table>
<tr><th></th><th>2020s</th><th>2020s</th><th>2050s</th></tr>
<tr><th></th><th>Low</th><th>Medium High</th><th>Medium High</th></tr>
<tr><td>Alpha</td><td></td><td rowspan="2">1.4-1.8%</td><td></td></tr>
<tr><td>Beta</td><td></td><td>2.7-3.7%</td></tr>
<tr><td>Gamma</td><td>0.9-1.2%</td><td rowspan="2">1.0-1.3%</td><td></td></tr>
<tr><td>Delta</td><td></td><td></td></tr>
</table>

Industrial/commercial demand

	2020s	2020s	2050s
	Low	**Medium High**	**Medium High**
Alpha		1.7-2.7%	
Beta		1.8-3.0%	3.6-6.1%
Gamma	1.8-2.9%	2.0-3.1%	
Delta		1.7-2.7%	

Agricultural demand

	2020s	2020s	2050s
	Low	**Medium High**	**Medium High**
Alpha		19%	
Beta		19%	26%
Gamma	18%	19%	
Delta		20%	

(Source: Downing et al., 2003)

The predicted increase in water demand due to climate change has obvious implications for groundwater, since it accounts for a significant proportion (>30%) of the nation's public water supply and an even greater proportion (>70%) in the south-east of England where demand is expected to increase the most. Moreover, the reliance on groundwater can only be expected to increase in the face of climate change, since the impact on surface water resources will probably be more immediate (groundwater as a resource reacts more slowly to pressures).

Increased pressure on groundwater will impact the water industry, and ultimately the consumer in the form of increased costs. Impacts on the water industry are likely to involve an increase in both operating costs (due to increased depth of pumping) as well as capital costs (development of new sources; installing treatment at sources that may earlier have been uneconomic, e.g. due to pollution).

The unhappy combination of increased water demand with more severe and frequent groundwater droughts in certain areas may lead to more hose pipe bans and drought orders in the future. Hose pipe bans involve a loss of social welfare. Drought orders affect both the agricultural and industrial sector and lead to economic losses.

7.2 CLIMATE CHANGE AND AGRICULTURE

Climate change may affect UK agriculture through a number of mechanisms:

- Changes in land area under cultivation, e.g. some areas may become unsuitable for cultivation due to increased flooding or drought.
- Change in cropping mix: new crops may become viable, others may become unsuited to the altered climate.
- Change in cropping patterns, e.g. due to a longer growing season.
- Change in consumer preferences: longer hotter summers may lead to increased demand for salad crops, which are water-intensive.

All of these factors will impact the demand for water, and therefore the demand for groundwater, within the agricultural sector.

Table 4 indicates that the impact of climate change on agricultural water demand is likely to be very significant. Substantial regional variation is expected; the major increases are likely to occur in the Thames, midlands, Anglian and southern regions, while irrigation water demand could decline by about 4% in the northwest. According to DEFRA (2004), irrigation water demand for crops such as potatoes, sugar beet and vegetables will increase in drier areas of the country, due to a decline in summer rainfall. In addition to the arable crops sector, this study also reported on the potential impacts of climate change on the grassland and livestock sectors. Grass is acutely affected by summer drought; possible adaptation strategies for farmers include switching to non-grass forage such as maize forage or forage legumes, which grow successfully under dry summer conditions.

In addition to the quantity aspect, climate change may also be expected to impact groundwater quality via its impact on the agricultural sector. Changes in weather conditions may lead to increased incidence of particular weeds or pests, in turn leading to increase in the application of chemical herbicides and pesticides (see Section 6.6).

Given the considerable regional variation in the effects of climate change across different areas of the UK, a regional focus is required in studies attempting to explore the impact of climate change on the agricultural sector. The largest study of this type is the RegIS study (Holman et al., 2002), which integrated climate change and socio-economic scenarios to predict the likely impacts of climate change in two regions of the UK – East Anglia and the North West. The two regions were chosen in order to provide a suitable contrast to each other. While East Anglia has a dry climate, low-lying topography and intensive agriculture, the North West region has a wet climate, uplands dominated by extensive grazing, and highly urbanized lowlands.

The climate change scenarios used in the RegIS study were the UKCIP98 *High* and *Low* scenarios for the 2050s. The socio-economic scenarios used were a *Regional Enterprise* scenario (similar to the *National Enterprise* scenario under UKCIP) and a *Global Sustainability* scenario. The *Regional Enterprise* scenario was combined with the *High* climate change scenario, while the *Global Sustainability* scenario was combined with the *Low* climate change scenario. The choice of these particular combinations was deliberate. The *Regional Enterprise* scenario, with its vision of semi-autonomous regions maximising economic growth, represents an adverse case in which society does not devise appropriate responses to the threat of climate change. Such a society may reasonably be expected to give rise to high levels of emissions, and therefore produce greater climate change impacts. In contrast, the *Global Sustainability* scenario, which reflects a world in which global approaches to conserving environmental systems and natural resources are given high priority, may be expected to control emission levels, and therefore is more naturally associated with the *Low* climate change scenarios.

Overall, the RegIS study found that, except in areas that may be at risk of flooding due to climate change, socio-economic trends (e.g. trade liberalisation, CAP reform) were more important in determining cropping patterns than climate change effects (e.g. crop growth pattern; change in land availability). Socio-economic factors such as the level of environmental awareness and demand for organic produce also significantly affected the use of chemical inputs in agriculture, with obvious implications for groundwater: under the *Regional Enterprise* storyline, the amount of nitrogen fertiliser applied to fields in East Anglia could increase by more than 60%.

These results indicate the importance of incorporating socio-economic scenarios into analyses of climate change impacts:

> *"While uncertainties remain, RegIS has shown it is clear that socio-economic developments are likely to have a major influence on the size of climate change impacts and be crucial in determining the future of the two regions studied. Society has an important opportunity to manage the impacts through policy choices and adaptation." (Holman et al., 2002)*

7.3 GROUNDWATER DROUGHT

Climate change is likely to increase the frequency and severity of groundwater drought in areas of the UK, particularly in the south and east of England. The potential socio-economic and environmental impacts of groundwater drought are illustrated in Figure 4 and briefly described below. Sources of value for aspects of the environment affected by groundwater drought are also briefly mentioned.

Direct impacts of groundwater drought include impacts on the water industry. Water companies may find it difficult to fulfil their mandate of supplying clean water in drought years and will incur higher costs in doing so. The problem can be expected to particularly acute in southeast England, where groundwater dependency is very high, accounting for more than 70% of the public water supply in some areas. In addition, population increase and planned housing development in this region is expected to create significant increases in water demand over the next several decades.

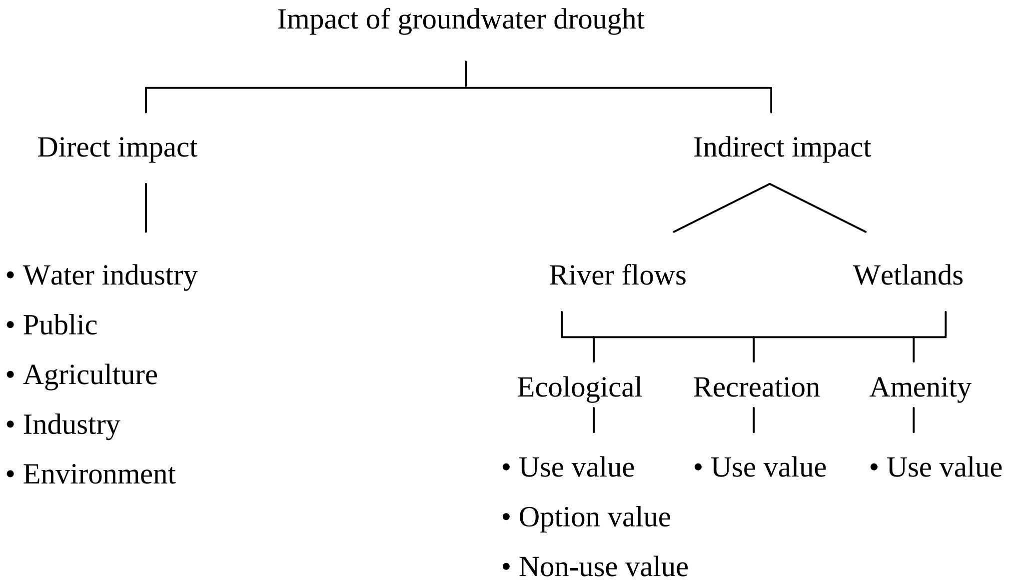

Figure 4 Socio-economic impacts of groundwater drought

Groundwater drought will lead to crop yield losses in the agricultural sector. Studies that have examined the impact of drought (not specifically groundwater drought) on the agricultural sector include Richter and Semenov (2005), who modelled the impacts of climate change on the yield of winter wheat in England and Wales. Since a quarter of the total wheat production of the UK is on droughty soils, drought could pose a quite significant risk to future wheat production. The study concluded, however, that the direct positive effect of increasing CO_2 concentration on crop development and growth would more than compensate for the negative effect of drought on wheat yields.

In addition to its direct effect on agricultural yields, groundwater drought may also affect yields by making the soil drier, and thereby increasing its vulnerability to soil erosion.

Groundwater drought is likely to lead to the introduction of water conservation measures such as hosepipe bans and drought orders, which are a source of disutility to individuals and of economic losses to industry and agriculture. An illustrative example can be found in Carrow (2006), which lists the various categories of benefits that are lost when water use on turf is reduced. For individuals, these include recreational and aesthetic benefits. Economic benefits include income and employment on golf courses and benefits to the local economy in those areas where tourism is centred around golf. Environmental benefits include the mitigation of soil loss through wind and water erosion.

The indirect impact of groundwater drought stems from its role in supporting river flows and groundwater-dependent wetlands. Rivers and wetlands provide ecological (e.g. habitats for flora and fauna), recreational (e.g. fishing, swimming) and amenity (e.g. landscape) services. These services are associated with different sources of economic value, including use, option and non-use value, all of which together make up the total economic value of the environmental asset.

The use value includes both direct and indirect use value. In the case of river flows, for instance, the direct use value may be via commercial fisheries that operate in the river, while the indirect use value may be via supporting (through the food chain) bird species that are used for recreational purposes, e.g. viewed by bird-watchers or hunted for sport.

The option value of a natural resource represents the willingness to pay (WTP) to preserve it, in order to preserve the option of using it in the future. In addition, non-use values have also been found to be significant for certain types of environmental assets. Non-use value implies that people are often willing to pay to conserve aspects of the natural world that they are never likely to use.

Valuation techniques have been developed within the environmental economics discipline to derive monetary estimates of the different types of economic value. These include a loss of earnings/loss of productivity approach to estimate the impact of environmental changes affecting goods and services that are traded in the marketplace. The value of the environment in providing recreational opportunities can be measured using a travel cost approach, which uses data on the expenditure (including the opportunity cost of time) incurred in travelling to and from the recreation site to derive WTP estimates. Having scenic views or an area of natural beauty nearby can raise property prices. Econometric techniques can be used to isolate the environmental effect from all the other variables that also drive property prices. Option value and non-use value are measured using stated preference approaches such as contingent valuation.

7.4 GROUNDWATER FLOODING

The most common forms of flooding in the UK are from rivers and coasts. Nearly 2 million properties and 5 million people are at risk from these types of flooding. Climate change is expected to increase the likelihood not only of these types of flooding events, but also of groundwater flooding. Vulnerability to groundwater flooding is high, with an estimated 380,000 properties on the exposed chalk aquifers of southern England at risk from groundwater floods (Every and Foley, 2005).

The potential impacts of groundwater floods may include: damage to buildings and infrastructure (physical assets); damage to farmland, agricultural produce and agricultural soils (through soil erosion)[1]; impact on human health (injury, death, mental health impacts such as anxiety and depression); flooding of wetlands and marshes and the consequent impact on plant and animal species.

No studies were found in the socio-economics domain that specifically examined the issue of groundwater floods. Hall et al. (2003) is a more general attempt to quantify the extent and scale of flood risk in England and Wales in the future, as a result of climate change. The term ‘risk’ in this context was taken to incorporate both the likelihood of there being a flooding event, and the likely damage from such an event. The study integrated climate change and socio-economic scenarios in order to assess future flood risks. The UKCIP02 scenarios were used for the former. For the latter, the Foresight Futures scenarios were used. These were developed by the DTI and were a forerunner for the UKCIP socio-economic scenarios. Key results from the analysis are presented in Table 5.

[1] Approximately 12% of the agricultural land of the UK is now considered to be at risk from flooding or coastal erosion (EA, 2001)

Table 5 Summary of flood risk assessment for England and Wales (excluding sewer flooding)

	2002	World markets 2080s	National enterprise 2080s	Global sustainability 2080s	Local stewardship 2080s
Number of people within the indicative floodplain (millions)	4.5	6.9	6.3	4.6	4.5
Number of people exposed to flooding (depth>0 m) with a frequency >1:75 years (millions)	1.6	3.5	3.6	2.4	2.3
Expected annual economic damage (residential and commercial properties) (£ billions)	1.0	20.5	15.0	4.9	1.5
Annual economic damage relative to GDP (%)	0.10	0.14	0.31	0.06	0.05
Expected annual economic damage (agricultural production) (£ millions)	5.9	34.4	41.3	43.9	63.5

(Source: Hall et al., 2003)

8 Modelling responses to climate change

Leavesley (1994) discusses many of the issues that are associated with the use of models when simulating the effects of climate change. In doing this the author categorises model into four groups: empirical models, water balance models, conceptual lumped parameter models and process based distributed parameter models. Leavesley recognises the advantages of process based models but also highlights some of the difficulties associated with their use when investigating climate change effects. As the author states, the use of conceptual models, based on effective parameters, to investigate future scenarios is questionable because they are based on historic data and therefore, only represent the relationship between the input stimuli and output response for the period in which they were developed.

Process based models can better simulate conditions outside of the range of those found during the calibration period, however, it is possible that characteristics of a basin might change during the period of modified climate, which these models can not simulate adequately. Furthermore, Leavesley highlights some of the other issues that must be considered when using process based models in climate change investigations. These relate to the estimation of the model parameters, which include:

- The limited length of the historic data record.
- Minimal or no information on the acceptable range of parameter values.
- Incorporation of model and data errors in parameter values.
- Inter-correlation of parameters that inadvertently improve the simulation.
- Non-uniqueness of parameter sets.
- Dependence of model parameters on sequence of climate variables.

In consideration of these problems, Leavesley cites some criteria to determine the suitability of a model for application to the assessment of climate change, which were proposed by Klemes (1985). These are that:

- The model structure must have a sound physical basis.
- Each structural component must permit separate validation.
- The model must be geographically and climatically transferable.

Finally, Leavesley discusses the validation of models that are used for the assessment of climate change effects. He states that the problem of defining quantitative measures of model performance in terms of its ability to simulate new conditions adequately is formidable. However, Leavesley cites a test that Klemes (1985) recommends, which addresses the assessment of the climatic transferability of a hydrological model. In this test, two periods of different climate are identified, e.g. a dry and wet period and the model is calibrated separately using each. The model calibrated using the dry period is then validated using the wet period and vice versa.

Arnell (1998) discusses some of the issues relating to the use of hydrological models when simulating the effects of climate change. In particular he highlights the problems associated with the prediction of extreme events. This is difficult because of the uncertainty associated with the prediction of climate variability and the difficulty in developing hydrological models that can consistently reproduce extreme conditions; most models are only good at reproducing average behaviour.

8.1 ASSESSMENT OF UNCERTAINTY

Wilby and Harris (2006) address the quantification of uncertainty when linking GCMs to hydrological models. They present a probabilistic framework to present the uncertainty associated with (i) hydrological model parameters, (ii) the ability of different GCMs to reproduce present day climate variable used in impact assessment, (iii) downscaling GCM output to define regional climate change scenarios and, (iv) CO_2 emission scenarios.

Uncertainty is quantified by undertaking a Mote Carlo analysis considering the factors described above. Hydrological model parameter uncertainty arises from, for example, the choice of calibration period, model structure and non-uniqueness in model parameter distributions. These factors are represented in the Monte Carlo analysis by selecting "the 100 most skilful model simulations" of the CATCHMOD hydrological model of the Thames basin, UK. The uncertainty associated with the GCM is formulated by constructing an "Impacts Relevant Climate Prediction Index (IR-CPI)" that weights each GCM according to its ability to reproduce present day climate variables used as input for the hydrological model. The Monte Carlo analysis does not, however, include runs to incorporate the uncertainty associated with downscaling because the authors find that when applying the Statistical Downscaling Model (SDSM) developed by Wilby et al. (2002), the differences between the downscaled and observed daily rainfall and potential evapotranspiration are negligible.

The study concludes that uncertainties in river flow projections due to emissions and hydrological model uncertainty are comparable but that the current differences between GCMs introduce the most significant degree of uncertainty. Consequently, it is considered that the basis of climate change studies on a single GCM is of limited value at this time.

Khan et al. (2006) also examine the uncertainty associated with statistical downscaling methods used to transfer climate data from GCMs to catchment-scale models. Three different methods are assessed by comparing downscaled daily precipitation and, daily maximum and minimum temperatures with the historic record. The three methods are the Statistical Downscaling Model (SDSM) (Wilby et al., 2002), the LARS weather generator (Semenov and Barrow, 1997) and an artificial neural network developed by Coulibaly et al. (2005). The work supports that of Wilby and Harris (2006) and concludes that the SDSM is the most capable of reproducing various statistical characteristics of the observed data.

9 Conclusions and recommendations for future research

This scoping study has reviewed much of the published literature in the field of climate change and groundwater research. Whilst it is not exhaustive with regard to groundwater quality issues, most of the published literature relating to climate change and groundwater resources, particularly in the UK, is covered. Further work is required to identify current research needs relating to the effects of climate change on groundwater quality.

The study of the effects of climate change on water resources is a relatively immature area of scientific research. Consequently, there are relatively few studies relating to possible future effects of climate change on groundwater. This may be partly due to the significant degree of uncertainty associated with the prediction of future climate and therefore the prediction of effects on aquifers.

It is worth noting that a distinction is generally made between *effects* and *impacts*. The quantification of *effects* is generally taken to represent the response of an environmental system neglecting changes in management practice. The term *impact*, however, is used to represent the predicted change in a system when taking anthropogenic factors into consideration. For example, the effect of climate change on groundwater recharge would not consider changes in land-use a result of changing agricultural practice.

GENERATING FUTURE CLIMATE CHANGE SCENARIOS

The prediction of the effects of climate change on groundwater systems obviously requires information on possible future climate. In the studies reviewed as part of this work climate scenarios are constructed using a number of methods. For example historic time-series of climate variables can be scaled, either by arbitrary factors or by the difference between current and future climates as simulated by GCMs. Statistical weather generators can also be used to develop new scenarios based on wet and dry subsets of the historic record. The implementation of any of these methods, however, preserves the variability of the historic time-series in the scenario generated, which is erroneous; a trend in the seasonal variability of rainfall is already distinguishable in the historic rainfall record for the UK with winters becoming wetter and summers drier.

The most defensible approach of constructing scenarios of future climate variables required by hydrological or groundwater models is through the more direct use of use of GCM output. This is performed by downscaling GCM output to the catchment scale or by the direct application of RCM output. More recent studies have adopted this approach, however, they have tended to apply output from only one GCM, generally that from the UKCIP for considering UK studies. This is problematic because most of the uncertainty associated with predictions is related to the variations in the results produced by different GCMs. This leads to the following recommendation**:**

> *Given the current differences between global climate models, any future modelling studies undertaken by BGS should consider the use of a suite of GCMs. In this way the uncertainty associated GCM selection can be quantified.*

Whilst downscaling data from GCMs is one of the most defensible approaches to adopt when generating climate scenarios at the catchment scale it is not a straightforward process and can be time-consuming. Therefore, with regard to possible future BGS research the following step-wise approach could be adopted:

> *A good starting point for the assessment of GCM scenario data is the UKCIP02 scenarios. Initially this is likely to involve using output from the UKCIP 50km RCM*

and applying it to examine impacts on a particular feature of a groundwater system. Subsequent research could then examine the differences between impact studies conducted using output from the Hadley Centre's RCM and data downscaled from the HadCM3 GCM directly. After considering applying scenario data from the Hadley Centre's climate models, other GCMs should then be used to assess impacts.

By adopting this approach it will be possible to examine changes in the *severity*, *persistence* and *frequency* of the impact of climate change on a particular process because it does not require the use of historic time-series to generate future scenarios. Generally previous impact studies have only provided information on changes in average conditions. However, one notable exception is the study by Herrera-Pantoja and Hiscock (in press) which examines changes in recharge to the Chalk of eastern England. The approach will also enable the comparison of impacts derived using regional climate models (RCMs) with those obtained using statistical downscaling methods. The implementation of both methodologies would address one of the findings of UKWIR (2005, report number 05/CL/04/3) which states that whilst both RCMs and downscaling methods can reproduce current climate with similar degrees of accuracy they can produce significantly different predictions for future climate.

THE APPLICATION OF CATCHMENT MODELS IN CLIMATE CHANGE IMPACT STUDIES

Some of the literature that has been reviewed discusses the applicability of catchment scale hydrological and groundwater models in climate change impact assessments. As Younger et al. (2002) state it is inadvisable to apply empirical models, based on a relationship between inputs and outputs, to conditions that fall outside of the historic calibration period. The application of physically based models is more defensible. Process based models can better simulate conditions outside of the range of those found during the calibration period, however, it is possible that characteristics of a basin might change during the period of modified climate, which these models can not simulate adequately. As discussed previously, Klemes (1985) proposes some criteria with which to judge the suitability of a model for application to the assessment of climate change. These criteria should be applied to future BGS research thus leading to the following recommendation:

Any model used to investigate changes to an aquifer system as a result of climate change should fulfil the following criteria:

- *The model structure must have a sound physical basis.*
- *Each structural component must permit separate validation.*
- *The model must be geographically and climatically transferable.*

The climate transferability of a model can be tested by calibrating it twice, once using data from a wet period and once using data from a dry period of the historic record. The model calibrated using the dry period is then validated using the wet period and vice versa.

RECHARGE

Many of the studies in the field of *groundwater* and climate change have focused on the prediction of changes in groundwater recharge. This is partly because the quantification of recharge relates to the overall resource but also because, using Penman-Grindley type soil moisture balance methods, it is relatively easy to model. Whilst it is straightforward to model recharge, this does not mean that the results are certain even for historic simulations.

One of the problems with the development of recharge models is that they are rarely validated by direct comparison with observed data. Rather they tend to be assessed by examining the results of groundwater flow models to which the calculated recharge is applied. Furthermore, recent research as part of the LOCAR Programme (Mathias et al., 2005; Mathias et al., 2006) suggests the concept of ‘field capacity’ applied in soil-moisture balance methods may not be valid for the Chalk. This is because it is likely that vegetation on chalk soils, transpires at the potential rate for the majority of the year due to the hydraulic properties of the bedrock.

For these reasons, a valid area of research would be to develop physically based recharge models that can be tested against observed data, such as those collected from the recharge sites installed as part of the LOCAR Programme or as part of BGS’s FLOOD1 project. Once such a calibrated model has been developed, climate change scenarios could be applied to examine future effects. This approach would be more rigorous than those undertaken to date.

Whilst the approach to quantify the impacts of climate change on groundwater recharge proposed above would be an improvement on previous work undertaken in the UK, it still suffers from some assumptions. One of these is that land-use remains the same during the prediction period and another is that the dynamics of plant growth and transpiration do not change under an increased CO_2 climate.

One area of research that has not been reviewed as part of this scoping study is the prediction of land-use change in the 21st century. Whilst this could theoretically be incorporated in an assessment of the impacts of climate change on recharge, it is likely to incorporate a high degree of uncertainty.

The effect of changing plant dynamics with changing concentrations of atmospheric CO_2 is stated in a number of peer reviewed journal papers to be important when considering its affect on recharge. For example, as reviewed previously, Eckhardt and Ulbrich (2003) state that plant stomatal conductance has been shown to decrease by up to 40% in increased CO_2 atmospheres. Consequently, the SWAT model, which incorporates the effect of changes in atmospheric CO_2 on plant growth is applied in their study to quantify recharge. Such a model could be applied in the study of a UK catchment, however, this would probably require collaboration with a plant biologist. This is because these type of models contain complex processes and a number of assumptions.

As Younger et al. (2002) state few studies have examined the role of aquifers in transforming recharge to discharge. They state that, up to 2002, most studies examining the possible effects on aquifers of changes in climate were largely restricted to evaluations of changes in recharge and that these tended to assume that total groundwater discharge would equal total recharge under future conditions. That is, these studies did not consider the inter-annual or sub-annual variations in groundwater discharge rate and the degree to which an aquifer transforms a recharge time-series into a discharge time-series. This is another area of possible groundwater and climate change research but would probably require the use of a good regional groundwater model.

A final piece of work relating to recharge that could be undertaken by BGS is the development of a UK recharge model. Whilst this may suffer from the problems associated with recharge models in general i.e. the difficulties associated with validating the results, this would provide a valuable tool with which to address national climate change issues. However, when considering the development of a national recharge model, the capabilities of the Met Offices’s MOSES PDM model should be borne in mind. Climate change scenarios can be applied to the MOSES PDM model to predict future changes in groundwater recharge and this may negate the development of a national soil-moisture balance model. It is believed that such simulations are underway or are planned by the Met Office (pers. comm. John Finch, CEH, 8th May 2006).

SALINE INTRUSION

Most of the studies examining the impact of sea-level rise on saline intrusion to coastal aquifers suggest that this would probably not be significant or its impact outweighed by the existing contamination of the aquifers caused by historic over-abstraction. The only study undertaken in the UK (Clark et al., 1992) is not recent but considers that the effects of sea level rise on yields would be minor and lead to a reduction of coastal borehole yields of 1-2% only. It is stated that these could be offset easily by moving the boreholes inland. However, it must be noted that the impact of sea-level rise on saline intrusion depends on a number of factors, such as the thickness of the aquifer and the discharge to the sea. Therefore, there will obviously be variations in the impacts of sea-level rise around the UK coast.

A secondary threat of saline contamination of groundwater may occur where salt concentrations in estuary water increase as a result of sea level rise. This could lead to increased saline concentrations in coastal aquifers. Such a phenomenon would benefit from research but is local in its nature.

WATER QUALITY

This review has generally focused more on current and previous research relating groundwater *resource* issues. Consequently, further work is required to complete a review of research needs in the field of climate change and groundwater quality.

Two studies by the British Geological Survey (2004) and ADAS (2004) review the possible effects of climate change on pesticide transport and changes in nitrate leaching from soils. The studies also review the applicability of models for the investigation of changes in these contaminants under climate change scenarios. They highlight that very little modelling work has been undertaken in this area. As ADAS (2004) state previous climate change impact studies have examined the effects on agriculture but have focused on changes in crop yields, crop types and possible farmer adaptation.

The important climate variables in the nutrient cycle/loss process are identified as rainfall volume and intensity, mean temperature, potential evapotranspiration and wind speed. In addition to representing these variables there are a number of key soil-vegetation processes that directly affect the availability and loss of N and P in the soil. Consequently, the accurate description of changes in contamination from diffuse nitrate pollution, for example, requires the use of modelling tools that incorporate these processes.

Various mathematical models are used to predict the fate and transport of pesticide. As BGS (2004) discuss the EU funded FOCUS forum has suggested a number of models and associated use scenarios for predicting surface and groundwater concentrations but their applicability under future climate change needs to be assessed.

Although not a weakness of the climate change scenarios themselves, the main problem in applying the climate change scenarios in a research context is the present lack of understanding of the complex interdependencies of climate sensitive processes in the environment as a whole. In addition, the level of confidence that can be attached to any climate change impact assessment is limited by uncertainties associated with the effects of climate change on economic and social factors. Agriculture and agricultural practices are generally very responsive to social and environmental change. In the long-term, land-use change driven by changes in climate may have a more significant effect on pesticides in the environment than the direct impacts of climate change on specific pesticide fate and transport processes.

BGS (2004) identify four areas of work that would enable the development of an improved understanding of the implications of climate change on the fate and transport of pesticides in the environment, which are still valid:

- *Climate sensitivity analysis of the FOCUS scenarios and models, particularly under extreme climate conditions.*
- *Systematic analysis of selected historic pesticide use, fate and transport and climate data.*
- *Catchment-based modelling study of pesticide behaviour under a range of climate change scenarios.*
- *A desk study to provide an overview of the relationships between climate-driven long-term land use change and the implications for pesticides use, fate and transport.*

EXAMINING TRENDS

Few studies have examined the historical records of recharge, precipitation, baseflow or groundwater storage in search of climate induced changes. Those that have attempted the identification of such trends, for example in river flows (Arnell and Reynard, 1996), have had difficulty in identify any observable responses to climate change.

Reynard and Young (2002) propose that work should be carried out to detect the beginning of a trend if it is predicted by modelling. If such a trend is not detectable then the results of the model predictions may be of dubious value.

RESEARCH PROPOSED BY UKWIR

UKWIR are active in groundwater and climate change research and the consultant Entec is examining the impact of climate change on groundwater levels as part of a current UKWIR project. This project is led by HR Wallingford who are tasked with updating the Excel spreadsheet tool, developed as part of a previous UKWIR project, that enables the rapid assessment of the impact of climate change on water resources in the UK using UKCIP data. The updated spreadsheet tool will contain information based on six GCMs rather than just that from the Hadley Centre’s climate models. The updated tool will be made available via UKWIR in 2006.

Whilst UKWIR has commissioned a number of climate change projects examining the impacts on groundwater recharge and storage these areas of research are still worthy of further investigation. In particular the following areas of research, which they propose, are still valid:

- The assessment of climate variability in impact assessment rather than just average effects.
- The assessment of uncertainty.
- The investigation of the relative impacts of anthropogenic changes and natural climate variability.
- Comparison of approaches that downscale data from GCMs with those that use regional climate model outputs.

- Sensitivity analysis of models to identify if threshold levels of climatic changes exist, and if so, at what point water resources are affected beyond the natural climatic variation.
- Assessment of the impact of climate aquifer storage and yield of sources.

The final point is likely to be contained in future requests to tender by UKWIR. Therefore, BGS will need to address this issue. The assessment of source yield under climate change is likely to be a complex task because it requires a sound understanding of both regional flow in the aquifer and the characteristics of the aquifer in the vicinity of the borehole.

DEVELOPMENT OF BGS GROUNDWATER AND CLIMATE CHANGE RESEARCH DURING THE 2005-2010 SCIENCE PROGRAMME

Whilst a number of areas of areas of research are identified above that BGS could develop, the Groundwater and Climate Change project needs to adopt an approach that both develops the Programme's expertise but ensures that it produces some research outputs within the first year. Research in subsequent years can then build on these developments. For this reason a step-wise approach is sensible, that starts by considering tractable problems. The possible steps may involve:

Step 1

Obtain and process the UKCIP02 data from the regional climate model.

Apply this to a simple problem for example:

- Develop a numerical model of a conceptual sandstone and Chalk aquifer that can be transferred between different UK settings. These models can then be used to examine regional climate change impacts on groundwater recharge and levels. The work could focus on the severity, persistence and frequency of events in a manner similar to that of Herrera-Pantoja and Hiscock (in press).

Step 2

Apply the UKCIP02 data to the model of the Berkshire and Marlborough Downs and Chilterns after it has been satisfactorily refined. The model can then be used to address changes in river baseflows, groundwater recharge and storage and the effects on borehole yields under climate change.

Step 3

Downscale data from multiple GCMs and apply these climate change scenarios to the Berkshire Downs model. Because the uncertainty associated with climate change impact assessment is dominated by the selection of the GCM a number of different GCMs should be applied. One of these will the UK Hadley Centre's model but the remainder will be those developed by international climate change research organisations.

Step 4

Apply the UKCIPNext scenario data (launched in spring 2008) to provide probabilistic estimates of climate change impacts on groundwater.

FUTURE CLIMATE CHANGE SCENARIOS

In spring 2008 UKCIP is due to launch its next set of climate change scenarios. This will present rainfall and potential evapotranspiration in a probabilistic form. BGS climate change and groundwater programme should be in a position to use this new data set when it is released.

Appendix 1 List of global climate models

Table 2 lists the global climate models cited by the IPCC in the Third Assessment Report (IPCC, 2001) and models, which may potentially be used in the Fourth Assessment Report.

Table 6 List of global climate models

Centre	**Country**	**Models used in Third Assessment Report**	**Models to be used in Fourth Assessment Report**
Australia's Commonwealth Scientific and Industrial Research Organisation	Australia	CSIRO-Mk2	Mk3.0
Beijing Climate Center	China		CM1
Bjerknes Centre for Climate Research	Norway		BCM2.0
Canadian Center for Climate Modelling and Analysis	Canada	CGCM2	CGCM3 (T47 resolution), CGCM3 (T63 resolution)
Center for Climate System Research National Institute for Environmental Studies	USA	CCSR/NIES AGCM & CCSR OGCM	
Centre National de Recherches Meteorologiques	France		CM3
Geophysical Fluid Dynamics Laboratory	USA	R30	
Goddard Institute for Space Studies	USA		AOD, E-H, E-R
Hadley Centre for Climate Prediction and Research	UK	HADCM3	HadCM3, HadGEM1
Institute of Atmospheric Physics	China		FGOALS-g1.0
Institut Pierre Simon Laplace	France		CM4
Institute for Numerical Mathematics	Russia		CM3.0
Max Planck Institute für Meteorologie	Germany	ECHAM4/OPYC3	ECHAM5-OM, ECHO-G*
Meteorological Research Institute	Japan		CGCM2.3.2
National Centre for Atmospheric Research	USA	NCAR-CSM, NCAR-PCM	CM2.0, CM2.1, PCM, CCSM3
National Institute for Environmental Studies	Japan		MIROC3.2 hires, MIROC3.2 medres

* In collaboration with the Meteorological Institute, University of Bonn.

Glossary

ABI	Association of British Insurers.
ADAS	A consultancy providing science-based information, advice and implementation services to governments and organisations working in the environmental, agricultural and rural sectors.
ANIMO	Agricultural NItrogen MOdel developed by DLO Winand Staring Centre (SC-DLO) Department of Soil and Water Research, Netherlands.
BRMC	GCM developed by Australian Bureau of Meteorology Research Centre.
CATCHMOD	A water balance model used by the Thames Region of the EA for water resources planning. (See Davis, R.J., 2001. The effects of climate change on river flows in the Thames Region, *Water Resour. Hydrol. Hydrom. Report 00/04*, Environment Agency, Reading, UK).
CCCMA	Canadian Centre for Climate Modelling and Analysis.
CCIRG	UK Climate Change Impacts Review Group.
CEH	Centre for Ecology and Hydrology, UK.
CGCM	Global climate model developed by the CCCMA.
CSIRO	Australian Commonwealth Scientific and Research Organization.
CSIRO9	Global climate model developed by the CSIRO.
DEFRA	UK Government Department for Environment, Food and Rural Affairs.
DTI	UK Government Department of Trade and Industry.
ECHAM4	GCM developed by the Max Planck Institute, German Climate Research Centre.
EA	Environment Agency of England and Wales.
EEA	European Environment Agency.
EN	English Nature.
EPSRC	The Engineering and Physical Sciences Research Council. A UK Government funding agency for research and training in engineering and the physical sciences.
ESRC	The Economic and Social Research Council. A UK Government funding and training agency addressing economic and social concerns.
ETC	European Topic Centres are lead by the EEA and are multi-institutional research consortia consisting of a lead organisation, which provides the ETC manager, and a number of partner organisations.
FOCUS	FOCUS is a forum for the co-ordination of pesticide fate models and their use. The forum is an initiative of the European Commission to harmonise the calculation of predicted environmental concentrations of active substances of plant protection products.
GCM	Global climate model.
GFDL	GCM developed by the General Fluid Dynamics Laboratory, USA.

GISS GCM developed by the Goddard Institute for Space Studies (USA).

Global Sustainability UKCIP socio-economic scenario One of the four UKCIP's socio-economic scenarios based on economic and political power being retained at the national level and values shaped by a concern for the common good.

HadCM2 Second generation GCM developed by the Hadley Centre, UK.

HadCM3 Third generation GCM developed by the Hadley Centre, UK.

Hadley Centre The Hadley Centre for Climate Prediction and Research is part of the UK Met Office.

HadRM2 Second generation RCM developed by the Hadley Centre, UK.

HadRM3 Third generation RCM developed by the Hadley Centre, UK.

HOST Hydrology of Soil Types: a classification of soil types based the physical properties of soils that have a major influence on catchment hydrology (www.macaulay.ac.uk/host/index.html).

IPCC Intergovernmental Panel on Climate Change.

IR-CPI Impacts Relevant Climate Prediction Index: An index that weights each GCM according to its ability to reproduce present day climate variables used as input for the hydrological model.

INTERREG INTERREG III is an EC initiative to promote transnational co-operation on spatial planning by encouraging harmonious and balanced development of the European territory. The overall aim is to ensure that national borders are not a barrier to balanced development and the integration of Europe and to strengthen co-operation of areas to their mutual advantage. The Initiative runs from 2000 to the end of 2006. (www.interregiii.org.uk).

LARS weather generator A stochastic weather generator producing artificial time series of weather data of unlimited length for a location based on the statistical characteristics of observed weather at that location. (See Semenov, M.A., Brooks, R.J., Barrow, E.M. and Richardson, C.W. (1998): Comparison of WGEN and LARS-WG stochastic weather generators for diverse climates. Climate Research 10, 95-107).

Local Stewardship UKCIP socio-economic scenario One of the four UKCIP's socio-economic scenarios with economic and political power at the regional level and values shaped by a concern for the common good.

MIRO Mineral Industry Research Organisation.

MOSES-PDM MOSES is a land-surface parametrisation scheme that aims to model the complex physical interactions between the land surface and the atmosphere and the associated the fluxes of heat and moisture. MOSES has four soil layers for both temperature and moisture, and includes a treatment of the energy associated with the phase change of the water. MOSES also explicitly parametrises the influence of atmospheric variables - such as temperature, humidity and radiation - on the stomatal resistance of vegetation. The MOSES-PDM includes CEH's Probability Distributed Moisture (PDM) scheme.

MPI Max Planck Institute, Germany.

MWGEN — A modified version of the WGEN stochastic point weather generator (See Richardson and Wright, 1984, WGEN: A model for generating daily weather variables, U.S. Dept of Agriculture, Agricultural Research Service Report ARS-8).

National Enterprise UKCIP socio-economic scenario — One of the four UKCIP's socio-economic scenarios with economic and political power retained at the national level and the freedom of the individual dominant.

NERC — Natural Environment Research Council.

NCAR — National Centre of Atmospheric Research (USA).

NFU — National Farmers' Union.

PE — Potential-evapotranspiration.

RCM — Regional climate model.

RegIS — A DEFRA and UKWIR funded research project as part of the UKCIP programme to investigate climate change impacts and socio-economic trends in East Anglia and the North-West of England.

SDSM — Statistical Downscaling Model: The statistical downscaling model (SDSM) calculates statistical relationships, based on multiple linear regression techniques, between large-scale (the predictors) and local (the predictand) climate. These relationships are developed using observed weather data and, assuming that these relationships remain valid in the future, they can be used to obtain downscaled local information for some future time period by driving the relationships with GCM-derived predictors. (See Wilby, R.L., Dawson, C.W. and Barrow, E.M. (2002): SDSM - a decision support tool for the assessment of regional climate change impacts. Environmental Modelling Software, 17, 145-157).

SMD — Soil moisture deficit.

SRES scenarios — Scenarios describing the emission of greenhouse gases in to the atmosphere in the future have been developed by the IPCC (IPCC, 2000). These are referred to as the SRES scenarios (Special Report on the Emission Scenarios).

Statistical Downscaling Model — See SDSM.

SUTRA — Finite-element simulation model for Saturated-Unsaturated fluid-density-dependent ground-water flow with energy transport or chemically-reactive single-species solute TRAnsport.

SWAP — Soil Water Atmosphere Plant model developed by Wageningen University and Reseach centre.

SWAT — Soil and Water Assessment Tool: a river basin, or watershed, scale model developed by the US Department of Agriculture. SWAT predicts the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time.

Tyndall Centre — The purpose of the Tyndall Centre for Climate Change Research is "to research, assess and communicate from a distinct trans-disciplinary perspective, the options to mitigate, and the necessities to adapt to, climate

	change, and to integrate these into the global, UK and local contexts of sustainable development”.
UEA	University of East Anglia.
UKCIP	UK Climate Impacts Programme: set up in April 1997, UKCIP is funded by the DEFRA and based at the University of Oxford. It works with stakeholders and co-ordinates research on how climate change will have an impact at regional and national levels.
UKCIP98	UKCIP’s climate change scenarios published in 1998 based on the HadCM2 model.
UKCIP02	UKCIP’s climate change scenarios published in 2002 based on the HadCM3 model.
UKCIPNext	UKCIP’s climate change scenarios due for release in spring 2008.
UKWIR	United Kingdom Water Industry Research.
UKTR	The Met Office, UK.
UNEP	United Nations Environment Programme.
VEMAP	Climate & Global Dynamics Division, University Corporation for Atmospheric Research, USA.
WAVES	Soil moisture and unsaturated zone model developed by Dawes and Short (1993).
WMO	World Meteorological Organisation.
World Markets UKCIP socio-economic scenario	One of the four UKCIP’s socio-economic scenarios dominated by the drive to private consumption and personal freedom and the rights of the individual.

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