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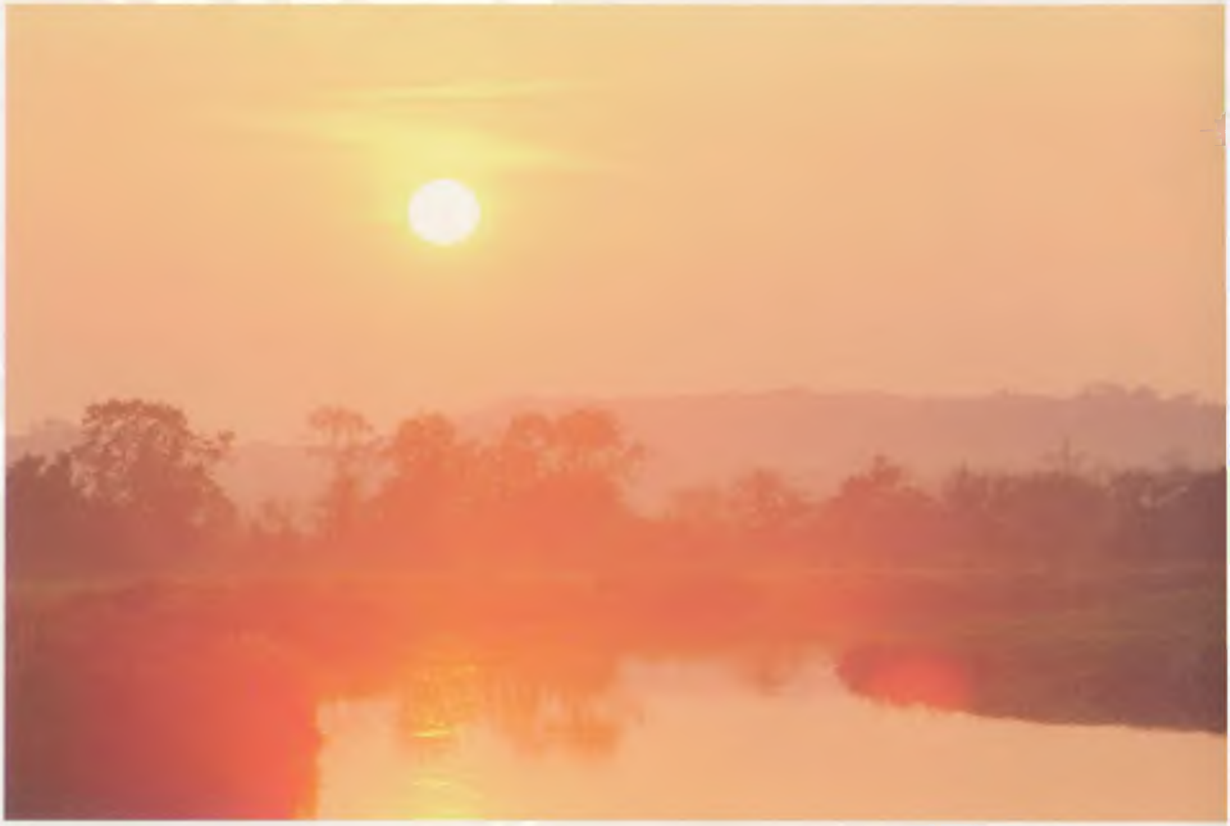
The Implications of Climate Change for the National Rivers Authority



Institute of Hydrology

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National Rivers Authority

R&D Report 12

Project 358

The Implications of Climate Change for the National Rivers Authority

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Statement of Use

This Report is released for information purposes to enable NRA staff, and those dealing with them, to consider the potential implications of climate change on NRA activities.

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FOREWORD

The National Rivers Authority commissioned a review of the sensitivity of NRA activities to climate change in order to assist in the need for, and if so, the development of responses to climate change by its different core functions.

This report sets out the findings of the review. The NRA will use these findings, in discussion with other organisations involved with climate change, to help it to develop management actions - in operational activities, policy development or further studies - which, where necessary, take due account of the potential impact of climate change.

The report is based on a review of the published literature, on research currently in progress, on informed speculation, and on discussions with NRA staff from each core function and most regions. The NRA emphasises that the report is released for general information, and does not in itself represent NRA policy or operation guidance.

The NRA has determined that any response which it makes to climate change should be guided by due consideration of the precautionary approach to preventing environmental degredation adopted in the 1992 Rio Declaration on Environment and Development.

In considering the implication of the findings of the R&D project, the NRA will need to be sensitive to further information on likely climate change predictions to ensure it is basing its decisions on the most up to date forecasts.

DR C J SWINNERTON
Director of Water Managment

March 1994

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EXECUTIVE SUMMARY

The possibility that global warming due to an increasing concentration of "greenhouse gases" might result in significant climate changes has been at the forefront of scientific, political and public attention since the late 1980s.

The objective of this report is to estimate the sensitivity of NRA activities to climate change and to assist in the development of a strategy for NRA response.

Global warming might lead to an increase in mean global temperature of 0.3°C per decade and an increase in global mean sea level by 2030 of 0.18 m. There are indications that winter rainfall in the UK will increase, and the best estimate for summer rainfall is for there to be no change. The impact of changes in temperature, rainfall, evaporation and sea level on rivers and aquifers, however, are very dependent on local catchment and geological conditions, so changes are difficult to generalise; nevertheless, the effects of climate change on water systems managed by the NRA might be noticeable within 30 years.

The water environment is both naturally complex and heavily managed, so a change in climate can have many effects on different aspects of the NRA; climate change may impact on one core function of the NRA through the actions of another. The impact of climate change is not a simple response to the degree of forcing, because the water systems are characterised by a number of critical thresholds, beyond which the response changes markedly. Also, the water environment is subject to many other pressures which are leading to change: in many instances these "non-climatic" changes, such as land-use change and changes in demand for water, may be more significant for water management than climate change.

Two reasons are often cited for doing nothing about climate change: (i) the impacts are very uncertain and (ii) if they do occur, they will happen well into the future. This report explains that whilst there is considerable uncertainty on the impact of climate change, the impacts may be very large and may be felt within planning horizons currently used in the NRA. Each NRA core function, however, will need to respond differently to climate change. This is partly because of the different degrees of sensitivity and uncertainty in different areas, and is partly due to the different time-scales involved in implementing a response. The longer the lead time required, the sooner action needs to be taken; however, the earlier the action, the greater the uncertainty in the estimated impact of change.

The most important implications of climate change for the NRA are listed below:

1. An increase in the risk of coastal flooding, and a reduction in standards of service provided by exisiting flood defences.

2. A change in the characteristics of coastal ecosystems. Higher sea levels will threaten a number of important coastal ecosystems.

3. A change in the variability of river flows. This will affect many NRA interests, including water resources, water quality, fish habitat, riverine ecosystems and the aesthetic quality of river corridors. The extent of changes in river flow regimes is unknown, and in many regions the direction of change differs according to the climate change scenario considered. In some catchments it will be possible to cope with future changes in flow regime without major alterations to operating systems and rules; in others, maintaining reliable water supplies could entail providing new or enlarged reservoir storage. It is difficult at present to generalise.

4. A change in the risk of fluvial flooding. It is probable that the risk of fluvial flooding will increase, but the extent of change is still very uncertain.

5. A change in groundwater recharge, and hence the reliability of groundwater resources. The direction of change is again uncertain, and different - feasible - scenarios suggest either an increase in recharge or a reduction.

The report identifies climate parameters relevant to the NRA, and indicates how the NRA should build on intergovernmental and UK Government initiatives for developing climate change scenarios (Chapter 4). It goes on to review the detailed implications of climate change for each core function of the NRA, and outlines possible responses.

The final chapter brings together themes common to all or many NRA functions. It recommends the application of the precautionary approach by the NRA in considering its response to climate change in any area of activity. It suggests that the NRA, alongside other organisations, develops generic supporting tools for determining such responses, including "approved" climate change scenarios and a methodology for climate change impact assessment.

The final chapter also outlines four general principles which should underpin NRA response to climate change:

1. Multi-functional impacts imply a multi-functional response, preferably through the medium of catchment management plans;

2. An uncertain future implies flexibility in water management;

3. Identify critical thresholds for important activities;

4. An uncertain future implies continual monitoring and review of further predictions of change.

These principles also underlie sound water management in general. Many of the responses discussed in this report could be justified for reasons other than the management of climate change, and some are already being implemented or considered for these other reasons.

It is therefore emphasised that response to climate change must be considered within the framework of existing NRA developmental initiativies and managment activities.

KEY WORDS

Climate Change, Global Warming, Water Resources, Water Quality, Flood Defence, Fisheries, Conservation, Recreation, Navigation

1. INTRODUCTION

1.1 Objectives of Report

The threat of climate change due to the "greenhouse effect" and global warming became an important scientific, political and public issue during the 1980s, and is certain to keep its high profile through the 1990s.

The overall objective of this report is to describe, given current knowledge, the sensitivity of National Rivers Authority (NRA) activities to climate change and to assist in the development of NRA response to climate change. Specific objectives are listed below:

1. To summarise the current state of knowledge of possible climate changes in England and Wales, and review the rate at which information on possible climate changes might be improved.

2. To estimate, given current knowledge, the sensitivity of each NRA core function to climate change, and indicate both the key impact areas and the uncertainties in current assessments.

3. To identify the parameters of climate change of greatest relevance to the NRA.

4. To assist the NRA to develop a management and related research strategy in response to climate change.

1.2 The Role of the National Rivers Authority

The NRA was established by the 1989 Water Act as a Non-Departmental Public Body. It has statutory responsibilities for water resources, pollution control, flood defence, fisheries, conservation, recreation and navigation in England and Wales, and these seven areas represent the core functions into which the NRA is organised. The NRA is both an *executive* authority - in flood defence, conservation and navigation in particular - and a *regulatory* authority.

The NRA has responsibilities to the Department of the Environment (DoE), the Ministry of Agriculture, Fisheries and Food (MAFF) and the Welsh Office. The DoE is the agency ultimately responsible for meeting government and EC policy directives on water, and discharges this responsibility with regard to the water environment through the NRA and Her Majesty's Inspectorate of Pollution (HMIP). The DoE also sets performance targets, approves Drought Orders and must give permission for large investments and activities. MAFF and the Welsh Office are involved in flood defence, and give grants to the NRA to undertake flood defence schemes. The NRA is responsible for licensing abstractions of water and discharges to surface and groundwater bodies, and therefore liaises closely with the ten water service companies and the statutory water companies.

The NRA needs to be informed about climate change (i) to help in its executive role, (ii) to help in its regulatory and monitoring role, (iii) to assist in long-term strategic planning, and (iv) to understand the pressures and problems facing those it regulates. The NRA needs to be in a position to be able to react to climate change in the most pragmatic and cost-effective way, as appropriate to its responsibilities in each of its functions.
The NRA currently has a cross-functional coordinator for climate change issues (see inside cover).

1.3 Structure of Report

The report summarises current understanding of the effects of climate change due to global warming on each NRA core function. Chapter 2 summarises the current scientific understanding of global warming and climate change, and Chapter 3 provides a framework for the evaluation of impacts and potential responses to climate change. Chapter 4 reviews the possible impact of global warming on climate change and the hydrological system in England and Wales.

Chapters 5 to 11 describe the implications of climate change for the seven NRA core functions. Each chapter has a similar structure. Potential impacts are listed and reviewed, and a number of possible NRA responses are summarised.

Chapter 12 attempts to draw some general conclusions about the potential implications of climate change for the NRA, and indicates common themes that run through several core functions.

Appendix A lists recent and current research projects, and a list of abbreviations and acronyms is provided in Appendix B.

The report does *not* indicate ways in which the NRA might seek to reduce the emission of greenhouse gases produced by its own activities or by those organisations that it regulates.

1.4 Climate Change Research in the UK

1.4.1 Institutional arrangements

The Global Atmosphere Division of the Department of the Environment is the lead government agency in the field of climate change. It has a number of roles:

1. Formulation of government policy towards global warming.

2. Support for the Hadley Centre for Climate Prediction and Research at Bracknell, Berks. This is the main centre for climate modelling in the UK, and is a part of the Meteorological Office.

3. Support for a number of projects investigating processes involved in global warming.

4. Support for the UK contribution to the Intergovernmental Panel on Climate Change (IPCC). The IPCC was established by the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP) to provide information on climate change to decision-makers (Section 2.1).

5. Support for the Climate Change Impacts Review Group (CCIRG). The CCIRG was set up, under the chairmanship of Professor Martin Parry, to consider the potential impacts of climate change in the UK. It has produced one report (CCIRG 1991) - to which the NRA contributed technically - and is maintaining a watch on UK and international developments.

6. Support for the Climate Impact LINK project to relate the output of climate models (such as those from the Hadley Centre) to the demands of the impact assessment community. This project is based at the Climatic Research Unit of the University of East Anglia.

7. Support for a "core-modelling" project, centred at the Institute of Terrestrial Ecology and the Institute of Hydrology, which aims to develop methodologies for assessing the ecological and biogeochemical impacts of climate change, respectively.

8. Coordination of policies towards climate change of other government departments.

The Global Atmosphere Division of DoE does not support research into impacts in specific areas, and this is the responsibility of the interested departments or agencies, such as the NRA, which form the impacts community.

Basic research is also conducted through the Research Councils. The Research Councils coordinate through the Inter-Agency Committee on Global Environmental Change (IACGEC), which is comprised of the Chairmen of the five Research Councils, the Chief Scientist of the DoE, the Chief Executive of the Meteorological Office, and the Director General of the British National Space Centre (BNSC). An overview of UK research into global environmental change - which is broader than global warming - was published in April 1991 (IACGEC 1991). The secretariat for the IACGEC is provided by the Global Environmental Research Office which also maintains a database of research activities and publishes a quarterly bulletin entitled *The Globe.*

The science behind global warming is summarised in Chapter 2, but the remainder of this chapter reviews international and UK research programmes involved with climate change. Table 1.1 shows such programmes under a number of headings. Note that it does not include individual projects which are not part of a coordinated climate change programme.

1.4.2 Greenhouse gases

An increasing concentration of so-called "greenhouse gases" lies at the heart of global warming (Chapter 2), and estimated impacts of climate change depend ultimately on the understanding of the sources of these gases, on their transformations in the atmosphere, and on how they are taken up by the biosphere and ocean.

Studies to estimate the sources, fate and sinks of greenhouse gases in the atmosphere are being coordinated by the Intergovernmental Panel on Climate Change Working Group I, which is setting a number of guidelines for national assessments. The International Global Atmospheric Chemistry (IGAC) core project of the International Geosphere Biosphere Programme (IGBP) acts as an international forum for scientists studying greenhouse gases in the context of biosphere processes (the IGBP is itself a programme of the International Council of Scientific Unions (ICSU)).

There are several major UK research programmes which consider sources and sinks of greenhouse gases. Those that concern atmospheric and terrestrial chemical processes include the Biogeophysical Ocean Flux Study (BOFS) and the Terrestrial Initiative in Global Environmental Research (TIGER) programme.

Table 1.1 International and UK research programmes in global warming and climate change

	International	UK Programme	UK Timescale
Sources and sinks of greenhouse gases	IPCC	BOFS	1987-1992
	IGAC	TIGER I,II	1992-1995
		MAFF EPD	1992-1994
Climate change processes and feedbacks	WOCE	TIGER III,IV	1992-1995
	GEWEX, GCIP	UGAMP	1988-
	BAHC		
Numerical climate simulation	IPCC	Hadley Centre	1990-
		UGAMP	1988
Creating climate change scenarios		DoE GA	1991-1993
Climate change impacts	WMO/UNEP WCIP	CCIRG	1990-
	IPCC	DoE GA	1991-1994
		DoE WD	1990-1993
		MAFF EPD	1992-1994
		AFRC BAC	1992-1996
Monitoring and databases	GCOS	ECN	1992-
		GENIE	1992-

BOFS is an NERC-sponsored programme aimed at measuring and modelling the exchange of carbon dioxide between the atmosphere and the ocean. Fluxes between the atmosphere and the land surface are being investigated in the NERC TIGER programme, which finishes in 1995. TIGER I is concerned with measuring and modelling the carbon cycle on land, whilst TIGER II focuses on other trace gases (particularly methane and nitrous oxide). Both BOFS and TIGER support research in universities and in NERC institutes. An SERC-funded programme is largely interested in the chemical transformations in the atmosphere; the DoE Global Atmosphere Division also supports work on atmospheric chemistry.

The MAFF Environmental Protection Division programme is concentrating on measuring methane and nitrous oxide emissions associated with agricultural practices. Industrial emissions and possibilities for limiting them are under consideration in programmes organised by branches of the energy industry, with basic co-ordination by the Watt Committee on Energy.

1.4.3 Climate change processes and feedbacks

There are several large international collaborative programmes investigating the processes involved in climate change (Table 1.1 omits those programmes which are not concerned explicitly with global change). The following paragraphs emphasise those that relate most strongly to the NRA.

The World Ocean Circulation Experiment (WOCE) is concerned with modelling ocean circulation patterns and identifying global scale mass and energy transfers. It is supported by the World Meteorological Organisation (WMO) and the International Oceanographic Commission. The Global Energy and Water balance Experiment (GEWEX) is a suite of programmes covering radiation, clouds and integrated hydrometeorlogical modelling (GCIP: the GEWEX Continental-scale International Project). It is supported by WMO and the International Council of Scientific Unions. GEWEX is a long-term research programme, scheduled to run into the 21st century. GCIP - the component most relevant to impacts of climate change on water resources - is planned to finish in 1999.

The Biospheric Aspects of the Hydrological Cycle (BAHC) programme is a core project of the International Geosphere and Biosphere Program (IGBP). BAHC is concentrating on the relationships and feedbacks between atmosphere and the terrestrial biosphere, and liaises closely with GEWEX. BAHC began in 1991 and, like GEWEX, should run into the 21st century.

TIGER is the major integrated programme on climate change processes and feedbacks within the UK. TIGER III is concerned with measuring and simulating energy and water balances at the land surface, and many TIGER III projects are contributions to both GEWEX and BAHC. TIGER III includes a project to develop continental-scale hydrological models which will be able to simulate the effects of climate and other environmental change in large basins (and is a contribution to GCIP). The project is being undertaken by the Institute of Hydrology, Newcastle University, Imperial College and University College London; it is concentrating on the Thames and Tyne basins, and the first phase will be completed by 1995.

TIGER IV is concerned with the effect of climate change on ecosystems, and in particular on the feedbacks between climate and vegetation. An important emphasis on the way is that vegetation responds to elevated atmospheric CO_2, in particular in water use efficiency. Again, results will be available by 1995.

1.4.4 Numerical climate simulation

The most important numerical global climate simulation models are currently operated by the Hadley Centre for Climate Prediction and Research (UK), the Geophysical Fluid Dynamics Laboratory (GFDL: USA), the Goddard Institute for Space Studies (GISS: USA), the National Center for Atmospheric Research (NCAR: USA), the Max Planck Institute for Meteorology (Germany), the Canadian Climate Centre (CCC) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO, Australia). The UGAMP consortium in the UK undertakes basic research into atmospheric modelling, including physical and chemical aspects. The UK-WOCE project contributes knowledge on ocean circulation and its simulation in climate models.

Global climate models rely on the basic research undertaken by national and international programmes into climate change processes and feedbacks, and also use global-scale data sets for model validation. Model development is a continuous process, and refined estimates of future climates are continually being produced (see Section 2.2.5 for a discussion of the rate at which climate model simulations are improving).

1.4.5 Creating climate change scenarios

The Global Atmosphere Division of the Department of the Environment initiated the Climate Impact LINK project in 1991 to create climate change scenarios for the UK impacts community (Section 4.12.2); the project acts as a link between the Hadley Centre and the impacts research community. The MAFF Environmental Protection Division also supports a study into the creation of climate change scenarios which, like the DoE project, is based at the Climatic Research Unit, University of East Anglia.

1.4.6 Climate change impacts

There have been many studies into climate change impacts in the UK, but there are really only five coordinated programmes. The Climate Change Impacts Review Group (CCIRG) was set up by DoE Global Atmosphere Division in 1990 to summarise current estimates of the impacts of climate change in the UK (Section 1.4.1). It has not directly supported new research, but has brought research results and the impacts research community together. The four other programmes are aimed at conducting new research into climate change impacts.

The DoE Global Atmosphere Division Core Modelling project is developing a methodology for using integrated physically-based models to estimate impacts of climate change on, at first, ecological systems and water and soil chemistry. The research is being undertaken by the Institute of Hydrology, the Institute of Terrestrial Ecology, and the Universities of Sheffield and Durham. The project is designed to provide the modelling capability for studies into climate change impacts, and not to perform impact assessments on specific systems; it will finish in 1994.

The DoE Water Directorate funded, between 1990 and 1993, an integrated project to assess the potential implications of climate change for UK water resources. The project considered river flows (Arnell and Reynard 1993), demand for water ((Herrington 1994), stream water quality (Jenkins *et al.* 1993), stream water temperature (Webb 1992) and estuarine water quality (Dearnaley and Waller 1993). Research was undertaken by the Institute of Hydrology, the Universities of Exeter and Leicester, and HR Wallingford.

The MAFF Environmental Protection Division programme contains several projects studying changes in soil characteristics, arable and vegetable crops, crop and animal pests and diseases, and agricultural potential. Several institutions are contributing to 14 different projects.

The Agriculture and Food Research Council (AFRC) programme Biological Adaption to Global Environmental Change (BAC) is also concerned with animal and vegetation response to CO_2 and climate, which may have some relevance to water resources.

The Scottish Office Agriculture and Fisheries Department (SOAFD) funds a coordinated programme on the implications of climate change for agriculture and other land uses in Scotland. Components include production models for arable crops, grassland and animals, forest trees, artificial weather simulation, farming operations, Geographical Information Systems (GIS) for climatic and soil data, and an economic synthesis. The work is carried out at the Macaulay Land Use Research Institute, the Scottish Agricultural College and the Scottish Crop Research Institute.

1.4.7 Monitoring and databases

At the global scale, the World Meteorological Organisation is currently initiating a Global Climate Observing System (GCOS). This will receive data from a number of existing and new observing networks, concentrating on climate and ocean data. It builds on the existing World Weather Watch and will provide assimilated fields of relevant parameters including those needed for global study of the hydrological cycle.

In the UK, the Environmental Change Network (ECN) comprises a network of sites established both for long-term monitoring purposes and as locations for field experiments. The ECN is concentrating on ecological monitoring, but as part of this climatic and hydrological data are being collected. Funding for the ECN comes from several government agencies and NERC; the NRA supports seven river monitoring sites in the ECN in England and Wales.

The ESRC has created a Global Environmental Change Data Management Centre and Federal Network Facility (the GENIE project) as part of its contribution to global environmental change research. This centre, based at Loughborough University of Technology, aims to act both as a "shop window" for data sets held by other organisations and as a means to encourage the transfer of data.

Finally, both the Hadley Centre and the Climatic Research Unit at the University of East Anglia are assembling global data sets of temperature and precipitation for global and regional monitoring purposes.

1.4.8 Dissemination of results

Most of the research described in Section 1.4 is aimed at improving the understanding of the processes behind global warming and climate change, and at improving the simulation of global climate. The results of these studies will be disseminated amongst the scientific research community, and will be passed through to the impacts community in terms of refined *climate change scenarios*. The DoE Climate Impact LINK project (Sections 1.4.5 and, in more detail, 4.12.2) provides the link between improved understanding and simulation of global climate processes and the impacts community in the UK.

2. THE GREENHOUSE EFFECT AND CLIMATE CHANGE

2.1 Introduction

The aim of this chapter is to summarise the processes which lie behind global warming and to look at evidence for ongoing climate change.

The information in this chapter is largely drawn from the reports of the United Nations Intergovernmental Panel on Climate Change (IPCC). The IPCC is sponsored by two United Nations bodies, namely the World Meteorological Organisation (WMO) and the United Nations Environment Programme (UNEP). It was established in 1988, and three Working Groups submitted their reports at the Second World Climate Conference in Geneva in November 1990. Working Group I concentrated on the scientific aspects of climate change (IPCC 1990a), whilst Groups II and III reviewed impacts (IPCC 1990b) and policy responses (IPCC 1991) respectively.

One hundred and seventy scientists from 25 countries contributed to Working Group I on the scientific assessment of climate change, and a further 200 were involved in the peer review of the report; the report is therefore widely accepted as the most authoritative statement on the current understanding of climate change due to increasing concentrations of greenhouse gases. A supplementary report updating the 1990 assessment was published in May 1992 (IPCC 1992), to provide information for the negotiations for the International Convention on Climate Change for consideration at the United Nations Conference on Environment and Development (UNCED) in Brazil in June 1992.

2.2 Climate Change: Processes and Prediction

2.2.1 The physics behind global warming

The Earth's climate system is driven by energy emitted from the Sun. Some of the solar radiation (approximately a third) is reflected directly back into space, whilst the rest is absorbed by the land, sea and, to a much lesser extent, the atmosphere. The Earth's surface is warmed by this absorbed radiation, and emits long-wave infra-red radiation back towards the atmosphere. Some of this long-wave radiation, however, is absorbed and then re-emitted by a number of trace gases. This leads to an increase in radiation received at the surface, and hence further warming. This property of long-wave absorption and re-emission is known as the "greenhouse effect", because the trace gases which are transparent to the incoming short-wave solar radiation whilst blocking the outgoing long-wave radiation are acting in a similar way to the panes of glass in a greenhouse. Figure 2.1 illustrates the greenhouse effect.

If it were not for the greenhouse effect, the mean temperature of the Earth's surface would be approximately 33°C cooler than it is at present. The problem of global warming arises because of the increasing concentration of the important trace gases in the atmosphere, so strictly it should be termed the "enhanced greenhouse effect".

There are three other major factors which influence the energy budget in the lower atmosphere, and hence global temperatures. The first is the long-term variation in the output of radiation from the Sun; there is some variability over the 11-year solar cycle, and there may also be longer-period changes. Variations are, however, small in comparison with the radiative effect of increased greenhouse gas concentrations.

The second is long-term change in the Earth's orbit, affecting the seasonal and latitudinal distribution of energy received; these changes are probably responsible for the periodic cycling between interglacials and ice ages. Again, variations over the decadal timescale are minimal compared with the radiative effect of greenhouse gases. Neither of these factors are affected by human activity. The third factor affecting global energy budgets is the presence of aerosols, or small particles, in the atmosphere. Aerosols reflect and absorb radiation. The most important natural perturbations arise from volcanic eruptions, when large quantities of dust are ejected into the lower stratosphere. Aerosols are also formed from man-made emissions into the atmosphere, and the 1992 Supplement to the IPCC Scientific Assessment (IPCC 1992 concluded that sulphate aerosols resulting from sulphur emissions (from industry and power generation) had mitigated to an extent the effects of increasing greenhouse gas concentrations (although this does not mean that sulphur emissions are "good"; they are responsible for acid rain and, as emission controls become more effective, their role in curbing the greenhouse effect will diminish).

Finally, it is important to remember that global temperatures vary from year to year or decade to decade *without* any changes in components of the global energy balance. Most of these variations give rise to random fluctuations; however some give rise to quasi-periodic

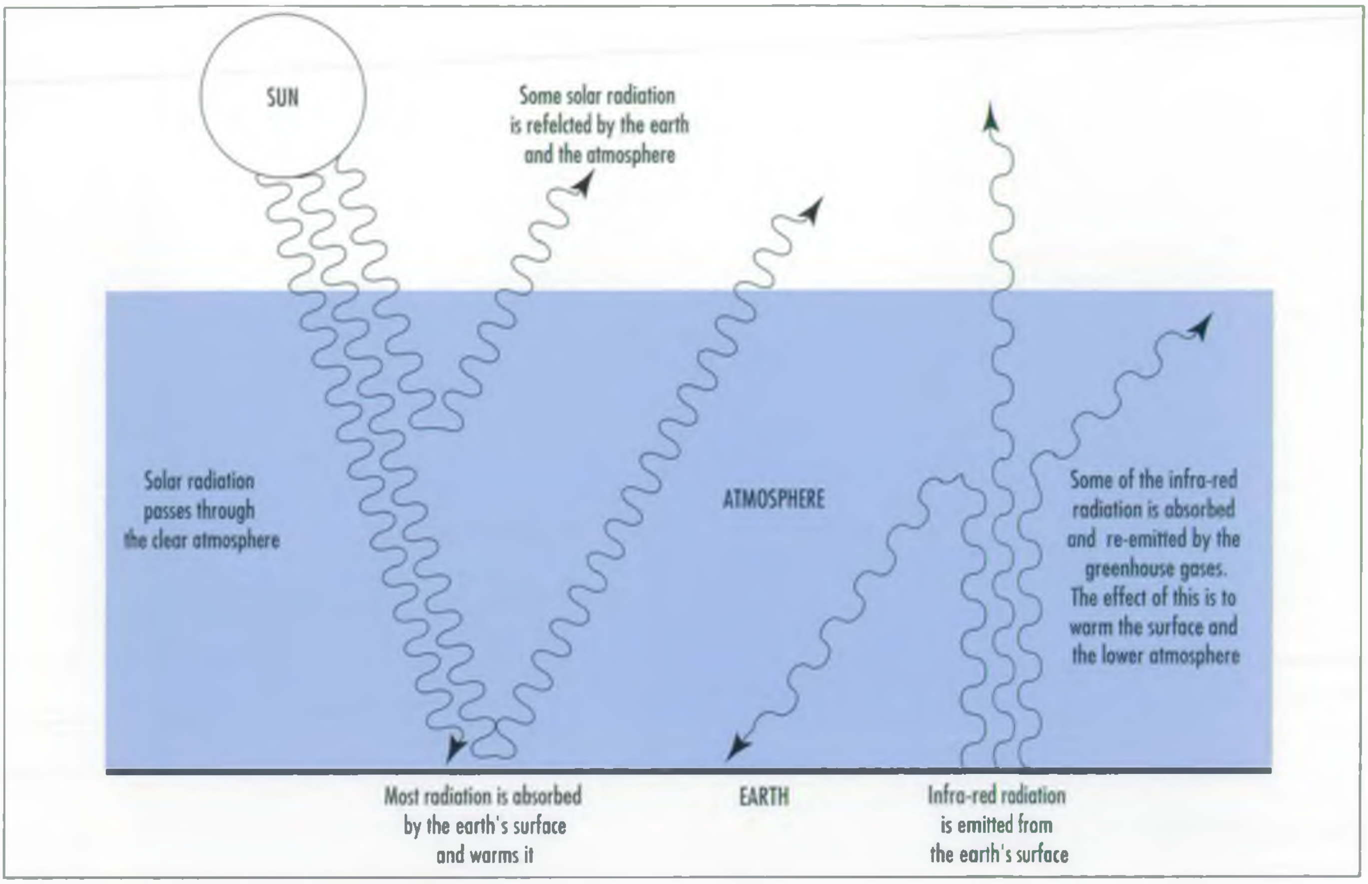

Figure 2.1 The greenhouse effect (IPCC 1990a)

fluctuations, of which the El Nino, which affects periodically at least the Pacific Ocean, is the best known. Other quasi-periodic fluctuations give rise to the extended spells of relatively wet and relatively dry weather in the Sahel region of West Africa.

2.2.2 Greenhouse gases

Water vapour is by far the most important greenhouse gas, and the other natural greenhouse gases are carbon dioxide, methane, nitrous oxide and tropospheric ozone. The concentrations of these latter trace gases in the atmosphere have increased due to human activity, and another group of man-made gases - the chlorofluorocarbons (CFCs) - were not present in the atmosphere before their invention in the 1930s. The concentration of water vapour in the atmosphere is not directly affected by human activity, but is instead determined within the climate system; water vapour in the atmosphere will increase with global warming, and further enhance it. Table 2.1 shows the key greenhouse gases, indicating pre-industrial and present atmospheric concentrations, the annual rate of increase, and the major human-influenced sources.

Carbon dioxide is the most important greenhouse gas apart from water vapour, and the increase is primarily due to the combustion of fossil fuels and deforestation. Emissions of carbon dioxide into the atmosphere depend on economic development and the efficiency of energy use and can be estimated and modelled with reasonable accuracy, but other terms in the carbon balance are known only approximately so overall there is a considerable uncertainty about the rate of change of atmospheric carbon dioxide concentrations.

Methane is produced by a variety of anaerobic (i.e. oxygen deficient) processes, and the major human-influenced sources are paddy rice and ruminants. Biomass burning, coal mining and the venting of natural gas have also increased atmospheric concentrations, and fossil fuel combustion may have led to a reduction in the rate of operation of chemical reactions which remove methane in the atmosphere. One (as yet unsubstantiated) concern is that global warming may release the large stocks of methane which are currently held in the frozen Arctic tundra.

The sources of nitrous oxide are less well-known, although it is likely that agriculture has played a part in the increase in concentrations in the post-war period.

Table 2.1 Important greenhouse gases (IPCC 1990a: * denotes value revised in IPCC 1992)

	Pre-industrial concentration	Present (1990) concentration	Annual rate of increase	Major sources
Carbon dioxide	280 ppmv	353 ppmv	0.5%	fossil fuels combustion, deforestation
Methane	0.8 ppmv	1.72 ppmv	0.6%*	rice production, cattle rearing, industry
Nitrous oxide	288 ppbv	310 ppbv	0.25%	internal combustion engine, agriculture
Tropospheric ozone	no data	no global estimates	no data	
CFC-11	0 pptv	255 pptv *	4%	aerosols, refrigeration
CFC-12	0 pptv	453 pptv *	4%	aerosols, refrigeration

ppmv parts per million by volume

ppbv parts per billion by volume

pptv parts per trillion by volume

Tropospheric ozone is a greenhouse gas, but is not emitted directly by human activities. Instead, it is formed in the atmosphere by photo-chemical transformations of other gases including carbon monoxide, nitrogen oxides, methane and hydrocarbons which can have human-influenced sources. Tropospheric ozone has a short lifetime, so its concentration varies over space and time.

Chlorofluorocarbons (CFCs) are not only implicated in the destruction of stratospheric ozone, but are also greenhouse gases. The 1992 IPCC Supplement has suggested however that the depletion of ozone in the stratosphere has approximately offset the radiative effect of CFCs, so that the net contribution of CFCs to global warming may be less than previously assumed.

In terms of radiative effect per kilogram, carbon dioxide is the least effective greenhouse gas. One kilogram of methane is estimated to have at least 11 times the effect of a kilogram of carbon dioxide, and the difference is even greater once the indirect effects arising from the chemical transformations of methane in the atmosphere are considered (IPCC 1992). Other greenhouse gases are even more potent than methane; the direct effects of CFCs are several thousand times greater than those of carbon dioxide. However, whilst carbon dioxide has the lowest radiative effect per kilogram, it is emitted in far greater quantities than the other gases. It is difficult to estimate the lifetimes of some gases and the gases resulting from their chemical transformations, but over the next 100 years the increase in carbon dioxide will account for over 60% of the total enhanced greenhouse effect (IPCC 1990a).

2.2.3 Modelling the climatic effect of increasing greenhouse gas concentrations

Increases in greenhouse gas concentrations alter the energy budget in the lower atmosphere, which leads to increased temperatures which in turn result in changes to global and regional climate patterns. The links between human activity, greenhouse gas emissions, greenhouse gas concentrations, atmospheric temperature and regional climate are, however, very complicated and are characterised by a number of important positive and negative feedbacks, some of which have been mentioned in the previous section.

The effects of increased greenhouse gas concentrations on regional climate can realistically be simulated only using a three-dimensional physically-based representation of atmospheric and oceanic processes. General Circulation Models (GCMs) are based on the laws of physics and currently operate on a grid network of at least 250 x 250 km at mid-latitudes (the Hadley Centre model runs at a resolution of 2.5° x 3.75°, and some others have a much coarser resolution). The models use parameterised descriptions of those physical processes, such as cloud formation, which operate at a finer spatial scale. An atmospheric model - which is essentially the same as a weather forecasting model, although it is run for a period of several decades rather than a few days - is coupled with an equally complex model of ocean circulation.

Most climate change experiments have compared a simulation of the current climate with a simulation assuming a doubling of atmospheric carbon dioxide concentrations (the assumed doubling allows for the effect of the other greenhouse gases). The simulations show the *equilibrium* or long-term average climate under current and future stable higher-greenhouse gas conditions, and the change in global average temperature due to a doubling of carbon dioxide predicted by different GCMs lies between 1.5° and 4.5° (Bolin *et al.* 1986; IPCC 1990a; IPCC 1992). It is important to note that these simulations show only the long-term *stable* effect of a doubling of carbon dioxide concentrations, and they do not indicate *when* these effects will be reached.

In practice, greenhouse gas concentrations are continually increasing and the climate system takes time to respond to the changed energy balance. Even if carbon dioxide were to stabilise once it had doubled, it would take several years before the climate system had reached a stable response. A small number of experiments have therefore used GCMs to simulate the time-dependent or *transient* response of climate to an increasing concentration of greenhouse gases. These transient models must include a more realistic dynamic simulation of the interactions between the atmosphere and the oceans, because it is these interactions which determine the time taken by the climate system to respond. Transient simulations, however, require massive computing resources and so cannot at present be used to compare the effects of different greenhouse gas emissions scenarios or different assumptions about the feedbacks between greenhouse gas sources and sinks (it took nine months of continuous computer time to simulate 150 years of weather with the UK Meteorological Office model in 1991: new computing facilities at the Hadley Centre mean that such a run would now "only" take around three months).

Current GCMs simulate the characteristics of the present general circulation reasonably well, although all are less good at simulating rainfall than temperature. There are, however, a number of limitations to current models:

1. Their spatial resolution is coarse: GCMs work on a grid spacing that is at least 250 km wide.
2. GCMs use "parameterisations" of processes which operate at scales smaller than the grid resolution. These processes include cloud formation and the exchange of mass and energy with the land surface. Some of the parameterisations are very simplified, and GCM estimates of the effects of climate change have been shown to be quite dependent on, for example, the model used for cloud formulation (IPCC 1992). Data are not available, however, to determine which of a number of different schemes most closely resemble reality.
3. The links between the ocean and the atmosphere are currently not represented very realistically but, as is the case with clouds, observational data to help choose between alternative formulations are lacking. This is particularly important when simulating the dynamic evolution of climate.

These limitations mean that high resolution and short-duration climate characteristics - such as the occurrence of heavy hourly rainfall over south east England - cannot be simulated at present, and that it is not realistic to use GCMs directly to estimate possible changes in such characteristics. In the most general terms, climate modellers are confident about model predictions of global average temperature change, quite confident about regional seasonal temperature changes, not confident about seasonal rainfall changes, and very sceptical about regional predictions of rainfall at durations of less than a month. They also have very little confidence in predictions of changes in year-to-year variability.

2.2.4 Improving the spatial resolution of global climate models

Current climate models operate at a grid resolution of several hundred kilometres (in the Hadley Centre model each grid point represents approximately 80,000 km^2). This scale is far too coarse to simulate regional climate patterns, and there are two possible ways of adding further spatial detail (apart, of course, from waiting for GCM resolution to improve).

The first is to embed a higher-resolution regional climate model into the GCM. To simulate UK climate, for example, a 50 x 50 km resolution model of the North Atlantic and Europe could be nested within the GCM, and this is currently being attempted by the Hadley Centre. The high resolution model uses inputs from the coarser-scale global model; a fully coupled nested model would send information back to the global model.

The second approach is to add spatial detail to the GCM data by statistical methods. The simplest way is just to interpolate from the GCM grid points down to a finer resolution using a standard statistical interpolation routine. This does not, however, account for any known climatic pattern within the region of interest, so more complicated procedures use statistical relationships between observed point time series and either a regional average time series (for example Wigley *et al.* 1990) or an index of regional weather circulation type (for example Bardossy and Plate 1992). The success of the method depends on the strength of the relationship between point climate and the regional index. It has been found that the method can be used to estimate spatial patterns in temperature data from a single regional average temperature value, but that relationships between point and regional average rainfall are very poor.

A problem common to all attempts to add spatial detail to coarse GCM simulations is that the quality of the derived spatial pattern is determined by the quality of the input data; if the global climate model produces poor estimates for the coarse grid network, then no method will produce "realistic" spatial detail.

2.2.5 When will it be possible to rely on climate model simulations?

Although this appears to be a simple question, it is in fact very difficult to answer. There are two problems:

Firstly, although it is possible to validate the ability of a climate model to simulate current climate, it is not possible to evaluate the reliability of a *predicted* change (without waiting for that change to take place). Some indication of the range in possible changes can be obtained by comparing results from different models, but a narrow range does not mean that precision is high; the models could all be making the same mistakes.

Secondly, the ability of a climate model to simulate climate depends on the spatial and temporal scale considered. The coarser the spatial scale and the longer the time step, the higher the skill. A model may be "good" at simulating, for example, European-scale annual rainfall, but be very bad at simulating winter rainfall in southern England.

It is, therefore, not possible to predict the rate at which climate model simulations will improve.

2.3 Climate Change Scenarios

2.3.1 The scenario concept

For the reasons outlined in Section 2.2, it is not possible to produce predictions of future regional climates, especially for a region as small as England and Wales. Estimates of the implications of global warming must therefore use scenarios of future climate change. A climate change scenario is a *feasible, internally-consistent, hypothetical estimate of possible future climatic conditions.* It is not to be considered as a forecast or a prediction, and any impact analysis must consider a range of feasible scenarios.

2.3.2 Creating climate change scenarios:

There are at least four basic methods of creating climate change scenarios:

Using information from the past
This approach uses information from warm periods in the past instrumental or historical record to construct a climate change scenario. The main problems with the method are that change in the future may not take the same form as past changes, and that it can be difficult to get information from periods sufficiently warmer than the present to act as an analogue for the mid-21st century.

Using palaeoclimatic analogues
This approach uses data from previous warm epochs (such as the post-glacial climatic optimum 5000 to 6000 years ago) to create climate change scenarios. The two major problems are that the boundary conditions (such as solar radiation receipts) at such periods in the past were different to those at present, and that the data that are available are far too coarse in both space and timescale for application in hydrological studies.

Arbitrary changes in climate parameters
Many studies have looked at the *sensitivity* of a system to climate change by making arbitrary changes to the input climate parameters. These are not climate change impact studies as such - because the scenarios are not meant to represent future conditions - but do indicate how a system might respond to climate change.

Using climate model output
Most climate change impact studies have used scenarios based on the output from global climate models. Model data can be used in several different ways. At one

extreme, the climate data as generated by the model are used directly as input to an impacts model. The major disadvantage of this approach is that estimates for individual model grid cells are not necessarily very reliable, and may show some systematic bias. At the other extreme, a visual analysis of climate model simulations is used to make a qualitative assessment of possible changes ("winters will be wetter", for example), which are then expressed in "rounded" terms and applied to observed climate data. Most studies fall between these two extremes, and apply quantitative changes derived from one or more model simulations to observed climate data. The two main problems with using climate model results directly are that regional estimates of change may be inaccurate, and that the spatial resolution of model estimates is often far larger than the spatial resolution of interest (although, as indicated in Section 2.2.4, some detail - which may be spurious - can be added).

At present there are very few transient climate change simulation results, and it is too expensive to use a GCM to simulate the regional effects of a number of different transient emissions scenarios. A "two-stage" approach has therefore been developed (at the Climatic Research Unit, Norwich) to produce regional transient climate change scenarios from global climate model simulations.

The first stage uses a relatively simple model to simulate *global average temperature changes.* These models (such as STUGE (Sea-level and Temperature Under the Greenhouse Effect): Wigley *et al.* 1991) start off with assumptions about economic development and energy policy, and run through a number of linked modules to estimate subsequent transient changes in global average temperature. They do not at present include all the known feedbacks in the system (such as those resulting from the release of methane when permafrost thaws), but they do include all the most important ones.

The second stage adds regional detail using the results of GCM simulations expressed as change (in regional temperature or rainfall, or any other characteristics) per degree of global average warming; the patterns are simply rescaled using the estimated change in global average temperature. For example, if a GCM simulates a 10% increase in annual rainfall over a particular region for a 4°C increase in global average temperature (corresponding to a 2.5% increase per degree of global warming), then a 3.0°C increase in global average temperature predicted by the simple model for a particular emissions scenario will result in an estimated 7.5% increase in rainfall. The approach assumes both that the spatial pattern of change will not vary as climate evolves, and that there is a linear relationship between global temperature and regional temperature and rainfall. Both of these assumptions are unrealistic, but at present there is no other way of estimating the transient regional implications of different emissions scenarios.

2.3.3 IPCC climate change scenarios

The 1990 IPCC report created a number of climate change scenarios using four different assumptions about the future emissions of greenhouse gases (IPCC 1990a). The baseline "Business-as-Usual" scenario assumed that steps taken to limit greenhouse gas emissions were not accelerated, and that emissions increased in line with predicted global economic development. This scenario produced a "best" estimate of change of 0.3° per decade, with a range of between 0.2° and 0.5° per decade. The other three scenarios introduced increasingly stringent emissions control policies; the fourth scenario assumed draconian controls leading to a reduction in carbon dioxide emissions to 50% of 1985 levels by the middle of the next century.

The 1992 Supplement (IPCC 1992) introduced updated greenhouse gas emissions scenarios, reflecting revised assumptions about economic and population growth rates, changes in eastern Europe and the former Soviet Union, new international emissions control protocols, and improved scientific understanding of some of the sources and sinks of greenhouse gases. Six scenarios were created, covering a range of assumptions about future economic and population growth and emissions policies. Under a scenario assuming mid-range estimates for economic, population and resource growth and implementation of existing policies (scenario IS92a), global temperature would increase by 2.5° over present levels by 2100 (Wigley and Raper 1992), or by approximately 0.23°C per decade (with a range of 0.15 to 0.35°C per decade). The six different emissions scenarios produced different rates of change in temperature, but there was little difference until after 2050.

The lack of difference between the different emissions scenarios in the short and medium term arises because of the time taken for past changes to work through the atmospheric and, particularly, the ocean system. This is known as the climate change "commitment". Even if emissions of greenhouse gases were to be significantly reduced tomorrow, there would still be some increase in global temperature.

2.4 Evidence for Climate Change

2.4.1 The global context

Analysis of observational temperature records has shown (IPCC 1990a) an increase in global average temperature since 1900 of around 0.5°C. 1990 was the warmest year since the beginning of the global average time series in 1861, and 1991 was the second warmest: the seven warmest years on record have occurred since 1980. Figure 2.2 shows the time series of estimated global average temperature from 1861 to 1991, expressed as a departure from the 1951 to 1980 average. Climate model simulations with a gradually increasing concentration of atmospheric carbon dioxide show a slightly higher rate of increase of temperature since the late 19th century than found in the observed record (IPCC 1990a), but a closer match is found once some account is taken of the cooling effect of aerosols (Section 2.2.1; Wigley and Raper 1992).

The graph, however, does not prove that global warming is taking place. There are four problems:

1. The evidence is circumstantial: there is no *proven* link between increasing greenhouse gas concentrations and the graph of increasing temperatures, although a physical explanation has been proposed.
A sceptic could contrast the smooth progression in the CO_2 record with the stepped nature of the temperature record.

2. The observed temperature record could reflect "ordinary" decade-to-decade or long-term fluctuations, occurring either as a result of inbuilt rhythms within the global climate system or from changes in solar radiation (although, as mentioned in Section 2.2.1, variations in solar radiation received are small compared with the radiative effects of higher greenhouse gas concentrations).

3. The global average temperature record is produced from many records covering different periods of time and using different methods. One potential problem is that a sizeable number of land-based temperature-recording sites have been increasingly surrounded by urban areas, and that temperatures will therefore have increased; Jones *et al.* (1989) estimate a maximum bias

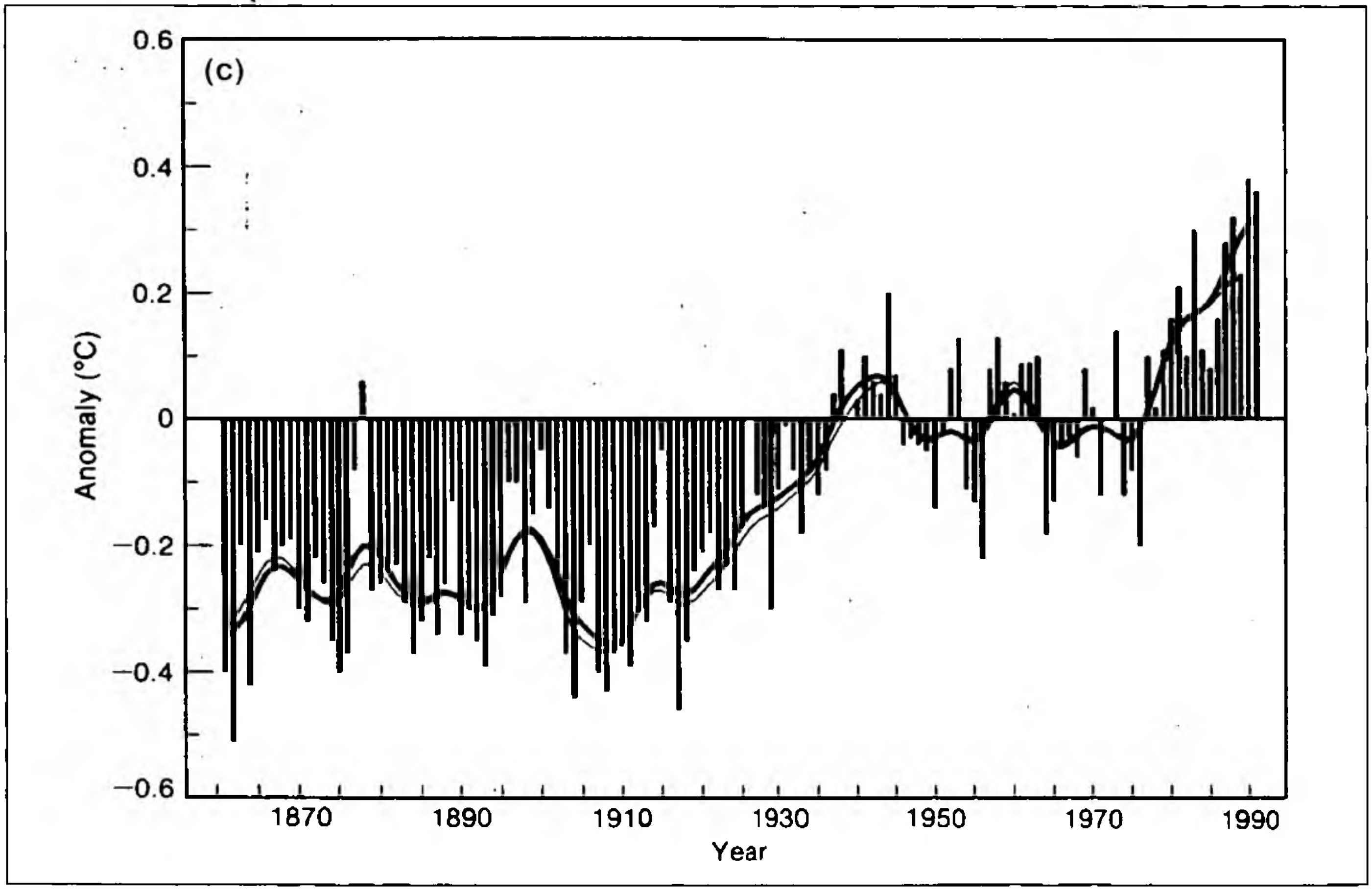

Figure 2.2 Global annual average temperature 1861-1991, as anomalies from the 1951-1980 average (IPCC 1992)

The thin line shows the filtered average as presented in IPCC (1990); the thick line shows the filtered average calculated in the1992 Supplement using an updated data set.

in global temperature due to urbanisation of 0.1°/100 years, so urbanisation around temperature recording sites cannot account for all the observed increase. Differences in measurement technique have been corrected for in the records wherever possible.

4. The observed *regional* temperature changes do not everywhere match the changes predicted by climate models. This could, of course, be because the climate model simulations are locally wrong.

This last problem draws attention to the point that possible future changes in climate will not be uniform. The very large regional variability in response to global warming means that it is not possible to use local data alone to detect change.

Although it is not possible at present to prove conclusively that global warming is taking place, there is no evidence to suggest that increased greenhouse gas concentrations are *not* leading to global warming. The detection of climate change, however, is difficult both because the signal is uncertain - globally and regionally - and because it will be masked by large year-to-year variability. The difference in global average temperature between the warmest and coolest year in a decade at present is approximately 0.7°. This difference is over twice the possible trend due to increased greenhouse gas concentrations (0.3° per decade): year-to-year variability in a small region is even greater. The IPCC in 1990 predicted that "the unequivocal detection of the greenhouse effect from observations is not likely for a decade or more" (IPCC 1990a, p.xxix), and this was reinforced in the 1992 Supplement.

2.4.2 The 1988 to 1992 drought in south east England

Large parts of southern, central and eastern England experienced prolonged drought conditions starting in the summer of 1988. Over this period the low flow statistics for many lowland rivers have been largely redefined. The drought cannot be definitively attributed to greenhouse-induced climate change, however, for several reasons:

1. Although extreme, recent hydrological events are not outside the limits of *historical* behaviour. The drought of 1975/76 was more intense in most regions.

2. Year-to-year and decade-to-decade variability are too great for significant departures from "average" behaviour to be detected over a period of just a few years.

3. It would be easier to attribute the drought to climate change if the climate of recent years (dry in the south east and very wet in the north and west) were similar to predictions of the future climate of the UK. However, the UK is represented by only four or five GCM grid points on the westernmost extreme of a continent, and the south east has just one point. GCMs cannot therefore be expected to simulate well current UK climate - and its spatial variability - and comparisons between recent observed anomalies and future simulated climatic patterns cannot be made with any confidence.

3.IMPACTS AND RESPONSES: A FRAMEWORK

3.1 Introduction

This chapter explains the framework which is used in this report for assessing both the *impacts* of climate change on the NRA and the possible NRA *responses* to climate change.

3.2 The Impacts of Climate Change

3.2.1 Introduction

The impacts of climate change on a specific system are difficult to infer from the climate change alone, for several reasons. Firstly, the environment is inherently complex, is affected by many human decisions, and is deliberately managed. Secondly, the presence of critical thresholds means that a small climate change may have a very large impact on a system. Thirdly, there are uncertainties in both the estimated changes in climatic parameters and the relationships between those parameters and other environmental characteristics: these uncertainties are discussed further in Chapter 4.

This section discusses the consequences of complexity, management intervention and thresholds for the impacts of climate change, and finishes by summarising ways of assessing the implications of climate change for a specific system.

3.2.2 A complex hierarchy of climate change impacts

The environmental system is complex, hierarchical, and characterised by multiple interactions and feedbacks. Negative feedbacks work to *reduce* the consequences of the initial change and act as some form of regulator; positive feedbacks have the effect of exaggerating the initial impact. The environmental system is also affected by human decisions, and is also deliberately managed. Figure 3.1 shows, in a general way, the effect of climate change on NRA activities. It is useful to consider Figure 3.1 in three parts, representing the environmental system, the human system and the impact of changes unconnected with climate change.

The environmental system
Figure 3.2 attempts to summarise the impact of an *increasing concentration of greenhouse gases* on various elements of the environmental system; it corresponds to the "climate change" and "climate change impact" boxes in Figure 3.1.

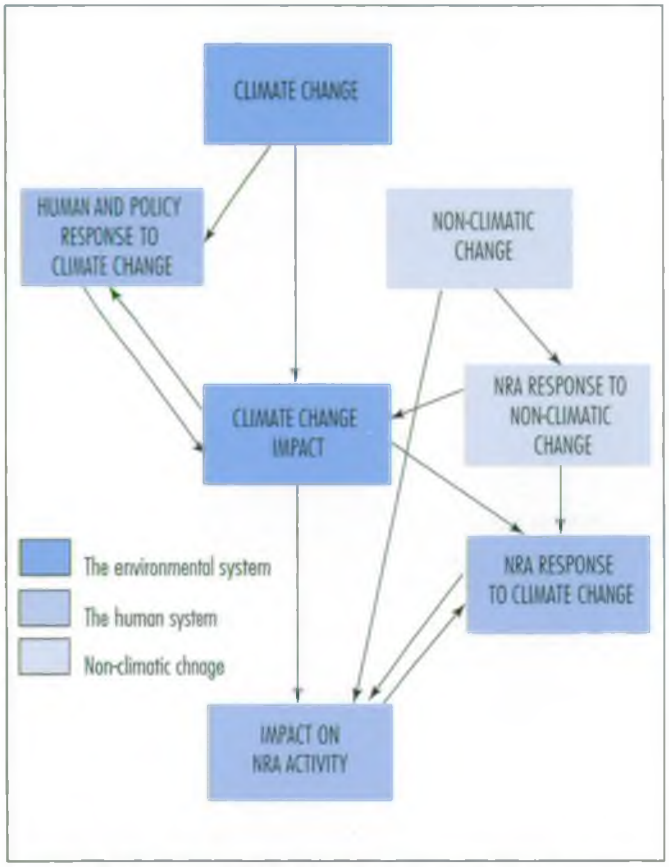

Figure 3.1 The impact of climate change on the NRA

The increase in greenhouse gas concentrations results in an increase in *net radiation* at the earth surface (Chapter 2), which itself leads to an increase in *temperature,* which in turn produces regionally variable changes in *rainfall and evaporation regimes* and *soil moisture regimes.* All these factors contribute to plant growth, and hence changes in *ecosystem characteristics* such as plant mix and growth patterns. Higher temperatures lead to an increase in *sea level* (through thermal expansion of sea water and ice melt; rainfall and evaporation over the sea may also contribute), which affects coastal ecosystems.

Changes in rainfall, evaporation and soil moisture also lead to changes in *river flows and groundwater recharge,* which together with changes in temperature and sea level can lead to a change in *water quality.* A change in catchment ecosystem characteristics means a change in the mix of *land cover* within a catchment, which in turn affects potential evaporation (and hence actual evaporation, river flows and recharge) and catchment water quality.

All these links and interactions occur in a pristine "natural" environment untouched by human activity

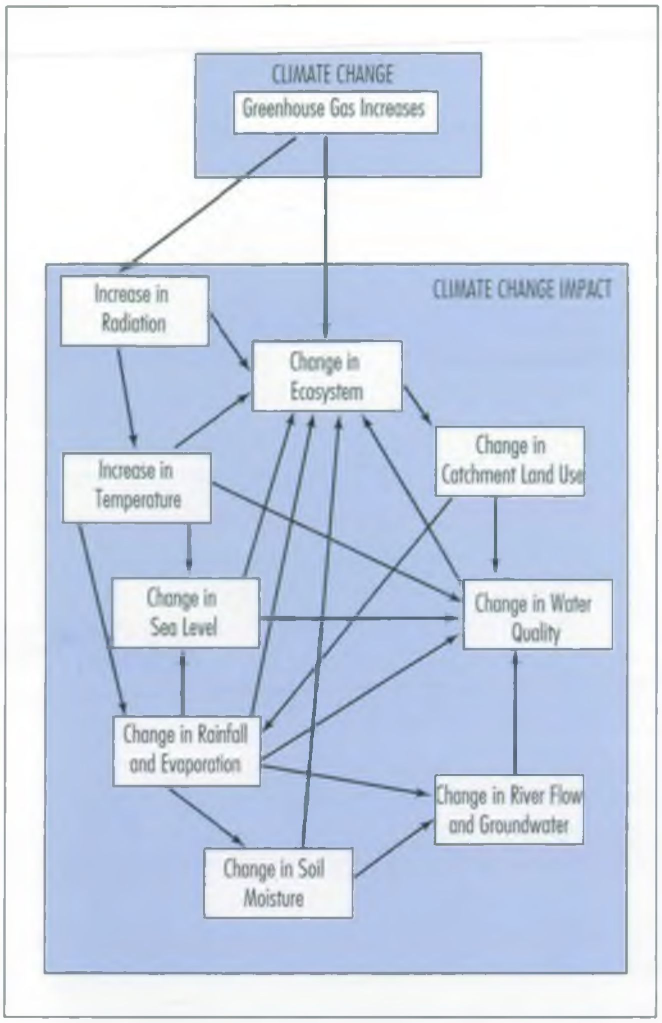

Figure 3.2 The impact of climate change on the hydrological system in a "pristine" environment

(which is very rare in the UK). The system is complicated considerably when human actions - inadvertent or deliberate responses to climate change - are added.

Human influence and management

Human decisions and actions will have very significant effects on the impact of climate change on the hydrological system. At the highest level, an increasing concentration of greenhouse gases might trigger a policy of tree planting for carbon sequestration, which would affect catchment evaporation and hence catchment water balance. Afforestation for carbon sequestration has been recommended by the Working Group on the Greenhouse Effect of the Watt Committee on Energy (Thurlow 1990). Changes in climate at the European scale might be expected to impact upon the EC Common Agricultural Policy, which would influence farmers in the UK and affect catchment water balance and the use of agricultural chemicals. Farmers' decisions will also be affected by the actual and perceived direct impact of climate change on their crop yields and profitability.

Higher temperatures and changing rainfall, evaporation and catchment land use, together with human response to climate change, will all affect the *demand for NRA services.* Finally, and very importantly for the NRA, the *response of the NRA to climate change* in one area may have major implications for another NRA activity. The most obvious example is where flood defence works triggered by the threat of climate change have conservation implications, but other examples will be presented in other areas in subsequent chapters.

The importance of other changes

The third part of Figure 3.1 refers to the effects of changes which are occurring *independently of climate change*. These might be affecting catchment land use (urbanisation or increasing set-aside of agricultural land, for example), flow regimes (by water management structures), water quality (by changes in the use of agricultural chemicals) and the demand for NRA services.

The changes might affect both the impact of climate change and the *NRA's response to climate change*; the NRA's response to the non-climatic changes will also affect how it responds to climate change. The non-climatic changes may be more important than climate change, and no less uncertain.

3.2.3 Non-linear system response to climate change

Section 3.2.2 has indicated the strong degree of interconnection between the components of the "natural" and "managed" water environment. The water system is also characterised by a number of *thresholds*. If a controlling variable - such as temperature or river flow - passes a critical threshold, the system moves into a different state.

The simplest example is where a system goes from a state of being "able to meet design standards of service" to one where "standards of service are not being met". A more complex example is of an ecosystem which undergoes a change in species composition once a certain temperature threshold is passed.

The presence of such thresholds means that a system will respond to climate change in a non-linear way; the effect of a 10% increase in rainfall may be very different - in both quantitative and qualitative terms - from the effect of a 5% increase, for example. Some thresholds are inherent in the environmental system, and others are characteristic of the operating rules used by water managers.

3.2.4 Climate change impact assessments

There are three basic approaches to climate change impact assessment (Carter *et al.* 1992). The first, and simplest, is termed the *impact approach*. It follows a change in input variables through the environmental and management system to the "end result". In other words, it asks the question (Parry and Carter 1988):

For a given variation in climate, what is the effect on the system of interest?

It is also possible to ask this question the other way round, in order to determine the type and extent of climate change which would have the greatest impact on a system (Parry and Carter 1988):

To what aspects of climate is the system especially sensitive?

What changes in these aspects are required to perturb the system significantly?

The second approach to impact assessment is the *interaction approach*, which recognises that climate is only one of a set of factors which influence the system of interest. It therefore takes into account effects of other changes - such as changes in land use - and also considers explicitly feedbacks between controlling factors.

The *integrated approach* is the most comprehensive, and aims to consider not just the links between the factors affecting a particular system, but also the interactions between systems and economic or environmental sectors.

Most of the research summarised in this report has followed the first approach and estimated the impacts of particular climate changes without considering the simultaneous effects of other changes. The report highlights the areas where these other non-climatic changes are most important: the biggest single other change which will affect NRA activities over the next few decades is land use change. The report itself can be seen as an example of an *integrated impact assessment*, because it addresses - albeit in largely qualitative terms - the impact of climate change throughout the NRA and considers the interactions between parts of the NRA and related external organisations.

3.3 NRA Response to Climate Change

3.3.1 The importance of catchment management plans

Both the complex impact of climate change and the fact that NRA activities in one area affect other functions of the NRA imply that the NRA needs to take a multi-functional approach to managing climate change. *Each NRA function needs to consider and cost the implications for other functions when developing its response to climate change.*

Although the NRA is divided into seven core functions, in practice there is considerable day-to-day cooperation between the functions. The development of catchment planning within the NRA has encouraged a more formal consideration of issues which cross function boundaries (Gardiner 1990; Gardiner and Cole 1992). Catchment planning is the process of ensuring that all the problems and opportunities resulting from the demands on a river catchment are presented within a management framework which aims to maximise the overall well-being of the catchment. Plans should allow the development of multi-functional management strategies within the NRA which consider explicitly all aspects of the water environment, and should also influence the actions of external agencies dealing with, for example, land use planning, heritage and landscape. Catchment planning is identified as a key component in NRA corporate planning. ***Both the concept of catchment planning and the technical developments which underpin catchment management plans (catchment hydrological and hydraulic models) provide the appropriate vehicle for the management of NRA response to climate change.***

3.3.2 Types of NRA response

How, in the most general terms, should an organisation respond to the possibility of climate change? For each potential impact it needs to consider several questions:

1. How real is the threat, and how certain is it? Is there uncertainty over the existence of the threat, or just over the degree of threat?

2. How "big" is the threat, and how does it compare with other changes that are going on? It is possible that, even under the most pessimistic assumptions, the threat is quite small and so can be ignored. The scale of the threat controls the degree of seriousness of response.

3. Is there already a management or operational policy in place that can cope with the threat? If there is, then what seems at first to be a major threat might in practice have very little operational impact.

4. How does the impact or proposed response affect activities in another part of the organisation?

There are five responses to a climate change threat. These responses are to an extent complementary, and different responses may be appropriate for different dimensions of the threat.

Do nothing
This is appropriate if the threat is small, or if existing management systems and structures (physical or organisational) can cope with it. It is not appropriate if the threat is simply uncertain.

Conduct research into the threat
If the threat is uncertain, but is potentially very severe, then it will be necessary to conduct research to attempt to narrow the range of uncertainty. The research could take the form of an impact assessment using current models of the water system; it may require the development of models which can be used to estimate the effects of climate change on a particular system. Ideally, all investigations into climate change impacts should be integrated (or at least coordinated), to ensure that all the feedbacks and interactions are considered. The response to the threat should of course be reviewed after the research is completed.

Monitor
It is possible both to monitor research being undertaken by other organisations and to monitor the environment to check whether critical thresholds are being exceeded. Again, responses can be reviewed once more information is available.

Conduct a feasibility study
This is appropriate when a number of possible actions have been identified, and the implications and appropriateness of each needs to be assessed.

Take action
This is appropriate either where the impact is very definite or where the impact *might* be very significant, but where lead times are so long that delay in initiating an action would mean that adverse impacts could not be averted. There are two possible types of action:

1. Make specific changes to design or operation to cope with a specific climate change. This may be done now, or at a defined point in the future (once a critical threshold has been passed or expenditure becomes economically justifiable). The changes could be based on a "best guess" or a worst case scenario. The approach is only appropriate where it is impossible to alter a scheme once it has been implemented. Uncertainty in future climate change, however, makes the approach difficult to adopt in practice.
2. Build in flexibility into design or operation. This would mean that the particular scheme would be able to cope with possible changes in climate (or indeed any other important variable). Under a "no-regrets" strategy, nothing is done now to respond directly to climate change, but at the same time nothing is done which would make it more difficult to respond to change if it occurred in the future.

3.4 Structure of subsequent chapters

Subsequent chapters review NRA responses to climate change for each core function within this general framework. Key climate change issues are identified for each function. The following points are covered for each issue:

- a summary of the relevant climate change parameters;
- review of the current understanding of the potential threat;
- an assessment of the significance of the potential threat; and
- a number of possible responses to the potential threat (where the threat is deemed significant enough to merit a response). The information requirements for each response are summarised, together with possible problems with implementation.

Underpinning all assessments of the potential implications of global warming on NRA activities and policies, however, is an appreciation of its effects on the environmental characteristics relevant to the NRA. Many of these characteristics - especially river flow - are important for most or all core functions.

Chapter 4 therefore reviews current knowledge of the effects of climate change both on what might be termed "first order" climate characteristics (such as temperature, rainfall and sea level rise) and on "second order" environmental characteristics (such as river flows and water quality). The chapter finishes by indicating how scenarios of change might be improved. The assessments of implications of climate change for each NRA core function are based on the information summarised in Chapter 4, and the estimated rate of "improvement" in climate change scenarios outlined in Section 4.12 controls the timing of the implementation of NRA responses to climate change.

4. CLIMATE CHANGE IN ENGLAND AND WALES

4.1 Introduction

The aim of this chapter is firstly to present climate change scenarios for England and Wales, and secondly to summarise the current understanding of the effects of climate change on the environmental parameters relevant to NRA operations. These parameters measure changes and variations in, for example, river flow regimes, groundwater recharge, water quality, storminess, and sea and estuary levels. The final section indicates how climate change scenarios can be improved. It discusses the DoE Climate Impacts LINK project, and assesses the potential contribution of the NRA in improving estimates of changes in environmental parameters relevant to the NRA.

Table 4.1 lists a number of critical climatic and environmental variables affected by climate change, and indicates the NRA core function affected. Temperature, rainfall, evaporation, CO_2, storminess and sea level changes can be regarded as "first order" impacts of climate change. Alterations to river flows, groundwater recharge and water chemistry and biology can be seen as "second-order" impacts, although as Figure 3.2 emphasises, there are complicated feedbacks in the relationships between all the components of the environmental system. It is also important to emphasise that the impact of climate change on an NRA activity may be felt through the actions in response to climate change of other parts of the NRA or other agencies; this point is developed in subsequent chapters. Non-climatic changes, such as land use change, will also have an impact over the same time horizon.

Different dimensions of climate change will impact upon different NRA core functions. A change in river flow regime, for example, would affect all functions. A change in rainfall alone, on the other hand, would directly affect only the Water Resources (primarily through demand), Water Quality (pollutant pulses following heavy storm rainfall) and Flood Defence (sewer surcharge) functions. The detailed implications of

Table 4.1 Dimensions of climate change and affected NRA functions

	Water Resources	Water Quality	Flood Defence	Fisheries	Conservation	Recreation	Navigation
Change in temperature	■	■	■	■	■	■	
Change in rainfall	■	■	■		■		
Change in evaporation	■				■		
Direct effects of CO_2	■	■			■		
Change in river flows	■	■	■	■	■	■	■
Change in groundwater recharge	■	■			■		
Change in water chemistry and biology	■	■		■	■	■	
Change in storminess			■		■		
Sea level rise	■	■	■		■		
Response of NRA and other agencies to climate change	■	■	■	■	■	■	■

Table 4.2 Climate change scenarios for the UK (CCIRG 1991), expressed as a change from the present climate

	2010		2030		2050	
	Summer	Winter	Summer	Winter	Summer	Winter
Temperature (°C)	0.7	0.8	1.4	1.5-2.1	2.1	2.3-3.5
Precipitation (%)	0 (±5)	3 (±3)	0 (±11)	5 (±5)	0 (±16)	8 (±8)

climate change for each NRA core function are discussed in subsequent chapters; this chapter concentrates on changes in environmental parameters.

4.2 The Climate Change Impacts Review Group

As explained in Section 1.4, the Climate Change Impacts Review Group (CCIRG) was established by the Department of the Environment in 1990 to review the implications of climate change for a wide range of activities within the United Kingdom (CCIRG 1991). As part of its review, the CCIRG created a set of climate change scenarios for the UK.

The scenarios (Section 2.3.1) were produced using the methods summarised in Section 2.3.2; estimates of global average temperature changes under different emissions scenarios were based on relatively simple one-dimensional energy balance models, and particular estimates for the UK were interpolated from several climate models. Higher resolution spatial detail was added to the coarse-scale GCM output by interpolating between GCM grid points. The scenarios provided changes in seasonal rainfall and temperature, and are detailed in Section 4.3 below.

4.3 Changes in Temperature and Precipitation

Most climate change scenarios are expressed in terms of changes in average monthly or seasonal temperature and precipitation. Table 4.2 shows the climate change scenarios created for the UK by the Climate Change Impacts Review Group (1991).

The summer temperature increases were assumed to be constant across the UK. There is, however, a gradient of change in winter temperature across the UK, with the biggest winter increases in the north. This means that the winter temperature gradient from north to south would lessen. An increase in winter temperature of around 1.5° by 2030 in southern England would imply temperatures similar to those currently experienced in Bordeaux, France (CCIRG 1991).

The rainfall change scenarios assume increased rainfall in winter and no change in summer rainfall, although as Table 4.2 indicates there is considerable uncertainty. Spatial patterns of change in rainfall are even more uncertain because of the differences between different climate models, but there are indications that the future chance of drier summers relative to present may be slightly higher in the south of the UK than in the north (Santer *et al.* 1990; CCIRG 1991).

The scenarios in Table 4.2 show changes in mean rainfall and temperature. Climate models are not yet sufficiently reliable to estimate with confidence changes in the year-to- year variability in these parameters, and the CCIRG assumed that the standard deviation of seasonal rainfall and temperature would not change. Under the simplifying assumption that the mean changes but not the variability about the mean, it is possible to estimate the frequency of extreme seasonal events. Figure 4.1 shows the frequency distribution of central England summer (June to August) temperatures under current conditions and with the mean increased to represent conditions in 2010, 2030 and 2050 (CCIRG 1991). It is clear that the frequency of warm summers increases considerably. At present the chance of summer temperature exceeding 17.7° (as in 1976) is approximately 0.1%; by 2030 the probability could increase to 10%.

Figure 4.2 shows, in a similar way, summer rainfall for England and Wales. Under current conditions the probability of summer rainfall being less than experienced in 1976 is around 0.7%; if summer rainfall were to reduce by 16%, then the probability of such a low rainfall total would increase to 3.1% (or nearly 1 in 30).

Current climate models also cannot be used to estimate changes in short-duration climate characteristics - such as daily or even weekly rainfall - so the CCIRG made

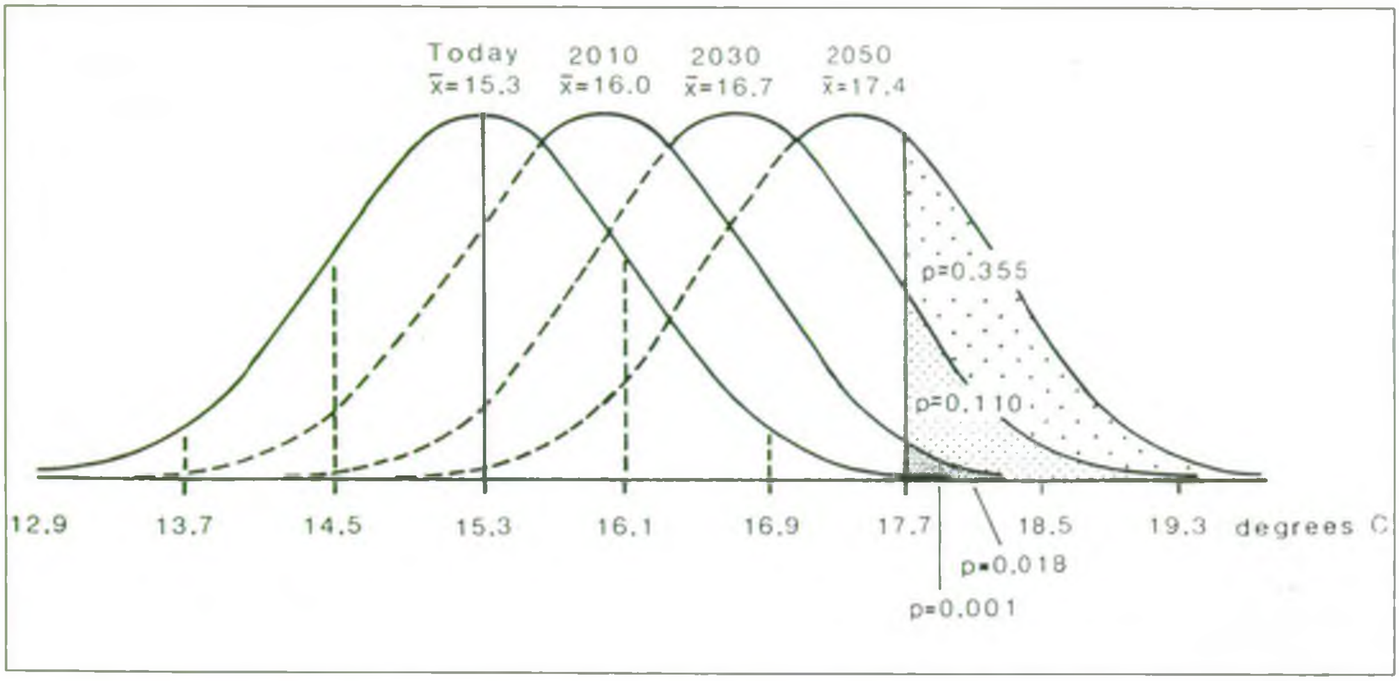

Figure 4.1 Effect of a shift in the mean on the probability distribution of central England summer temperatures

The shaded areas denote changes in approximate exceedance probabilities for the reference hot summer of 1976 (CCIRG 1991).

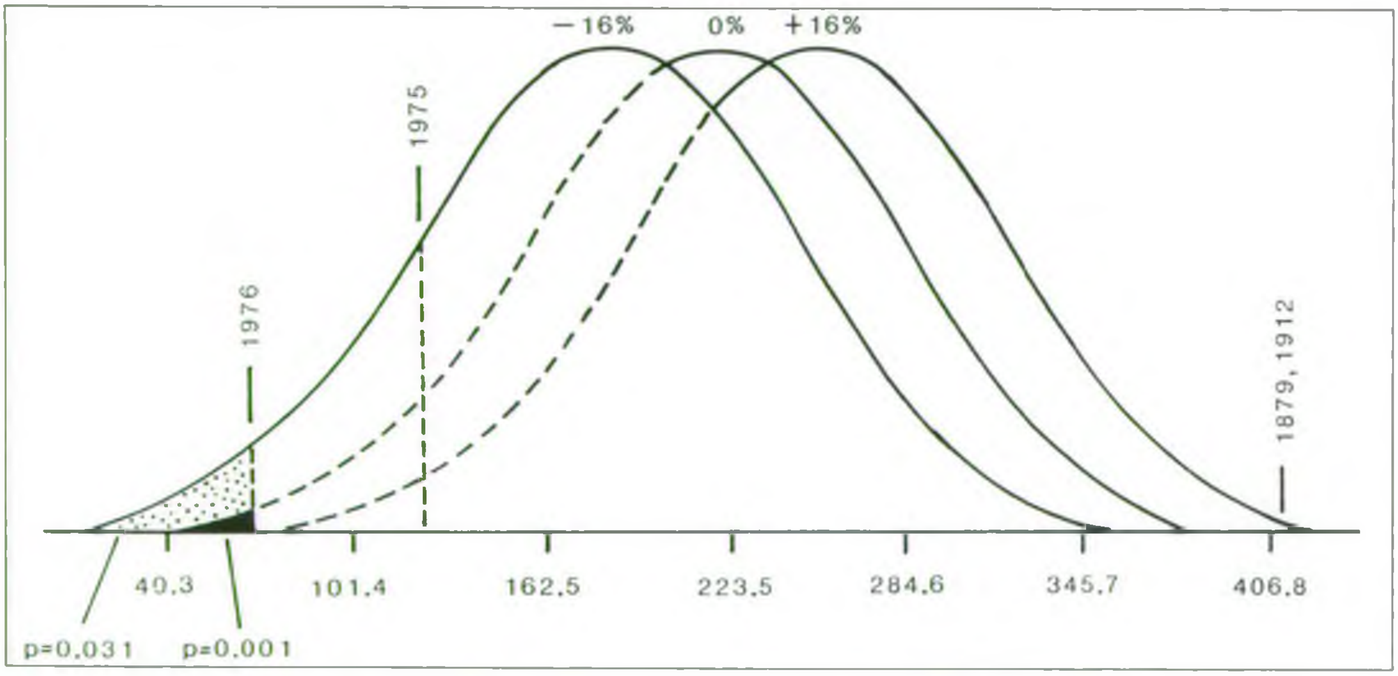

Figure 4.2 Effect of a shift in the mean on the probability distribution of England and Wales summer rainfall

The shaded areas denote changes in approximate exceedance probabilities for the reference hot summer of 1976 (CCIRG 1991).

no suggestions about changes in such events. Some analysis of climate model simulations, coupled with application of meteorological principles, indicate that summer rainfall in the future might occur as more intense falls on fewer days.

4.4 Changes in Evaporation

The CCIRG made no attempt to create scenarios for possible changes in potential or actual evaporation, which are of course extremely important elements in the hydrological cycle for the NRA. An increase in temperature would be expected to increase the rate of *potential* evaporation (by, according to Budyko (1980), 4% per degree Celsius), but the changes in potential evaporation would also depend on changes in humidity, windspeed and net radiation. Changes in *actual* evaporation would also depend on changes in the availability of water for evaporation. Arnell *et al.* (1990) used two scenarios of change in potential evaporation in their simulation of the effects of climate change on UK river flow regimes. One assumed an increase of approximately 7% by 2050 (with the greatest percentage increases in winter), whilst the other assumed an increase of 15%.

Sensitivity studies at the Institute of Hydrology as part of the DoE Water Directorate project have shown that the effects of a given temperature increase on potential evaporation are very dependent on the assumed change in humidity, particularly in winter (Arnell and Reynard 1993). If relative humidity were to increase then the effect of the increased temperature would be offset; if it were to decrease, however, then the increase in potential evaporation would be even higher. The relative importance of changes in temperature, humidity, net radiation and windspeed varies between seasons. In winter, for example, change in humidity is very important, but in summer the relative significance of changes in net radiation increases. Estimates of change in potential evaporation therefore need scenarios for changes in humidity, windspeed and net radiation, as well as changes in temperature. Scenarios for these variables do not currently exist - and there is considerable uncertainty over the direction of change in some of them - but the DoE Climate Impacts LINK project will be creating them (Section 4.12.2). In the meantime, the IH sensitivity study used three scenarios, reflecting three different sets of assumptions about changes in the controlling variables. The annual increase in potential evaporation ranges from around 9% (by 2050) to approximately 30% under the most extreme set of changes (Arnell and Reynard 1993).

Total catchment evapotranspiration will also be affected by changes in transpiration from plants and in evaporation from water intercepted by plant leaves. A changed vegetation mix would alter evapotranspiration totals, and a change in plant growth rates would affect the timing of evaporative demands. Increased plant growth early in spring, for example, would lead to an earlier upswing in the evapotranspiration rate after winter than at present.

4.5 Effects of CO_2 Enrichment

The rate of transpiration from plants will be affected not just by changes in climate, but also by changes in plant physiology associated with increasing atmospheric carbon dioxide concentrations. Experimental evidence shows that plant stomatal conductance reduces as carbon dioxide levels increase, and plant transpiration - and hence water use - therefore declines (Drake 1992). However, plant growth increases as carbon dioxide levels increase (Drake 1992), and whilst transpiration per leaf will decline, the number of leaves might be expected to increase.

The effect of an increase in CO_2 on plant growth and transpiration depends on plant characteristics, and in particular on how the plant responds to the intake of CO_2. The C_3 plants, which include almost UK plant species, are most sensitive to increased CO_2 concentrations. C_4 crops (which include maize) show little change in plant growth with increased CO_2, but do exhibit an increase in stomatal resistance and hence a reduction in transpiration per leaf.

It is, however, difficult to transfer results from controlled experiments to the "real" catchment. In the field, a lack of nutrients might prevent a plant from responding to increased CO_2 levels, and the effects of changes in CO_2 might be limited by changes in temperature and rainfall occurring at the same time. MAFF-funded studies are under way into the effects of changes in CO_2 and climate on several agricultural crops (particularly wheat), but the studies are concentrating on plant growth and are not considering water use. Other programmes, such as the NERC TIGER programme and the AFRC Biological Adaption programme (Chapter 1), are addressing such questions at the physiological and ecosystem level.

4.6 Soil Moisture

Estimates of changes in soil moisture content can be derived directly from climate model simulation output or by applying rainfall and potential evaporation scenarios to a soil moisture accounting model.

Climate models contain a soil moisture component because soil moisture content affects land surface energy and water balances. Climate model output can be used to show continental or global scale changes in soil moisture (as in the IPCC report: IPCC 1990a), but is not appropriate for local or regional scale assessments because the spatial scale of simulation is very coarse. The present Hadley Centre climate model has a grid size of nearly 80 000 km^2; it assumes representative values and parameterises the effect of variability across the cell.

In reality, of course, the effect of climate change on soil moisture content will vary rapidly over space, so the most appropriate way of estimating local changes is to use a locally-calibrated soil moisture model with scenarios for changes in rainfall and potential evaporation. Ideally, this model should also account for changes in soil properties, such as enhanced soil fissuring and changes in soil organic matter content, which might result from climate change: these will influence not only intrinsic storage, but also throughflow and runoff behaviour. The Soil Survey and Land Research Centre (SSLRC) is currently using soil moisture models to estimate possible changes in soil workability, with funding from the MAFF Environmental Protection Division. The SOAFD group are using soil moisture models to investigate effects on production by arable crops, grassland and trees, and on some farming operations.

4.7 Climate Change and River Flow Regimes

4.7.1 Introduction

There have been over 30 different studies worldwide into the implications of climate change for river flow regimes, and over 120 papers have been published (by 1992) in the scientific literature. Four of the studies have looked at river flow regimes in the UK (Palutikof 1987; Arnell *et al.* 1990; Cole *et al.* 1991; Arnell and Reynard 1993). The studies have used different methodologies and climate change scenarios, but all agree that the effects of a given climate change scenario can vary considerably between catchments. In general, the more arid the catchment the greater the relative effect of changes in rainfall and evaporation on runoff, and catchment geology affects the distribution of changes in runoff through the year.

Climate models produce estimates of river runoff, but these estimates cannot be used to determine implications of climate change for local or regional water resources for two main reasons. Firstly, the spatial scale of present climate model simulations is very coarse (approximately 80 000 km^2). Secondly, climate model "runoff" does not allow for time delays due to routing of water through soil, groundwater and the river channel network. Research is currently in hand to attempt to improve the simulation of river flows within climate models - as part of the NERC TIGER project (Chapter 1) - and first results are expected by 1995. In the meantime, studies of the impact of climate change on river flow regimes must continue to use either data from different periods in the past or, as is much more common, a catchment runoff simulation model together with scenarios of changes in rainfall and potential evaporation.

Each component of the hydrological system can be expected to change as climate changes. It is useful to distinguish between the *direct effects* on river flows of changes in rainfall and evaporation inputs and the *indirect effects* of changes in land cover, plant water use and soil structure consequent upon climate change.

Practically all catchment-scale impact studies have concentrated on the direct effects of climate change. They have ignored the potential effects of changes in plant physiology and catchment vegetation mix on evaporation (Section 4.5). They have also not considered possible changes in soil structure. Quantitative information on such changes is not yet available, but a number of suggestions have been made: higher temperatures alone would lead to a loss of organic matter, for example, and hence a decrease in the ability of the soil to hold moisture; higher temperatures could also encourage clay soils to crust, shrink and crack. Increased waterlogging, on the other hand, would encourage the development of gleyed profiles (CCIRG 1991) and at the same time limit the effect of mineralisation on organic matter loss. The timescale of such soil changes is uncertain, but MAFF-funded work at SSLRC will provide valuable information.

4.7.2 Change in annual and monthly flow regimes

The effect of climate change on annual runoff depends on both the assumed change in rainfall and potential evaporation and the current climate regime. In the most general terms, the smaller the proportion of annual rainfall that goes to runoff, the greater the percentage impact of a given change in rainfall and potential evaporation. In practice, the compensating effects of an increase in both rainfall and potential evaporation complicates this general pattern, but the driest parts of England and Wales are most sensitive to climate change.

Figure 4.3 shows the simulated change in average annual runoff, by 2050, under four different climate change scenarios based on the CCIRG (Arnell and Reynard 1993: the maps are similar to those produced by Arnell *et al.* 1990). The first two both assume no change in summer rainfall but an increase of 8% in winter (Table 4.2): one assumes an increase in potential evaporation of around 9%, and the other assumes an increase averaging 30%. The other two maps show the "wettest" and the "driest" CCIRG scenarios (Table 4.2). Average annual runoff was estimated by applying a daily rainfall runoff model in each MORECS

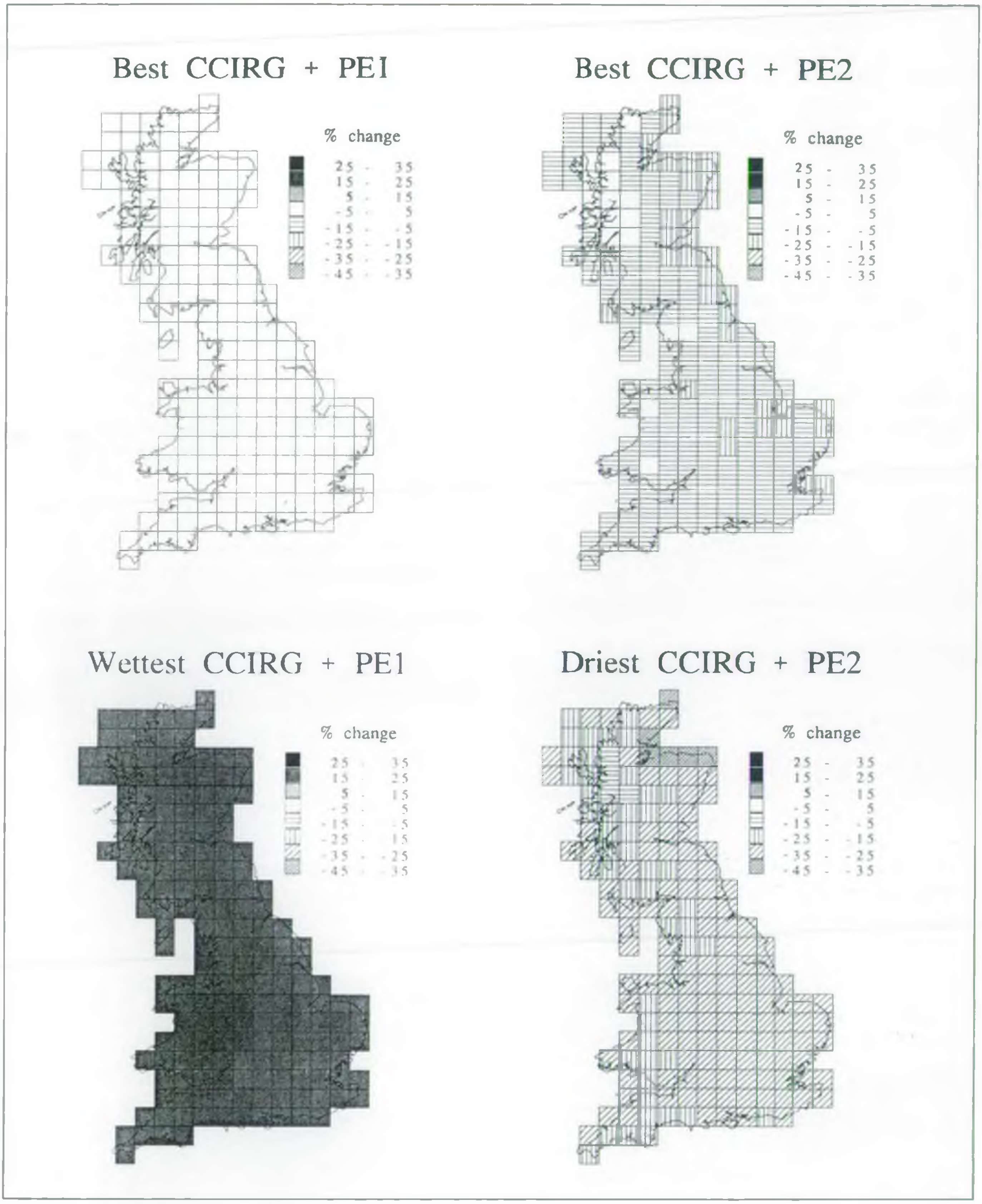

Figure 4.3 Simulated percentage change in average annual runoff by 2050

Details of the scenarios used are given in the text and Table 4.2 (Arnell and Reynard 1993).

(Meteorological Office Rainfall and Evaporation Calculation System) box, using 1961-1980 baseline rainfall and potential evaporation data from MORECS (Thompson *et al.* 1981).

There are two important points to note from Figure 4.3. First, there is a very large difference in estimated change in runoff in the four different scenario combinations. There is also a big difference between the two scenarios using the same CCIRG rainfall change estimate but different assumptions about changes in potential evaporation. Second, there is a large difference in impact across the UK, with the driest parts of southern and eastern Britain showing the greatest relative change.

Figure 4.4 illustrates further the difference between different climate change scenarios. It shows change in average annual runoff for a group of MORECS cells covering part of south east England. The shaded area defines the range of estimated annual runoff spanned assuming the rainfall scenario above and the two potential evaporation scenarios. The upper line shows the effect of the wettest CCIRG rainfall scenario (Table 4.2) with an increase in evaporation of just 9%, whilst the lower line shows the effect of the driest CCIRG rainfall scenario with a 30% increase in evaporation. The area of uncertainty within the upper and lower limits is obviously rather large, and serves to indicate how differences between different climate change scenarios are *amplified* when the scenarios are applied to a hydrological system.

The effect of a given climate change scenario on *monthly* flow regimes depends on the current climate of the catchment and catchment geology (Arnell *et al.* 1990; Arnell and Reynard 1993). Under a very dry scenario, for example, lowland catchments tend to show the largest percentage reduction in runoff in late autumn or winter, whilst upland catchments have the greatest increase earlier in the year. This is due to differences in catchment summer water balances. Lowland catchments currently have a summer water balance deficit because potential evaporation is considerably higher than rainfall, so little rainfall goes to runoff. Warmer, drier summers would result in little change in summer runoff, but because soil moisture deficits would be larger and last for longer into the year, autumn and early winter flows could be considerably reduced. In upland catchments summer evaporation is currently close to rainfall, and soil moisture deficits tend to be of limited magnitude and duration. An increase in potential evaporation would increase soil moisture deficits and hence reduce the amount of summer rainfall going to runoff; summer flows would therefore be reduced by a large percentage.

Groundwater-dominated catchments are particularly affected by changes in groundwater recharge during the

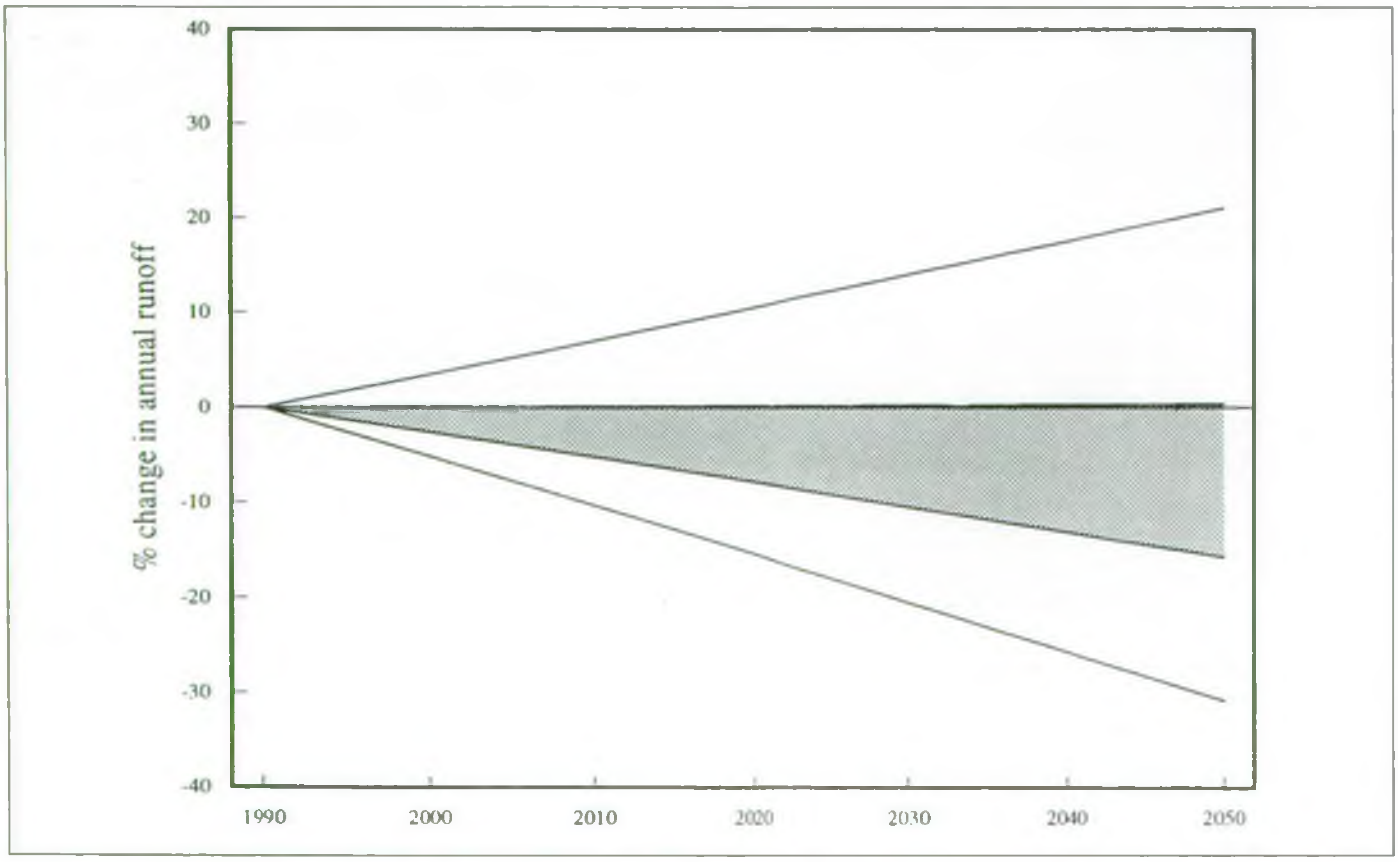

Figure 4.4 Effect of different climate change scenarios on average annual runoff by 2050 for a portion of south east England

winter recharge season. The slow drainage from groundwater means that it is possible that flows could be higher in summer than at present, even under warmer and drier summer conditions, if winter recharge were to increase. Conversely, flows would be significantly reduced throughout the year if recharge were to be reduced.

Higher temperatures also mean less snowfall and therefore a reduced snowmelt contribution to river flows (Arnell and Reynard 1993). Winter rainfall would generate river flow earlier in the year, leading to a relative increase in winter runoff and a relative reduction in early spring runoff (given the same total precipitation amount).

4.7.3 Changes in low flows

Arnell *et al.* (1990) attempted to estimate changes in low flow characteristics using monthly data, but success was limited by the coarse time step. Cole *et al.* (1991) simulated daily flows, but did not present any results showing changes in low flows. Gellens (1991), however, has presented results from a simulation of changes in daily river flows in three catchments in Belgium. The three catchments have characteristics that are comparable with a number of lowland UK catchments, and the climate change scenario used by Gellens (1991) was not very different from that proposed by the CCIRG (1991) for 2050.

In Gellens' work, low flows in the most responsive catchment were reduced under the climate change scenario, and the time that flows were below a low threshold increased by 25%. In the groundwater-fed catchment, however, low flows were increased during summer, and low flow thresholds were therefore passed less often.

Low flows in the UK tend to occur in late summer after prolonged dry periods. They therefore depend on the interaction between the recession characteristics of the catchment, the amount of effective rainfall before the dry period and the duration of the recession period. The first of these characteristics is largely influenced by basin geology and soil properties, whilst the second two are climatically-determined. The precise effect of climate change on low flow characteristics will therefore depend on the way in which changes in climate - effective rainfall and durations of dry spells - combine with catchment physical properties. Low flows in highly responsive, high evaporation catchments might be little affected by climate change, whilst low flows in responsive upland catchments would be more greatly affected. In these catchments a drier climate would mean greater opportunity for flows to recede to low levels.

4.7.4 Changes in flood occurrence

Very little attention has been paid to the implications of climate change for fluvial flooding in the UK (or indeed anywhere in the world). Three categories of fluvial flood may be recognised in the UK:

1. Floods caused by prolonged heavy rainfall; these tend to occur between autumn and spring. They are controlled by both antecedent moisture conditions (reflecting rainfall over a period of several days) and the magnitude of the rainfall over the wettest one or two days.

2. Floods caused by intense rainstorms; these can be very localised, and tend to occur most frequently in summer. The largest short-duration rainfall totals come from such events. They are primarily affected by the short-duration peak rainfall, both from high-intensity cells within frontal systems and from convective storms.

3. Floods caused by snowmelt; the rate of snowmelt is liable to be enhanced by rainfall. Snowmelt floods are rare across central, southern and eastern England, but those that have occurred have been responsible for some of the largest floods on record in this region. Snowmelt-based floods tend to affect large areas. The factors controlling snowmelt floods are the volume of snow accumulated, the temperature rise which triggers melt, and the amount of rain that falls during the melt period.

Although it might be possible to infer from climate models that if total winter rainfall increases then the antecedent conditions necessary for flooding would occur more frequently, it is not possible to estimate changes in the rate of occurrence of short-duration rainfall totals (although meteorological experience suggests that an increase in stable anti-cyclonic conditions in summer would lead to an increasing frequency of intense summer thunderstorms). Possible changes in the frequency of rainfall-induced floods are therefore very difficult to assess.

As is the case with longer-duration river flow regimes, the effect of a given climate change on flood frequencies will vary between catchments. As catchment size increases, changes in the characteristics of short-duration rainfall will be less important, and the flood frequency curve of the catchment will be more sensitive to changes in longer-term (such as weekly or even monthly) rainfall totals. A slowly-responding catchment, such as one underlain by chalk, will also be more sensitive to rainfall integrated over a long period than to changes in short-duration rainfall events.

The proportion of event rainfall that produces a flood hydrograph is influenced partly by the antecedent wetness of a catchment - in the winter season related largely to long-term rainfall totals - and partly by the soil characteristics of the catchment. The greater the ability of the soil to absorb rainfall, the lower the proportion of the rainfall total that goes to generate the flood hydrograph. The degree of catchment urbanisation is also important; the greater the proportion of the catchment covered by urban development, the greater the proportion of the rainfall that generates the flood hydrograph. The lag between rainfall and peak flow, and hence the size of the peak for a given volume of rainfall, is controlled by the characteristics of the channel network (such as its density and configuration), the channel slope and again by the degree of urbanisation. The steeper, denser and more "efficiently packed" the network, the shorter the lag time and the greater the peak flow for a given rainfall volume.

Although no numerical calculations have been made, it is possible to suggest three hypotheses:

1. A change in the volume of long-duration rainfall, and hence catchment wetness, will have the greatest effect on rates of flood occurrence in large catchments, in unresponsive catchments, and in catchments which at are present "dry" for long periods.

2. A change in the rate of occurrence of extreme short-duration rainfall totals will have the greatest effect on flood occurrence in small, responsive catchments with efficient channel networks.

3. A change in soil properties, particularly soil organic matter content, will affect the transformation of storm rainfall into flood runoff.

The implications of climate change for the frequency of occurrence of floods of a particular size depends on the shape of the flood frequency curve as well as the change in the rainfall parameters controlling flooding in the catchment. In general, it can be expected that a relatively small change in the magnitudes of floods would have a very large effect on the frequency of particular events, with the greatest effect where the coefficient of variation of annual floods is lowest (and the flood frequency curves are therefore flattest).

The volume of water stored as snow would *reduce* as temperatures rise, but *increase* if cold-season rainfall were to increase. There have, however, been no studies conducted in the UK on the effects of a 1.5 to 2.1° increase in temperature (by 2030) and an increase in winter rainfall (of around 5% by 2030) on snowpack volumes. The greater the proportion of precipitation that currently falls as snow, the less the relative effect of increased temperatures on snowpack volumes.

4.8 Climate Change and Groundwater Recharge

Groundwater is a major supply source in large parts of southern and eastern England, but there have so far been only two studies (Hewett *et al.* 1992; Wilkinson and Cooper 1993) of the potential implications of climate change for groundwater recharge and storage in the UK (and indeed, there have been very few studies anywhere else).

Groundwater recharge in the UK generally takes place in winter, once potential evaporation rates fall below rainfall and the soil moisture deficits that built up over summer are replenished. Recharge largely ceases in spring when soil moisture deficits begin to develop again. Some well-fissured or shallow aquifers can be recharged during summer, but as a general rule the most important aquifers are recharged only during the winter season.

The effect of climate change on groundwater recharge will therefore depend on the extent to which any *shortening of the recharge season* - due to more persistent soil moisture deficits in a warmer world with drier summers - is compensated by an *increase in rainfall* during winter. Lower spring rainfall would have major implications for the availability of groundwater resources during the summer. Experience during the winters of 1988/89 and 1989/90 suggests that aquifers recharge better with limited rainfall in early spring rather than slightly more effective rainfall earlier in the recharge season. Prolonged steady rain is also more effective at recharging groundwater than short-period intense rainfall, so if winter rainfall in the future were to be concentrated into shorter periods, recharge would be reduced.

Hewett *et al.* (1992) applied Arnell *et al.*'s (1990) rainfall and evaporation scenarios to a model of the North Downs chalk aquifer in Kent. Under all the scenarios considered, groundwater levels at different points in the aquifer increased, reflecting the assumed increase in winter rainfall. Wilkinson and Cooper (1993) investigated the effects of assumed changes in recharge on groundwater storage using an idealised aquifer/river model. They showed that for slowly responding aquifers, an increase in the volume of winter recharge may result in increased baseflow to rivers throughout the year, even when the recharge period is reduced: for quickly-responding aquifers, baseflow would be reduced. Their results also indicated that slowly-responding aquifers may show a considerable delay before reaching a new storage equilibrium.

4.9 Climate Change and Water Chemistry and Biology

4.9.1 Introduction

Consideration of the effects of climate change on water chemistry and biology are conveniently split into two distinct areas, the uplands and the lowlands. Upland streams tend to be fast flowing and relatively oligotrophic, high in dissolved oxygen and with catchments wholly, or significantly, draining land which is not under intensive cultivation. In such systems the water quality reflects primarily the physiographic characteristics of the catchment, that is, soil type and bedrock geology, but often modified by the input of anthropogenic pollutants from the atmosphere, mainly acidic compounds. Lakes in upland areas are usually relatively unproductive but many are deep and become strongly thermally stratified in summer.

Lowland rivers, on the other hand, are generally slower flowing, with low turbulence and so dissolved oxygen content is generally below saturation. These rivers drain areas of large population and their catchments are intensively utilised in agricultural production and so tend to have high nutrient concentrations. Lakes in lowland areas tend to be shallow and relatively productive, and may develop an anaerobic hypolimnion when they become chemically stratified in summer.

Figure 4.5 summarises the climatic and non-climatic factors controlling water quality: it is important to emphasise that *land use* has a very significant effect on water quality, and may be directly and indirectly affected very strongly by climate change.

Before considering the potential effects of climate change on upland and lowland water chemistry and biology in detail, it is worth reviewing possible changes in stream water temperature.

4.9.2 Stream water temperature

The implications of climate change for stream water temperature in the UK have been reviewed by the University of Exeter as part of the DoE Water Directorate climate change impact project (Webb 1992).

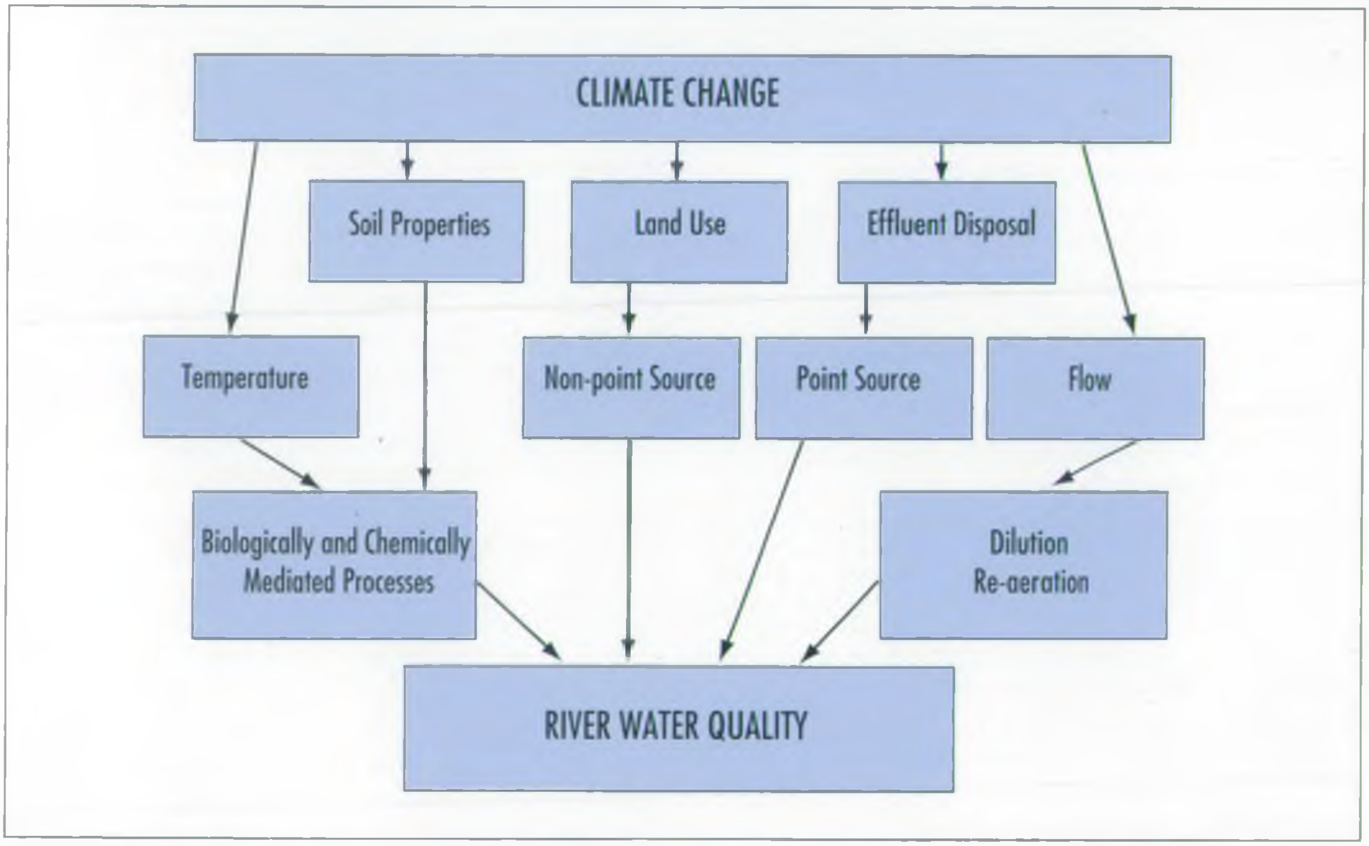

Figure 4.5 Climatic and non-climatic controls on water quality

The study developed regression relationships between air and water temperature using data from a number of rivers across the UK. A given increase in air temperature would produce a slightly smaller increase in water temperature, with the effect varying between catchments; the greatest increase is in small upland basins and where there are no riparian forests. The results implied that an increase in air temperature of 3°C would produce, on average, a 2.8°C increase in water temperature. Minimum water temperatures were found to be more sensitive to air temperature increase than maximum temperatures.

Variations in river flow would have only a small effect on river water temperatures, and the study concluded that it was unlikely that changes in flow regime alone would alter river water temperature by more than 1°C.

4.9.3 Upland water quality

The quality of upland streams may be considered to be essentially controlled by "natural" processes within their catchments and represent the "background" water quality on which the downstream pollution is imposed. There are three main possible effects of climate change:

Increased nitrate concentrations

The main direct impact of increased temperature would be an increase in nitrate concentrations through mineralisation of organic nitrogen in the soil. This might be enhanced by a more seasonal rainfall regime causing increased soil moisture deficits in some areas. The result would be an increase in surface water nitrate concentrations; this is unlikely to cause lake productivity to increase because freshwater systems are usually phosphate-limited.

A change in soil properties due to climate change will also affect nitrate concentrations. Most upland soils have organic surface layers, and if these layers become drier it is likely that they will become hydrophobic. This means that they will shed water more rapidly, with implications for inputs of nitrogen and phosphate into river channels.

A change in climate might mean that marginal areas become economically viable for land improvement with a subsequent increase in stocking density and fertiliser or pesticide application. This is, however, unlikely given present agricultural and set-aside policies.

Climate change and surface water acidification

Present water quality problems in upland areas stem mainly from increased acidity in response to the deposition of anthropogenic sulphur and nitrogen compounds.

This deposition generally takes the form of "occult deposition", whereby plant and ground surfaces filter moisture droplets directly from clouds. If cloud cover were to increase as a result of global warming, the pollutant loading would be enhanced in sensitive upland areas (especially in upland forests). A change in circulation patterns would also change the frequency of occurrence of air-streams bringing acid rain.

Increased rainfall may concentrate flow through the upper soils with low acid neutralisation capacity and so increase the frequency and magnitude of acid episodes. Increased drying of soils in summer would cause sulphur and nitrate mineralisation and hence promote increased acidification.

All of these effects must be considered in the light of possible future *decreases* in pollutant emissions. Furthermore, many of these effects may prove to be transient; nitrate mineralisation, for example, will only occur until the source of available nitrogen is depleted and changes in flow pathways might be influenced by long-term changes in soil structure. These potential impacts form the central theme of the DoE Global Atmospheres Division Core Model project (Chapter 1), which aims to develop a framework for linking models, databases and GIS technologies to assess future climate change scenarios on biogeochemical systems across the UK.

Water discoloration

The discoloration of water by peat decomposition products (McDonald *et al.* 1991, Naden 1992) will be enhanced under suggested climate change scenarios. Higher summer temperatures, especially if coupled with lower summer rainfall, will lead to an increase in soil moisture deficits and, thus, an increase in the rate of peat decomposition by bacterial action. Organic fractions with the ability to discolour water are one of the products of this decomposition. The take-up of these products is dependent on pH, whilst removal of the resulting discoloured water is directly proportional to the rate of water throughflow. Increased winter rainfalls will exacerbate the washout of these coloured waters, which may also be increased by changes in soil structure.

Thus, it is likely that there will be a greater rate of both colour production and release. Furthermore, a more variable climate, with a greater propensity for dry summers, would lead to a bigger build-up within the peat of the organic fractions which cause water discoloration, resulting in enhanced autumn flushes of colour, as has already been witnessed following recent dry summers.

4.9.4 Lowland water quality

River water quality problems in the lowlands can arise from (i) high concentrations of a wide range of pollutants including nutrients and toxic chemicals, or (ii) from low concentrations of "beneficial" elements, notably dissolved oxygen. Both direct and indirect climatic influences will inter-react to cause a change in pollutant concentrations. Changes in *temperature* will affect the rate of biological activity, and changes in *river flow regimes* will affect dilutions, concentrations and residence times. Changes in *land use* might result in changes in the input of pesticides and fertilisers. Alterations in *rainfall patterns* and *soil moisture* will affect flow pathways through soil and therefore the rate at which substances applied to the land surface reach water courses and groundwater.

The complex interactions between all these potential changes mean that it is difficult to make generalisations about changes in water quality. The potential impact of climate change on stream water quality has been investigated at IH (Jenkins *et al.* 1993). The water quality model QUASAR (Quality Simulation Along Rivers: Whitehead *et al.* 1981) was applied to several catchments in the UK to simulate the effects of changes in flow regime and water temperature.

The remainder of this section considers, as examples of potential changes, the impact of climate change on toxic chemicals and pathogens, nitrate concentrations and dissolved oxygen.

Toxic chemicals and pathogenic bacteria

The concentrations of toxic chemicals will be directly affected by changing flow conditions. An increased flow would produce a dilution and a decreased flow a concentration effect, providing the input flux remains constant. High temperatures alone will, for example, decrease the survival time of pathogenic bacteria, but increase their division rate. Other organisms such as protozoal cysts survive best in a cool, dark, moist environment and so milder wetter winters will provide ideal conditions for survival. The Public Health Laboratory is currently gathering information on the potential effects on water-borne diseases of a change of water resources due to the greenhouse effect.

Possible changes in nitrate concentrations

Nitrate concentrations in rivers are determined through a complex series of mechanisms, involving chemical reactions, bacterial transformations and flow. In simple terms, assuming no additional terrestrial inputs, nitrate concentration in a river reach is the product of the initial concentration minus losses from denitrification and plant uptake plus addition through nitrification processes.

The initial concentration is a function of the flow rate whilst both nitrification and denitrification are biologically mediated reactions which are influenced by the water residence time in the reach and the temperature. Increased temperature will cause an increase in the rates of both reactions through increased microbial activity and decreased flow in the reach increases the water residence time allowing more time for microbial breakdown to occur and so should reduce nitrate concentrations. However, if effluent inputs remain constant and river flows are reduced, then initial nitrate concentrations would increase as a result of lower dilution. Model calculations indicate that the effect of the increased initial concentrations may outweigh the effects of the increased residence time and greater microbial activity, and downstream nitrate concentrations would therefore *increase.* Figure 4.6 gives an example simulation using data from the River Thames.

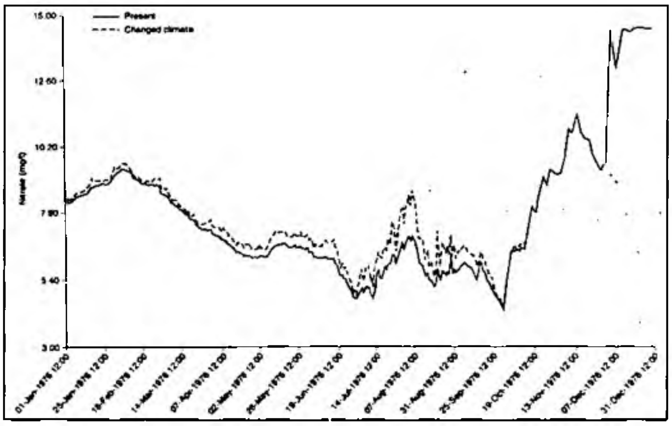

Figure 4.6 Observed nitrate concentrations in the River Thames at Romney during 1976 compared with those predicted for a flow regime with greater seasonal variation using a water quality model

The simulation assumes no change in inputs.

During warm and dry summers inorganic nitrogen accumulates in the soil. This supply of nitrogen is flushed into the water course in autumn. If the first flushing rainfall event is large, then nitrate concentrations in the water course may increase very rapidly for a short time (as occurred following the break of the 1976 drought, for example). An increasing frequency of dry, warm summers could therefore result in an increased risk of very high nitrate concentrations in early autumn.

Possible changes in dissolved oxygen content

The dissolved oxygen (DO) content of a water course would be affected by changes in flow, an increase in temperature, and an increase in aquatic plant growth (which may itself be temperature-related). Lower flows would mean that an input Biological Oxygen Demand (BOD) load would be less diluted, and warmer water is able to hold less oxygen. A rise in temperature would increase both the rate of biological activity (and hence de-oxidation) and the rate of re-aeration, but the effect on de-oxidation is greater so the oxygen level in the water course would be reduced (Jacoby 1990).
Figure 4.7 shows dissolved oxygen concentrations in the Thames under current conditions and two climate change scenarios (both of which assume increased temperatures). The dissolved oxygen concentration does not change much if the increase in water temperature is associated with increased flows, but if flows are reduced there can be a very large fall in dissolved oxygen. This, of course, has major implications for oxygen-dependent life, such as fish.

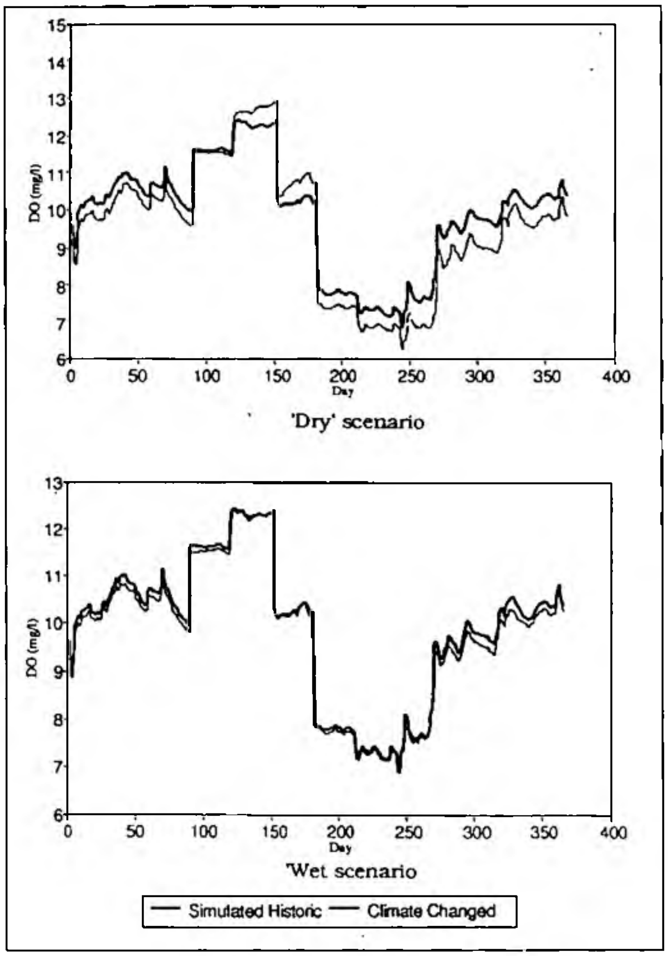

Figure 4.7 Observed dissolved oxygen concentrations in the River Thames at Datchet during 1974 compared with those for wetter and drier climates

4.9.5 Algal blooms

Deoxygenation can also be brought about by the growth of algal blooms and a scenario of lower flow and higher nutrient concentrations might promote algal growth. Such occurrences can cause fish kills, clogging of river intakes and lead to toxicity problems. There is controversy, however, over whether recent blooms of toxic blue-green algae, experienced particularly in 1989, 1990 and 1991 result from "natural" processes or as a result of increased agricultural pollution. These years were certainly characterised by higher-than-usual temperatures (and particularly warm summers following mild winters), but the blooms may have been due to increased concentrations of phosphates derived from farmland. In practice, the answer is probably some combination of the two and this represents a case-in-point of the uncertainties in purely climate-induced water quality impacts.

Most species of planktonic algae can survive and grow at temperatures well in excess of those predicted for a warmer world. Diatoms grow best at temperatures below 25°C and blue-green algae at temperatures above 30°C (Hawkes 1969) although, in physiological terms, most groups of algae photosynthesise most efficiently at temperatures of around 25°C. The rate of carbon fixation could therefore increase with increasing temperature, but factors other than temperature usually limit net production. In a warmer world, the net annual production of some Scottish lochs could conceivably increase but increases elsewhere would probably be checked by qualitative changes in the plankton.

In UK lakes and reservoirs, the most pronounced effect of global warming will be those related to the growth and succession of different species of algae. Phytoplankton growth increases rapidly at temperatures between 10 and 20° and only begins to decline at temperatures above 25°. Winter temperatures in the UK are predicted to increase by 2.3 to 3.5° by 2050. Such an increase would accelerate the spring growth of phytoplankton but could also influence patterns of succession much later in the year. For many slow-growing species of phytoplankton, their growth rate in early summer is often controlled by the number of cells that overwinter in the open water. Mild winters invariably increase the size of this spring inoculum which often provides the springboard for subsequent summer blooms.

The seasonal succession of phytoplankton in lakes is now also known to be influenced by the timing as well as the strength of wind-induced mixing

(George *et al.* 1990). Model simulations (Reynolds 1984) show that the first species to appear in spring are the diatoms that can grow when lake water is cold and the days are relatively short. These diatom blooms can collapse for a variety of reasons, but thermal stratification and sedimentation usually accelerates their rate of decline. Once the diatoms have gone, a variety of small flagellates then tend to dominate the plankton. These small forms have high rates of growth but can only survive if the water column is periodically mixed by the wind. When the water is warm and there is relatively little wind, slow-growing forms like the bloom-forming species of blue-green algae become dominant. Many of these bloom-forming species are able to move freely in the water column by regulating their buoyancy so are unaffected by long periods of calm weather. In some shallow, highly eutrophic lakes, dense blooms of blue-green algae appear every summer. In deeper lakes, however, their summer growth is largely controlled by week-to-week changes in the intensity of wind mixing. The blue-green alga *Oscillatoria agardhi*, for example, grows well in a stable water column but growth can be suppressed by quite short periods of intense mixing (Talling 1989). Figure 4.8 contrasts the summer phytoplankton of Windermere in a calm year (1989) and a windy year (1985). In 1989 (Figure 4:8a) the late summer plankton was dominated by *Oscillatoria* but in 1985 (Figure 4.8b) this "climax" community was suppressed by periodic wind mixing.

It is not yet known whether calm summers will become more common in a warm world. Problem blooms of algae will, however, appear much earlier in the year and will thus be able to take advantage of any calm periods that do occur.

The factors that influence the growth and decline of river plankton differ fundamentally from those that control the dynamics of lake plankton. At one time it was assumed that the "retention time" of most rivers in the UK was too short to support sustained growths of algae. In recent years, however, it has become clear that traditional Fickian type dispersion models underestimate the retention times of nutrients and plankton within a particular river reach (Bencala and Walters 1983). Experimental and remote sensing studies (Reynolds *et al.* 1991) confirm the widespread existence of local patches of slow-moving water wherever there are well-developed pools and meanders. Theoretical calculations demonstrate that some of these dead zones can remain isolated from the main flow for up to 25 days. Dense populations of planktonic algae can thus develop in these dead zones and act as "seed" populations for the main flow. In a warmer world, with reduced summer flows these "seed" populations can be expected to grow and have a more pronounced effect on downstream water quality.

Growth rates are also affected by flows. The lower the flow, the larger the residence time, so the greater the growth. Figure 4.9 shows a model simulation of the predicted downstream concentrations of chlorophyll given a specified inoculum and a range of mean flows (Institute of Hydrology 1990). For example, with an upstream concentration of 50 mg ch m^{-3}* and a mean flow of 10 m^3s^{-1}, the downstream concentration of

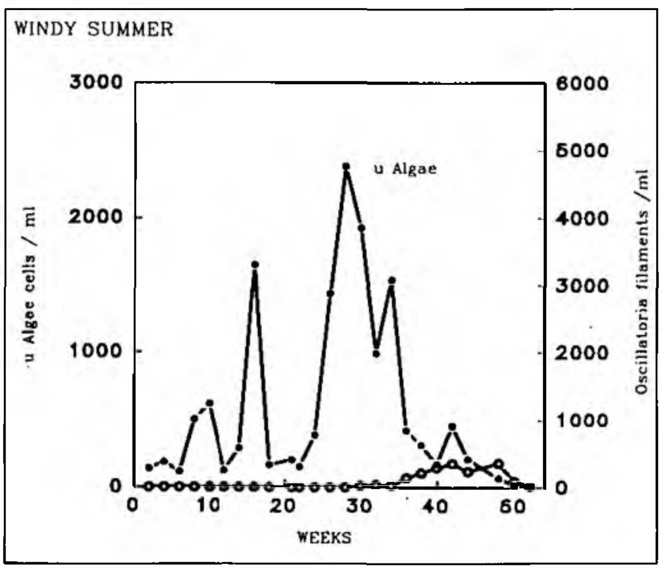

Figure 4.8a The seasonal succession of phytoplankton in the south basin of Windermere in a calm year

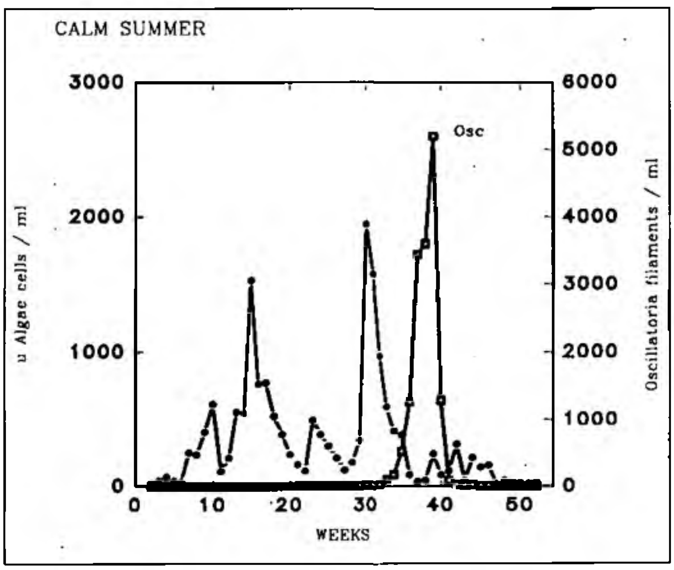

Figure 4.8b The seasonal succession of phytoplankton in the south basin of Windermere in a windy year

o *oscillatoria* filaments per ml; ● microalgae cells per ml (unpublished data supplied by S.I.Heaney).

* mg ch m^{-3} denotes milligrams of chlorophyll per cubic metre.

chlorophyll would be approximately 80 mg ch m^{-3}; a flow of just 2 $m^3 s^{-1}$ would produce a concentration of 500 mg ch m^{-3}. This is a "worst case" simulation, but does indicate the potential change in the risk of algal bloom growth in rivers.

4.9.6 Erosion and sedimentation

Erosion of material from the land surface and its transport into the river system will be affected by changes in rainfall characteristics and changes in vegetation cover and soil structure. It is probable that the effects will be highly non-linear, as the impacts of change will depend on whether critical thresholds of erodibility are crossed. Changes in management practices and land use - particularly planting of winter wheat - will also have very significant effects on soil erosion, and may be far more important than the effects of changes in climate. Model simulations (Boardman *et al.* 1990) suggest that, assuming no change in management practices, climate change would result in greater losses from arable lowlands, but lower losses from uplands where the warmer climate would produce longer growing seasons.

A change in river flows would affect both the erosion of material from river banks and sediment deposition. Higher flows imply an increased potential for erosion but also an increased ability to transport sediment (how would this increased ability offset possible increases in sediment becoming available to the river?); lower flows imply increased deposition. There have been no studies in the UK on possible changes in sediment transport, river erosion and sedimentation, and this is clearly a research gap.

4.10 Climate change and sea level rise

A change in global temperature and precipitation would lead to a change in the global mean sea level. Factors contributing to a change in sea level are (i) thermal expansion of sea water in a warmer world, (ii) the melting of valley glaciers and (iii) changes in the Antarctic and Greenland ice sheets. The IPCC concluded (IPCC 1990a) that thermal expansion and glacier melt would have the greatest effect, but also stated that uncertainty in changes in the large ice sheets make a major contribution to the uncertainty in predicted sea level change. Increased precipitation on

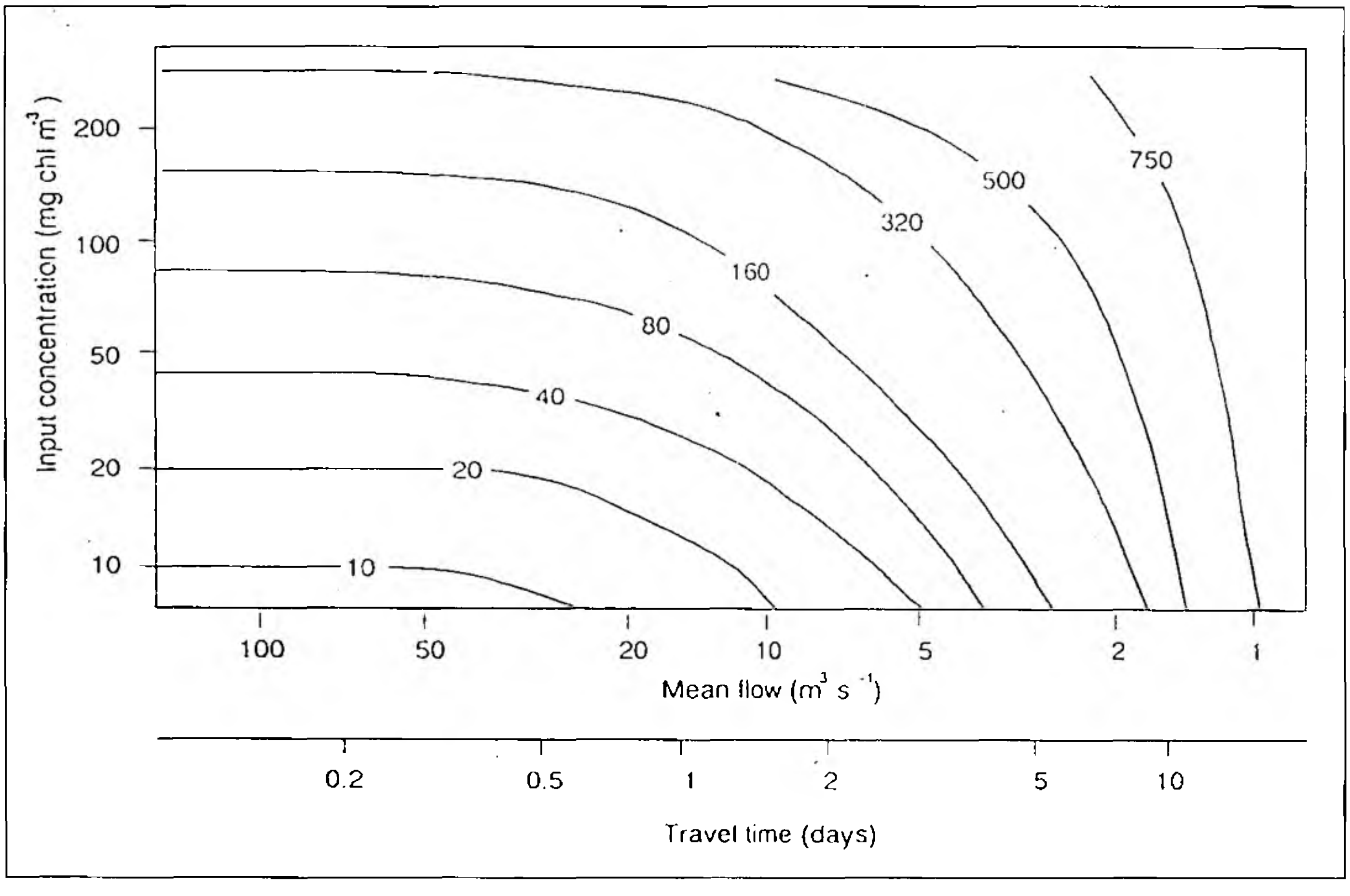

Figure 4.9 Downstream concentrations of chlorophyll in a river reach, given different upstream concentrations and flows (Institute of Hydrology 1990)

the Antarctic ice sheet, for example, would mean that more precipitation is stored as snow and that sea level would fall slightly. The IPCC estimated a rise in global mean sea level by 2030 of 180 mm, with a range of 80 to 290 mm (the emissions scenarios used in the 1992 Supplement result in a slightly lower sea level rise by 2030: Wigley and Raper 1992).

The UK Climate Change Impacts Review Group assumed similar figures for changes in mean sea level around the UK, as shown in Table 4.3 (the differences between the IPCC and CCIRG values reflect the use of a slightly different model). The local effect of a rise in sea level, however, depends on tectonic or isostatic changes in the land surface; south east England is falling relative to mean sea level, whilst north west England and Scotland is rising. The NRA has combined estimates of changes in global mean sea level with isostatic changes to produce the regional estimates of change in sea level shown in Table 4.4.

Table 4.3 Change in mean global sea level (CCIRG 1991)

	2010	2030	2050
Change in sea level (mm)	80 (40 - 130)	190 (90 - 290)	310 (150 - 450)

4.11 Climate Change and Storminess

A change in the frequency of extreme storms could have significant consequences for both inland and coastal flooding. However, climate models do not simulate small-scale disturbances such as storm systems at all well. Both the IPCC and the CCIRG stated that it was impossible at present to create feasible scenarios of changes in storm frequency (IPCC 1990a; CCIRG 1991). Mid-latitude storms, such as those which affect the coasts of the UK, are driven by the equator-to-pole temperature gradient, and if global warming causes this gradient to be reduced (because the poles may warm by a greater amount than the equator) then storm frequency would be expected to reduce (IPCC 1990a). Storm tracks may change, however, so a particular location might suffer more frequent or more intense storms.

Holt (1991) attempted (under contract to NRA Anglian Region) to use climate model simulations to assess possible changes in storm frequency and intensity in the North Sea. He found that climate models indicated a slight increase both in windspeed (and hence storm intensity) and the frequency of occurrence of gales. The increase, however, was well within the variability that has been experienced over the last 100 years.

4.12 Improving Climate Change Scenarios

4.12.1 Introduction

This chapter has reviewed the current status of scenarios for future values of parameters relevant to the NRA. This last section indicates how these scenarios might be improved, distinguishing between "first order" parameters such as temperature, rainfall, evaporation and sea level rise, and "second order" parameters such as river flows, groundwater recharge and water quality. The first order parameters are those produced from global climate models, whilst the second order parameters are based on the application of a local model with the first order parameters as input.

There are therefore two levels of uncertainty in estimating the impacts of climate change on a particular system. Firstly, there is uncertainty in estimating potential changes in the first order climate parameters. Secondly, there is uncertainty in knowing how a given change in the relevant first order parameters will actually affect the system of interest. In some areas the link between climate and response is well known (as is the case with rainfall-runoff simulation) so this second type of uncertainty is relatively small compared to the uncertainty in climate inputs. In other areas the links

Table 4.4 Assumed rise in sea level, by NRA Region (NRA 1991a)

Region	Rise in mm/year	Total rise by 2030 over 1990 levels (mm)
Anglian, Thames and Southern	6	240
North West, Northumbria	4	160
Severn Trent, South West, Welsh, Wessex and Yorkshire	5	200

between climate and response are less well-known, so the uncertainty in the final impact assessment is considerably increased.

This section considers how first and second order parameter scenarios can be improved, and indicates the potential contribution of the NRA. The most important single element in the improvement of climate change scenarios for the UK, however, is the DoE Climate Impact LINK project, and this is discussed next.

4.12.2 DoE Climate Impact LINK project

During 1990 and 1991 it became clear that several climate change impacts projects required scenarios at a finer space and time-scale than was currently available, and needed a consistent set of change scenarios. The DoE Global Atmosphere Division Core Modelling project and the DoE Water Directorate "Impact of climate change on water resources" (Chapter 1) study in particular required detailed climate change scenarios. The demand from the impact research community was sufficiently strong for the DoE Global Atmosphere Division to fund a project specifically to create climate change scenarios and to provide a link between the Hadley Centre for Climate Prediction and Research and the diverse impacts community. The project will exploit General Circulation Model simulations to create climate change scenarios at time- and spacescales relevant to impacts researchers.

The project is based at the Climatic Research Unit of the University of East Anglia, and benefits from close liaison with a DoE-funded climate model validation project (GCM Validation and Climate Change Detection, Contract No. PECD/7/12/78), a MAFF-funded project to create transient climate change scenarios, and the considerable expertise that exists there. The overall aims of the project are:

- to liaise with the impacts community to determine the nature of their climate change data requirements;
- to provide information to the impacts community to help them become familiar with the correct interpretation of GCM data;
- to liaise with the Hadley Centre so that archived GCM data can be tailored to the needs of the impacts community (climate model simulations produce vast quantities of output; only a small proportion is stored); and
- to develop and provide a range of climate change scenarios for the UK at space-and timescales suitable for use by the impacts community.

The project commenced in October 1991, and a workshop held in July 1992 (Viner and Hulme 1992a) discussed in detail the requirements of the climate change impacts community, including those relevant to the NRA.

The project will provide scenarios for changes at daily, monthly, seasonal and yearly time series as well as monthly means for the primary, secondary and tertiary climatic variables as listed in Table 4.5 (Viner and Hulme 1992b). Scenarios will be provided at climate model resolution (2.5 x 3.75° for the current Hadley Centre model), and the method outlined in Section 2.3.2 will be used to create scenarios for different time periods and emissions scenarios. The changes in the climate parameters will be expressed as a change per °C of average global warming, and the Climate Impact LINK project will provide information on global temperature changes at different time periods under different emissions scenarios. Climate change scenarios for the site of interest are created by the user, who must rescale the Climate Impact LINK project data fields by assumed changes in global temperature and then apply these changes to observed baseline data. First scenarios from the Hadley Centre climate model became available at the end of 1992.

The project will ensure that consistent climate change scenarios are being used in studies in different sectors, and will also mean that climate modellers are aware of the types of information required by those interested in the impacts of climate change. It is strongly recommended that the NRA continues to take advantage of the services provided by this project; all NRA climate impact studies - whether research or operational - should use scenarios produced by the Climate Impact LINK Project.

4.12.3 First order climate parameters

Table 4.6 summarises the current reliability of scenarios for the first order climate parameters temperature, rainfall, potential evaporation, storminess and sea level rise, and Table 4.7 indicates the NRA requirements for such scenarios. Table 4.8 summarises ways in which scenarios can be improved to meet these requirements.

Table 4.5 A summary of the projected output of the DoE Climate Impact LINK project

Primary variables			
Mean surface air temperature	Precipitation	Mean sea level pressure	
Secondary variables			
Maximum and minimum temperature	Relative humidity	Mean windspeed	Sunshine hours
Cloud cover	Vapour pressure	Soil temperature	Snow depth
Tertiary variables			
Soil moisture deficit	Potential evapotranspiration	Radiation	

Table 4.6 Reliability of scenarios for climate change parameters of interest to the NRA

	Reliability of current predictions (relative to global temperature)	Reliability expected in the medium term (5-10 years)
Temperature		
air temperature	●●●●	●●●●
Precipitation		
monthly rainfall	●●	●●●
"flood-producing rainfall"	●	●●
Sea level		
mean sea level	●●●	●●●●
Storminess		
occurrence and intensity	●	●●●
Potential evaporation	●●	●●●
Sunshine	●●	●●●

Key to reliability:

●●●●●	very good (relative to global air temperature)
●●●●	good
●●●	adequate
●●	just usable with extreme caution
●	should not be used

Temperature

Estimates of global and regional temperature will improve as climate models become more refined, but the CCIRG scenarios provide an initial set of estimates. The Climate Impact LINK project provides changes in monthly mean, maximum and minimum temperature. Estimates of changes in daily temperatures can be made by either perturbing a historical daily temperature series, by generating *daily* temperatures from a sine function based on mean, minimum and maximum temperatures, or by the use of stochastic weather generators which generate synthetic data given parameters describing the properties of daily temperature data. The NRA can take advantage of the scenarios and techniques that already exist or are under development.

Table 4.7 NRA scenario requirements

	Time step	Time horizon
Temperature	Daily	Transient, 1990-2050
Rainfall	Daily	Transient, 1990-2050
Potential evaporation	Daily	Transient, 1990-2050
Storminess	Daily	Transient, 1990-2050
Sea level rise	Annual	Transient, 1990-2050

Rainfall

Rainfall is the most important climate change parameter for the NRA, but rainfall scenarios are currently very uncertain. The CCIRG produced scenarios of mean seasonal rainfall changes by different times in the 21st century, and the DoE Climate Impact LINK project provides scenarios for monthly rainfall. These too show the change in rainfall from present values over the next few decades.

There are several possible ways of creating daily rainfall scenarios from monthly change scenarios. The simplest is to apply the monthly percentage changes to an observed daily series, but this means that the number of rain days stays the same. It is possible to perturb a historical daily rainfall record to reduce or increase the number of days on which rain falls. Arnell and Reynard (1993) used a method which basically chose at random days to gain or lose rainfall. Another approach is to use a stochastic model to generate daily rainfall data from monthly rainfall parameters, such as mean rainfall, the standard deviation, the number of rain days and the amount of day-to-day correlation. This method was used by Cole *et al.* (1991), and is currently the subject of much international research. However, whilst it is possible to create reasonably accurate daily rainfall generation models, it may difficult to know how to change parameters (other than the mean) of such complex models; it is relatively easy to perturb the parameters of simple stochastic models, but these tend not to simulate daily rainfall patterns very well. A third approach is to develop empirical relationships between daily "weather type" (such as cyclonic, westerly or anticyclonic) and local rainfall, and apply these relationships to daily weather type information provided by climate models (Bardossy and Plate 1992). However, the relationships between daily weather types and local rainfall amounts have been found to be very unstable (Wilby 1993 pers. comm.), and climate models do not necessarily simulate weather types very well.

Research is therefore needed to refine ways of creating scenarios for changes in daily rainfall from the changes in rainfall characteristics provided by the Climate Impact LINK project. The NRA should consider supporting such a project or reviewing the increasing international activity in this area, but it is not the only organisation interested in this issue.

It will *not* - in the foreseeable future - be possible to use climate model-generated sequences of daily rainfall in climate change impact studies.

The precision of rainfall scenarios depends mainly on the refinement of the climate simulation model. Improvements in climate models should therefore lead

Table 4.8 Improving climate change scenarios (first order parameters)

	How can scenarios be improved?	Who else is interested?
Temperature	Improve climate models	Everybody
Precipitation	i) Improve climate models ii) Meso-scale models iii) Stochastic models	DoE, MAFF, NERC, AFRC, PLCs
Potential evaporation	i) Scenarios for components ii) Meso-scale models	DoE, MAFF, NERC, AFRC, PLCs
UK coastal sea level	Temperature-level models	DoE, MAFF, NERC
Storminess	Meso-scale models	DoE, MAFF, NERC

Table 4.9 Improving climate change scenarios (second order parameters)

	How can scenarios be improved?	Who else is interested?
Soil moisture	Soil moisture models	DoE, MAFF, NERC, AFRC
Vegetation characteristics	Interactive vegetation models	DoE, NERC, MAFF
River flows	i) Physically-based models ii) "Macromodel"	DoE, PLCs, NERC, MAFF
Groundwater recharge	Recharge models	DoE, PLCs, NERC
Water quality	Physically-based models	DoE, PLCs, NERC, MAFF

to an increase in the precision of rainfall scenarios, but these improvements must be made at the global scale; it is not possible to tinker with a global climate model just to improve rainfall predictions for the UK.

One way of improving the precision of rainfall simulations from a global climate model is to nest a higher resolution "meso-scale" climate model within the global model. Work is already under way at the Hadley Centre to nest a meso-scale model for the UK within the global climate model; the marginal contribution of the NRA to this large modelling effort would be small.

Potential evaporation

The potential evaporation scenarios that have so far been developed (as part of the DoE Water Directorate climate change impact project) are necessarily based on some rather arbitrary assumptions about changes in climate parameters such as humidity and net radiation. More specific scenarios for such parameters will be produced by the DoE Climate Impacts LINK project, which will enable the development of more plausible evaporation scenarios. Again, however, the reliability of estimates of the climatic components of potential evaporation are dependent on the quality of climate model simulations.

Potential evaporation is an important element in the water budget, and scenarios are currently very uncertain. The NRA should consider supporting a project to produce feasible scenarios for changes in potential evaporation, given assumptions about changes in climatic characteristics and vegetation characteristics.

Sea level rise

Sea level rise is largely a non-linear function of temperature, and although there are some uncertainties in the form of this function, estimates of changes in sea level are rather more reliable than estimates of change in rainfall. The NRA has already accepted a set of coastal sea level rise scenarios for England and Wales, and there is no need to sponsor further work at present. The scenarios can be revised as additional estimates of changes in global sea level are made.

Storminess

Estimates of changes in storm intensity and frequency are dependent on the skill of climate models. The quickest route to improved estimates is via the use of nested meso-scale models, but the marginal contribution of the NRA to such an effort would be small.

4.12.4 Second order parameters

These parameters are estimated by applying changes in the first order parameters with a catchment or local model. Table 4.9 indicates how they might be improved, given also the improvements in the first order parameters outlined in the previous section.

Soil moisture

Estimates of changes in soil moisture need to be based on physically-realistic soil moisture accounting models, which also incorporate the effects of possible changes in soil structure. The impact of climate change on the development of fissures is particularly important for soil moisture (and indeed for river flows). Such models are being developed by SSLRC.

Vegetation characteristics
Catchment vegetation will change in response to increasing concentrations of CO_2, to changes in temperature and rainfall, and also to changes in land use management decisions. MAFF is funding some work on potential changes in arable crops. SOAFD is funding work on modelling the effects of climate changes on arable crops, grassland, tree growth and rural land use in Scotland. Models which simulate grass growth given climatic and nutrient conditions are being developed by the MAFF Field Drainage Experimental Unit and by the University of Sheffield, as part of the DoE Global Atmosphere Division Core Modelling project. A consortium led by the Environmental Change Unit at Oxford University began in 1992 investigating the sensitivity of land use to changes in climate, as part of TIGER IV (Chapter 1). The results from this project will be very valuable to the NRA.

River runoff
Impact studies really need to be based on simulations of daily flow regimes, and it would be interesting to conduct some simulations showing the possible rate at which flow regimes may change from decade to decade (Figure 4.4 gives an indication of the possible rate of change, but does not show how the underlying trends compare with year to year variability). Arnell and Raynard (1993) addressed both these issues in the DoE Water Directorate project, but the studies need to be repeated with the transient scenarios produced by the DoE Climate Impacts LINK project.

Changes in river flow regime will be affected not just by changes in rainfall and temperature, but also by changes in catchment vegetation (mix and physiology) and soil structure. It is necessary to conduct a sensitivity study into the relative importance of all these influences: it is possible that some will be minor - at the catchment scale - compared with others. The study must use physically-based models of runoff generation processes, and will need information on changes in soil and vegetation characteristics. It will also contribute greatly to an understanding of potential effects of climate change on water quality. The HOST (Hydrology Of Soil Types) project, being undertaken by SSLRC, Macaulay Land Use Research Institute (MLURI) and IH, can provide a basis for an assessment of the implications of changes in soil properties on hydrological response.

Hydrological models are currently being developed under the TIGER III programme which can use output directly from a climate model to simulate river flows throughout a basin, and which could be incorporated as an interactive component within a climate model. First versions of these "macromodels" should be available by 1995.

Groundwater recharge
No detailed studies into climate change and groundwater recharge in England and Wales have been published, and none are under way. Some hypotheses have been formulated (Section 4.8), and need to be tested using realistic groundwater recharge models.

Water quality
Both the DoE Water Directorate project and the DoE Global Atmosphere Division Core Modelling project are estimating impacts of climate change on water quality. The Water Directorate project has produced some first results (Jenkins *et al.* 1993), and the Core Modelling project will provide the framework for physically-based site specific assessments and a wider spatial application across the UK in the future. There is a need for a review of the potential impacts of climate change on erodibility and sediment transport in rivers.

Another way of estimating potential changes in water quality is to examine behaviour during past extreme events. Experience gained during both the drought of 1976 and the 1988-1992 drought will be very useful when assessing what may happen under periods of higher temperatures and lower rainfall.

4.12.5 Summary

It is clear that improved assessments of the impact of climate change on the NRA require (i) more precise climate change scenarios - especially rainfall - and (ii) physically-based models of the processes resulting in runoff, recharge and water chemistry. The NRA is not alone in these demands (Tables 4.8 and 4.9), and much work is currently under way with sponsorship from DoE, MAFF and NERC.

Improvements in scenarios for changes in the climatic parameters driving the hydrological and aquatic system will come largely through improvements to climate models and through the DoE Climate Impacts Link project. *The marginal contribution of the NRA to global or even meso-scale climate modelling, for climate change purposes, would be very small.* A larger collaborative effort with other government agencies to develop meso-scale models might, however, mean that better UK-scale climate predictions are obtained more quickly (although the Hadley Centre is at present uncertain whether better regional predictions can be made by feeding global model data - with their own large errors - into a higher resolution regional model).

The NRA could take full advantage of the climate change scenarios produced by the Climate Impact LINK project. This project already plans to provide scenarios for the climate change parameters of greatest relevance to the NRA. *Some additional effort may be needed to develop daily change scenarios from changes in monthly rainfall characteristics* (either as a specific extension to the Climate Impact LINK project or as a separate study).

The NRA could make a greater contribution - often in collaboration with other parts of the impacts community - to research to estimate the implications of climate change for "second order" parameters. There is a particular need for the development of a physically-based model which can simulate runoff generation, recharge and water chemistry and biology under a changing climate, catchment land cover and soil structure. Most current assessments use models with parameters calibrated on current conditions; more reliable - and scientifically credible - estimates of the impact of change need physically-based models. Some models are already being developed (particularly under the TIGER and DoE Global Atmosphere Division programmes), and the first integrated impact assessment models should be available by 1995.

5.WATER RESOURCES

Climate change has four potential implications for water resources:

1. **Reliability of river flows and groundwater recharge**

   Changes in the volume and timing of river flows and groundwater recharge could have major implications for source reliability, with impacts depending on both the catchment and the characteristics of the supply system. However, there are currently very large differences between the predictions from climate change scenarios. Some imply a significant reduction in source yields - particularly in the south and east - whilst others imply an increase.

2. **Saline intrusion into estuaries**

   A higher sea level would mean increased saline intrusion into the lower reaches of estuaries. Saline intrusion would also be affected by changes in river flow regimes; increased flow in winter would tend to limit intrusion, but lower summer flows could exacerbate problems. Studies have shown, however, that saline intrusion would only directly affect a small number of abstraction points.

3. **Saline intrusion into aquifers**

   A higher sea level could also mean increased penetration of saline water into coastal aquifers, threatening supply boreholes. Studies have shown that, at the national scale, the threat to groundwater resources is slight, and that the cost of relocation of exposed sources would be small in comparison with ongoing maintenance and exploration costs.

4. **Demand for water**

   Domestic and agricultural demand for water is increasing, and climate change may add further pressures. Particularly sensitive areas are demands for garden watering and personal showering and demands for spray irrigation. The frequency of pipe bursts *might* fall, and demands for cooling water might increase. The instream demands of the aquatic ecosystem can also be expected to change.

5.1 Introduction

The NRA aims to assess, manage, plan and conserve water resources and to maintain and improve the quality of water for all those who use it. More particularly, the NRA manages resources through abstraction and impounding licences. Licence applications are evaluated on the basis of the availability of water and the environmental consequences of the abstraction or impoundment, and are reviewed against the framework of a national and regional water resources strategy. The NRA itself operates some river flow augmentation schemes - such as the Ely-Ouse transfer scheme in Anglian Region - which are primarily designed to support abstractions. It also has a programme to alleviate low flow problems (caused by overabstraction over a long period) in a number of specific problem catchments.

Climate change will affect both the ability of rivers and aquifers to *supply* water and the *demands* (environmental and economic) for water. Table 5.1 summarises the key areas of concern within the NRA's Water Resources function, and indicates which dimensions of climate change are *directly* relevant (note that rainfall, for example, affects the reliability of resources indirectly through river flows and groundwater recharge).

Climate change is not the only change which will be affecting water resources. Demand for water will increase according to population growth, consumption per person (affected by ownership of appliances and the use of domestic meters), the level of economic activity, and progress made in reducing leakage and losses. The NRA's Water Resources Development Strategy Discussion Document (NRA 1992) estimates that the demand for public water supply alone will increase by 18% between 1990 and 2021. This *extra* demand - nearly 3200 megalitres per day (Ml/day) over the whole of England and Wales - is concentrated in south and east England and is similar to the total amount currently withdrawn for public supply in the Wessex and Southern Regions combined. If there is no further resource development, the reliable yield would be insufficient to sustain public water demands by 2021 in Anglian, Thames, Southern, Wessex and the South West Regions (NRA 1992). Even with the implementation of planned resource developments, it is likely that major water imports will be needed into the south east of England. Climate change will be superimposed on these very large changes. In some cases the effects of climate change will further aggravate pressures; in others, the effects of climate change may be insignificant compared with the other changes taking place.

5.2 Reliability of Surface and Groundwater Resources

5.2.1 Background

Changes in the volume of river flows and groundwater recharge would affect the ability of a water resources system to meet abstraction demands and dilute effluents, and would also have very significant environmental implications (as discussed in detail in Chapters 6, 8 and 9).

Chapter 4 reviewed the potential implications of climate change for river flow regimes and groundwater recharge. To recap, the basic conclusions are that there is a very large difference between the different climate change scenarios currently available - so estimated effects are very uncertain - and different catchments and aquifers are likely to respond to the same climate change in different ways. Resources with large storage capacities are particularly sensitive to changes in winter rainfall, perhaps over several winters. Reservoirs with a storage capacity small in comparison with annual runoff would be more affected by changes in the duration of dry spells (Law 1989).

There have been a few studies into the implications of changes in river flow regimes for water yields and the reliability of reservoired systems.

Cole *et al.* (1991) applied some flow sequences representing current and future conditions as inputs to a representative reservoir to perform a storage-yield analysis. They found that relative changes in reservoir reliability (expressed in terms of failure to supply a given yield, or the yield available with a given reliability from a specific storage volume) were greater than the percentage changes in inflows. A reduction in reservoir inflows of 8% in the south east, for example, led to a

Table 5.1 Climate change and the NRA's Water Resources function: areas of concern and relevant dimensions of climate change

	Reliability of river flows and groundwater recharge	Saline intrusion into estuaries	Saline intrusion into groundwater	Demand for water
Change in temperature				■
Change in rainfall				■
Change in evaporation				■
Direct effects of CO_2				■
Change in river flows	■	■		
Change in groundwater recharge	■		■	
Change in water chemistry and biology				■
Change in storminess				
Sea level rise		■	■	
Land use change	■			■
NRA management response in other functions to climate change	■			

reduction of between 8 and 25% in the hypothetical yield of hypothetical reservoirs having a range of sizes. The differences between different climate change scenarios would therefore be amplified even further when fed through a hydrological model into a water resources system model.

Bunch and Smithers (1992) ran a number of climate change scenarios through models of a single supply source - Stocks Reservoir - and of the Lancashire Conjunctive Use Scheme; both are operated by North West Water Ltd. Runoff change scenarios were taken from Arnell *et al.* (1990). The study found that the single reservoir direct supply system was quite insensitive to climate change, probably because the storage in the reservoir was large enough to sustain yields through drier summers. The conjunctive system could also maintain current yields under all the climate change scenarios considered, but operating costs might be significantly increased if runoff were to be reduced because the more expensive groundwater sources would be used more intensively.

Binnie and Herrington (1992) inferred possible changes in yield reliability from the changes in monthly flow regimes estimated by Arnell *et al.* (1990). They noted the large difference between scenarios, and also that it was difficult to generalise across different catchments and reservoir systems; it was estimated that yields of most reservoir sources would be affected by less than 10% under the alternative scenarios considered. Hewett et al. (1992) applied changes estimated by Arnell et al. (1990) to a time series of inflows to Weir Wood Reservoir in the headwaters of the River Medway in Sussex. They found that all the scenarios considered resulted in a yield gain - because extra runoff during winter compensated for lower runoff in the rest of the year - and that the larger the reservoir capacity, the larger the percentage increase in yield (it is possible that the CCIRG rainfall scenario would lead to a slight reduction in yield, although this was not tested in the study).

There are three general points to make from the results of these studies.

Firstly, it will be very difficult to predict the effects of a change in climate on a specific system without undertaking a detailed modelling study. Figure 5.1 shows the stages in the simulation of the effects of climate change on water supply system reliability. At each stage is a "filter", which may amplify the change being passed through the chain or possibly dampen it down. Different catchments will respond in different ways to changes in climate inputs, and the response of a water supply system will depend on how it is configured, and particularly on reservoir capacity.

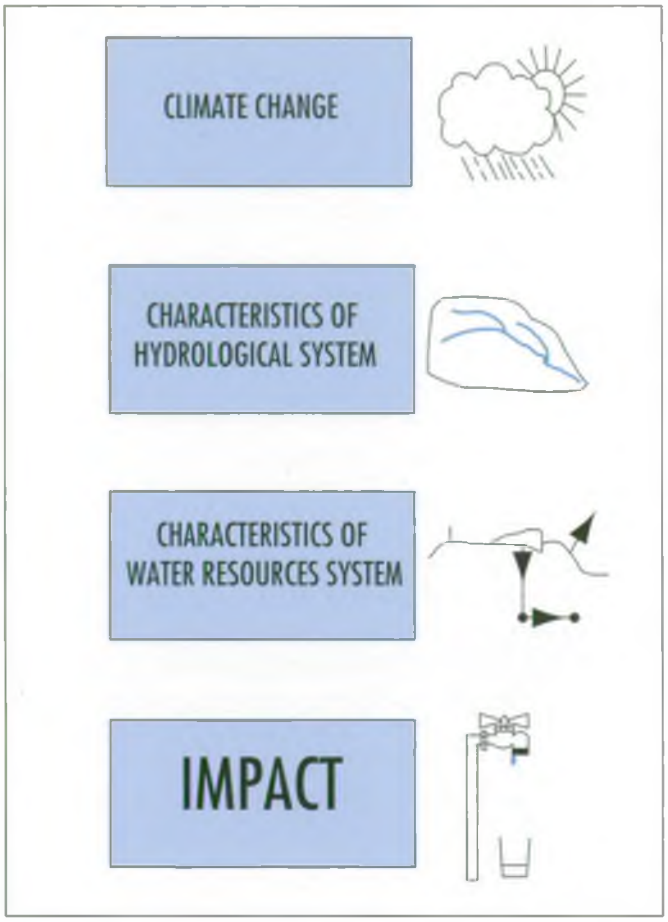

Figure 5.1 A climate change passes through several systems before resulting in impacts on water resource availability

Secondly, the impact of climate change on a system will depend on the pressures the system is currently under. A highly-pressured system - with high demands and little spare capacity, for example - will be sensitive to a much smaller change in river inflows or groundwater recharge than a system with a greater amount of buffering capacity or redundancy.

Thirdly, the more inter-connected the system and the greater the use of different sources, the better it will be able to cope with changes in climatic inputs.

There are several implications for the NRA Water Resources function of changes in river flows and groundwater recharge.

Monitoring of licensed abstractions

The NRA currently monitors compliance with licence requirements. Under an evolving climate it might be necessary to undertake more monitoring both to ensure that abstractors continue to meet licence conditions and, perhaps more importantly, to assess whether the licence conditions remain appropriate. It might be the case that lower river flows or groundwater levels mean that licensed amounts would need to be reduced; in other cases, an increased availability of water might mean that larger volumes could be abstracted.

Drought response

Staff time is under heavy pressure during drought conditions. Resources need to be assessed, supplementary sources located, abstractors and public liaised with, river flow support schemes implemented, and Drought Order applications reviewed. An increasing frequency of droughts would obviously mean that such activities become more frequent, and could become the norm. In the extreme case, the NRA would have to treat summer drought conditions as routine rather than as some kind of emergency. Increased familiarity with drought should mean that more effective drought management plans are developed and followed, and a greater experience of appropriate responses built up.

Operation of river support schemes

The NRA operates a number of river support schemes to enable downstream abstractions. Examples include the Ely Ouse/Essex transfer and the Trent-Witham-Ancholme schemes. These schemes need to be operated as effectively as possible both to safeguard abstractions and to satisfy instream requirements for conservation, fisheries and recreation. A change in flow regimes and groundwater recharge could mean changes in the need for river support and in the ability to provide that support. For example, lower summer flows in the Ancholme would imply greater transfers from the Trent into the Witham; whether this would be feasible would depend on changes in flow regimes in the headwaters of the Trent.

Alleviation of low flows

The NRA has already identifed 40 sites where long-term overabstraction has led to an adverse environmental impact, and has begun to develop low flow alleviation schemes for the top 20 priority locations. A change in climate - particularly groundwater recharge - might mean that more (or fewer) catchments would begin to suffer from high abstraction rates, that the ability actually to alleviate low flows could change, and that the priorities attached to different problem sites might alter.

Regional assessments of water resource potential

Changing river flows and groundwater recharge mean that the potential water resources within a region are also evolving; regional assessments may therefore become out of date. The rate at which assessments date will depend on the rate and amount of climate change. Figure 4.4 implies that, under the driest scenario, average annual runoff in part of south east England would reduce by up to 7% per decade: within 20 years, therefore, resources available may be well over 10% less than initially estimated (other regions might not show such a rapid change).

Afforestation for carbon sequestration

One potential action to limit global warming is to plant forests to absorb more carbon from the atmosphere ("carbon sequestration": see Chapter 3). Large-scale afforestation might have significant implications for river runoff in particular, and could lead to large reductions in the volume of water available. The effect would depend on the species used for afforestation. Widespread planting of broad-leaved species, for example, would have relatively little effect on water availability (Harding *et al.* 1992).

5.2.2 Does the issue deserve further attention?

The effects of climate change on river flows and groundwater recharge are potentially very large, particularly in south and east England and when combined with increasing demands. Effects would be least in well-watered areas, and climate change would have least effect on water supply reliability in regions with large spare storage capacity.

The details of the threat are, however, very poorly understood, and this is due largely to the uncertainty in the predictions of future rainfall and potential evaporation regimes. River flows and recharge might either increase or decrease, although the current "best" estimate is for there to be a slight reduction in annual river runoff (Chapter 4) across most of England and Wales associated with an increase in the range in flows experienced during the year.

Despite the uncertainty, the potential for a very significant impact means that the issue demands further attention.

5.2.3 What are the management options?

The "do nothing" option is not appropriate, given the potentially large impacts. Several complementary management responses are possible.

Allow for revision of licence conditions

The changing availability of water over time means that the NRA needs the flexibility to change or possibly revoke abstraction licences (NRA policy is for new licences to contain a provision requiring abstraction to cease when a prescribed flow or level is reached). There are three possibilities:

1. Introduce licences which can be changed at any time. These would also help NRA management of water resources during droughts.

2. Introduce licences valid only for a fixed time period. Although there is considerable uncertainty over the rate of change in resources, it is unlikely that change will be large - relative to year-to-year variability - over a ten-year period: Ten-year licences therefore seem feasible. The NRA already grants some time-limited abstraction licences. One refinement to this option might be to add a time limit only on the peak excess over the base licence.

3. Introduce licences with regular periodic review. Again, a ten-year review period might be appropriate.

The NRA can currently, where necessary, include in new licences a provision requiring abstraction to cease when a prescribed flow or level is reached, and can also issue time-limited licences (usually for ten years). It is, however, difficult to change existing licence conditions without the risk of paying large sums in compensation. The widespread replacement of existing licences with "flexible" licences will require legislative change. The major problem with flexible licences is that they make long- term planning by water supply utilities difficult.

To implement flexible licences the NRA would need to:

1. initiate research to identify key institutional and technical obstacles to the widespread introduction of flexible licences, and the revision of existing licences;

2. initiate a feasibility study into ways of changing licence regulations and legislation; and

3. initiate research to identify appropriate time limits for fixed-period licences. This can be based on scenarios assuming an extreme rate of climate change. The results of the DoE Water Directorate study into rates of change in flow regimes between 1990 and 2050 (Arnell and Reynard 1993) may provide enough information to set time limits.

There are pressures from other directions - particularly drought management and low flow alleviation - for the more widespread adoption of flexible licensing procedures.

Base licence assessments on future flow and recharge regimes
Some abstractors require long-term licences: a water supply utility planning a major resource development is unlikely to accept even a 10-year licence. In such cases it might be necessary to base licence conditions on future flow and recharge regimes over the next few decades. This would require:

1. scenarios of rainfall and evaporation changes which produce runoff and recharge estimates within an "acceptable" range for a given date (how wide is this range: ±10%?); and

2. models to translate climate change scenarios into river runoff and groundwater recharge.

The potential NRA contribution to scenario development is detailed in Chapter 4. Several simulation models are already applied in the NRA (NRA 1991b), and a review would be needed of models which can be readily applied in any catchment (such models would be more generally useful to the NRA).

There are two main problems with basing licences on long-term resource assessments:

1. Predictions could be open to legal and technical challenge. Challenges could be prevented by the introduction of legislation or a DoE directive requiring the NRA to use some approved "best possible methodology and scenario".

2. There will be practical problems in actually estimating future river flow and groundwater conditions. It will be time-consuming, and estimates will always be very uncertain.

Long-term licences allowing for climate change would only be appropriate for major applications which need a long-term perspective, and even then would be difficult to issue given the current state of climate change scenarios. Flexible licences would be more appropriate in most cases.

Monitor flows, groundwater levels and rivers to ensure licences remain appropriate
River flows, groundwater levels and the state of rivers are currently monitored, and the NRA has set targets for inspecting all licences; highly critical licences are being inspected annually. This monitoring will be even more important under a changing climate.

Consider climate change when planning water resources, river support and low flow alleviation schemes
Water resources, river support and low flow alleviation

schemes are planned over long time horizons (over 20 years), and may be exposed to climate change over this period. Climate change might therefore need to be considered in scheme design and evaluation. The NRA would require three sets of information:

1. How much might climate, river flows and recharge vary over the design horizon? Figure 4.4 implies a maximum rate of change of annual runoff of just over 5% per decade, which would be superimposed on year-to-year variability. The DoE Water Directorate study into flow regimes from 1990 to 2050 provides some information on possible rates of change (Arnell and Reynard 1993); the NRA would need to decide whether these trends were sufficiently important relative to the year-to-year variability to merit action.

2. How far could the amount of water available be reduced before the scheme ceases to be economically viable, and how does this reduction compare with changes which might be expected due to global change? In other words, would climate change be large enough to push the proposed scheme across the threshold of viability?

3. If trends over the planning time horizon were sufficiently large, the NRA would need to use a climate change scenario to simulate future flows.

Climate change should be considered in parallel with other changes - such as demand changes and alterations to abstractions - which will also affect the scheme over the design horizon.

Assess Regional water resources under different climate change scenarios

Each NRA Region has to assess the water resources currently available in that Region, and to predict what resources will be available over a planning horizon of the next few decades. The NRA National Water Resources Development Strategy estimates resources and demands in 2021. By then average annual runoff may (in some regions at least) be over 15% different from at present.

It would be necessary to assess regional water resources first over a standard period (1961-1990), and then using an approved range of climate change scenarios.

First estimates of future resources could be made, using the scenarios developed for the Climate Change Impacts Review Group (Section 4.2), or the scenarios developed in the Climate Impacts LINK project (Section 4.12.2). The differences between scenarios will at present be very large (Figure 4.4), but the regional studies would indicate (i) the possible range in responses (and degree of potential change) and (ii) the most sensitive regions. The results of these studies may indicate that climate change can be ignored in some regions, because its impact would be very small relative to year-to-year variability.

It would also be valuable to determine the reduction in runoff and recharge which would cause "significant" problems, and compare that reduction with the possible effects of climate change. This requires the definition of critical thresholds of water resource availability.

Initiate periodic reviews of resource availability

As more data are recorded and climate change scenarios are refined it will be necessary to review regional water resources assessments. These reviews could operate on a ten-year cycle.

Encourage greater inter-connection between water supply systems

Isolated water supply systems with a single source are the most sensitive to climate change, and the most robust system is one with access to water from a variety of sources which will be affected by climate change in different ways. The most cost-effective way of maintaining supply reliability might therefore be to link different systems together rather than develop new sources.

Climate change can be expected to lead to a shift in the balance of water resources across Britain, and to increase the differentials between the north west and south east. This strengthened gradient increases the already strong incentives for large inter-regional transfers, a number of which have already been identified. The NRA would need to consider future climate change when evaluating transfer schemes. This requires a set of scenarios and a capability to translate these scenarios into river flows at the regional and national scales. It is important to include consideration of climate change as soon as scheme evaluation begins, because climate change might have a very significant impact on scheme viability. There may be considerable differences between scenarios, but information on sensitivity to climate change and the potential magnitude of effects on scheme viability will help in the evaluation of a transfer scheme.

Ensure NRA involvement in afforestation policy

The widespread planting of forests for carbon sequestration would have significant implications for the NRA Water Resources function. The NRA needs to ensure that it is consulted when policy decisions concerning afforestation are being made (by the Department of the Environment and the Forestry Commission), and should be able to advise on suitable sites.

5.3 Saline Intrusion into Estuaries

5.3.1 Background

Approximately 35 public supply abstraction points are located close to the tidal limits of a river (Clark *et al.* 1992). NRA policy is to favour abstractions near the tidal limit (NRA 1992), because upstream abstractions remove water along the whole length of the river. However, abstraction points close to the tidal limit may be affected by saline intrusion if sea level rises and freshwater flows are reduced.

Two research projects have considered saline intrusion into estuaries. The Water Research Centre (WRc) has concluded (Clark *et al.* 1992) that the effects of sea level rise would be minor, compared to the spring-neap variation or to differences between present high and low freshwater inflows. A rise in sea level of 0.6 m would lead to increased penetration of the salt front (with a salinity of 0.5 ppt) by between 0.1 and 1.3 km in the Thames and Lune estuaries. Studies using hypothetical estuaries indicated greater penetration in shallow, flared estuaries, and these conclusions are supported by earlier NRA studies on the Severn estuary which can be used to show a 3.5 km increase in saline intrusion along the Severn estuary for a 0.6 m rise in sea level. HR Wallingford reached similar conclusions - in different estuaries - to WRc (Dearnaley and Waller 1993).

For most river intakes above tidal limits, a 0.6 m rise in sea level (well above the "best" IPCC and CCIRG assumptions: Chapter 4) would therefore have no impact on abstractable quantities, but problems will arise where intakes currently suffer from occasional saline intrusion under low freshwater flow and high tide conditions. The WRc concluded that the intake on the Severn at Gloucester is most exposed, but is in an exceptional position because of the large range of tides in the Bristol Channel. The WRc suggested that relocation of intakes would only be necessary in one or two cases. Local land subsidence might aggravate the effects of a rising sea level in some areas.

5.3.2 Does the issue deserve further attention?

The results of recently completed research studies indicate that saline intrusion into estuaries is not a major issue.

5.3.3What are the management options?

NRA policy is to favour abstractions close to the tidal limit. When applying this policy, the NRA would need to ensure that the abstraction point was not so close as to be affected by sea level rise and changes in freshwater flows; it would be up to the applicant to demonstrate that sea level rise would not adversely affect the proposed abstraction.

5.4 Saline Intrusion into Aquifers

5.4.1 Background

The Water Research Centre has, under contract to the NRA, surveyed coastal aquifers potentially at risk from saline intrusion (Clark *et al.* 1992). All ten[1] Regions of the NRA have aquifers which may suffer from saline intrusion, although most of the 29 at-risk units are along the south coast.

At the national scale, the effect of sea level rise on groundwater resources will be minimal, but local problems might arise. Case studies showed that a rise in sea level of 0.6 m would necessitate reductions in current or proposed safe yield abstraction rates by between 1 and 2%. Alternatively, yields could be maintained by moving boreholes inland. The WRc concluded that the cost of relocation of sources arising from sea level rise would be small in comparison with ongoing maintenance and exploration costs. The WRc study did not consider the possible effects of changes in groundwater recharge on saline intrusion.

5.4.2 Does the issue deserve further attention?

Saline intrusion into coastal aquifers does not appear to be a major problem in the foreseeable future.

5.4.3 What are the management options?

Although very few aquifers are currently at risk, the NRA would need to ensure that future abstractions will not cause or be affected by saline intrusion. It would be the responsibility of the applicant to demonstrate that saline intrusion would not be a problem.

[1] Since this work was completed, the number of NRA Operational Regions has been reduced to eight.

5.5 Demand for Water

5.5.1 Background

Water resources systems are designed to satisfy consumers' demands for water, and are increasingly being managed to ensure that the demands of the environment (termed "instream demands") are met.

Demand for public water supplies in England and Wales is projected to rise by 18%, or nearly 3200 Ml/day, by 2021 (NRA 1992). Over 85% of this growth is expected in the five NRA regions in the south and east of the country. The demand increase is believed to be independent of climate change, and it is likely that global warming will lead to further increases. The implications of climate change for the demand for water have been studied at the Department of Economics at the University of Leicester under contract to the Water Directorate of the Department of the Environment (Herrington 1994). The study, although largely exploratory, has drawn several conclusions:

The greatest impact of climate change is likely to be on demands for garden watering and personal showering, and on the demand for summer spray irrigation. Losses through burst pipes might change, and higher water temperatures could lead to changes in demand for cooling water. Finally, changed flow regimes, water temperature and water quality would affect the instream demands of river ecosystems.

Garden watering and personal showering

Domestic garden watering by hosepipe or sprinkler can consume up to 1000 l/hour/property, and is the major contribution to peak demands in southern and eastern England. Daily and weekly peaks tend to occur after a few very warm and dry days in June or July. In the south and east of the country the demand for garden watering is estimated to represent nearly 5% of the total volume of water supplied to domestic customers during a climatically average year, but even without climate change it is forecast that this could rise to over 7% by 2021. Superimposition of climate change may increase this further to over 11%. Public water supply system seven-day peak factors which are at present around 1.20 are forecast to rise to around 1.25 in the next 30 years without climate change and perhaps to 1.35 when account is taken of climate change (Herrington 1993). These results are, at this stage, very speculative. Nevertheless, they suggest that domestic peak seven-day demands (in per capita terms) could rise by as much as 60% in the next 30 years as average demands for domestic purposes rise by 35%. Such increases could have very important implications both for water resource availability during summer and the ability of the water distribution system to cope with peaks. Changes in the demand for garden watering will also be affected by pricing policies introduced over the next few years; the precise effect of different tariff structures (and of bye-law controls) awaits further study.

The peak demands across most of England and Wales are in summer and result from garden watering, but in the north and west peak demands arise from pipe bursts in winter. As demand for garden watering increases, it is possible that the peak demand in parts of the north and west will shift from winter towards summer. This would mean a shift in the timing of abstractions through the year.

Demands for personal showering are likely to increase both as temperatures rise and as living standards increase. The rate of change is, however, difficult to estimate, although information from warmer countries with similar economic conditions might help.

Spray irrigation

Spray irrigation in England and Wales tends to be undertaken to maintain high quality produce - especially of vegetables - rather than to allow crop production to take place at all. Many vegetable farmers have contracts which specify that their produce must reach certain quality standards, and in many areas in southern and eastern England this quality can only be guaranteed by irrigating during summer dry spells. Around 56% of spray irrigation licences in England and Wales are in Anglian Region, and a further 18% are in Severn-Trent (NRA 1992). Abstraction for spray irrigation is already restricted in particularly dry years, and was banned completely in Anglian Region for part of the summers of both 1990 and 1991. Higher temperatures and possibly drier summers can be expected to lead to increased demand for spray irrigation over the next few decades, although the rate of change may be more greatly influenced by economic factors such as the price of vegetables, supermarket supply contract quality conditions, the price of water and MAFF and EC policy changes. A change in agricultural land use - for climatic or non-climatic reasons - would also lead to changes in the demand for irrigation water. The direct effect of CO_2 enrichment on plant transpiration (Section 4.5) might mitigate to some extent the effects of higher temperatures, as might the introduction of more drought-resistant crops.

Burst pipes

Peak demands can be affected in the very short term by a very severe frost freezing customers' pipes. This only lasts a few days as household leaks are obvious.

A prolonged frost period can increase water put into supply over a longer period as it takes time to find and repair burst water mains.

It is obvious that one cause of pipe burst is ground movement as a result of freezing and thawing soil, but large changes in water temperature in the pipes is also thought to have an effect. A prolonged drought can also produce ground movement of a similar order, and cause an increase in burst water mains.

Demands for industrial cooling water
The remaining area which might be influenced by climate change is the demand for industrial cooling water. Higher river water temperatures (Section 4.9.2) would mean that more water would be required to perform the same amount of cooling. There is, however, little information on the effect of water temperature on industrial cooling water requirements. An increased use of air conditioning might also affect the demand for water.

Instream demands
Changes in the instream demands of aquatic ecosystems and water quality maintenance are considered in detail in Chapters 6 and 8.

It is important to emphasise that climate change will not be the only factor affecting demand for water over the next few decades. The introduction to this section quoted the NRA estimate of an 18% increase in demand for public water supplies in England and Wales by 2021, due largely to population changes and large-scale economic development. Demand will also be affected by factors such as the use of water-efficient appliances and, perhaps most significantly, by the more widespread introduction of metering of domestic consumption (the actual effect will depend on tariff structures). The University of Leicester study compared the effects of climate change with such "secular" influences (Herrington 1994).

The most immediate impact of changed demands for water on the NRA will be an increase in the demand for licences to abstract water, with perhaps increased competition amongst different users and the needs of the instream environment. At present the NRA receives 1500 new licence applications each year, and processes many more enquiries.

5.5.2 Does the issue deserve further attention?

Although information is currently sparse, there are indications that the effects of climate change will compound further the challenges posed by increasing demands. It is an important issue.

5.5.3 What are the management options?

Research impacts of climate change on spray irrigation demands
Research into spray irrigation changes is particularly important because most irrigation is in areas with the fewest resources, with the greatest increase in demand, and most sensitive to climate change. The agricultural industry and the Ministry of Agriculture, Fisheries and Food would be particularly interested in the results of studies into climate change and irrigation.

Monitor demand management research
The NRA would also need to monitor research currently being undertaken into demand management, and especially the National Metering Trials. This research will indicate the feasibility of attempting to curb increases in demand. Particular attention needs to be paid to methods for managing demands for garden watering, and it may be necessary to initiate a feasibility study - jointly with the water supply industry - into alternative methods.

Encourage winter abstraction
The NRA currently encourages farmers to irrigate in summer using water stored during high flows in the previous winter. As this practice increases - aided by tariff incentives encouraging winter abstraction - a greater proportion of the summer irrigation requirements will be met from winter river flows, so demands from rivers in summer might be reduced. Current NRA policy might, if successful, therefore reduce the sensitivity of water resource systems in spray irrigation areas to climate change.

Research impacts on frequency of pipe bursts
Changes in the frequency of pipe bursts and hence short-term peak demands are unknown. The problem is largely one that affects the PLCs, so they should consider undertaking studies into possible changes.

Research impacts of climate change on instream demands
The instream demands of a water course are increasingly influencing abstraction licensing policy and practice. Chapter 8 concentrates on the assessment of the impacts of climate change for aquatic ecosystems.

6. WATER QUALITY

Water chemistry and biology will be affected by changes in water temperature, by changes in river flow regimes, and by changes in flow pathways through the soil. They will also be influenced by changes in land use practice; these changes - such as altered use of agricultural chemicals - may also be responses to climate change.

1. Maintenance of Statutory Water Quality Objectives (SWQOs)

Current NRA policy aims to set discharge consents to ensure that the receiving waters meet SWQOs. These discharge consents must be based on the flow, chemistry and biology characteristics of a river, and a change in these characteristics should mean a change in consent conditions. The extent to which consents would need to be changed to maintain current (and anticipated future) standards is currently unknown.

2. Management of algal blooms

Algal blooms are caused by a combination of mild winters, warm summers, application of phosphates in the catchment and point-source inputs (especially from sewage treatment works); global warming would seem therefore to increase the risk of algal blooms in lakes and rivers.

3 Management of estuarine and coastal water quality

Water quality in estuaries and along the coast is a function of effluent inputs, freshwater inflows, sea level, and water temperature. Higher sea levels in particular might exacerbate problems in estuaries, whilst higher temperatures will affect the survival of pathogens in sea water.

4. Design and operation of sewer systems

A change in storm rainfall characteristics will mean a change in the performance of sewer systems; surcharge frequency could increase, and there could be increasing flushing of pollutants into watercourses.

5. Pollution incidents

Polluting incidents will not necessarily change in a warmer world, but the *sensitivity* of the aquatic environment to pollution might be increased.

6.1 Introduction

The NRA aims to achieve a continuing improvement in the quality of rivers, estuaries and coastal waters through the control of water pollution. To ensure that dischargers pay the costs of the consequences of their discharges, polluters can be taken to court. The NRA issues licences to those who wish to discharge to NRA-controlled waters. It will impose conditions on the consents which depend on the characteristics of the receiving waters.

To date the quality of rivers and some tidal waters has been managed in relation to informal water quality objectives and the standards laid down in an increasing number of EC Directives. Initial consultation on Statutory Water Quality Objectives (SWQOs), which are to be set by the Secretaries of State for the Environment and for Wales, was commenced by the NRA in 1991 (NRA 1991c). These proposed statutory objectives and standards will incorporate a set of water use categories, each with appropriate water quality standards, and a revised water quality classification scheme which will have wider application. SWQOs can then be set for individual stretches of water by identifying the appropriate use classes and the corresponding quality standards and incorporating any further standards required under EC legislation. This system will enable target water classes to be achieved taking both diffuse source and point source pollutants into account. The NRA is also establishing water protection zones to prevent the contamination of water sources. It has so far concentrated on the definition of nitrate-sensitive zones around groundwater sources, and a number of test zones have been defined. The bulk of the NRA water quality management and pollution control activities, however, are directed towards river and groundwater pollution both from point-sources (such as discharges from sewage treatment works, storm drainage systems and industry) and from non-point sources (such as farmland).

Climate change will affect water quality and pollution both directly and indirectly, and Table 6.1 summarises the impact of different climate change variables on a number of key water quality issues. Direct impacts may be considered to stem from the changing climatic inputs to the hydrological system, the alteration of the processes and pathways by which water reaches river channels and by changing the flow regimes within channels. Indirectly, the changed climate regime will potentially promote a change in land use which will in turn impact upon water quality. The complex system of

Table 6.1 Climate change and the NRA's Water Quality function: areas of concern and relevant dimensions of climate change

	SWQOs	Algal blooms	Estuarine and coastal water quality	Sewerage systems	Pollution incidents
Change in temperature	■	■	■	■	■
Change in rainfall				■	
Change in evaporation			■		
Direct effect of CO_2					
Change in river flows	■	■	■	■	■
Change in groundwater recharge					
Change in water chemistry and biology	■	■	■		■
Change in storminess	■	■		■	
Sea level rise			■		
Land use change	■	■	■		■
NRA management response to climate change		■	■		

feedbacks and responses to both climatic and non-climatic controls (Figure 4.5) makes the climatic induced signal in water quality hard to detect and also may cause the climate signal to be masked by other future changes such that the impact of climate change may, in operational terms, be considered to be less significant. At the same time, however, climate change and its effect on water quality will be set against increasing public interest in water quality, an increasingly tight regulatory framework (SWQOs), and the need for long-term planning for water resource management systems within a changing environment. Meanwhile, the water industry will be becoming increasingly concerned about how it can pay for the improvements in water quality demanded by the CEC, the NRA and the public.

6.2 Maintenance of Statutory Water Quality Objectives

6.2.1 Background

The NRA sets the consent conditions and standards for effluent discharges but does not design and implement waste water collection and treatment systems. Its planning work includes advising on water quality objectives and protection. Long-term planning work involves setting water quality objectives and identifying source protection zones. Statutory Water Quality Objectives (SWQOs), expressed in terms of indicators such as dissolved oxygen, are determined for individual river reaches on the basis of the reach characteristics and flow regime, together with an assessment of the water quality that the reach can reasonably achieve.

Climate change might have three potential impacts on the maintenance of SWQOs. First, a change in temperature and flow regime may necessitate a change in the specified SWQO for a given river reach. Second, the consents issued to point discharge sources might need to be revised in order to maintain SWQOs. Third, non-point pollutant input into rivers and aquifers might be affected not just by changes in climatic characteristics but also changes in catchment land use. Pollutants of major concern include agrochemicals such as pesticides, nitrate fertilisers and organic material.

Change in flow/water quality relationships

This will be affected by all factors influencing flow regimes as well as the direct impact of increased temperature on biological activity. Effects will vary in response to the spatial variation in climatic parameters and also in response to changes in land use. These changes in land use may be the result of climate change or induced by non-climatic factors such as the level of agricultural subsidies and the EC Common Agricultural Policy. Any change in pollutant inputs to rivers and their catchments, in the form of effluent discharges and agrochemicals, or in water abstraction from the river system will affect the water quality flow relationship. These impacts and their uncertainties can only be addressed through the application of simulation models.

Regulation of point sources

There is unlikely to be a climate-induced change in *demand* for discharge consents, and the greatest effect of climate change will arise from changes in the ability of the receiving waters to accept effluent discharges. Consents will have to be geared to, for example, a lower flow value (at present, consents are generally based on the flow exceeded 95% of the time; this flow volume is likely to change). Lower stream discharges might mean that absolute discharge consents would need to be reduced and there may be a need to *ensure* that reviews take place regularly. Discharge consents expressed in terms of the quality of the receiving water will not be affected, but non-compliance is likely to occur unless the discharger improves the quality of the effluent.

Management of diffuse sources

It is clear that a climate-induced change in land use policy will influence the flux of pollutants to the river from diffuse sources and so change the water quality. Clearly any change toward increased use of potential pollutants would be to the detriment of water quality, and a reduction in the use of potential pollutants would lead to improved water quality; not all changes will necessarily be bad. It is also possible that a changed rainfall regime may alter hydrochemical flowpaths and processes within the soil. Wetter winters might result in increased slurry runoff problems, putting extra strain on waste storage facilities.

Increased magnitude of autumnal flushing

This may cause operational concern in both the uplands and lowlands and will depend crucially on the pattern of rainfall in the catchment through the year, in particular summer and autumn. Any increase in application of agrochemicals to farmland would exacerbate the problem, as would any significant change towards rapid transit flow pathways perhaps brought about through increased cracking in drier soils. This problem would be easily overcome by relatively small changes to operational policy at the relevant times.

Changes in upland water quality

Climatic parameters potentially exert the most influence in the determination of upland water acidity and colour, for example, providing acidic deposition and land use remains unchanged. It is likely, however, that international legislation will call for decreased acidic deposition and so the trend toward surface water acidification should reverse even under changed climatic conditions. There exists a clear need in this respect, however, to determine the relationships between water quality, land use change and soil chemical/physical change in response to a change in climate. Afforestation will probably continue to exert a significant influence on surface water chemistry. Increased summer temperatures and/or drier summers may lead to more intense autumnal colour flushes.

Establishment of protection zones

The NRA is presently beginning to identify a number of groundwater protection zones, and is considering how best to define zone boundaries in a consistent manner. One approach is to consider travel times to the water abstraction point, whilst another is to select a standard distance. Neither method of identifying zone limits would apparently be affected by climate change. It is possible, however, that if groundwater recharge rates are significantly decreased then the catchment area required for each source will need to be enlarged.

6.2.2 Does the issue deserve further attention?

The framework already in place and proposed for dealing with surface and groundwater quality through the SWQO system is completely adequate for dealing with potential impacts due to climate change, but the potential scale of those impacts and hence economic implications are unknown.

6.2.3 What are the management options?

Review the implications of climate change for reach SWQOs
A change in flow regimes and water temperature may make the SWQO in a reach unattainable. It will be necessary to review reach SWQOs under climate change. An initial study would investigate the degree of sensitivity of reach SWQOs (for a few selected case study reaches) to climate change in order to identify the potential scale of the problem. Revision of individual SWQOs could be made at relatively short notice. A mechanism needs to be in place to allow the periodic revision of reach SWQOs.

Review the implications of climate change for consents which satisfy SWQOs
How far might consents have to be changed to maintain SWQOs? The answer to this question will determine the economic implications of climate change for effluent dischargers and guide their medium- and long-term investment plans.

The NRA needs to quantify the likely magnitude of changes in discharge consents which may be necessary to meet SWQOs. This will differ in every catchment system and it will be difficult to generalise the outcome. It will be necessary to use physically-based models of stream water quality together with a standard range of climate change scenarios. The scenarios currently available are too coarse for use, and the wide range between scenarios would lead to very large differences in estimated impacts. The study should use daily resolution climate change scenarios produced by the DoE Climate Impacts LINK project (Chapter 4), and simulate possible changes in consents over a 30-year planning period. It should concentrate at first on one case study catchment.

Dischargers should be informed of the possible changes in consents over the next, for example, 30 years.

Review individual discharge consents
Discharge consents are currently reviewed periodically, and this policy will help the NRA cope with the effects of climate change. It might, however, be difficult to justify changing consents on the basis of long-term predictions of change (because the discharger would not want to make any changes now), so alterations would need to be based on recorded experience over a period of a few years. The NRA would therefore need to be convinced - and be able to convince the discharger - that "unusual" behaviour over a few years did represent changed conditions and was not simply a rare event which could be discounted in the longer term.

Allow for climate change when setting consents
Consents could be changed now if the future flow regime was known. Consent calculation models are calibrated on historical flow and quality data and so changes in those data will automatically affect consent calculation. There is unlikely, therefore, to be any problem in practice but a clear need for an awareness of the likely changes because of the lead time often involved in uprating treatment works and other facilities to cope with changed consent conditions in the future.

Attempt to exert influence over land use decisions
Changes in land use - which may be due to climate change - will have very important implications for water quality. Major land use changes are usually the result of a determined and large-scale policy decision and such decisions have long lead times. The NRA should strive to exert as much influence over land use decisions as possible (which is currently an objective of the NRA), concentrating in particular on the use of agricultural chemicals, management of livestock slurries and afforestation, whether for carbon sequestration, private investment or community use.

The NRA input to land use change decisions must be based on sound scientific knowledge and a good database; research is needed into the effects of land use change on water quality in a wider variety of landscapes.

Monitor water quality
If the sensitivity of receiving waters to pollution increases due to climate change, then there will be a greater need for monitoring.

6.3 Management of Algal Blooms

6.3.1 Background

In 1989, 1990 and 1991 there were several outbreaks of blue-green algal blooms in lakes, reservoirs and some lowland rivers, attributable to a combination of mild winters, warm summers, calm summer weather and reduced dilution capacity due to decreased rainfall.

Algal blooms have very significant implications for the biology of the water body, and for users of the water (especially recreation, fisheries and water treatment plants; see Chapters 8 and 10). Blooms in natural lakes primarily present a mainly aesthetic problem but can have severe ecological consequences, due to reduced nocturnal dissolved oxygen levels, etc., and dense shoreline accumulations can also give rise to human and animal health problems (Turner *et al.* 1990). In the UK, the species implicated in most poisoning incidents are the bloom-forming genera of blue-green algae although not all blue-green blooms are toxic. The treatment problems posed by local accumulations of algae in water supply reservoirs can, to a large extent, be mitigated by using alternative draw-off points.

Climate change is likely to increase the frequency of algal blooms (Chapter 4), although management policies that are currently being introduced - such as requiring phosphate stripping at sewage treatment works - may mitigate the problem in some instances.

There is also a risk that NRA water management actions could lead to accelerated rates of growth in some river systems. Large-scale transfers from the lower reaches of one river system into the upper reaches of another are seen by the NRA as one way of coping with water shortages in the south and east of England (NRA 1992). They could, however, greatly increase the bloom-forming potential of the receiving waters: this needs further study.

6.3.2 Does the issue deserve further attention?

The NRA is currently reviewing policies for the management of algal blooms in lakes, reservoirs and rivers; climate change may make the management task marginally more difficult.

6.3.3 What are the management options?

Allow for climate change in the algal bloom management strategy
The NRA algal bloom management strategy needs to be sufficiently robust to remain appropriate under changed climate conditions. Little can be done to control the "climatic" causes of algal blooms, but policies being developed to limit phosphate concentrations (which are thought to encourage the formation of algal blooms) need to be sufficiently flexible to cope with changed flows and altered water chemistry. Target standards for water bodies should not be expressed in terms of phosphate concentrations alone, because with lower flows and higher water temperature the chance of blooms forming with a given phosphate concentration may be higher. Standards could be based on the risk of bloom formation, but this would need a detailed understanding of controls on algal bloom growth.

Consider possible changes in algal blooms when assessing inter-basin transfers
The assessment of inter-basin transfers needs to give consideration to the risk of increasing bloom-forming potential. This too requires information on the dynamics of river plankton and their life cycle (a report has been prepared for the NRA by Reynolds and Glaister 1992).

6.4 Management of Estuarine and Coastal Water Quality

6.4.1 Background

There are three main water quality issues in estuaries and the tidal reaches of rivers. The first is the presence of saline water for part of the tidal cycle. The second is the distribution of sediments and their movement during the tidal cycle. Thirdly, pollution brought down into the tidal reach from the non-tidal river may become trapped by the interactions of river flows and tides. Sea level rise, lower freshwater inflows to the estuary and increased temperatures and sunshine will have an impact on all of these estuarine water quality issues, and coastal water quality will be affected by increased temperatures.

Higher sea levels
This would tend to force the salt front to penetrate further up the estuary during each tidal cycle, and the implications of saline intrusion along estuaries for water abstraction points were discussed in Chapter 5. A change towards lower freshwater inflows would also tend to encourage further penetration of saline water up the estuary. Patterns of sediment movement might alter within the estuary, leading both to navigation problems and water quality concerns (because heavy metal pollutants in particular tend to be associated with sediment particles).

Lower freshwater inflows
Decreased river flows, either throughout the year or seasonally, would affect saline intrusion, sediment patterns and the flushing of pollution out of the estuary. Problems arise in several estuaries at present during low flow conditions, when flows are too small to flush sewage effluents. Low flows combined with higher temperature makes this worse and can result in a de-oxygenated "slug" of water oscillating in the estuary on the tide. Sometimes this can become anoxic resulting in smell nuisance, toxic effects to aquatic organisms and a barrier to migratory fish.

Increased temperatures and insolation
Generally higher temperatures would mean that biogeochemical processes would operate at a faster rate, and might contribute to a lessening of water quality problems. Increased temperatures and insolation can also be expected to improve the quality of coastal bathing waters.

Both estuarine and coastal water quality are currently very heavily influenced by sewage effluent discharges, and changes in discharge policies (towards secondary treatment) may well have a far greater effect on water quality than changes in climate.

6.4.2 Does the issue deserve further attention?

Some work on the impact of climate change on water quality in estuaries has been undertaken as part of the DoE WD research programme by HR Wallingford (Dearnaley and Waller 1993). There is, however, little that can be done to help the situation. Current solutions to existing pollution problems in estuaries will relieve the potential impact from climate change. Knowledge of estuary systems will grow considerably during the NERC Land Ocean Interface Study (LOIS), which is planned to run from 1993 to 1998.

6.4.3 What are the management options?

There is no need to do any more than carry out existing solutions to this problem.

Further study of flow regimes and model applications would help to determine the possible extent of future water quality problems, but such studies would need to incorporate the effects of changes in effluent discharge policy.

6.5 Design and Operation of Sewerage Systems

6.5.1 Background

Urban storm drains are designed to remove storm runoff from urban surfaces. The bulk of the storm sewerage system in old urban areas is combined with the foul sewerage system. Surcharging of these combined systems therefore means that untreated sewage is also discharged into the receiving watercourse. Runoff from separate urban storm drain systems is also often extremely dirty, and contains in particular heavy metals and hydrocarbon-based pollutants. Long dry spells often result in low sewage flows and as a consequence solids are deposited in the sewerage system during these periods. Following heavy rainfall these anaerobic solids are re-suspended and discharged through storm overflows into rivers which are at relatively low flow levels. The extreme de-oxygenating effect of this discharge produces conditions most likely to result in fish kills. An increased frequency of occurrence of intense rainstorms, greater than the design standard of the storm drain system, would therefore have very important implications for water quality in and immediately downstream of urban environments.

Higher temperatures should mean that the biological processes in a sewage treatment works would operate at a faster rate, and that it should be easier to ensure that sewage treatment works outflows meet NRA discharge consents. However, movement of the odour threshold around key works is very uncertain.

6.5.2 Does the issue deserve further attention?

Design of sewerage systems and urban storm run-off systems is driven by the requirements of water quality objectives and new urban development. These are currently designed with regard to existing rainfall/run-off relationships and rainfall magnitude/frequency relationships. There urgently exists a need to assess potential changes in these relationships so that new engineering designs can incorporate added safety factors as required.

6.5.3 What are the management options?

The "do nothing" option is not acceptable since it is difficult and expensive to upgrade sewerage systems after a development is completed and these schemes tend to have long lead times.

Develop procedures for incorporating climate change in the design of sewerage systems
Methods for incorporating climate change in sewerage system and stormwater detention tank design need scenarios for possible changes in storm rainfall patterns and totals and, as Chapter 4 emphasises, these are currently not available.

There are therefore two stages of response:

1. Require a sensitivity analysis of sewerage and stormwater detention tank design using arbitrary changes to the design rainfall totals. The NRA should recommend some "standard" arbitrary changes, based on current understanding of changes in extreme

rainfall characteristics, including the pattern and distribution of rainfall.

2. Initiate a research project into possible changes in the characteristics of storm rainfall. This will require analysis of the output from the Hadley Centre meso-scale model simulating climate over the UK, and should only be done once short-time scale simulations from the meso-scale model have been validated.

6.6 Pollution Incidents

6.6.1 Background

The NRA responds to emergencies resulting both from pollution events and from natural (or semi-natural) events.

Pollution incidents arising from accidents or spillages are unlikely to be affected by climate change, but farm-based incidents might increase. Higher winter rainfall, for example, might lead to increased livestock pollution if existing slurry management practices are continued.

Even if the incidence of pollution events were to remain constant, the effect of a given event might change. Lower river flows could mean that an event would have a greater effect, whilst higher water temperatures could help to ameliorate the impact of the pollution. Changed hydrological and temperature conditions are likely to mean that the *sensitivity* of a river (or indeed aquifer) to pollution changes; increased temperatures might have particularly significant effects on the sensitivity to algal blooms.

"Natural" events include flushes of discoloured water from desiccating peat bogs. A changed climate might mean that such events occur with a different frequency, and again, the sensitivity of the aquatic system to such events might be altered. Prolonged summer dry periods may also promote the breakdown of soil organic matter. This will potentially lead to problems following heavy rain when nutrients and pollutants will be flushed into waterways, particularly during the autumn. In the uplands this may cause problems as organic nitrogen is mineralised to more soluble forms leading to acid pulses in oligotrophic streams.

6.6.2 Does the issue deserve further attention?

Pollution events in the uplands (and lowlands to some extent) will essentially be driven by natural processes. Monitoring and process studies of terrestrial systems and links with upland water quality need immediate research since models of upland catchment systems are not yet sufficiently detailed to incorporate the relevant temperature and rainfall induced processes. There is a need to ensure that an appropriate level of resources is aimed at farm pollution control in order to counter any tendency for problems to increase.

6.6.3 What are the management options?

The rigorous action now being taken to modify and contain the impact of pollution incidents (both agricultural and industrial) will need to continue for the foreseeable future.

7. FLOOD DEFENCE

1. Increase in coastal flood risk

The increase in coastal flood frequency due to higher sea levels and possible changes in storm frequency and intensity is one of the biggest issues facing the NRA. A sea level rise of only 0.2 m can have a major implication for the frequency with which a defence is overtopped. Higher sea levels and changed wave and storm patterns also affect the integrity of coastal defence structures. The NRA already takes the threat of higher sea levels very seriously.

2. Fluvial floodplain inundation

An increase in winter rainfall and a possible increase in peak summer rainfall intensities would increase the risk of riverine flooding. Possible changes, however, are very uncertain at present and the effect would vary considerably between catchments.

3. Integrity of riverine flood defences

Riverine flood defences may be affected by changed erosion and sedimentation. Possible increases in weed growth will mean the discharge capacities of channels will reduce and maintenance requirements increase.

4. Development control

The NRA already generally recommends against development in flood-prone areas. A change in flood risk will affect mapped frequency-based flood risk zones, but the degree of change is difficult to estimate at present. An increase in extreme rainfall totals would imply a change in the performance of structures built to mitigate the downstream effects of development.

5. Flood emergencies

Climate change is is likely to have relatively little effect on the performance of flood forecasting systems (although a change in rainfall characteristics could conceivably mean shorter warning times). The systems might, however, be used more often.

6. Urban storm drainage

An increased frequency of high intensity short-duration rainfall events would result in frequent surcharges of storm drainage systems.

7.1 Introduction

The National Rivers Authority has powers to exercise a general supervision over flood defence and land drainage. In practice, this means that the NRA constructs and maintains flood defence schemes to alleviate loss and damage from coastal and fluvial floods, implements flood warning schemes, liaises with planners to encourage wise use of flood-prone land and to ensure that development elsewhere does not increase flood risk, and responds to flood emergencies. In 1991/92, £91.3 million was spent on capital programmes along the coast, and a further £87 million was spent on schemes along inland rivers.

There is an important difference between coastal flooding and fluvial or inland flooding. Design standards have historically been higher along the coast - because of the greater risk of loss of life - and the structural responses to coastal and fluvial flooding are quite different. Coastal and fluvial flooding are also affected by different climate change parameters.

Table 7.1 summarises the key impacts of climate change on the NRA Flood Defence function, and indicates which dimensions of climate change are relevant.

It is important to emphasise here that the NRA's response to the effect of climate change on flood defence may have a significant impact on other NRA functions; decisions would therefore need to consider other functions, particularly Conservation (Chapter 9).

7.2 Increase in Coastal Flood Risk

7.2.1 Background

The impact on coastal flooding of rising sea levels and a possible change in storm frequency and intensity is one of the biggest issues facing the NRA. Rising sea levels and changes in storm occurrence can mean not only that defences are overtopped more frequently, but also that breaches are more likely to occur. Reference to sea level rise was made in the 1990/91 NRA Corporate Plan (NRA 1990), and the NRA and other agencies have already funded several studies into the possible consequences of increased coastal flooding (Appendix A, Table A.4).

The Climate Change Impacts Review Group (CCIRG 1991) assumed an average increase in mean sea level around the UK coast of 0.19 m by 2030, and the

Table 7.1 Climate change and the NRA's Flood Defence function: areas of concern and relevant dimensions of climate change

	Increase in coastal flood risk	Fluvial floodplain inundation	Integrity of riverine flood defence	Development control	Flood emergencies	Urban storm drainage
Change in temperature						
Change in rainfall					■	■
Change in evaporation						
Direct effects of CO_2						
Change in river flows		■	■	■	■	
Change in groundwater recharge						
Change in water chemistry and biology						
Change in storminess	■	■	■	■	■	■
Change in sea level	■				■	
Land use change		■		■		
NRA management response to climate change	■					

NRA in Policy Implementation Guidance Note TE/FD/001 assumed increases ranging from 0.16 m by 2030 in the north of England to 0.24 m along the east and south coasts (Table 4.4).

The permanent flooding of land currently above sea level is likely to be of limited economic importance (with a rise by 2030 of between 0.16 and 0.24 m around the coast), because there are very few areas of unprotected land lying so close to the current sea levels. Higher sea levels would of course have important implications for the owners of coastal facilities such as docks and wharves, and must also increase pumping costs for the drainage of low-lying land; at the most extreme, the pumping costs might increase so much as to make pumping uneconomic. Impacts on the NRA, however, would be small. The MAFF, Scottish Office and NRA Advisory Committee on Flood and Coastal Defence (1992) recommended research before 1996 into the impact of sea level rise on pumping from lowland pumped catchments.

Far more important is the effect of higher sea levels and a possible change in storm occurrence on flooding during extreme events. Four factors affect the possible change in flood risk; a rise in mean sea level, a change in the intensity and rate of occurrence of extreme storms, a change in wave climates and heights, and a change in the risk of scheme failure.

A rise in mean sea level

A rise in mean sea level of only a few centimetres can have a very big impact on the frequency at which specific thresholds - such as the height of a defence structure - are crossed. The actual impact depends on the slope of the level-frequency curve at a site. Figure 7.1 (CCIRG 1991) shows the effect of a 0.2 m increase in sea level on return periods for two typical coastal flood frequency curves. A level of 3.2 m currently has a return period of 100 years in both cases. The return period of this value falls to 25 years with curve B, and just five years with curve A. Curve B is characteristic of the east coast of England, whilst curve A is more representative of the south coast (CCIRG 1991). This implies that a

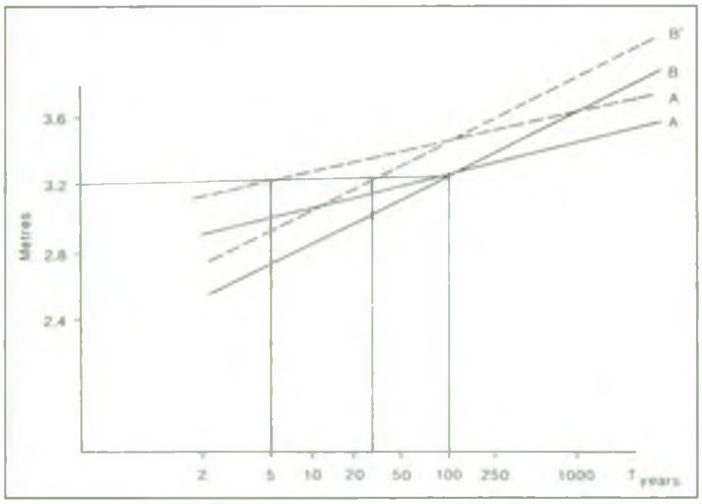

Figure 7.1 The effect of a 0.2 m change in sea level on return periods of the flood (at 3.2m) with a return period at present of 100 years (CCIRG 1991)

rise in sea level would have a greater effect on flood risk along the south coast of England than along the east coast.

The effects of a rise in sea level on flooding along estuaries would depend also on both the configuration of the estuary (and the effects of a higher sea level on the tidal cycle) and on changes in freshwater inflow regimes. No case studies have yet been completed to show the potential change in flood risk along an estuary.

A change in storm frequency and intensity

The flood frequency curve at a site would be altered further if the frequency and intensity of coastal storms were to change. It is, however, very difficult to estimate at present possible changes in storm occurrence (Chapter 4), although there are indications that both storm intensity and frequency might increase slightly (Holt 1991; Chapter 4).

A change in wave heights

Higher sea levels and possible changes in storm tracks would also affect wave climates, and hence the height of waves when they break on the shoreline and against coastal defences. The effect of an increase in wave height following a sea level rise will depend on local beach morphology and the characteristics of the flood defence structure. The gentler the beach gradient, the greater the increase in wave height for a given increase in sea level.

A change in the risk of failure

A change in erosion and sedimentation patterns associated with a rise in sea level and change in storminess would affect the ability of coastal defence structures to meet design standards, and might also increase the risk of breaching. The beach protecting the toe of a structure might be affected by erosion (or, perhaps by sedimentation under some circumstances), and a higher sea level would mean the erosion of protective salt marshes if they could not keep up with the rate of rise. Bank stability is also affected by moisture content, which might change following an alteration in rainfall regimes.

An increase in the frequency with which coastal defences are overtopped or breached would have major economic implications. Flood losses during the 1953 East Coast floods reached £30 million (at 1953 prices: over £350 million at 1991 prices), and since then there has been considerable development in coastal flood risk areas. The GeoData Institute estimated the value of coastal land along the south coast between Bournemouth and Bognor Regis to be up to £5745 million (£45 million of agricultural land, £1700 million of industrial or commercial assets and up to £4000 million of residential property), depending on planning policies following loss (Ball *et al.* 1991).

Bateman *et al.* (1991) reviewed, for MAFF, the cost of sea level rise along the East Anglian coast between Hunstanton and Felixstowe. They estimated, for example, that the present value of flood losses between 1990 and 2050 would be between £174 million and £188 million for a sea level rise of 0.2 m (note that under the CCIRG assumptions, sea level would rise by around 0.3 m by 2050: Table 4.4), if defences were maintained at their current heights. In an extension of the study for the NRA, Doktor *et al.* (1991) refined these estimates with different assumptions about flood warnings, land values and adaption to the flood risk. They also showed that, taking the East Anglian coast as a whole, the maintenance of current structures was far more economically cost-effective than abandonment, and that improving structures to ensure that current design standards continue to be met produced even higher economic benefits.

7.2.2 Does the issue deserve further attention?

The impact of climate change on coastal flooding is a major issue, and is probably the single most important implication of climate change for the NRA. Considerable attention has already been given to the issue. A methodology for assessing the impacts of sea level rise on coastal defence was developed as part of the Anglian Sea Defence Management Study (University of Durham 1991), and the NRA has already issued guidance (PIGNTE/FD/001: NRA guidance 1991a) detailing ways of coping with future sea level rise.

7.2.3 What are the management options?

There are several possible - complementary - responses to the threat of increased coastal flooding. Some specific research topics are proposed in Bray and Owen's (1991) review for the NRA of coastal and estuarine flood defence R&D, and some topics are also raised in the report of the Advisory Committee on Flood and Coastal Defence (1992). It is taken for granted that decisions about coastal defence in the face of climate change will consider conservation interests (Chapter 9).

Review the effect of climate change on levels of service

Asset management involves the review of the ability of flood defence schemes to meet their design standards. The NRA has recently reviewed sea defences, and has looked in particular at the standard of service provided by each scheme, the current maintenance costs and the likely rate of deterioration of the asset. This review could be supplemented by an assessment of the implications of climate change: the Advisory Committee recommended research on methodologies for assessing the effects of changes over time (and one methodology has already been developed: University of Durham 1991).

For each structure, it would be necessary to consider the points listed below:

1. The effect of sea level rise on the risk of overtopping, and *when* target standards of protection are exceeded (see also Bray and Owen 1991: Project 5.15). This analysis would be straightforward, and would use the changes in mean sea level assumed in the NRA PIGN TE/FD/001.

2. The effect of changes in storm frequency and intensity on the flood frequency relationship at the site. This is much more difficult at present, because estimates of changes in storminess are very uncertain. The NRA would need to:

- conduct a sensitivity analysis to compare the effects of changes in storm frequency and intensity and a rise in sea level on flood frequency curves. Is the effect of a 0.3 m rise in sea level so great that any feasible change in storminess would have only a small additional effect?, and

- monitor work on improving estimates of changes in storm frequency and intensity. These improvements will come from the Hadley Centre: the marginal contribution of the NRA would be small (Section 4.12).

3. The effect of changes in sea level on wave climate and wave heights at the structure. This requires the application of a wave height simulation model for each study shoreline and structure (Bray and Owen 1991: Project 5.6). Alternatively, "standard" estimates of the effect of a given sea level rise on wave heights for different shoreline gradients could be developed.

4. The effect of climate change on scheme integrity and maintenance requirements. This too would require information on possible changes in wave climate.

Assess the costs and benefits of maintaining target standards in the face of climate change

This is necessary to estimate the scale of response which might be needed to maintain standards, to identify priority areas and to assess the future timing of necessary remedial expenditure. It should be done after, or in parallel with, the review outlined above.

For each coast defence management unit, it would be necessary to:

1. estimate *when* action is necessary (based on the review assessment of when target standards cease to be met);

2. estimate the benefits of maintaining the target standard. This would need a set of standard guidelines on assumptions about future land use change in the flood-prone area. The evaluation should make reference to the environmental benefits of flood defence; and

3. estimate the costs of maintaining the target standard. The evaluation should make reference to the environmental costs of flood defence.

The East Anglia coastal study conducted by the University of East Anglia (Bateman *et al.* 1991; Doktor *et al.* 1991) provides a model for further regional evaluations. The Advisory Committee recommended research into investment prioritisation under conditions of climate change (Project C1.3).

During the course of this review it is possible that some areas will be found where the costs of maintaining standards are higher than the benefits, even allowing for environmental costs and benefits. Current policy states that uneconomic schemes should not be supported from public funds, and uneconomic schemes would not go ahead unless the land owners involved contributed. The abandonment of land is a contentious political issue, and the NRA would need to be aware that any proposed abandonment would be the subject of considerable public debate.

Allow for climate change when designing new schemes
The NRA guidance note PIGN TE/FD/001 gives recommended rates of sea level rise to use when evaluating the implications of climate change for coastal defence standards, but stops short of recommending that the allowance be incorporated now directly in design. Instead, it states that "regions will develop a flexible approach and will decide on the timing for building in the allowances into their defence structures".

If it would be very expensive to modify a scheme in the future, then it is appropriate to design *now* to accommodate future climate change (using the estimated rate of change in sea level from PIGN TE/FD/001 and a sensitivity analysis to investigate the extra effect of possible changes in storm frequency and intensity). More generally, schemes should be designed so that they can be revised as sea level rises or better predictions of change are made. In particular, the PIGN suggests that foundations are designed and constructed so that defences can be readily raised, but adds the important qualification that the scheme should still be economically-effective.

Investigate sensitivity of different designs to climate change, and develop robust schemes
Some types of coastal defence designs are more affected by a change in sea level than others. HR Wallingford reviewed alternative coastal defence designs (both embankments and vertical sea walls) and made some suggestions for flexible design (Owen and Steele 1991). Research has been proposed into the effect of sea level rise on "soft" defences and saltings (Bray and Owen 1991) and into flood defence techniques which can reconcile conservation interests with protection against a rising sea level.

Allow for climate change when assessing the benefits of a scheme
At present the benefits of coastal flood alleviation schemes are assessed assuming that the average annual damage remains constant over time. Climate change, and an increasing flood risk, will mean that average annual damage will increase over time and thus the benefits of flood alleviation will increase.

The effect of an increase in average annual damage over time, however, is reduced to an extent by discounting. If average annual damage increased by 20% over a 30-year period, for example, then with a discount rate of 5% the present value of damages would be only 7% higher than if average annual damage had been constant.

The methodology for estimating benefits exists - average annual damage is simply adjusted each year - but to be applied requires information on the rate of change of flood risk in the flood-prone area. It is important that the environmental costs and benefits of coastal flood protection (and the environmental opportunities afforded by sea level rise and flood protection) are included alongside the more conventional economic costs and benefits.

Allow for the variation over time in the chance of an event when setting design standards
The current design philosophy is based on the chance of an event occurring in any one year; the 100-year event, for example, is exceeded in any year with a probability of one in a hundred. Such an approach assumes that there is no change over time in the chance of an event occurring, which is obviously inappropriate if climate change is occurring.
There are three ways around this problem:

1. State that the design standard is calculated under current conditions, and accept that it will change over time. This might mean that the scheme does not provide all the protection over its lifetime that it was designed to provide. Such a scheme would be underdesigned.

2. Design the scheme so that it can cope with the specified target standard at the end of its lifetime (in other words, design for the 100-year flood under 2020 conditions, for example). This requires information on the rate of change of flood frequency over time, and would also lead to increases in initial scheme costs. Such a scheme would be overdesigned.

3. Express the design standard in terms of the probability of an event exceeding capacity at least once during the scheme design life. For example, the scheme design standard could be "a 25% chance of being exceeded in the next 30 years" (which is approximately equivalent to having a 1% chance of being exceeded in any one year, assuming no change in flood frequency over time). This approach can cope with a change in the flood frequency relationship over time, although research is needed to develop a practical methodology.

Investigate effect of sea level rise on estuarine flooding
High value developments occur along many estuaries in England and Wales, but it is rather harder to estimate changes in flood risk in estuaries than along the open coast. The configuration of the estuary affects the way an increased sea level alters tidal regimes and the propagation of storm surges along an estuary, and changes in river inflows might also influence the overall flood risk.

A sensitivity analysis of the effects of climate change on tidal propagation along estuaries was recommended by Bray and Owen ; this review should concentrate on the estuaries with the greatest exposure to flood risk.

7.3 Fluvial Floodplain Inundation

7.3.1 Background

There have so far been no studies into the potential implications of global warming for fluvial flooding in the UK. However, increased winter rainfall implies a greater frequency of winter flooding, and more frequent intense summer rainfalls suggest a greater risk in the future of summer "flash" floods (Chapter 4). The risk of fluvial flooding is likely therefore to *increase*, although the amount of change is currently very uncertain and will vary between catchments. The flood risk in a catchment may also be influenced by changes in land use (field drainage and catchment urbanisation) and by upstream channel works; these influences may be independent of climate change.

The major implication of climate change for fluvial flood defence is that protection levels fall below target standards of service. Most flood defence schemes were built to design standards specified by the agency promoting the scheme (the old River Authorities and Water Authorities) for different types of land use. Urban flood defence was usually built to withstand at least the one-in-50-year flood, for example, whilst schemes intended to protect predominantly agricultural land were designed for floods with return periods as low as once in five years (depending on the type of cropping the land could sustain). In practice, some flood defence schemes were built to the most cost-effective design standards. Different authorities, however, had different policies with respect to design standards, and the NRA has been developing a consistent national framework. This framework is based on the concept of level of service. Floodplain land is allocated to one of five land use classes according to the density of development expressed as a number of "house equivalents" in the reach. Each of the five land use classes has a specified level of service; Class A land, for example ("highly urbanised") has a target protection standard of at least one in 50 years. Any new scheme must satisfy benefit-cost criteria laid down by the government.

At present, therefore, every floodplain reach is either meeting its particular level of service, or is not (although reviews have not yet been completed). A change in climate might mean that a reach moves from a satisfactory status to an unsatisfactory one. As an example, assume that the flood frequency distribution at a site follows an EV1 (or Gumbel) distribution, with a typical coefficient of variation of 0.4. If the mean annual flood increases by 10% over 30 years, and there is no change in the coefficient of variation, then a flood that currently has a return period of 100 years will in 30 years time have a return period of just over 50 years. A scheme with a design standard of 100 years - well within the target for Class A urban land - would therefore after 30 years only just be meeting its target level of service. Although this is a simplistic example, it does indicate that climate change may have a major effect on the attainment of NRA standard of service targets.

7.3.2 Does the issue deserve attention?

Climate change *might* have a major effect on the frequency of floodplain inundation and on NRA levels of service. The extent of impact is currently unknown, but its potential magnitude means that the NRA needs to investigate the issue.

7.3.3 What are the management options?

There are several possible responses to the threat of changed flood risk.

Review the potential effect of climate change on flood frequency
The potential magnitude of the effect of climate change on flood frequency is unknown. The simple example in Section 7.3.1 implies that a 10% increase in the mean annual flood would have very significant impacts on the frequency of exceedance of a particular discharge, but how likely is it that the mean annual flood will increase by 10%? Also, will climate change mean that the slope of the frequency relationship changes? Information on the potential rate and degree of change is needed before any other management action is considered.

A research project would need to create scenarios of changes in the characteristics of flood-producing rainfall, and use a flood flow generation model to estimate changes in flood frequency characteristics. It is, however, difficult to estimate changes in flood-producing rainfall (Chapter 4), so two stages might be necessary:

1. Use the current Flood Studies Report unit hydrograph approach (NERC 1975; IH 1985) and conduct a sensitivity analysis by simply changing the storm rainfall by arbitrary amounts. This would indicate the scale of sensitivity to climate change, and allow the identification of particularly sensitive catchments.

2. Use more specific scenarios of changes in flood-producing rainfall and physically-based flow generation models. This would have to wait until "acceptable" scenarios of short-term rainfall were available (see Chapter 4).

Review the effect of climate change on levels of service

A review of the effects of changes in flood frequency on levels of service would indicate *where* and *when* the most significant problems will occur. It should be based on the results of the review of climate change and flood frequency outlined above.

A review of a specific scheme would need to determine the amount of change in the flood frequency relationship which would result in the scheme failing to meet set standards of service, and to ascertain the chance of such a change occurring (using the results from the study above).

Assess the costs and benefits of maintaining levels of service

Such a review would assess the scale of response needed to maintain standards, to identify priority areas, and to assess the future timing of necessary remedial expenditure. It should be done after, or in parallel with, the review outlined above. As with the coastal review, it would be necessary to (i) estimate when action is necessary, (ii) estimate the benefits of maintaining the target standard, and (iii) estimate the costs of maintaining levels of service.

The urgency of this review will depend on the estimated rate at which flood frequencies change, which will emerge from the studies outlined above. The greater the rate of change, the sooner it will be necessary to upgrade levels of protection.

Allow for climate change when assessing the benefits of a scheme

At present the benefits of flood alleviation schemes are assessed on the assumption that average annual damage remains constant over time. This will not be the case under climate change, and continued use of the assumption may mean that flood alleviation benefits are underestimated. The methodology for estimating benefits in a changing environment exists, but to be applied needs information on the rate of change of flood risk over scheme design life.

It is possible that the review of possible changes in flood risk shows that changes in average annual damage over time will be small, and therefore can be ignored.

Review the effect of climate change on flood estimation procedures

Current flood estimation procedures are based on the Flood Studies Report (NERC 1975) and subsequent updates (in particular Flood Studies Supplementary Report 16). Flood Study methods, like all conventional frequency estimation procedures, assume that flood frequencies are constant over time. This assumption will be untenable in the face of climate change, and research will be needed into the development of design flood estimation techniques that can cope with a changing climate.

The rainfall-runoff approach to estimating design floods combines a rainfall-runoff model (at present a unit hydrograph) with estimates of design storm rainfall. This approach could be refined to allow for climate change by using firstly a model which is not too conditioned on current climate conditions, and secondly scenarios for possible changes over time in storm rainfall characteristics (Chapter 4).

A refinement to the statistical approach to flood estimation (which uses dimensionless regional flood frequency curves and a set of procedures for estimating the mean annual flood) would need to include information on the rate of change in mean annual flood and flood variability. This information would have to come from a generalisation of the results from rainfall-runoff modelling studies. An equation could perhaps be developed estimating the rate of change in mean annual flood, for example, for a given climate change scenario, depending on relevant catchment characteristics.

Both approaches could be revised to express design standards in terms of chance of occurrence over the design horizon, rather than in any one year (see Section 7.2.3).

Allow for climate change in scheme design

Current estimates of changes in flood frequencies are too uncertain to be included directly in design now, but it is likely that climate change will affect the performance of schemes that are begun now over their design lifetime. There are two ways in which climate change might be considered in design:

1. Design the scheme to allow for upgrading as more information on climate change appears. This is already recommended under PIGN TE/FD/001 for coastal flood defences. Some fluvial flood defence designs will be more capable of upgrading than others; research into flexible design methods is necessary.

2. Evaluate the effect of a small number of climate change scenarios (which requires the modelling capability outlined above), and assess sensitivity of scheme performance to climate change. Then increase the normal freeboard allowance as necessary.

7.4 Integrity of Riverine Flood Defences

7.4.1 Background

The standards of protection provided by river flood alleviation schemes may be affected by erosion, sedimentation and weed growth. Erosion threatens the integrity of defence structures, and sedimentation affects the capacity of channels to transmit flood discharges. Weed growth also affects channel capacity; changes in flow regimes, water quality and water temperature might lead to greater growth and changes in plant growth patterns.

However, it is very difficult to predict possible changes in erosion, sedimentation and plant growth. Changes in river flow regimes at timescales relevant to erosion and sedimentation are very uncertain (Chapter 4), and no attempts have been made to relate changes in flow to erosion potential and sedimentation.

Sediment in upland rivers derives largely from local landslips near to river channels and from disturbances due to human activities such as ditching for afforestation. Some of the sediment transported during extreme events is also relict, and originates from sediment deposited during earlier more active periods in the river's history. Climate change might affect the frequency of upland landslips by changing the frequency with which triggering thresholds are exceeded (Harvey 1991), and hence alter sediment delivery rates, but the effects are very difficult to quantify or generalise.

Sediment in lowland rivers comes mainly from human activities and from bank erosion. Changed flow regimes would affect erosion potential, whilst changes in land use would affect "non-point" inputs.

7.4.2 Does the issue deserve attention?

Changes in river flow regimes and weed growth will probably have an effect on channel capacity and flood defences: work is needed to determine the scale of the impact and to identify schemes most at risk. However, if weed is already managed by major seasonal maintenance works it is difficult to see that climate change will do other than alter marginally the effort for the task, or its timing in the year.

7.4.3 What are the management options?

Several research projects are necessary before any operational actions can be considered.

Review the effect of climate change on weed growth, and therefore on maintenance regimes

How would changes in temperature, flow regime and water quality affect the growth of aquatic weeds? Would weed growth begin earlier in the spring, when river flows are higher, and therefore increase the flood risk?

Review the effect of climate change on erosion and sedimentation patterns

This study requires information on changes in daily flow regimes (see Chapter 4), which must be applied with sediment transport models to predict erosion and sedimentation patterns. It would allow the identification of river systems most prone to erosion and sedimentation problems in the future, which could affect the design of new flood alleviation schemes and lead to changes in medium-term maintenance plans.

7.5 Development Control

7.5.1 Background

At present the NRA advises planning authorities on development proposals in flood risk areas, but the advice is not binding on the planning authority. In general, the NRA recommends *against* development in the floodplain, both because of the risk to any property occupants and because of the floodplain storage that might be lost. Flood risk zones are mostly based on the area inundated in the largest recorded flood, as shown for most regions on Section 24(5) maps produced in the late 1970s and early 1980s. Floodplain maps are not, with a few exceptions, based on particular frequency events (such as the 100-year flood), although there is a move in the NRA towards the use of frequency-based risk maps (this would of course be costly, and would represent a major effort).

Climate change is unlikely to have an important effect on NRA floodplain development policies or advice. A particularly large event could result in the NRA increasing the size of a designated floodplain, but this will happen eventually regardless of climate change.

Frequency-based risk maps would need to be revised if climate and hence the flood frequency curve were to change, but the amount of uncertainty in floodplain determination might not be much less than the effects of the change in flood risk.

Attitudes in planning authorities to development in the floodplain might alter as climate changes, particularly if a sequence of damaging events occur which can be attributed - even vaguely - to climate change. The draft DoE, MAFF and Welsh Office Circular (1992) on floodplain development reminds planning authorities of the threat of climate change.

The NRA also advises planning authorities on the conditions that should be attached to permissions for new developments off the floodplain. Planning authorities increasingly require developers to provide some means of mitigating the effects of their development on the downstream flood hydrograph and frequency curve. This mitigation often takes the form of a balancing pond; climate change may mean that these balancing ponds would need to be larger in the future.

7.5.2 Does the issue deserve further attention?

Climate change will probably not have much effect on NRA floodplain development control policies, and the issue is of low priority. The implications for the flood mitigation requirements of off-floodplain development are rather more important.

7.5.3 What are the management options?

Require flood mitigation plans to allow for climate change
Climate change will probably affect the performance of balancing ponds during the course of their design lifetime. It might be feasible to require balancing ponds (or other mitigation devices) to be designed to cope with the design storm as expected in, for example, 30 years time. This would require the development of "approved" methods for creating scenarios for changes in design storm rainfall (Chapter 4). It would not be appropriate to initiate such a policy until storm rainfall scenarios are refined further.

Review the implications of changes in flood frequency for floodplain zones
It is desirable to conduct a small sensitivity analysis to determine the sensitivity of frequency-based floodplain zone boundaries to changes in flood magnitude. How does the effect of a given increase in the 100-year flood estimate, for example (as obtained from the results of the review outlined in Section 7.2.3), compare with the estimation errors in floodplain delineation? If the effect is large, then it might be necessary to require floodplain zones to be based on estimates of flood magnitudes which allow for climate change.

7.6 Flood Emergencies

7.6.1 Background

This area covers emergency action during a flood and flood warning. Climate change would not have an effect on such activities, although it might mean that they were more frequently undertaken. An increased risk of flooding might also mean that flood forecasting schemes become more attractive in cost-benefit terms.

It is possible that a change in the rate of occurrence of extreme rainfalls would mean that forecasting models were used outside the range of calibration data, but most flow forecast models in regular use are already routinely reviewed and updated.

A change in the characteristics of extreme rainfalls might also mean that short-term rainfall forecast techniques developed in the past are less reliable. It is possible, for example, that warning times might be reduced, with implications for the ability to issue warnings and take emergency action.

7.6.2 Does the issue deserve further attention?

The issue does not require high priority attention at present, although the NRA would need to be aware that flood forecasting and warning might be required more frequently in the future.

7.6.3 What are the management options?

Regular review of flood forecasting models
It would be necessary to review the performance of forecasting models, although as noted above this is already done.

7.7 Urban Storm Drainage

7.7.1 Background

Urban storm drainage systems are implemented by developers and local authorities under agency agreements with the water service PLCs.

The NRA must approve storm drainage plans and sets design standards.

An increased frequency of high-intensity short-duration rainfall events would cause increased storm sewer surcharge, with implications both for "off-river" flooding nuisances and for flood risks in receiving channels. This would affect both the performance of existing storm drainage systems and the design of new systems. There are also water quality implications of an increase in storm sewer flows (Chapter 6).

7.7.2 Does the issue deserve further attention?

Flooding from urban storm drainage systems is currently a significant nuisance in some urban areas, and any increase in flooding would have very large economic implications for the water PLCs. It is costly to modify completed drainage systems to cope with changed conditions, so it is appropriate to consider now the effects of climate change; there may be noticeable effects on scheme performance over the next 30 years (see Section 7.3.1).

7.7.3 What are the management options?

Investigation of the potential changes in urban storm drainage surcharges would need to be undertaken in parallel with studies into changes in urban storm water quality (Chapter 6).

Review effects of climate change on storm rainfall and storm drainage systems
The effects of climate change on storm rainfall are currently not known (Chapter 4). There are therefore two possible responses:

1. Conduct a sensitivity analysis on storm drainage system performance, using arbitrary changes to design storm rainfall totals. This will indicate the significance of changes in storm rainfall amounts.

2. Create scenarios for changes in storm rainfall characteristics from the results of the Hadley Centre UK meso-scale model (Chapter 4). This must wait until the meso-scale model simulations have been validated.

Require storm drainage systems to consider climate change
Urban storm drainage systems have long lifetimes, are costly to upgrade, and will be exposed to a changing climate. The NRA may need to develop a policy requiring new urban drainage systems to be able to meet design standards over the next, for example, 30 years. Several approaches are possible:

1. Specify a set of arbitrary changes to storm rainfall totals, and require that the proposed scheme can cope with the altered storm inputs.

2. Specify a set of scenarios based on analysis of climate model output (see above). This is a longer-term action.

3. Recommend the implementation of urban storm drainage designs that can be upgraded as more information about changes in storm characteristics becomes available. This is becoming standard sewerage rehabilitation practice.

8. FISHERIES

A change in water temperature, water quality and river flow regimes will affect fish populations. There are four areas of impact:

1. Fish physiology

Higher water temperatures will affect the growth and survival rate of some fish species. Most species in the UK will be little affected, but it is possible that changes in trout growth rates and survival might destroy many important sport fisheries. Higher water temperatures might also affect the outbreak of fish diseases and fungal infections.

2. Fish habitat

Changes in river flows and water quality will affect the habitat suitability of a reach (which varies between species), and changes in potential habitat may be much more important for many UK fish species than increased water temperatures. A change in the frequency of drought conditions would be particularly significant for fish populations.

3. Food sources

Changes in river flows and water quality will also affect fish food sources, and especially the abundance of invertebrates.

4. Fish migration

The migration of fish within a river system will be affected by changes in river flow regimes. Migration of salmon from the sea will be influenced by river flows, and it is possible that, in a warm climate with lower summer river flows in some catchments, the summer run of salmon could disappear.

The NRA can do little to prevent the impact of climate change on fisheries, but can take a number of actions to mitigate their effect; these are detailed in this chapter.

8.1 Introduction

The aim of the NRA fisheries function is to maintain, improve and develop fisheries. The fisheries resource is managed by the NRA for three main reasons: firstly it is a resource exploited for recreation, secondly it is a wildlife resource in need of conservation, and thirdly it is a managed resource exploited commercially. The fisheries function is in practice closely integrated with the NRA's recreation, conservation and water quality functions.

Salmon and trout fisheries predominate in the north and west (and trout are important in many chalk streams in the south), and although coarse fisheries occur throughout the NRA's area, they have the greatest relative importance in the south, east and midlands.

The NRA is responsible for licensing abstraction and discharge consents for commercial fish farms (generally off-river) and the commercial netting of eels, elvers and migratory salmonids, and also issues rod licences for recreational fishing. Most of the 1.2 million licences sold each year are taken up by coarse anglers.

Table 8.1 summarises the parameters of climate change which might affect freshwater fish populations.

Table 8.1 Climate change and the NRA's Fisheries function: areas of concern and relevant dimensions of climate change

	Change in fish population
Change in temperature	■
Change in rainfall	
Change in evaporation	
Direct effect of CO_2	
Change in river flows	■
Change in groundwater recharge	■
Change in water chemistry and biology	■
Change in storminess	■
Sea level rise	
Land use change	■
NRA management response in other functions to climate change	■

8.2 Changes in Fish Populations

8.2.1 Background

The fish population in a reach is influenced by the interaction of four factors. Fish *physiology* - such as spawning, survival and growth - will be affected primarily by water temperature changes; fish *habitat* will be affected by changes in flow regimes and water quality (including short-term polluting events); fish *food sources* might change as flow regimes and water quality change; and finally changes in flow regimes and ocean circulation patterns might lead to changes in *migration* patterns. River management actions also affect fish habitat and migration patterns. Fish populations will also be affected by the introduction of *exotic* species.

Fish physiology

There have been several studies into the effects of temperature differences on spawning, embryonic development, growth and survival, although few have been concerned explicitly with climate change. Studies have also concentrated on species most sensitive to temperature, rather than on species most relevant to recreational anglers in the UK.

The projected increases in winter temperature could adversely affect the spawning and embryonic development of several fish species in the UK. The eggs and embryos of most fish tolerate a much narrower range of temperatures than those tolerated by juveniles and adults.

Table 8.2 Temperature limits for the eggs and adults of a number of common freshwater fish (all values to nearest °C)

		Temperature limits for eggs		Temperature limits for adult fish	
Species	Common name	Spawning temperatures	Lethal temperatures	Optimum range	Upper critical range
Coregonus lavaretus	Whitefish	0 - 4	> 8	8 - 15	20 - 25
Salvelinus alpinus	Charr	3 - 15	> 8	5 - 16	22 - 27
Thymallus thymallus	Grayling	6 - 10	> 14	4 - 18	18 - 24
Salmo trutta	Brown trout	1 - 10	> 13	4 - 19	19 - 30
Salmo salar	Salmon	0 - 8	> 16	6 - 20	20 - 34
Salmo gairdneri	Rainbow trout	4 - 19	> 20	10 - 22	19 - 30
Perca fluviatilis	Perch	5 - 19	> 16	8 - 27	23 - 36
Barbus barbus	Barbel	14 - 20	> 20	-	-
Esox lucius	Pike	4 - 17	> 23	9 - 25	30 - 34
Cyprinus carpio	Carp	12 - 30	> 26	15 - 32	30 - 41
Rutilus rutilus	Roach	5 - 22	> 27	8 - 25	25 - 38
Abramis brama	Bream	8 - 24	> 28	8 - 28	28 - 36
Tinca tinca	Tench	18 - 27	> 31	20 - 26	26 - 39
Alburnus alburnus	Bleak	14 - 28	> 31	-	~ 38

Table 8.2 summarises the documented range of spawning temperatures for 14 common species of freshwater fish and notes the upper lethal limits quoted for their eggs. The most temperature-sensitive fish in the UK are the whitefishes (*Coregonus sp.*) and the charr (*Salvelinus alpinus*). These species are often called "glacial relicts" and are assumed to be landlocked remnants of species which at one time migrated freely to and from the sea. The current geographical distribution of these species (Wheeler 1977) is clearly related to temperature. In a warmer climate, the winter temperatures in many of the lakes in which whitefishes and charr live could approach the thermal limits for successful spawning.

The spawning performance of most trout and salmon populations should not be adversely affected by the projected increases in winter temperature. Increased spring temperatures may, however, stimulate early emergence. The newly hatched larvae would therefore be smaller in size and also might not be able to find enough food to survive: however, higher temperatures might mean that fish food organisms would be more abundant. The possibility of increased spawning activity by rainbow trout (limited by temperature in the UK) also needs to be investigated. An increase in the number of breeding rainbow trout populations would affect native salmonid populations.

Most of the other species listed in Table 8.2 spawn much later in the year, and so would not be affected by climate change. Roach, bream, carp and perch spawn earlier in the year in Southern Europe so they would almost certainly adapt their reproductive behaviour to the changing climate.

Table 8.2 also lists the optimum and upper critical range of temperatures for adult fish (Alabaster and Lloyd 1980; Elliott 1981). The most vulnerable lake fish are again the whitefish (*Coregonus lavaretus*) and the charr (*Salvelinus alpinus*). In some lakes, these fish may be able to avoid high temperatures by moving deeper in the water column but in others the oxygen concentrations at depth may be too low. With climate change high surface temperatures and low deep water oxygen concentrations are certain to coincide. The charr would then be confined to a very narrow range of depths and would probably not be able to feed efficiently.

The most vulnerable river fish are the grayling and the native brown trout. The grayling is now quite widely distributed (Maitland 1972) but could disappear from some rivers in the south if summers become very much warmer. Most trout populations in the UK should be able to survive, but their growth rate would be very much slower than it is today. Elliott (1975 a, b and c) has published a series of papers that quantify the thermal limits for growth and survival in migratory

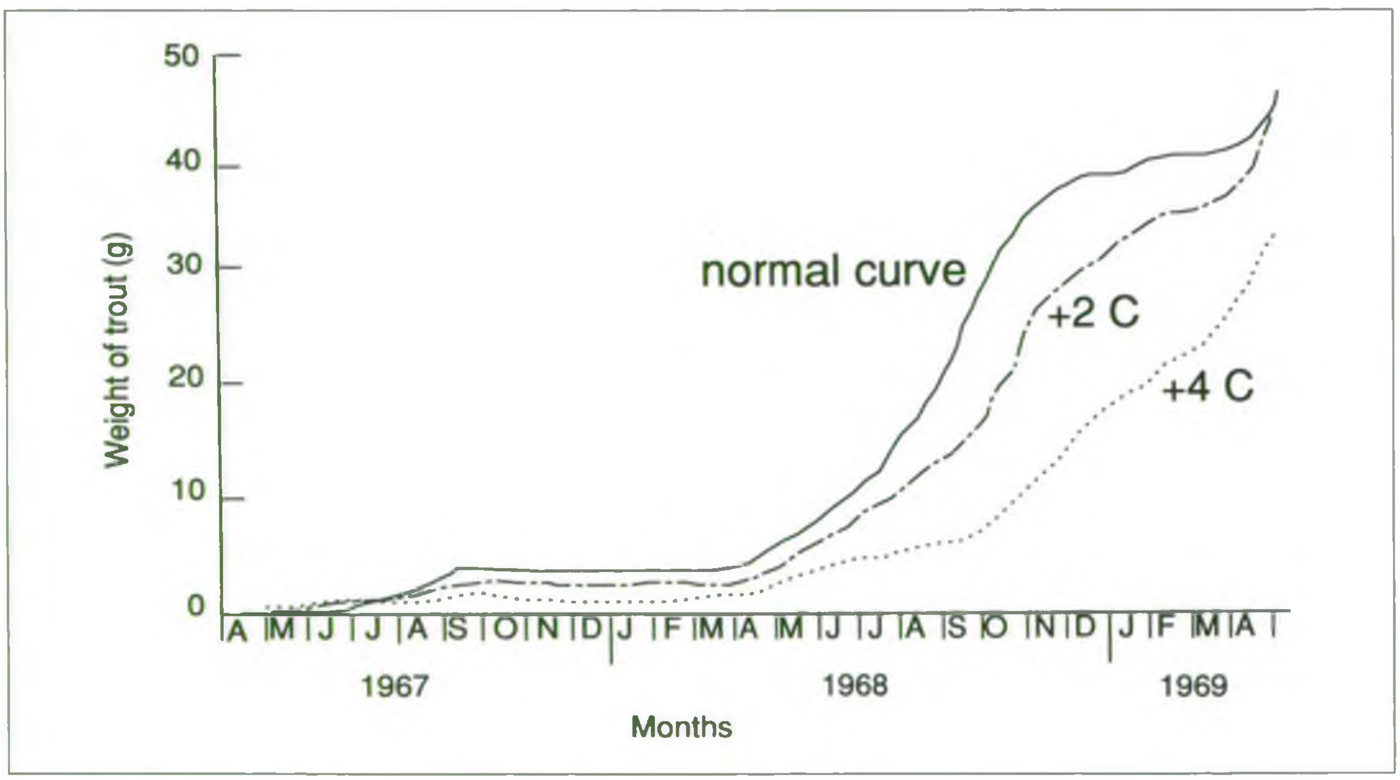

Figure 8.1 The predicted effects of increased temperature on the growth of brown trout (Elliott, unpublished data)

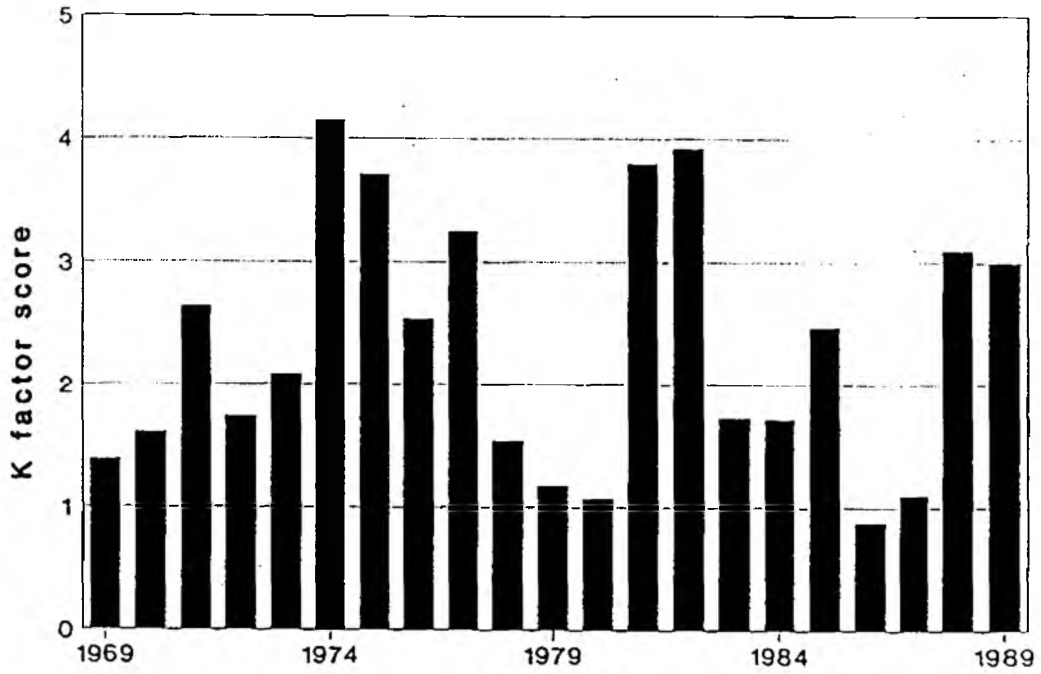

Figure 8.2 The year-to-year variations in the number of migratory brown trout lost in Black Brows, Cumbria, between the parr stages in May/June and the parr stages in August/September

The loss rates have been calculated by key factor analysis, and are expressed as k factor scores.

brown trout. At temperatures above 14°C the trout require large amounts of food to compensate for the energy lost in the faeces and in excretory products. Growth models based on these experimental results have recently been used to examine the effect of different temperature scenarios on the growth of brown trout.

Figure 8.1 shows a family of growth curves calculated using "full ration" rates incremented for every 15 days. The curves cover the growth of the trout for the first two years of their life (i.e. up to the time where they become smolts and, if they are sea trout, migrate to the sea). The "current" curve is based on measured temperatures in a Lake District stream, and the two simulated curves show the likely effect of increasing these average temperatures by 2 and 4°C. The growth curves in Figure 8.1 imply that an average rise of 2°C would produce trout that were at least 30% smaller at the end of their first year. Further increases in temperature would probably lead to a reduction in numbers as well as growth since small trout are less likely to survive the winter.

Such a reduction in growth rates could destroy many sport fisheries and lead to the virtual extinction of some sea trout populations if the young fish grow too slowly to smoltify.

There have been no studies of the effect of temperature change on the growth rates of other fish species more relevant to recreational anglers in the UK. Most of the coarse fish species listed in Table 8.2 grow very much faster in warm water, so should thrive in warm summers (unless flow rates fall: see below). This will mean the northward movement of the limit for some coarse fish, and hence a change in the relative abundance of different species in some northern rivers. Many fish species, however, are absent from catchments in which they could thrive, due to colonisation barriers. An increase in potential range may therefore not be realised.

Increased water temperatures might also result in a change in the incidence of fish diseases and fungal infections, with subsequent implications for the management of disease outbreaks. Mass mortality of common carp caused by abdominal dropsy is usually observed at the warmest times of the year (Alabaster and Lloyd 1980). Different fish pathogens, however, may respond in different ways to an increase in temperature. For example, Willoughby and Copland (1984) showed that some strains of the fungus *Saprolegnia* isolated from coarse fish tolerated much higher temperatures than those isolated from salmonids. Fungal infections are usually worse at lower temperatures because of reduced immune response, so higher temperatures should result in a reduction in the incidence of infection. However, higher temperatures might mean that some diseases and parasites which are currently not a problem in England and Wales become more significant.

Fish habitat

The physical habitat of a stream is influenced by water velocity and depth, channel substrate, in-channel vegetation, bank characteristics and bank vegetation, water quality (especially dissolved oxygen) and water temperature. These factors are themselves inter-related. Different fish species have different habitat requirements, and habitat preferences vary with fish life stage.

In recent years there has been an increasing interest in predicting fish habitats under different flow conditions, in order to define "ecologically acceptable low flows" (Bullock *et al.* 1991). This involves the development of relationships between habitat suitability and water depth and velocity for a number of common fish species and substrate types (Armitage and Ladle 1991). In principle, these relationships could be used with information on changed river flow regimes to estimate changes in habitat, but this has not yet been attempted; this is partly because the methodologies for relating habitat to flow are still being developed (under contract to the NRA). It is possible, however, to make some estimates of the effects of changes in flow regime on fish habitat.

As the UK climate becomes progressively warmer, summer droughts might become more frequent. Lake fish are relatively well buffered against these climatic extremes, but river fish are very susceptible to prolonged droughts. Not only may the actual depth of water available for the fish change, but lower flows may lead to a deterioration in water quality (Chapter 4) and hence more frequent fish kills.

Black Brows is a small stream in central Cumbria that normally has an equable flow regime. Long-term studies of the migratory brown trout populations in this stream (Elliott 1985), nevertheless, demonstrate that severe droughts can kill large numbers of young trout. Figure 8.2 summarises the average yearly losses recorded from the parr stages of trout in this over a 20-year period (1969-1989). Annual losses have been calculated using the well established method of key factor analysis. In this method, population density is expressed on a logarithmic scale and loss rates (k factors) calculated for successive stages in the life cycle: a high k factor represents a high loss rate. The time series of k factors demonstrates that recent "early summer" droughts have had little effect but the prolonged droughts of 1983 and 1984 killed large numbers of young trout.

Fish habitat is also affected by high flows or spates. Fish eggs and fish (particularly in early life stages) can be washed downstream and out of suitable habitats during high flows, and a change in the frequency of spates could have important implications for fish stocks.

Food sources

A change in flow regime and water quality will also affect fish food sources, and in particular the abundance of invertebrates. Habitat suitability relationships, relating invertebrate abundance to flow and channel characteristics, are currently being developed as part of the attempt to define ecologically acceptable low flows referred to above. The invertebrate community at a site is a dynamic system characterised by interactions between individual species (Armitage and Ladle 1991), and it will therefore be difficult to model the detailed effects of climate change. The most likely effect would be a shift in the dominance of species and increases or decreases in overall abundance, rather than radical changes in community composition; it would be difficult to assess the impact of such changes on fish populations. The greater the current pressures on food resources in a reach, the greater the impact of changes in those resources on the fish population.

Fish migration

The factors influencing fish migration patterns are currently poorly understood, although a number of radio tracking studies supported and undertaken by the NRA are beginning to provide useful information (Scottish Fisheries Research Station 1992). Climate change might conceivably affect all aspects of fish migration, including oceanic migration routes, entry into estuaries, entry into fresh water and movement along rivers.

It is possible that changes in ocean circulation patterns and temperatures in the North Atlantic might affect salmon migratory routes, and hence the abundance of salmon in UK rivers. The southern limit of migratory salmonids is temperature-limited, and at present lies close to the Spanish-Portugese border. Higher temperatures might mean a northwards movement of this limit, perhaps as far as southern England. A change in ocean temperatures may also affect the age structure of returning adults, by prompting earlier maturation. Younger smolts have a poorer survival rate to adult than older, larger smolts.

The timing of the passage of salmon into estuaries may be delayed by low river flows (Scottish Fisheries Research Station 1992), but the effect of river flows on movement into fresh water is less clear. In some rivers it seems that absolute threshold values of flow must be exceeded before salmon will move into the river, but in others it is a change in flow that influences entry (Scottish Fisheries Research Station 1992). A reduction in flows during the migration season and a reduction in the number of spates would tend to delay - but not prevent - migration, but movement is also affected by factors such as season, sexual maturity of the fish, light intensity and temperature.

Tracking studies suggest that the riverine migration of salmon may be split into three identifiable phases (Scottish Fisheries Research Station 1992). The first phase of migration follows river entry, and during this phase migration rates may be related to river flows; the higher the flow, the greater the rate of movement. During the second, quiescent, phase, the salmon remain at a particular location for long periods, and do not appear to respond to changes in flows (although in some rivers tracking studies show short periods of active migration during spates). Fish migration increases as spawning time approaches, and movement is very dependent on flows during this third phase of migration; the higher the flow (or the greater the increase in flow), the greater the rate of movement.

The effect of climate change on salmon migration would, it seems, depend particularly on how flows change during the migration seasons, which vary between catchments. Chapter 4 has shown that the change in river flows is very dependent on the assumed climate change scenario, but a future with higher late autumn, winter and early spring flows and lower flows in the rest of the year does not seem unreasonable. Changes in flow regimes might have the greatest effect on the timing of migration, rather than on the absolute numbers of fish that move during a year, although the longer the time that migratory fish remain in freshwater waiting to ascend to spawning grounds, the higher will be the mortality. If run-time is essentially genetic, rather than influenced by environment, then native stocks could have great difficulty in modifying their behaviour, with potentially disastrous results. However, without further research into all the environmental and physiological factors controlling fish migration, it is very difficult to estimate the implications of climate change.

Introduction of exotic species
Higher temperatures might mean that exotic fish species could become established in UK rivers, and alter the current population balance. The greatest concern is over the zander, a voracious predator that has become established in a few rivers in lowland England and which may be temperature-limited. The grass carp *Ctenopharyngodon idella* is currently stocked in parts of the UK for the purposes of weed management. It can be controlled at present because summer temperatures are too low for it to reproduce. If, however, temperatures were to increase, the fish might be able to breed in UK waters (although factors other than temperature affect breeding success); it would then be much harder to control and much less effective as a management tool. The rainbow trout is probably the most important alien species that might benefit from climate change.

Other exotic species already found in the UK are likely to remain isolated in reaches contaminated by thermal effluents.

8.2.2 Does the issue deserve further attention?

The impacts of changes in freshwater fisheries are difficult to quantify, but may be very significant in terms of the environmental quality of a river corridor and the potential for recreation (Chapter 10).

8.2.3 What are the management options?

The NRA can do little to counter the most extreme effects of climate change on freshwater fisheries, but there are a number of possible responses.

Review implications of climate change for "important" fish species
Much is known about the effects of temperature change on fish physiology, and many coarse fish in the UK are unlikely to be significantly affected. The migratory sea trout is perhaps the most important fish at risk. Less is known, however, about how changes in river flow regime and water quality might affect fish habitat, and these changes might be more important than an increase in water temperature.

The habitat-flow relationships currently being developed for the assessment of ecologically acceptable low flows (Section 8.2.1) provide the basis for an evaluation of the sensitivity of habitat to changes in river flow regimes. A study would concentrate on "important" fish species (such as the migratory sea trout) and potential nuisance species (such as the zander), and use river flow and water quality scenarios (Chapter 4) to estimate future changes in habitat. The study would identify critical thresholds, and determine whether these thresholds were likely to be crossed in the future.

Salmon are economically very important, and it is necessary to build on current work using radio tracking to determine the environmental and physiological factors controlling salmon migration. Further work is also necessary into the ability of migratory salmonids to modify the timing of their spawning runs. These studies can provide the basis for investigations into the impact of changes in river flow regimes and changes in water temperature.

Manage river water levels to maintain fish habitat

The greatest impact of climate change on most UK fish populations is likely to be via changes in habitat. Techniques currently being developed to estimate ecologically acceptable low flows can provide the basis for an active policy of managing flows and water levels in order to sustain important fish populations. The management of river water levels may involve the renegotiation of reservoir compensation flows. Habitat improvement work would help to provide refuges for adults and juveniles in periods of high winter spate and low summer flows.

Develop a selective breeding programme

It might be feasible to attempt to maintain stocks of important recreational fish by replacing "sensitive" strains of a particular species with more tolerant strains.

9. CONSERVATION

Conversation interests pervade all activities of the NRA. Climate change will therefore not only affect conservation activities directly, but will also affect conservation through the actions of the NRA in response to changes in, for example, flood risk and water source reliability.

1. **Changes in freshwater, wetland and river corridor ecosystems**

   Higher temperatures, increased atmospheric CO_2 concentrations and changes in water availability will affect the composition of river corridor ecosystems in ways that are currently unknown. Some systems and species will be more at risk than others, and there is also the possibility of invasion of "exotic" species. River corridor ecosystems are also affected by land use (which may change due to climate change) and river management activities.

2. **Changes in coastal ecosystems**

   A variety of ecosystems around the UK coast provide a wide range of habitats and form part of the coastal defence system. These will be affected particularly by sea level rise and NRA actions with regard to coastal flood defence.

3. **Changes in cultural heritage**

   Changes in river flow regimes in particular will have an impact on the perceived quality and visual amenity of the river corridor. This impact of climate change may be very visible to the public - and perhaps more so than changes in water source reliability.

Increases in flood risk can be used to the advantage of conservation interests if opportunities are taken to set up sacrificial flood zones that naturally benefit wetland communities.

9.1 Introduction

The NRA has a statutory duty to further conservation and to enhance wildlife, landscapes and archaeological features associated with the water environment. In practice, this means that the NRA is involved in conservation along river corridors, the coastal fringe and associated land. The NRA undertakes conservation work both to improve the environment (to "further conservation") and when designing and implementing flood defence, water resources and water quality schemes. Conservation interests may in some cases determine the NRA's response to a proposal to abstract or discharge water, and can have a very significant effect on the design of river and coastal defence schemes; in fact, conservation pervades all the NRA's activities, and provides a focus for assessing the overall state of the aquatic and associated environment.

Table 9.1 shows the various dimensions of climate change and indicates which affect NRA Conservation activities. It is important to emphasise here that NRA activities undertaken in response to climate change in other areas - especially flood defence and water resources - may have a very important impact on conservation interests; responses to climate change in other functions therefore need to consider explicitly conservation issues.

9.2 Changes in Freshwater Wetland and River Corridor Ecosystems

9.2.1 Background

Climate change might have three types of effect on ecosystems in freshwater wetlands and river corridors.

Direct effects of changes in climate

Cannell (in CCIRG 1991) estimated that an increase in temperature of 1° would significantly alter species compositions in over half of the statutory protected areas in the UK. Species most at risk are those at the present limits of their distribution or in isolated communities. There has so far been no work specifically on possible changes in wetland or river corridor ecosystems, although a 1° rise in temperatures would enable many dragonfly species to spread to northern England and higher temperatures could affect adversely the hibernation patterns of amphibians (CCIRG 1991). Higher temperatures might also mean the invasion of exotic species, and this might affect the integrity of river structures. Japanese Knotweed, for example, is an exotic with a foothold in British rivers which, by crowding out competition and dying back quickly in autumn leaves flood protection works and river banks bare of protective vegetation. Increases in CO_2 concentrations will affect different plants in a riverine ecosystem in different ways, and hence possibly lead to changes in ecosystem structure.

Table 9.1 Climate change and the NRA's Conservation function: areas of concern and relevant dimensions of climate change

	Freshwater wetlands and riverine ecosystems	Coastal ecosystems	Cultural heritage
Change in temperature	■	■	
Change in rainfall	■		
Change in evaporation	■		
Direct effect of CO_2	■	■	
Change in river flows	■	■	■
Change in groundwater recharge	■		
Change in water chemistry and biology	■		
Change in storminess	■	■	
Sea level rise	■	■	■
Land use change	■	■	■
NRA management response to climate change in other functions	■	■	■

Changes in soil water regimes and shallow groundwater levels will also have very big implications for wetland ecosystems. Soil water requirements have been defined for a number of plant species - at least qualitatively - but the requirements for wildlife such as birds are much harder to determine (Youngs *et al.* 1991). MAFF-funded research at Silsoe College (Youngs *et al.* 1991) has shown how a soil water model can be combined with information about flora and fauna soil water requirements to assess the influence of changes in soil water regimes on their conservation.

Changes in river flow regimes will affect channel morphology and instream aquatic habitats, influencing not just fish (Chapter 8) but also the growth of aquatic plants and invertebrate habitats. Downstream migration of the perennial head of many rivers (especially chalk streams), reduced flows or increased spatiness would all have important impacts on stream communities. A higher sea level would affect the composition of freshwater wetlands and riverine ecosystems close to the current tidal limit.

In general, the effects of climate change on ecosystem composition will depend on the degree of climate change, the rate of change, and the local availability of species suited to the changed conditions.

Changes in agriculture and land use

Changes in agricultural and land use practices - directly or indirectly dependent on climate change - will affect both species composition in riverine environments and, by altering catchment hydrological processes, water and nutrient supply. Many important riverine ecosystems in the UK rely on continued good agricultural practice (Youngs *et al.* 1991). However, there are conflicts between the interests of modern agriculture and conservation, particularly in the area of land management. It is likely that the need for the NRA to exercise some control over pumped drainage systems for the benefit of conservation will increase.

NRA water management activities

NRA activities in response to the effects of climate change on water resources, water quality and flood defence in particular will impact upon river and wetland ecosystems. These activities must be carried out in ways that minimise impacts, ameliorate any adverse impacts and incorporate enhancement measures wherever possible.

9.2.2 Does the issue deserve further attention?

Climate change may have a very significant impact upon freshwater ecosystems, but the NRA would not be able to protect against these impacts because it is impractical to attempt to maintain a particular ecosystem under changing conditions. However, the NRA needs to consider explicitly the impacts of climate change on freshwater ecosystems when planning and undertaking its own activities. Information on possible changes and rates of change would provide useful input into conservation management.

9.2.3 What are the management options?

It is taken for granted here that conservation issues are integrated in the design and planning of activities in other NRA functions.

Research sensitivity of wetland and riverine ecosystems to climate change

Very little is currently known about the sensitivity of wetland and riverine ecosystems to climate change. Would there be a major change in ecosystem structure, or would there just be change in some specific elements of the ecosystem? Would, for example, riverine wetlands dry up completely, or just undergo a small change in area or in species composition?

Research is therefore desirable into the potential changes in a number of key wetland and river ecosystems and, especially, into critical thresholds. Information on the possible extent and rate of change would allow the identification of particularly sensitive sites.

Research implications of climate change for specific species or systems

Several species and ecosystems are given special attention in the NRA, because of their rarity or importance in maintaining particular habitats. Research is desirable into the sensitivity of these species and systems to climate change; as above, this research would need to consider critical climatic and environmental thresholds for the species or system, and assess the likelihood of these thresholds being passed in the future.

It is also desirable to investigate the implications of climate change for "nuisance" plants and animal species (such as the Japanese knotweed mentioned above).

Monitor changes in ecosystems

Although climate change will affect ecosystem structure, it is inappropriate to assume therefore that all change occurring in an ecosystem is due to climate change; changes in land use or some other management activity may be more important. It is therefore necessary to monitor changes in wetland and riverine ecosystems, and to compare observed changes with those expected due to climate change. Where new species of value gain a localised hold they may well warrant conservation.

Investigate management options for sensitive sites

Although it is difficult in general for the NRA to prevent climate change from altering significantly an ecosystem, it may be possible to attempt to mitigate impacts on certain systems (whether Sites of Special Scientific Interest or Environmentally Sensitive Areas). It may be feasible, for example, to manage river flows or wetland water levels in order to maintain current conditions, or it may be appropriate to create corridors linking sites to allow migration. Alternatively, it might be necessary to control abstractions to a higher degree to conserve habitats. Such management options will require information on the potential change in the ecosystem, and an evaluation of the costs, benefits and consequences of attempting to maintain that ecosystem.

9.3 Changes in Coastal Ecosystems

9.3.1 Background

There is a variety of coastal ecosystems and habitat types around the UK coast, including sand dunes, salt marshes, mud and sand flats, shingle features, coastal lagoons, reedbeds and grazing marshes (Posford Duvivier 1991). These ecosystems provide bird habitats, are important for fisheries and can contribute to protection against flooding and erosion. Approximately 10% of the notified nature reserves of the UK occur near sea level on the coast. A review of the implications of changes in sea level, storminess and wave climates on coastal ecosystems is given by Posford Duvivier (1991), who also emphasise that the ecosystems are affected by a variety of non-climatic pressures. Estuarine systems will also be affected by changes in freshwater inflows. This section summarises briefly the effects of climate change on coastal ecosystems (Posford Duvivier 1991).

Sand beaches and dunes

A rise in sea level would mean an adjustment of the beach profile and shoreline retreat. The actual magnitude of retreat is dependent on the existing profile and sand supply, but could be up to 60 m for a 0.3 m rise in sea level (Wind 1987). Given the freedom to move, large dune sites are likely to be relatively unaffected - as a whole - by sea level rise (Boorman *et al.* 1989). Higher sea levels would also mean a rise in the freshwater table that sits above the underlying sea water, and an extension of dune slack plant communities. Small sand dune systems with limited scope for landward movement would be most affected by climate change, and may suffer major losses of habitat (Boorman *et al.* 1989).

Sandflats and sandbanks

The processes controlling sandflat and sandbank dynamics are not well known, so it is difficult to estimate the effects of climate change; a rise in sea level would, however, probably lead to erosion, but the impact of additional erosion would depend on sediment supply to the sandflat or sandbank.

Saltmarsh and mudflats

Saltmarshes and mudflats are a very important habitat. Vegetation in salt marshes and mud flats is distributed according to the tidal regime and the degree of submersion or emergence that the component plant species can withstand (Boorman *et al.* 1989). Sea level rise would mean both longer and more frequent submersion and increased erosion due to the more severe wave climate resulting from deeper water seawards. Salt marsh zones would be displaced landwards, with the amount of displacement depending on the local change in tidal range; as an example, Boorman *et al.* (1989) showed that a rise (admittedly extreme) of 0.8 m in sea level would lead to the elimination of the "general salt marsh" zone (the zone covered only in higher spring tides) along a 12 km stretch of coastline in Essex, and a reduction in the area of mud flats by at least 20%. Salt marshes are often a part of a coastal defence system, so any loss would have implications for the integrity of coastal structures.

The distribution of mud flat invertebrates depends on tidal range and the rates of erosion and sedimentation. In general, a rise in sea level would generally result in these communities becoming poorer and less diverse, and this would greatly reduce the large numbers of the many bird species that currently feed, breed and roost in salt marshes (Boorman *et al.* 1989). The reduced width of the shore zone would also force birds to feed at higher densities, increasing competition.

Shingle features

An increase in sea level is likely to produce a net change in beach profile, but the degree of change will depend on sediment supply; "fossil" features are particularly vulnerable to erosion.

Coastal lagoons

Coastal lagoons lie on the landward side of shingle ridges and in tidal inlets protected by shingle or sand spits. The particular characteristics of lagoon ecosystems are dependent on salinity levels, which are affected both by sea level - affecting percolation through or overtopping of the protecting barrier - and by freshwater inflows.

Reedbeds

Reedbeds occur along estuaries, and are affected by both freshwater river flows and sea level; again, salinity levels are very important.

Grazing marshes

Grazing marshes are, as their name suggests, used for occasional grazing, and are very much influenced by agricultural practices such as drainage, grazing regime intensity and the application of agricultural chemicals. As with salt marshes and coastal lagoons, a rise in sea level will mean increasingly severe and frequent flooding.

9.3.2 Does the issue deserve further attention?

Climate change may have very significant effects on coastal ecosystems, and both these effects and measures to counter them will have a major influence on flood defence policies. As with freshwater ecosystems, it will be difficult to prevent impacts of climate change.

9.3.3 What are the management options?

It is taken for granted that coastal flood defence policies consider explicitly the effects on coastal ecosystems, and that the conservation costs and benefits are included in scheme evaluation.

Research sensitivity of ecosystems to climate change

Some information is available about the possible effects of a rise in sea level on mudflats, saltmarshes and beaches, but there have been no studies into estuarine ecosystems affected by both changes in sea level and changes in freshwater inflow. Does the fact that such systems are already subject to considerable variations over time in both water level and salinity mean that they are less sensitive than coastal ecosystems? As with freshwater ecosystems, any research should concentrate on identifying critical thresholds and the likelihood of these thresholds being exceeded in the future.

Monitor coastal ecosystems

Although climate change will affect ecosystem structure, not *all* change is due to climate change. It is therefore necessary to monitor changes in coastal ecosystems, and to compare observed changes, especially those resulting from rare storms, with those expected due to climate change.

Managed retreat
A study for the NRA (Posford Duvivier 1991) has suggested that a policy of *managed retreat* in the face of sea level rise might not only be more cost-effective in some locations than providing higher flood defences, but would also offer considerable conservation benefits. Sites of nature conservation interest could be restored, created or allowed to move inland. Policy development here is co-ordinated by MAFF. Subsequent strategic research and/or management guidance should cover the experimental and monitoring requirements necessary for such a policy, and present a framework for ensuring that technical, economic and legal aspects are considered alongside site specific environmental and ecological issues.

9.4 Changes in Cultural Heritage Sites

9.4.1 Background

The NRA's Conservation function covers not just plant and animal ecosystems, but also aspects of the UK's cultural heritage associated with the aquatic environment. There are three possible effects of climate change.

First, changes in river flow regimes might affect the perceived quality of the aquatic cultural environment and river corridor, in both urban and rural settings. The most obvious example is the potential drying up of chalk streams and village ponds. Many such streams and ponds in southern England have been dry during the summers of 1989, 1990 and 1991, and there have been frequent references in the press to the "catastrophic" changes to village character. Although the causes are different - a combination of overabstraction and low winter rainfall - the experience of the last few summers does imply that a reduction in flows due to climate change might have a very significant "emotional" and aesthetic impact. A consequent cost in reductions in property values and reduced local tourism is possible.

Second, sea level rise will have implications for many of the 43 Heritage Coasts of England and Wales, as well as other lengths of coastline of conservation importance. These coastlines might suffer from changes in coastal ecosystems (as summarised above), but their quality may also be affected by erosion and sedimentation; coastlines with "soft" cliffs, shingle banks, dune systems and saltmarshes will be much more significantly affected than "hard" cliff coastlines.

Third, drying out of wetlands would affect floodplain archaeological sites. Sites could be disturbed, or even destroyed.

9.4.2 Does the issue deserve further attention?

The impacts of climate change on cultural heritage are hard to quantify, but may be very significant. The public may not "see" a change in water resource reliability, but would notice - and complain about - a change in a culturally-valued landscape such as a chalk downland stream. The NRA needs therefore to pay attention to potential threats to the cultural landscape.

9.4.3 What are the management options?

Management of village and urban streams
The impacts of a change in flow regime on perceived village and townscape "quality" are unquantifiable, but may be very important to both inhabitants and visitors. The NRA would need to review the chance of a "significant" reduction in flows in some important streams and rivers, and consider the costs and benefits of river flow augmentation. At present climate change scenarios are too variable for useful results to be obtained, and in any case alleviation works would have a relatively short lead time. The study can wait until rainfall and evaporation scenarios are refined (Chapter 4).

Review the impact of climate change on heritage coastlines
The implications of a rise in sea level for erosion and sedimentation along identified heritage coastlines could be reviewed, using the NRA guidance (PIGN TE/FD/001) about change in sea level. Such a review should indicate *when* problems are likely to appear, and should recommend management responses.

10. RECREATION

The *demand* for water-based recreation is changing continually for social and economic reasons, and it is very difficult to identify any particular impacts of climate change.

Higher temperatures are likely to encourage a greater public demand for water-based recreation, but any assessments would be very speculative.

The *recreation* potential of a watercourse would be affected by changes in flow regimes and water quality, although the degree of impact on an activity would depend on how sensitive the activity was to variations in flow and quality.

10.1 Introduction

Water-based recreation can take place on or in water (and includes canoeing, boating, water contact sports and angling) and along a river corridor or lake frontage. The aim of the NRA is to develop the amenity and recreational potential of waters and lands under NRA control. In practice this means developing recreation strategies, promoting recreational activities, and ensuring a clean water environment for recreation; increasingly, this means ensuring that water meets standards for specific water-based activities (such as the proposed Statutory Water Quality Objectives for Water Contact Activities and the EC Directive on Bathing Water Quality).

Table 10.1 shows the dimensions of climate change relevant to impacts upon recreation.

Table 10.1 Climate change and the NRA's Recreation function: areas of concern and relevant dimensions of climate change

	Change in recreation
Change in temperature	■
Change in rainfall	■
Change in evaporation	
Direct effect of CO_2	
Change in river flows	■
Change in groundwater recharge	
Change in water chemistry and biology	■
Change in storminess	
Sea level rise	
Land use change	■
NRA management response to climate change	■

10.2 Changes in Recreation

10.2.1 Background

The *demand* for tourism and recreation is very dependent on economic, social and technological changes, and is generally increasing. The NRA aims, for example, to manage an increase in the number of visitors to NRA facilities of 45% between 1989/90 and 1993/94 (NRA 1990). Against this background, climate change may be relatively unimportant.

Both the quantity and "quality" of tourism are, however, related in some way to climate, although little is known about weather-related holiday or recreation decisions (Smith, in CCIRG 1991). The number of UK residents heading to the Mediterranean for a summer holiday increases significantly following a wet English summer, for example (Smith 1990), and temperature, rainfall, cloudiness and humidity all affect the quality of the "holiday experience". For UK tourism, increases in rainfall may be more significant than temperature increases (CCIRG 1991). Much water-based recreation is short-term and often spontaneous, and it is very difficult to predict how it will respond to climate change beyond making the rather obvious guess that demand for all forms of water-related recreation will be higher if summers are warmer and drier. The Sports Council may have an interest in assessing the implications of climate change for recreation demand.

It is slightly easier to assess the implications of climate change on the *recreation* potential provided by a river or water-course. Water-based recreation is largely determined by water quality (Burrows and House 1989), and the possible changes in water quality outlined in Chapter 4 will have obvious implications for recreation. Changes in the frequency of occurrence of toxic algal blooms will be particularly important. Water depth affects the ability to perform certain activities - particularly boating - and also influences the visual amenity of the river corridor.

10.2.2 Does the issue deserve further attention?

It is very difficult to predict the effects of climate change on recreation demand and potential, and the effects may be small compared with those of other pressures. The NRA need pay no further attention to the potential impact of climate change on recreation, except insofar as other functions - such as conservation - need to consider implications for recreation when planning a response to climate change.

10.2.3 What are the management options?

There is nothing that the NRA needs to do at present, beyond being aware that changes in recreational use of waters might have conservation implications.

11. NAVIGATION

Climate change might have two possible impacts on river navigation:

Firstly, the *water available* for the navigation system - whether canal or river - may change. This may lead to problems in maintaining water levels, although the extent to which current operating systems are flexible enough to cope with possible changes in future flow regimes is unknown.

Secondly, changes in flow regimes will affect sedimentation in navigable river channels and hence *maintenance*. Again, the importance of any possible change is unknown.

11.1 Introduction

The aim of the NRA is to improve and maintain inland waterways and their facilities for use by the public where the NRA is the navigation authority. The NRA is the navigation authority for a number of navigable rivers in five Regions; these include parts of the Thames, Medway and lower Derwent, the Market Weighton Canal, some East Anglian rivers, the estuary of the Dee in North Wales, and Rye Harbour. The NRA ensures that the river is kept suitable for navigation and maintains and operates structures such as locks and weirs. In other areas, the NRA has powers to issue by-laws requiring riparian owners to maintain waterways and prevent obstructions, and to require all boats to be registered. The canal network and other navigable rivers are operated by other authorities, primarily the British Waterways Board (BWB).

The Navigation function is closely associated with recreation (because much navigation use of rivers is recreational) and is integrated with other functions and riparian interests. Most navigable waterways, for example, are also part of a flood defence system, so river level management needs to consider both navigation and flood defence requirements.

Table 11.1 shows the dimensions of climate change relevant to impacts upon recreation and navigation.

Table 11.1 Climate change and the NRA's Navigation function: areas of concern and relevant dimensions of climate change

	Change in navigation
Change in temperature	
Change in rainfall	
Change in evaporation	
Direct effect of CO_2	
Change in river flows	■
Change in groundwater recharge	
Change in water chemistry and biology	
Change in storminess	
Sea level rise	■
Land use change	
NRA management response to climate change	■

11.2 Changes in Navigation

11.2.1 Background

Climate change might have three main impacts on navigation.

Supply of water and operational river level management
A change in river flows and water availability might affect the ability of the navigation authority (whether the NRA or the BWB) to maintain water levels along the navigable reach. The less the amount of water available during summer, the less able the river or canal will be to enable navigation. Navigation is restricted in some rivers and canals in drought years, and in particularly extreme years can be prevented entirely; large parts of the canal network in southern and eastern England lacked sufficient water during the summer of 1976, and parts of the recently-renovated Kennet and Avon canal were closed in 1990, 1991 and 1992 because of a lack of water. 7.2% of the British Waterways canal network suffered navigation restrictions during the summer of 1990 (British Waterways 1991). The effects of climate change on a navigation system, of course, depend on the changes in water availability in the catchments providing water to that system (Chapter 4). Supplies to a canal often come from a number of small, independent, reservoirs, and these are likely to be particularly sensitive to climate change.

Maintenance in navigable rivers
Changed river flows would also affect sedimentation patterns within a navigable waterway (see Chapter 7), and perhaps lead to changes in dredging regimes.

NRA response to climate change
The droughts of 1991 and 1992 have given impetus to proposals to use the canal network to transfer water from the north and west to the south and east. If such a strategy were to be implemented as part of the NRA response to changes in water resources, there may be major implications for the operation of the canal network.

11.2.2 Does the issue deserve further attention?

Changes in river flows might have locally important implications for some of the rivers for which the NRA is the navigation authority, but any assessment of potential impacts should have a low priority.

11.2.3 What are the management options?

Review implications of climate change for river levels and sedimentation in important navigable rivers

This review would need to consider whether changes in flow regimes and sedimentation would be large enough to cause operational problems, or whether the current operating system can cope with them. The study should wait for "acceptable" flow scenarios (Chapter 4), and would be relatively simple given a suitable hydraulic model of the case study river.

12. SENSITIVITY OF NRA ACTIVITIES TO CLIMATE CHANGE

12.1 Climate Change and the NRA

This report has reviewed the implications of climate change for the NRA. It is clear that some potential impacts are quite well known, whilst others are extremely speculative and any assessments must be based on inspired guesswork. There are five general points to make from the review:

1. As indicated in Section 4.12.1, there are two levels of uncertainty in estimating the impacts of climate change. Firstly, the amount (and often direction) of change in relevant climate parameters is unknown and highly uncertain, although the degree of confidence varies with parameter. Secondly, there may be uncertainties in estimating the consequences of a given change in climate inputs, because the relationships between climate and response are poorly understood.

2. A change in any one environmental characteristic may influence many NRA activities. For example, a change in river flow regimes may affect water resource availability, stream water quality, the flood risk, fish habitats, wetland ecosystems, river corridor amenity value, recreation potential and navigation opportunities.

3. The impact of climate change on the NRA in one area may be very much influenced by the response of another part of the NRA to climate change. NRA Conservation activities are likely to be particularly affected by actions taken by other functions; the duty to further conservation will remain unchanged, but the efforts required to fulfil this duty may well increase.

4. A system will be able to cope with a certain amount of climate change, but might respond very differently once a critical threshold is reached. The impact of climate change is not therefore a simple linear function of the degree of "forcing".

5. Factors other than climate are also changing, and these factors may be more important for a specific system than climate change. Examples include changes in demand for water, changes in agricultural land use, changes in CEC environmental policy and changes in demand for recreation. All these changes are uncertain. Climate change is only one of the pressures affecting the NRA over the next few years and decades.

Table 12.1 lists all the identified sensitive activities, and indicates (i) the degree of uncertainty surrounding the relevant climate parameters, (ii) whether the links between climate and response are well-known at present, and (iii) a subjective assessment of the importance of the potential impact to the NRA. With respect to the climate parameters, the greatest uncertainty applies where the activity is sensitive to changes in *rainfall*; the shorter the duration of rainfall of interest, the greater the uncertainty. A "good" understanding of the links between climate change and response exists only with resource recharge, saline intrusion along estuaries and into aquifers, and coastal flooding. There is poor understanding of these links in the conservation and recreation areas in particular.

12.2 Coping with Climate Change: Some General Recommendations

Two reasons are often cited for doing nothing about climate change: (i) the impacts are very uncertain and (ii) if they do occur, they will happen well into the future. This report has shown that whilst there is considerable uncertainty in the impact of climate change on the NRA, the impacts *may* be very large, and *may* be felt within planning horizons currently used in the NRA. It is therefore recommended that the NRA adopts a precautionary response to the climate change.

Each NRA core function, however, will need to respond differently to climate change. This is partly due to the different degrees of sensitivity and uncertainty about climate change and system response, and is partly a result of the different timescales involved in implementing a response strategy. The longer the lead time required, the sooner action may need to be taken; however, the earlier the action, the greater the uncertainty in the estimated impacts of change.

Some possible responses to climate change are reviewed in Chapters 5 to 11. There are, however, several issues common to many or all core functions. As well as following the precautionary approach in its response to climate change, the NRA might consider developing common supporting tools for its corporate response to climate change, and emphasise a number of *general principles* to be applied when responding to climate change.

Table 12.1 Activities sensitive to climate change, and degree of uncertainty

	Degree of certainty in controlling climate parameters	Understanding of climate-response relationship	Importance to NRA
Water resources			
Reliability of surface and groundwater resources	●●	●●●	●●●●
Saline intrusion into estuaries	●●●	●●●●	●●
Saline intrusion into aquifers	●●●	●●●	●●
Demand for water	●●	●●	●●●
Water quality			
Maintenance of SWQOs	●●	●●●	●●●●
Management of algal blooms	●●	●●●	●●●
Management of estuarine and coastal water quality	●●	●●●●	●●●
Design and operation of sewer systems	●	●●●●	●●●
Pollution incidents	●	●●●	●●●
Flood defence			
Increase in coastal flood risk	●●●	●●●●	●●●●
Fluvial floodplain inundation	●	●●●	●●●●
Integrity of riverine flood defences	●	●●	●●●●
Development control	●	●●●	●●●
Flood emergencies	●	●●●	●●●
Urban storm drainage	●	●●●	●●
Fisheries, Recreation, Conservation and Navigation			
Fish populations	●●	●●	●●●
Freshwater wetlands and river corridors	●●	●	●●●●
Coastal ecosystems	●●●	●●	●●●●
Cultural heritage	●●	●	●●●
Recreation	●●	●	●
Navigation	●●	●●	●●
KEY	● bad	● not at all	● low
	●● poor	●● bad	
	●●● good	●●● can be quantified	
	●●●● very good	●●●● good	●●●● high

12.2.1 Supporting tools for NRA response to climate change

The NRA should consider the benefits of developing, or sharing with others, common technical support tools for use in its medium- and long-term planning.

1.A common set of "approved" climate change scenarios.
These scenarios would state assumed changes in temperature and potential evaporation, monthly and extreme rainfall (at least), and changes in sea level, by decade from 1990 to 2050. Several scenarios could be prepared, based on the work of the DoE Climate Impact LINK project (Section 4.12.2). It would not be necessary to present these scenarios as definite *forecasts* of the future. They should be seen as the basis for a *sensitivity analysis*. The scenarios would apply to all climate change impact assessments in all core functions, and could also be used by organisations regulated by the NRA.

2. **A set of models which can convert these climate change parameters into parameters of direct relevance to the NRA.**
These models would be physically based. It would not be appropriate to specify standard scenarios for hydrological parameters directly, because the effects of a given change in climatic inputs depend very much on local catchment conditions. Some models would be relevant to all core functions - in particular models to simulate the effects of climate change on river flow regimes - whilst others may be appropriate to one core function, spatial scale or time scale.

3. **A methodology for conducting a climate change impact assessment.**
Although a methodology has been developed for undertaking climate impact assessments (Chapters 3 and 4), it is desirable to refine this methodology to develop guidelines specific to the NRA, focusing on NRA practice and requirements. In particular, the guidance would refer to (i) the need to consider a range of options available for coping with the consequences of climate change for a particular scheme, (ii) the costs of each option (including environmental costs, benefits and opportunities), (iii) how other NRA interests can be included in an assessment, and (iv) how the assessment should handle uncertain estimates of future climate change. This methodology could be used both within the NRA and by organisations regulated by the NRA.

4. **A methodology for assessing strategy performance against a changing background.**
Current practice is to assume that climate will remain stable over a scheme planning horizon, but this assumption is inappropriate in the face of a changing climate; the performance of a scheme can be expected to vary over the planning horizon. A methodology would therefore need to be developed which can cope with this variation in performance over time. This methodology could also indicate how information on possible future changes can be used in conjunction with recorded observational data (which currently underpin the evaluation of scheme performance). The recommended methodology should be based on current procedures for simulating system behaviour over a long time scale. Again, this methodology could be used by the NRA and by organisations regulated by the NRA.

The emphasis given to climate change in the Government's policy document on Sustainable Development (1994) may provide the impetus for collaborative development of some of these tools.

12.2.2 General principles underpinning NRA response to climate change

This last section outlines four general principles which should underpin the NRA's response to climate change. To a large extent, these principles should apply to medium-and long-term planning even in the absence of climate change.

Multi-functional impacts imply multi-functional responses
A change in any one climate or hydrological parameter can impact upon many NRA activities, and NRA response in one area will influence the effect of climate change on another function. The NRA needs therefore to develop a multi-functional response to climate change. *Catchment management plans* provide the framework for such an approach. They consider explicitly the effects of climate change in a consistent and coordinated way across all functional activities.

An uncertain future implies flexibility in water management
An evolving and uncertain climate future necessitates a flexible or modular approach to water management. It is important that scope for revision and review is incorporated in both executive actions - such as building something that will last into the next century - and regulatory actions - such as issuing licences to abstract or discharge.

Identify critical thresholds for important activities
Climate change will have a significant impact upon an activity when it means that some critical threshold is passed (so that the "new" regime, for example, cannot be managed with existing operating rules). It is therefore necessary to seek to identify these critical thresholds for important activities and structures, and to ascertain the likelihood that these thresholds will be crossed in the future. In some areas, climate change would result in a gradual erosion or enhancement of resource potential.

An uncertain future implies continual monitoring
It is important to monitor changes in all aspects of the water environment, both to check to see how changes compare with those expected due to climate change and modify the management response accordingly, and to obtain data which will help define the relationship between climate and response. The Environmental Change Network (in which the NRA is involved: Chapter 1) provides a particularly strong basis for long-term monitoring. Existing networks should be reviewed to identify additional monitoring sites reasonably free of human interference (although in many regions it will be difficult to find natural recording sites). Long-term records can be used to place "unusual" events in a long-term context.

REFERENCES

Advisory Committee (1992) *Flood and Coastal Defence Research and Development.* MAFF, Scottish Office Environment Department and NRA. 78 pp.

Alabaster, J.S. and Lloyd, R. (1980) *Water Quality Criteria for Freshwater Fish.* Butterworths: London.

Armitage, P.D. and Ladle, M. (1991) Habitat preferences of target species for application in PHABSIM testing. in Bullock *et al.* (1991).

Arnell, N.W. (1992) Impacts of climatic change on river flow regimes in the UK. J. *Institution of Water and Environmental Management*, **6**, (4), 432-442.

Arnell, N.W. and Reynard, N.S. (1993) *Impacts of Climate Change on River Flow Regimes* in the UK. Institute of Hydrology. Report to Department of the Environment Water Directorate.

Arnell, N.W., Brown, R.P.C., and Reynard, N.S. (1990) *Impact of Climatic Variability and Change on River Flow Regimes in the UK.* Institute of Hydrology Report 107. Wallingford.

Ball, J.H., Clark, M.J., Collins, N.B., Gao, S., Ingham, A. and Ulph, A. (1991) *The Economic Consequences of Sea Level Rise on the Central Southern Coast of England.* GeoData Institute. Report to MAFF. 2 vols.

Bardossy, A. and Plate, E.J. (1992) Space-time model for daily rainfall using atmospheric circulation patterns. *Water Resources Research*, **28**, 1247-1259.

Bateman, I., Bateman, S., Brown, D., Doktor, P., Karas, J.H.W., Maher, A. and Turner, R.K. (1991) *Economic Appraisal of Climate-induced Sea Level Rise: A Case Study of East Anglia. University of East Anglia.* Report to MAFF.

Bencala, K.E. and Walters, R.A. (1983) Simulation of solute transport in a mountain pool-and-riffle stream: a transient storage model. *Water Resources Research*, **9**, 717-724.

Binnie, C.J.A. and Herrington, P.R. (1992) Possible effects of climate change on water resources and water demand. *Symposium on Engineering in the Uncertainty of Climatic Change.* Institution of Civil Engineers, London 28 October 1992.

Boardman, J., Evans, R., Favis-Mortlock, D.T. and Harris, T.M. (1990) Climate change and soil erosion on agricultural land in England and Wales. *Land Degradation and Rehabilitation,* **2**, 95-106.

Bolin, B., Doos, B.R., Jager, J. and Warrick, R.A. (eds) (1986) *The Greenhouse Effect, Climate Change and Ecosystems.* Wiley: Chichester.

Boorman, L.A., Goss-Custard, J.D. and McGrorty, S. (1989) *Climatic Change, Rising Sea Level, and the British Coast.* Institute of Terrestrial Ecology. Res. Publ. 1. HMSO: London.

Bray, R.N. and Owen, M.W. (1991) *Review of Coastal and Estuarial R&D Related to Flood Defence.* R&D Project Report 308/2/HO. NRA Bristol.

British Waterways (1991) *Annual Report and Accounts* 1991. British Waterways.

Budyko, M. (1980) Klimat v Proslom i Budustem. Cited in Nemec and Schaake (1982).

Bullock, A., Gustard, A. and Grainger, E.S. (1991) *Instream Flow Requirements of Aquatic Ecology in Two British Rivers.* Institute of Hydrology Report 115.

Bunch, A. and Smithers, H. (1992) The potential impact of climate change on regional resources in NWW Ltd. Manuscript. 10 pp.

Burrows, A.M. and House, M.A. (1989) Public's perception of water quality and the use of water for recreation. in Laikari, H. *River Basin Management-V.* Pergamon: Oxford. 371-379.

Carter, T.R., Parry, M.L., Nishioka, S. and Harasawa, H. (1992) *Preliminary Guidelines for Assessing Impacts of Climate Change.* Intergovernmental Panel on Climate Change Working Group II. Environmental Change Unit and Center for Global Environmental Research. 28pp.

Clark, K.J., Clark, L., Cole, J.A., Slade, S. and Spoel, N. (1992) *Effect of Sea Level Rise on Water Resources.* WRc plc. National Rivers Authority R&D Note 74.

CCIRG (Climate Change Impacts Review Group) (1991) *The Potential Effects of Climate Change in the United Kingdom.* HMSO: London.

Cole, J.A., Slade, S., Jones, P.D. and Gregory, J.M. (1991) Reliable yield of reservoirs and possible effects of climate change. *Hydrol.* Sci. J., **36** (6), 579-598.

Dearnaley, M.P. and Waller M. N. H. (1993) Impact of Climate change on Estuarine Water Quality. HR Wallingford Report SR 369. Report to Department of Environment Water Directorate.

DoE, MAFF and Welsh Office (1992) *Development in Flood Risk Areas.* Draft Circular.

Doktor, N.P., Turner, R.K. and Kay, R.C. (1991) *Economic Appraisal of Climate-induced Sea Level Rise: A Case Study of East Anglia - Extension Study.* University of East Anglia. Report to NRA.

Drake, B.G. (1992) The impact of rising CO_2 on ecosystem production. *Water, Air and Soil Pollution,* **64**, 25-44.

Elliott, J.M. (1975a) Weight of food and time required to satiate brown trout, *Salmo trutta* L. *Freshwater Biol.*, **5**, 51-64.

Elliott, J.M. (1975b) Number of meals in a day, maximum weight of food consumed in a day and maximum rate of feeding for brown trout, *Salmo Trutta* L. *Freshwater Biol.*, **5**, 287-303.

Elliott, J.M. (1975c) The growth rate of brown trout Salmo trutta L. fed on maximum rations. *J. of Animal Ecology*, **44**, 805-821.

Elliot, J.M. (1981) Some aspects of thermal stress in teleosts. in: Pickering, A.D. (ed) *Stress and Fish.* Academic Press: London. 209-245.

Elliott, J.M. (1985) Population dynamics of migratory trout Salmo trutta in a Lake District stream 1966-1983 and their implications for fishery management. *J. of Fish Biol.*, **27**, 35-43.

Gardiner, J.L. (1990) River catchment planning for land drainage, flood defence and the environment. J. *Institution of Water and Environmental Management*, **4**, 442-450.

Gardiner, J.L. and Cole, L. (1992) Catchment planning: the way forward for river protection in the UK. in Boon, P.J., Calow, P. and Petts, G.E. (eds) *River Conservation and Management.* Wiley: Chichester. 397-406.

Gellens, D. (1991) Impact of a CO_2-induced climate change on river flow variability in three rivers in Belgium. *Earth Surface Processes and Landforms.* **16**, 619-625.

George, D.G., Hewitt, D.P., Lund, J.W.G. and Smyly,W.J.P. (1990) The relative effects of enrichment and climate change on the long-term dynamics of Daphnia in Esthwaite Water, Cumbria. *Freshwater Biology,* **23**, 55-70.

Harding, R.J., Hall, R.L., Neal, C., Roberts, J.M., Rosier, P.T.W. and Kinniburgh, D.G. (1992) *Hydrological Implications of Broadleaf Woodlands: Implications for Water Use and Water Quality.* R&D Project Record 115/03/ST. NRA, Bristol.

Harvey, A.M. (1991) The influence of sediment supply on the channel morphology of upland streams: Howgill Fells, North West England. *Earth Surface Proc. and Landforms*, **16**, 675-684.

Hawkes, H.A. (1969). Ecological changes of applied significance from waste heat. In: Krenkel and Parker (eds) *Biological Aspects of Thermal Pollution.* Vanderbilt University Press. 15-53.

Herrington, P. (1994) Climate change and the demand for water. University of Leicester. Report to Department of Environment Water Directorate.

Hewett, B.A.O., Harries, C.D. and Fenn, C.R. (1992) Water resources planning in the uncertainty of climate change: a water company perspective. *Symposium on Engineering in the Uncertainty of Climatic Change.* Institution of Civil Engineers, London 28 October 1992.

Holt, T. (1991) *Storm Conditions over the North Sea: A Historical Perspective and Implications for the 21st Century.* Report to Halcrows, under contract to NRA Anglian Region as part of the Anglian Sea Defence Management Study. Climatic Research Unit, University of East Anglia. 110 pp.

Institute of Hydrology (1985) The FSR rainfall-runoff model parameter estimation equations updated. *Flood Studies Supplementary Report 16.* IH, Wallingford.

Institute of Hydrology (1990) *Maidenhead, Windsor and Eton Flood Alleviation Scheme*: Water Quality Study. Report to NRA Thames Region.

IACGEC (Inter-Agency Committee on Global Environmental Change) (1991) *Global Environmental Change: The UK Research Framework.* IACGEC, Swindon. 34 pp.

IPCC (Intergovernmental Panel on Climate Change) (1990a) Climate Change. *The IPCC Scientific Assessment. Houghton,* J.T., Jenkins, G.J. and Ephraums, J.J. (eds) Cambridge University Press: Cambridge.

IPCC (Intergovernmental Panel on Climate Change) (1990b) *Climate Change. The IPCC Impacts Assessment.* Tegart, W.J.McG., Sheldon, G.W. and Griffiths, D.C. (eds) Australian Government Publishing Service: Canberra.

IPCC (Intergovernmental Panel on Climate Change) (1991) *Climate Change. The IPCC Response Strategies.* Island Press: Washington D.C.

IPCC (Intergovernmental Panel on Climate Change) (1992) *Climate Change 1992. The Supplementary Report to the IPCC Scientific Assessment.* Houghton, J.T., Callander, B.A. and Varney, S.K. (eds) Cambridge University Press: Cambridge.

Jacoby, H.D. (1990) Water quality. in Waggoner, P.E. (ed) *Climate Change and US Water Resources.* Wiley: New York. 307-328.

Jenkins, A., McCartney, M., Sefton, C. and Whitehead, P. (1993) *Impacts of Climate Change on River Water Quality in the UK.* Institute of Hydrology. Report to Department of the Environment Water Directorate.

Jenkins, A., McCartney, M, and Sefton, C. (1993) *Impact of climate change on river water quality in the United Kingdom.* Institute of Hydrology. Report to Department of the Environment Water Directorate.

Jones, P.D., Kelly, P.M., Goodess, G.B. and Karl, T.R. (1989) The effect of urban warming on the Northern Hemisphere temperature average. *Journal of Climatology,* **2**, 285-290.

Law, F.M. (1989) Identifying the climate-sensitive segment of British reservoir yield. *Conference on Climate and Water*, Helsinki, Finland, 11-15 September 1989. Vol. 2 177-189.

Maitland, P.S. (1972) *Key to British Freshwater Fishes.* Freshwater Biological Association, Scientific Publication No. 27, 134 pp.

McDonald, A.T., Mitchell, E.N., Naden, P.S. and Martin, D.S.J. (1991) *Discoloured Water Investigations.* Final Report to Yorkshire Water plc. University of Leeds.

Naden, P.S. (1992) *Modelling Water Colour in Upland Catchments.* Report to Yorkshire Water plc. Institute of Hydrology, Wallingford.

National Rivers Authority (1990) *Corporate Plan 1990/91.* NRA, September 1990.

National Rivers Authority (1991a) *Climate Change - Sea Level Rise and Isostatic Variations.* Policy Implementation Guidance Note TE/FD/001. September 1991.

National Rivers Authority (1991b) *Survey of Water Resources Modelling Activities. Water Resources Managers Group.*

National Rivers Authority (1991c) *Proposals for Statutory Water Quality Objectives.* Water Quality Series Report 5, 99 pp.

National Rivers Authority (1992) *Water Resources Development Strategy.* A discussion document. National Rivers Authority, March 1992.

Natural Environment Research Council (1975) *Flood Studies Report.* HMSO: London. 5 vols.

Nemec, J. and Schaake, J. (1982) Sensitivity of water resource systems to climate variation. *Hydrol. Sci.* J., **27**, 327-343.

Owen, M.W. and Steele, A.J. (1991) *Sensitivity of Sea Defence Structures to Rise in Sea Level.* Report to National Rivers Authority. HR Wallingford. pp 16 +figs.

Palutikof, J.P. (1987) Some possible impacts of greenhouse gas-induced climatic change on water resources in England and Wales. *The Influence of Climate Change and Climatic Variability on the Hydrological Regime and Water Resources. International Association of Hydrological Sciences Publication,* **168**, 585-596.

Parry, M.L. and Carter, T.R. (1988) The assessment of effects of climatic variation on agriculture: aims, methods and summary of results. in Parry, M.L, Carter, T.R. and Konijn, N.T. (eds) *The Impact of Climatic Variations on Agriculture. Volume 1: Assessment in Cool Temperate and Cold Regions.* Kluwer: Dordrecht. 11-95.

Posford Duvivier (1991) *Environmental Opportunities in Low Lying Coastal Areas under a Scenario of Climate Change*. Report to NRA, DoE, NCC, Countryside Commission. R&D Project Report 255/2/T.

Reynolds, C.S. (1984). *The Ecology of Freshwater Phytoplankton*. Cambridge University Press, Cambridge.

Reynolds, C.S. & Glaister, M.S. (1992). *Environments of Larger U.K. Rivers*. Institute of Freshwater Ecology. Report to the NRA. 78 pp.

Reynolds, C.S., Carling, P.A. & Beven, K.J. (1991). Flow in river channels: new insights into hydraulic retention. *Archiv für Hydrobiologie*, **121**, 171-179.

Santer, B.D., Wigley, T.M.L., Schlesinger, M.E. and Mitchell, J.F.B. (1990) *Developing climate scenarios from equilibrium GCM results*. Max Planck Institut für Meteorologie Report 47, Hamburg, Germany.

Scottish Fisheries Research Station (1992) *Description of NRA Tracking Studies*. National Rivers Authority R&D Note 33.

Smith, K. (1990) Tourism and climate change. *Land Use Policy* 7, (2), 176-180.

Talling, J.F.T. (Ed) (1989). *A general assessment of environmental and biological features of Windermere and their susceptibility to change*. Commissioned Report to the North West Water Authority, 79 pp.

Thompson, N., Barrie, I.A. and Ayles, M. (1981) *The Meteorological Office rainfall and evaporation calculation system (MORECS)*. Hydrol. Mem. 45, Met. O. 8, Bracknell.

Thurlow, G.G. (ed) (1990) *Technological Responses to the Greenhouse Effect*. Watt Committee on Energy, Working Group on the Greenhouse Effect. Report 23. Elsevier: London. 98 pp.

Turner, P.C., Gammie, A.J., Hollinrake, K. and Codd, G.A. (1990). Pneumonia associated with contact with cyanobacteria. *British Medical Journal*, **300**, 1440-1441.

University of Durham (1991) *Impact of Sea-Level Rise*. Report to Halcrows, under contract to NRA Anglian Region as part of the Anglian Sea Defence Management Study. University of Durham. 13 pp.

Viner, D. and Hulme, M. (1992a) *Climate Change Scenarios for the Impacts Community: Report of Workshop*. Climatic Research Unit, Norwich.

Viner, D. and Hulme, M. (1992b) Climate Change Scenarios for Impact Studies in the UK: General Circulation Models, Data Sets, Construction Methods and Applications. Report to UK Department of the Environment, Contract No. 7/12/96. Climatic Research Unit, Norwich.

Webb, B. (1992) *Climate change and the thermal regime of rivers*. University of Exeter. Report to Department of the Environment Water Directorate.

Webb, B.W. (1992) *Climate Change and the Thermal Regime of Rivers*. University of Exeter. Report to Department of the Environment Water Directorate. 76 pp.

Wheeler, A. (1977). The origins and distribution of freshwater fish in the British Isles. J, **4**, 1-24.

Whitehead, P.G., Beck, M.B. and O'Connell, P.E. (1981) A system model of flow and water quality in the Bedford Ouse river system. II Water quality modelling. *Water Resources,* **15**, 1157-1171.

Wigley, T.M.L. and Raper, S.C.B. (1992) Implications for climate and sea level of revised IPCC emissions scenarios. *Nature,* **357**, 293-300.

Wigley, T.M.L., Jones, P.D., Briffa, K.R. and Smith, G. (1990) Obtaining sub-grid scale information from coarse resolution GCM output. *J. Geophysical Research,* **95**, 1943-1953.

Wigley, T.M.L., Holt, T. and Raper, S.C.B. (1991) *STUGE (an Interactive Greenhouse Model)*: User's Manual. Climatic Research Unit, Norwich.

Willoughby, L.G. and Copland, J.W. (1984) Temperature growth relationships of *Saprolegnia* pathogenis to fish, especially eels cultivated in warm water. *Nova Hedwigia,* **39**, 35-55.

Wilkinson, W.B. and Cooper, D.M. (1993) The response of idealised aquifer/river systems to climate change. *Hydrol. Sci.* J. **38**, 379-390

Wind, H.G. (1987) *The Impact of Sea Level Rise on Society*. Balkema: Rotterdam.

Youngs, E.G., Chapman, J.M., Leeds-Harrison, P.B. and Spoor, G. (1991) The application of a soil physics model to the management of soil water conditions in wildlife habitats. *Hydrological Basis of Ecologically Sound Management of Soil and Groundwater*. International Association of Hydrological Sciences Publication, 202, 91-100.

APPENDIX A: CURRENT CLIMATE CHANGE RESEARCH PROJECTS

This appendix lists just those projects concerned explicitly with climate change, and only those directly relevant to the NRA. The results of the many other projects studying environmental processes will also be valuable to climate change impact assessments. The list was compiled in summer 1993.

Table A.1 Climate change scenarios for the UK

Title	Funding agency	Contracting organisation	Status	Duration	Comments
Climate change scenarios for the UK	DoE (Global Atmosphere Division)	Climatic Research Unit	In progress	1991-1993	Climate Impacts LINK project
Transient climate change scenarios	MAFF	Climatic Research Unit	In progress	1991-1993	Input to agricultural impact studies

Table A.2 Water resources

Title	Funding agency	Contracting organisation	Status	Duration	Comments
Impact of climatic variability and change on UK river flow regimes	DoE (Water Directorate)	Institute of Hydrology	Complete	1986- 1989	Results presented in IH Report 107
Climatic change and its potential effect on UK water resources	NRA	Water Research Centre	Complete	1989-1990	Reported in Cole *et al.* (1991)
Impact of climate change on water quantity	DoE (Water Directorate)	Institute of Hydrology	In progress	1990-1993	Part of DoE Water Directorate "umbrella" project
Impact of climate change demand for water	DoE (Water Directorate)	Dept. of Economics, Univ. of Leicester	In progress	1991-1993	Part of DoE on Water Directorate "umbrella" project
Possible effects of sea level rise on water resources	NRA B277	Water Research Centre	Complete	1990-1992	See Clark *et al.* (1992)

Table A.3 Water quality

Title	Funding agency	Contracting organisation	Status	Duration	Comments
Impact of climate change on water quality	DoE (Water Directorate)	Institute of Hydrology	In progress	1990-1993	Part of DoE Water Directorate "umbrella" project
Impact of climate change on the thermal regime of rivers	DoE (Water Directorate)	Dept. of Geography Univ. of Exeter	In progress	1991-1992	Part of DoE Water Directorate "umbrella" project
Impact of climate change on estuarine water quality	DoE (Water Directorate)	HR Wallingford	In progress	1991-1993	Part of DoE Water Directorate "umbrella" project
Modelling the impact of climate change on biogeochemical processes	DoE (Global Atmosphere Division)	Institute of Hydrology	In progress	1990-1994	DoE "Core Modelling" programme, with ecological parts by ITE
Implications for changes in infectious disease patterns as a consequence of global warming	Public Health Laboratory Services	PHLS	Completed	1990-1992	Report published in Autumn 1992
The impact of climate change on the dynamics of lake plankton	NERC	Institute of Freshwater Ecology	In progress	1992-1994	

Table A.4 Flood defence

Title	Funding agency	Contracting organisation	Status	Duration	Comments
Impact of climate change on sea defences	NRA	Water Research Centre	Complete	1990-1991	
Economic appraisal of the consequences of climatic-induced sea level rise	MAFF	University of East Anglia	Complete	1990-1991	

Economic appraisal of the consequences of climatic-induced sea level rise	NRA	Halcrow	Complete	1990-1991	Extension to above MAFF project
Sensitivity of sea defence structures to greenhouse effect	NRA	HR Wallingford	Complete	1990-1991	
Beach development due to climatic change	NRA	HR Wallingford	In progress	1990-1992	
Climate change, sea level rise and associated impacts in Europe	CEC DGXI	Dept. of Geography, Coventry Poly.	In progress	1991-1993	Part of CEC-scale study and consortium
Impact of sea level rise on coastal lowlands	Several, including CEC	Environmental Research Centre, Univ. of Durham	In progress projects	1990-	Several linked
The economic impact of predicted sea level rise on the central southern coast of England	MAFF	Geo Data Institute, Univ. of Southampton	Complete	1990-1991	
Impact of sea level rise	NRA	Halcrow / Univ. of Durham	Complete	1990-1991	Part of Anglian Sea Defence Management Study
Impact of climate change on North Sea storm conditions	NRA	Halcrow / Univ. of East Anglia	Complete		1990-1991 part of Anglian Sea Defence Management Study
Methods of estimating the the effects of climatic variation on waves around the UK	MAFF	IoS Deacon Laboratory	Ongoing commission	1989-	
Wave climate change and its impact on UK coastal management	MAFF	HR Wallingford	Complete	1989-1991	HR Report SR260
Climatic change: UK sea level trends	MAFF	Proudman Laboratory	In progress	1989-	

Table A.5 Conservation

Title	Funding agency	Contracting organisation	Status	Duration	Comments
Environmental opportunities under a scenario of sea level rise	NRA	Posford-Duvivier	Complete	1990-1991	
Climate change, rising sea and the British Coast	DoE Air Quality Division	Institute of Terrestrial Ecology	Complete	1989	

APPENDIX B: GLOSSARY OF TERMS

AFRC	Agriculture and Food Research Council
BAC	Biological Adaptation to Global Environmental Change
BAHC	Biospheric Aspects of the Hydrological Cycle project
BNSC	British National Space Centre
BOD	Biochemical Oxygen Demand
BOFS	Biogeophysical Ocean Flux Study
BWB	British Waterways Board
CCC	Canadian Climate Centre
CCIRG	Climate Change Impacts Review Group
CCW	Countryside Council for Wales
CPRE	Council for the Preservation of Rural England
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
DO	Dissolved Oxygen
DoE	Department of the Environment
CEC	Commission for European Communities
ECN	Environmental Change Network
EN	English Nature
EPD	Environmental Protection Division (of MAFF)
ESRC	Economic and Social Research Council
FC	Forestry Commission
GA	Global Atmosphere Division (DoE)
GCIP	GEWEX Continental-scale International Project
GCM	General Circulation Model
GCOS	Global Climate Observing System
GENIE	Global Environmental Network for Information Exchange
GEWEX	Global Energy and Water Cycle Experiment
GFDL	Geophysical Fluid Dynamics Laboratory
GIS	Geographical Information System
GISS	Goddard Institute for Space Studies
HMIP	Her Majesty's Inspectorate of Pollution
HOST	Hydrology of Soil Types database
HR	Hydraulics Research, Wallingford
IACGEC	Inter-Agency Committee on Global Environmental Change
ICSU	International Council of Scientific Unions
IFE	Institute of Freshwater Ecology
IGAC	International Global Atmospheric Chemistry project
IGBP	International Geosphere-Biosphere Programme
IH	Institute of Hydrology
IPCC	Intergovernmental Panel on Climate Change
ITE	Institute of Terrestrial Ecology
LA	Local Authority
LOIS	Land Ocean Interface Study
MAFF	Ministry of Agriculture, Fisheries and Food
MLURI	Macaulay Land Use Research Institute
MORECS	Meteorological Office Rainfall and Evaporation Calculation System
NCAR	National Centre for Atmospheric Research
NERC	Natural Environment Research Council
NRA	National Rivers Authority

OFWAT	Office of Water Services
PIGN	Policy Implementation Guidance Note
PHLS	Public Health Laboratory Services
PLC	Private water services companies
QUASAR	Quality Simulation Along Rivers
SERC	Science and Engineering Research Council
SOAFD	Scottish Office Agriculture and Fisheries Department
SSLRC	Soil Survey and Land Research Centre
STUGE	Sea Level and Temperature Under the Greenhouse Effect
SWQO	Statutory Water Quality Objective
TIGER	Terrestrial Initiative in Global Environmental Research
UGAMP	Universities Global Atmospheric Modelling Project
UNCED	United Nations Conference on Environment and Development
UNEP	United Nations Environment Programme
WCIP	World Climate Impacts Programme
WD	Water Directorate (DoE)
WMO	World Meteorological Organisation
WOCE	World Ocean Circulation Experiment
WRc	Water Research Centre

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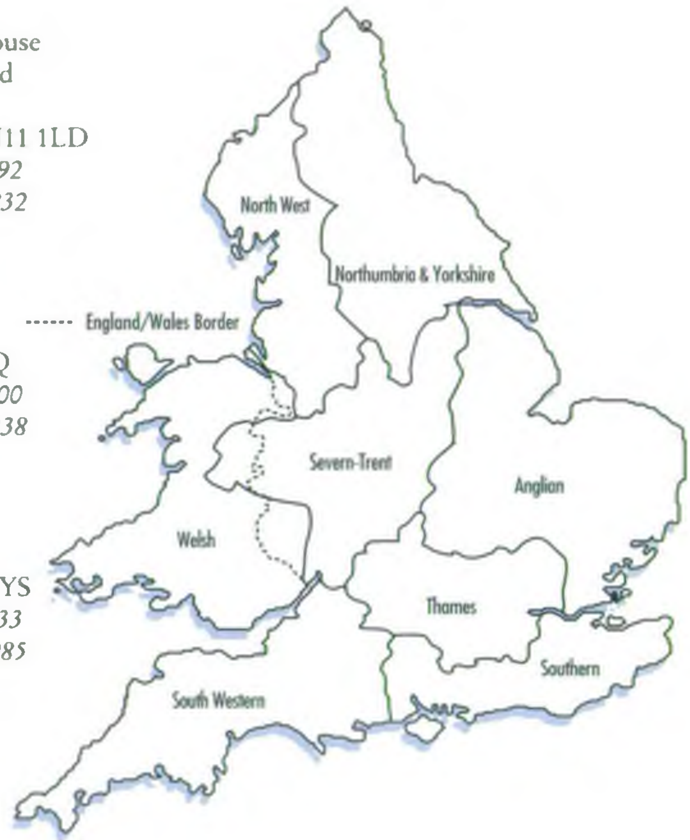

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