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THE POTENTIAL IMPACTS OF CLIMATE CHANGE ON THE NATIONAL RIVERS AUTHORITY

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DRAFT REPORT

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EXECUTIVE SUMMARY

The risk of climate change due to global warming became one of biggest scientific, political and public issues of the 1980s, and likely to remain important during the 1990s and into the next century.

The primary objectives of this report are to summarise the current scientific consensus on global warming, to review the implications of climate change for each of the NRA's seven core functions, and to identify climate change parameters of greatest relevance to the NRA.

The consensus of the Intergovernmental Panel on Climate Change is that, unless mitigating actions are taken, global temperatures will rise by approximately 3°C per decade and the global mean sea level in 2030 will be around 18cm higher than at present. However, these estimates are very uncertain, and their is even greater uncertainty in estimated changes at the scale of the UK and, especially, in rainfall. The best guess of the UK Climate Change Impacts Review Group is that by the middle of the next century winters in the UK will be wetter than at present, and for there to be no change in summer rainfall. Evaporation would be higher because of the increased temperature. These are not predictions of climate change, but are to be regarded as feasible, realistic *scenarios* of possible future conditions. Rainfall changes are of most significance for the NRA, but scenarios for rainfall change are particularly uncertain; estimates of possible changes in short-duration, flood-producing rainfall are extremely uncertain.

There are two levels of uncertainty in estimating the impacts of climate change in a particular sector. Firstly, there is the uncertainty in estimating possible changes in climate, as indicated above. Secondly, the relationship between climate and response may be poorly understood and inadequately quantified. Some of these relationships are quite well defined - such as those relating river runoff to rainfall and evaporation inputs - and it is possible to make quantified assessments of the implications of *given climate change scenarios*; other relationships - particularly in the ecological field - are less well known and it is currently *not* possible to make quantitative estimates of possible change.

The most important effects of climate change for the NRA will be on *coastal flooding* (which is likely to become much worse) and on *water resource availability* (which may either increase or decrease, depending on the exact climate change). There will be lesser effects on water quality, fluvial flooding (although this might be quite significantly affected; little is known), fisheries and conservation. The recreation and navigation functions will also be affected by climate change, but to unknown and uncertain degrees.

Most of the research effort has so far concentrated on the implications of climate change and sea level rise on coastal flooding (indicating its importance to the NRA), and there have also been a number of projects concerned with water resources. Other areas have received much less attention.

CONTENTS

1. INTRODUCTION: CLIMATE CHANGE AND THE NRA

1.1 Objectives of report

The objectives of this report are to:

1. Summarise for the National Rivers Authority the current status of the scientific understanding of global warming and the prediction of its effect.

2. Review the implications of climate change for all core function activities of the National Rivers Authority, given current information, and identify the most sensitive areas and activities.

3. Identify the climate change parameters of greatest relevance to the National Rivers Authority.

4. Identify recent and current research relevant to climate change and the NRA.

5. Identify a number of priority areas for future consideration.

1.2 The role of the National Rivers Authority

The National Rivers Authority (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 works closely with 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 through the NRA (?). It also sets performance targets, approves Drought Orders and gives permission for large NRA 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 needs to be informed about climate change (i) to help in its executive role, (ii) to help in its regulatory role (when approving licence applications and setting constraints) and (iii) to understand the pressures and problems facing those it regulates.

1.3 Structure of report

The report summarises current understanding of the effects of climate change on each of the seven NRA core functions. Each chapter describes a different core function (although recreation and navigation are combined), and has a similar structure covering (i) potential effects of climate change on the physical/biological system, (ii) implications for NRA activities, (iii) information required by the NRA and (iv) a summary of the key impacts and important climate parameters. Chapter 2 summarises the current scientific understanding of global warming and climate change to provide a background context.

A bibliography of relevant reports (published and unpublished) is given in Annex A, and Annex B lists recent and current research projects. Both are organised by core function.

1.4 <u>The organisation of climate change research in the UK</u>

The Global Atmosphere Division of the Department of the Environment is the lead government agency in the field of climate change. It works in the following main areas:

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

2. Support for the UK contribution to the Intergovernmental Panel on Climate Change (IPCC). The IPCC was established by WMO and UNEP to provide information on climate change to decision-makers.

3. 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), and is maintaining a watch on UK and international developments.

4. Support for a 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.

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

The Global Atmosphere Division of DoE does not support research into impacts in specific areas, and this is the responsibility of interested departments or agencies. The Water Directorate of the DoE, for example, has developed a programme concerned with the implications of climate change for water resources (Chapters 3 and 4), and the Environmental Policy Division of MAFF has a large programme (£1.075million in 1992/93) investigating climate change and agriculture. The Flood Defence and Land Sales Division of MAFF has supported work into the effects of sea level rise, as indeed has the NRA (Chapter 5).

Figure 1.1 summarises the relationships between the various committees with an interest in climate change in the UK, concentrating on those most relevant to the NRA. The DoE Water Directorate "Impact of climate change on water resources" Advisory Committee was established to oversee the Water Directorate's research programme, led by the Institute of Hydrology.

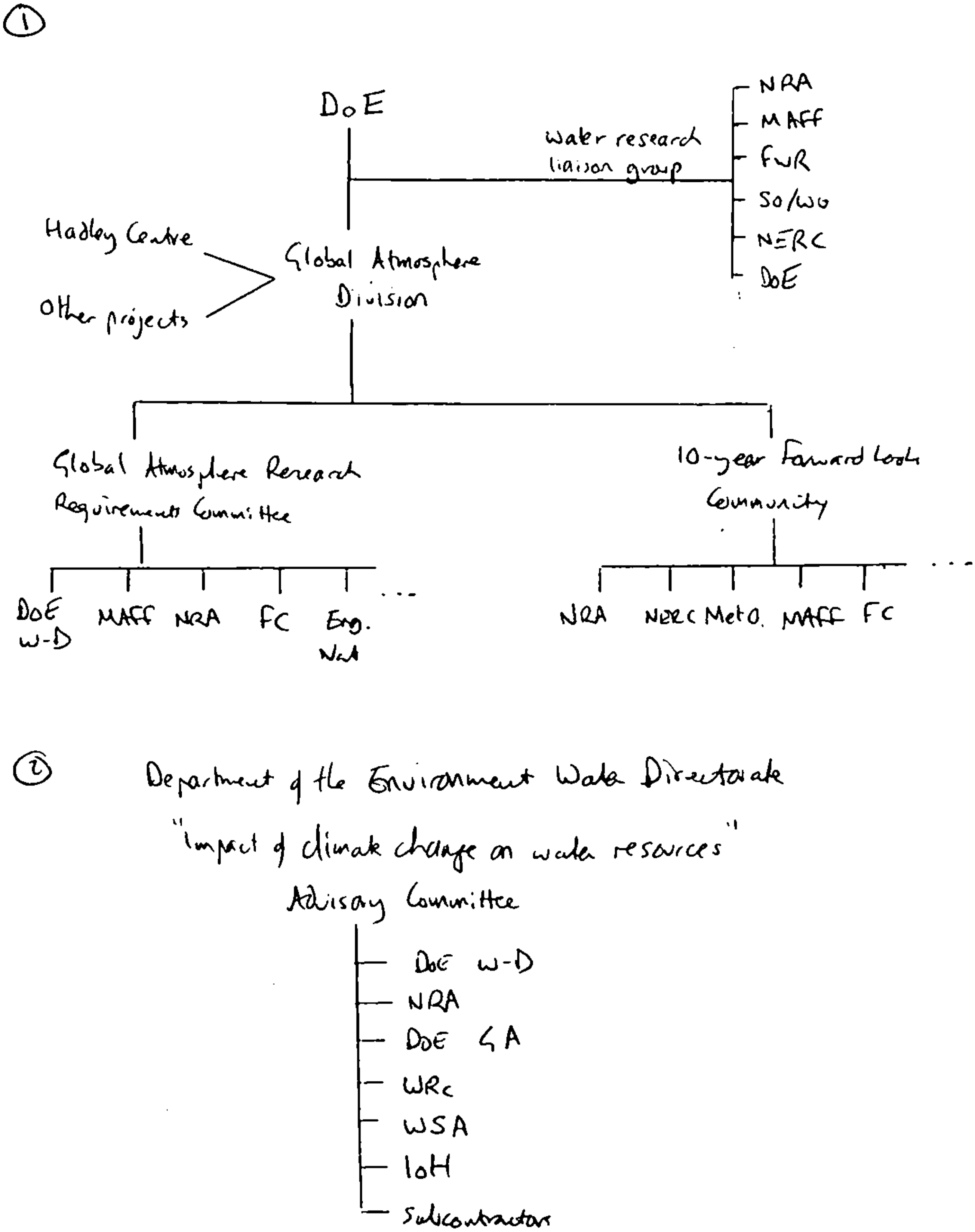


Figure 1.1: Relationships between committees concerned with climate change in the UK

2. CLIMATE CHANGE: PRINCIPLES AND SCENARIOS FOR ENGLAND AND WALES

2.1 Introduction

The aim of this chapter is to summarise the processes which lie behind global warming and to provide an introduction to the methods used to create scenarios for possible future changes in climate in England and Wales. The chapter also looks at evidence for climate change.

The information in this chapter is largely drawn from 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 One concentrated on the scientific aspects of climate change (Houghton et al, 1990), whilst Groups Two and Three reviewed impacts (Izrael et al, 1991) and policy responses (xxxx) respectively.

One hundred and seventy scientists from 25 countries contributed to Working Group One 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 April 1992 (reference..), to provide information for the negotiations for the International Convention on Climate Change which will be considered 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, and warms the surface and lower atmosphere. This is known as the "greenhouse effect", because the trace gases which are transparent to the incoming short-wave solar radiation but block 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^{o}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, and strictly 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 ice ages. Again, variations in the last few decades have been small 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 emitted into the atmosphere by human activity, and the 1992 Supplement to the IPCC Scientific Assessment 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. These fluctuations - the El Nino, which affects periodically at least the Pacific Ocean, is the best known - arise from the different response times of land and sea to seasonal temperature changes, and because it sometimes takes several years for conditions to build up to such a level that some threshold is crossed. These "natural" fluctuations are discussed further in Section 2.3.

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 deforestation and the combustion of fossil fuels. 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 there is a considerable uncertainty about the rate at which oceans and terrestrial biota can absorb extra carbon dioxide and so remove it from the atmosphere.

	Pre-industrial concentration	Present (1990) concentration	Annual rate of increase	Major sources
Carbon dioxide	280 ppmv	353 ppmv	0.5%	fossil fuels, deforestation
Methane	0.8 ppmv	1.72 ppmv	0.9%	rice production, cattle rearing
Nitrous Oxide	288 ppbv	310 ppbv	0.25%	internal combustion engine, agriculture
Ozone	no data	no data	no data	
CFC-11	0 pptv	280 pptv	4%	aerosols, refrigeration
CFC-12	0 pptv	484 pptv	4%	aerosols, refrigeration

Table 2.1: Important greenhouse gases (Houghton et al, 1990)

Methane is produced by a variety of anaerobic (i.e. oxygen deficient) processes, and the major human-influenced sources are rice production and cattle rearing. 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. 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 since pre-industrial times. Tropospheric ozone should have increased due to emissions of nitrogen oxides, hydrocarbons and carbon monoxide, although there are few measurements to quantify this increase; it 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 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 is less than previously assumed.

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 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.

The effects of increased greenhouse gas concentrations on regional climate can only be simulated using a physically-based representation of atmospheric and oceanic processes. General Circulation Models (GCMs) are based on the laws of physics and use parameterised descriptions of physical processes which operate at the smallest scale (such as cloud formation and deep mixing in the ocean). An atmospheric model - which is essentially the same as a weather forecasting model, although it is run for a period of several years rather than a few days - is coupled with an equally complicated 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 of carbon dioxide concentrations 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°C and 4.5°C (Bolin et al, 1986; Houghton et al, 1990). 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, take a very long time to run (XXX days for the UK Meteorological Office to simulate 100 years, for example) and are very expensive in computer 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.

A two-stage approach to estimating the regional effects of different greenhouse gas emissions scenarios has therefore evolved. The first stage uses a relatively simple model to simulate *global average temperature changes*; the second uses a GCM to estimate regional climatic changes, given the change in global temperature predicted from the first model.

Early one-dimensional models estimated changes in global average temperature from input changes in greenhouse gas concentrations, using simple representations of global average energy balances and oceanic upwelling and diffusion (Houghton et al, 1990). More recent models (such as IMAGE and STUGE: 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 changes in global average temperature; even these do not at present include all the feedbacks in the system (such as those resulting from the release of methane when permafrost thaws).

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 one GCM simulates a 10% increase in annual rainfall over a particular region for a $4^{o}C$ increase in global average temperature, then this is equivalent to a 2.5% increase per degree of global warming; if a particular emissions scenario results in a $3.0^{o}C$ increase in global average temperature by 2050, then annual rainfall over that region would be estimated to be 7.5% higher under that scenario. The key assumption here is that the spatial pattern of change will not vary as climate evolves; this is unrealistic - and has shown to be so from the results of the few long sequences that have been generated using a climate model with gradually changing greenhouse gas concentrations - but little else is feasible at present.

Current GCMs simulate the characteristics of the present climate 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 typically around 300km wide. Fine scale regional detail is therefore very difficult to simulate.

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 (reference..).

3. The links between the ocean and the atmosphere are currently not represented very realistically. 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 - are not necessarily simulated very accurately at present, and that it is not realistic to use GCMs 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 IPCC climate change scenarios

The Intergovernmental Panel on Climate Change made predictions of future global climate change using several climate simulation models and assumptions about future emissions of greenhouse gases, and these are summarised in Table 2.2.

Scenario	Increase per decade	Increase by 2030 over present value	Global mean sea level rise (cm) by 2030
Business-as-usual	0.3°C (0.2 to 0.5)	1.2°C (0.8 to 2.0)	18cm (8-29)
Scenario B	0.2°C	0.8°C	15cm
Scenario C	just over 0.1°C	0.5°C	15cm
Scenario D	0.1°C	0.4°C	14cm

Table 2.2 IPCC climate change predictions (Houghton et al, 1990). Some of the figures are read from graphs.

The four emissions scenarios represent different assumptions about future greenhouse gas emissions. The "Business-as-Usual" scenario assumes that few or no steps are taken to limit greenhouse gas emissions, and that they increase in line with predicted global economic development; the fourth scenario (Scenario D) assumes stringent controls, with a reduction in carbon dioxide emissions to 50% of 1985 levels by the middle of the next century. The 1992 Supplement saw no reason to change these estimates of change, despite the additional modelling studies completed since 1990. It is important to note that even if emissions of greenhouse gases were to be significantly reduced tomorrow, there would still be some increase in global temperature 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".

A change in global temperature and precipitation would also lead to a change in the mean global sea level. Factors contributing to a change in sea level are the thermal expansion of sea water in a warmer world, the melting of valley glaciers and changes in the Antarctic and Greenland ice sheets. The IPCC concluded that thermal expansion and glacier melt will have the greatest effect, but also stated that uncertainty in changes in the large ice sheets make a major contribution to the uncertainty in the predicted sea level change. Increased precipitation on the Antarctic ice sheet, for example, would mean that more precipitation is stored as snow and that sea level would fall slightly; at the other extreme it has been suggested (Tooley..) that a sudden outflow of ice from the West Antarctica ice sheet would lead to a rise in sea level of several metres. This is regarded by the IPCC as being highly unlikely. Table 2.2 also shows the IPCC estimates of changes in global sea level. The similar predictions for 2030 under emissions scenarios B, C and D reflect the current commitment to climate change; further in the future the predictions for these scenarios diverge.

2.3 Evidence for climate change

2.3.1 The global context

Analysis of observational temperature records has shown (Houghton et al, 1990) 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 1860, 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 1860 to 1991, expressed as a departure from the 1951 to 1980 average. Figure 2.3 compares the observed global temperature record with the simulated global temperature from one run of a climate model, in which the concentration of greenhouse gases in the atmosphere was gradually increased above pre-industrial levels (the model includes the effect of sulphate aerosols and stratospheric ozone depletion); there is a strong degree of consistency between the observed and simulated time series.

The graphs, however, do not prove conclusively that global warming is taking place. There are four problems.

1. The evidence is circumstantial: there is no *proven* link between the graph of increasing greenhouse gas concentrations and the graph of increasing temperatures, although a physical explanation has been proposed.

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 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 due to urbanisation of 0.1°C/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. Some regions will change more than others, and it is possible that some regions would become *cooler* in the future (this is shown by some transient climate model simulations). The 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 prove 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 IPCC in 1990 predicted that "the unequivocal detection of the greenhouse effect from observations is not likely for a decade or more" (Houghton et al, 1990, pxxix).

2.3.2 The 1988 to 1992 drought in south east England

Large parts of southern, central and eastern England have experienced prolonged drought conditions since 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 climate change, however, for several reasons:

1. Although extreme, recent hydrological events are not necessarily outside the limits of *historical* behaviour.

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 blame climate change for the drought 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 western-most 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.

2.4 Climate change scenarios for England and Wales

2.4.1 Scenarios

It is not possible to make accurate predictions of climate change for a region as small as England and Wales; the limitations and coarse spatial scale of current climate simulation models were mentioned in Section 2.2.3. 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.

2.4.2 The Climate Change Impacts Review Group scenarios

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 were produced using the methods summarised in Section 2.2.2; 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 determined by rescaling estimates made using several climate models. Table 2.3 summarises the CCIRG estimates of changes in mean temperature, precipitation and sea level by 2010, 2030 and 2050, under the IPCC "Business-as-Usual" scenario.

	2010		2030		2050	
	Summer	Winter	Summer	Winter	Summer	Winter
Temperature (^oC)	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)
Sea level (cm)	8 (4-13)		19 (9-29)		31 (15-45)	

Table 2.3 Climate change scenarios for the UK (CCIRG, 1991).

In general terms, the scenarios assume (i) increased rainfall in winter and (ii) no change in summer rainfall, but as Table 2.3 shows, there is considerable uncertainty over these estimates. The local effect of sea level change, of course, would depend on local land movements.

The scenarios show changes in *mean* rainfall, temperature and sea level. 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. 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 no assumptions about changes in such events.

2.4.3 Changes in potential evapotranspiration

The CCIRG also made no attempt to create scenarios for possible changes in evaporation, which is of course an important element in the hydrological cycle. An increase in temperature would be expected to increase the rate of evaporation (by, according to Budyko (19..), 4% per degree Celsius), but the changes in evaporation would also depend on changes in humidity, windspeed, net radiation and water availability. Arnell et al (1990), in their simulation of the effects of climate change on UK river flow regimes used two scenarios of change in potential evaporation. One assumed an increase of approximately 7% (with the greatest percentage increases in winter), whilst the other assumed an increase of 15%.

Sensitivity studies at the Institute of Hydrology (Reynard, 1992 pers. comm.) have shown that the effects of a given temperature increase on potential evaporation are very dependent on the assumed change in humidity. 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 vary between seasons.

There has been some controversy over changes in plant transpiration with increasing concentrations of greenhouse gases (reference.). Experimental evidence shows that plant stomatal conductance reduces as carbon dioxide levels increase, and plant transpiration (and hence water use) is reduced. However, plant growth increases as carbon dioxide levels increase, and whilst transpiration per leaf might decline, the number of leaves might increase. The effect of an increase in carbon dioxide depends on plant characteristics. In the field, however, a lack of nutrients might prevent a plant from responding to increased carbon dioxide levels. At the catchment scale, the volume of water evaporated by plants would change also as the vegetation mix within the catchment alters. This vegetation change might reflect directly changes in climate - an increase in plants which can tolerate summer drought, for example - or might reflect changes in farming and land use practice.

2.4.4 The Link Project

In the last few years there have been both rapid developments in the simulation of the climate system and increasing demands for climate change scenarios from impact researchers. The Global Atmospheres Division of the Department of the Environment therefore established a project to provide a link between the climate modelling research at the Hadley Centre for Climate Prediction and Research and the diverse impacts community. This link project is based at the Climatic Research Unit of the University of East Anglia (Mr David Viner), and has four aims (LINK Newsletter, 1992):

1. To liaise with the impacts community to determine the nature of their climate change data requirements.

2. To provide information to the impacts community to help them become familiar with the proper interpretation of GCM data.

3. 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 saved).*

4. To develop and provide a range of climate change scenarios for the UK in forms suitable for use by the impacts community.

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.

2.5 Estimating the implications of climate change

Attempts to estimate the implications of climate change can start from two different directions. One approach is to begin with a climate change scenario (or set of scenarios) and determine the consequences of that scenario for the activity of interest. The second approach is to identify a number of critical activities or concerns and work "backwards" to assess how sensitive they are to climate change, and what changes would cause most problems; these sensitivities can then be compared with feasible climate change scenarios.

Most climate change impact studies - in all fields - have so far followed the first approach, but it is likely that as attention shifts towards managed systems that the second approach will be increasingly used.

The outline methodology for a climate change impact study (following the first approach) is quite simple:

1. Define a set of climate change scenarios.

2. Apply a model of the system of interest with current climate data, and simulate system performance.

3. Apply the same model with climate data perturbed according to the climate change scenarios, and simulate system performance again.

4. Compare system performance under current and changed conditions.

The important part of this methodology - apart from the development of climate change scenarios, discussed in earlier sections - lies in the selection of an appropriate model of the system of interest. Ideally the model should be capable of being applied both under current conditions - where it was developed - and under a changed climate. Feasible models range from empirical-statistical models (such as those based on regression) to physically-based simulation models using a large number of measurable parameters. In practice, the parameters of empirical-statistical models tend to be strongly dependent on the data used for calibration, and the implied sensitivity to climate change may be controlled both by the exact magnitudes of the parameters and the form of the model itself. At the other extreme, physically-based models have large input requirements and operate at high time resolutions; Sections 2.2 and 2.4 have indicated that changes in such inputs cannot at present be estimated with reliability. Most climate change impact studies therefore use some form of "realistic" conceptual model, with physically-comprehensible parameters calibrated under current conditions.

2.6 Climate change parameters relevant to the NRA

The rest of this report reviews the possible implications of climate change for all NRA activities, but this final section to this chapter summarises the parameters of climate change that are of most relevance to the NRA.

Table 2.4 shows a number of important parameters, together with subjective assessments of the reliability of predictions of change.

The major implication of this table is that some NRA activities will have to wait longer for "reliable" estimates of relevant climate change parameters; high-intensity, short-duration rainfall is currently the most difficult to assess. This does not mean that it is too early to evaluate the sensitivity of these activities to climate change, but it does imply that some activities will have to use a rather wider range of scenarios than others and that it must be recognised that predictions are more uncertain.

	Current reliability from GCMs/models	Reliability in the medium term (5-10 years)	NRA activity
Temperature			
air temperature	****	****	all
water temperature	***	****	WQ,F
Precipitation			
monthly rainfall	**	***	WR,WQ,N
"flood-producing" rainfall	*	**	FD,WQ
snowfall	**	***	FD
winter rainfall	**	***	WR
Sea level			
mean sea level	****	****	FD,WQ,WR,N
storms and surges	*	***	FD
Evaporation			
monthly/weekly	**	***	WR,WQ
Insolation			
monthly/weekly	**	***	WQ,WR

Key to reliability:
- ***** very good
- **** good
- *** OK
- ** bad
- * awful

Key to NRA activities: WR = water resources, WQ = water quality, FD = flood defence, F = fisheries, R = recreation, C = conservation, N = navigation

Table 2.4: Climate change parameters of interest to the NRA, and their current and future reliability

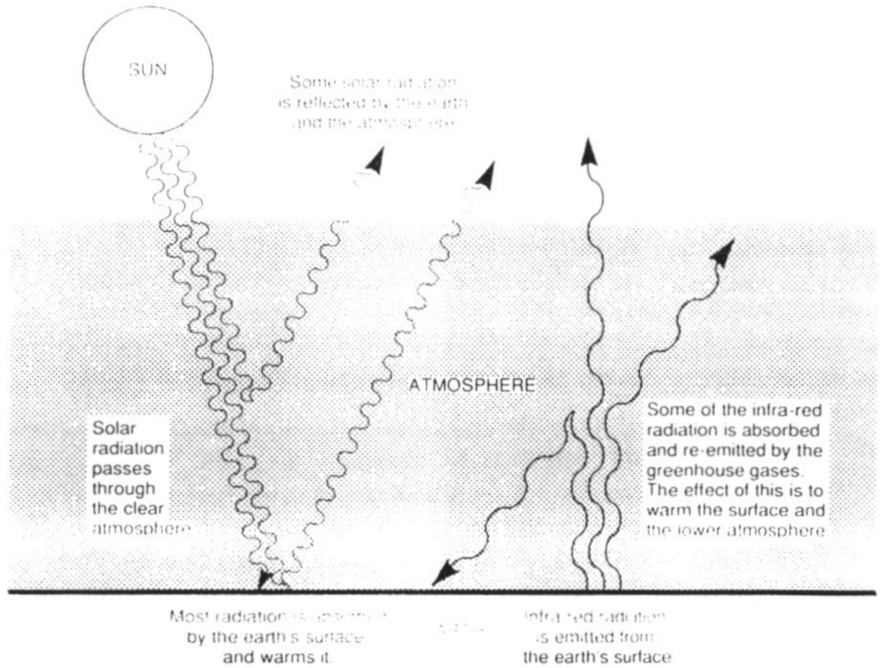


Figure 2.1: The greenhouse effect (IPCC, 1990)

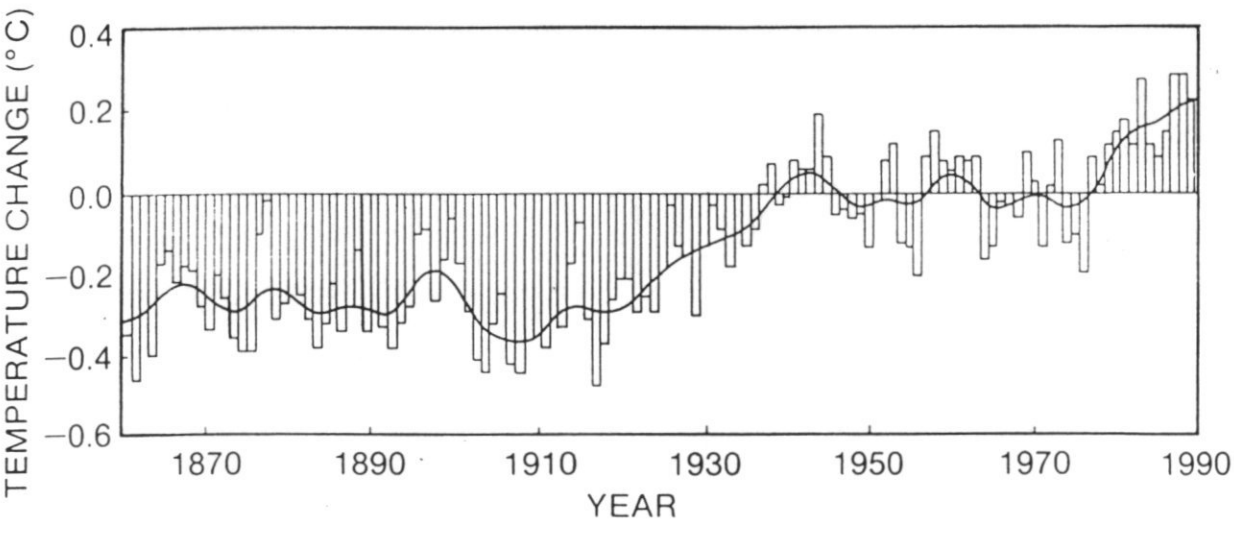


Figure 2.2: Global annual average temperature (IPCC, 1992)

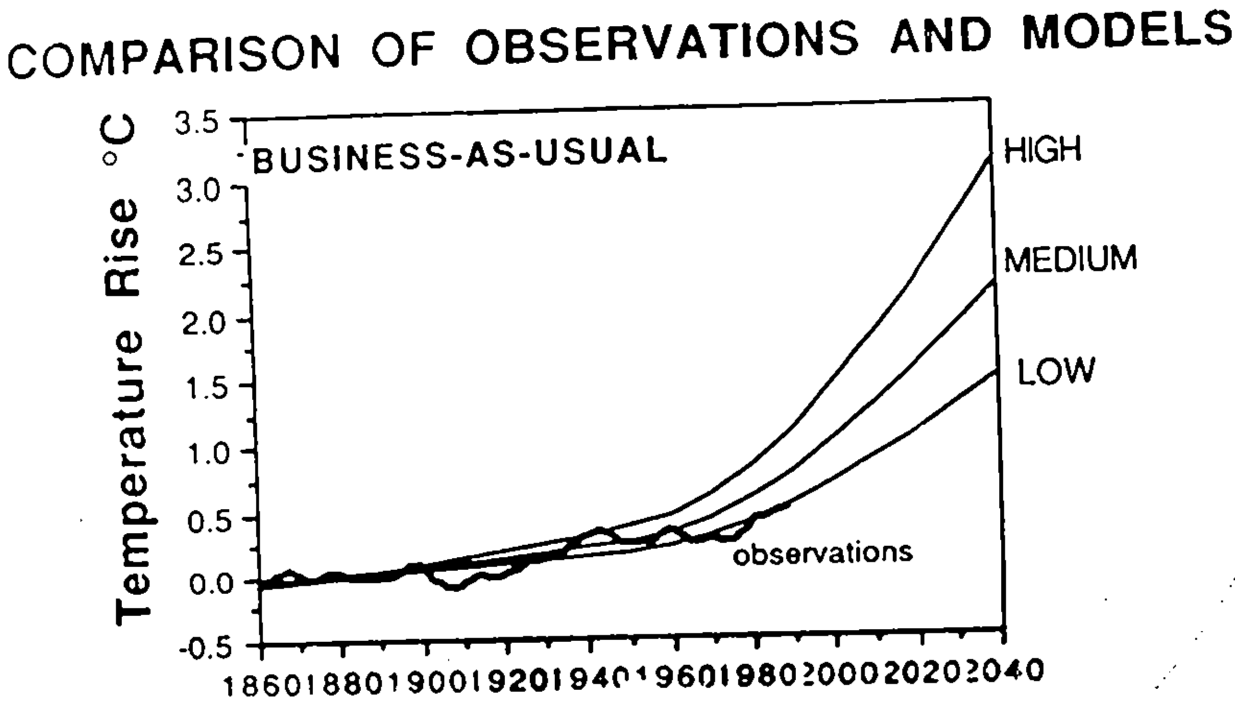


Figure 2.3: Comparison of observed and simulated global temperatures

3. WATER RESOURCES

3.1 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" (NRA, 1990; p24). More particularly, the NRA manages water 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.

Climate change due to global warming may affect the NRA's water resources activities in three main areas:

1. There may be a change in the ability of a water resources system to *supply* water.

2. There may be a change in the *demand* for water.

3. There may be a change in the *instream demands* of a river system necessary to maintain environmental quality.

Possible changes to the instream demands are covered in Chapters 4 and 6.

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. The *extra* demand - nearly 3200 ml/day over the whole of England and Wales - is similar to the total amount currently withdrawn for public supply in the Wessex and Southern Regions combined, and is concentrated in south and east England. If there is no further resource development, the available 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 exaggerate pressures further; in others, the effects of climate change may be trivial compared with the other changes taking place.

3.2 Changes in surface water resources

At the national scale, approximately two-thirds of all public water supplies are taken from surface water resources. Water is taken directly from rivers, from public supply reservoirs, from rivers regulated by upstream regulating reservoirs, and from rivers whose flow has been augmented by artificial recharge of groundwater.

There have been around 30 studies worldwide into the implications of climate change for river flow regimes, and over 100 papers have been published in the literature. Two of the studies have looked at river flow regimes in the UK (Arnell et al, 1990; Cole et al, 1991). The studies have used a variety of methodologies and climate change scenarios, but it is possible to draw one general conclusion: *the effects of a given climate change scenario can vary considerably between catchments*. The more arid the catchment the greater the relative effect of changes in rainfall and evaporation on runoff. Catchment geology affects the distribution of change through the year.

Figure 3.1 summarises the hydrological system in a simplified form, and indicates the areas of each component which might 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 and soil structure consequent upon climate change.

Practically all catchment-scale impact studies have concentrated on the direct effects of climate change. Attempts are being made at estimating the possible changes in land cover due to climate change (reference..) - although it is important to remember that land cover in the UK is largely a function of land use management decisions, not directly of climate - but there have been no attempts yet to tie these land use changes in with studies of the effects of changes in rainfall and evaporation. There have been very few studies into possible changes in soil structure, although a number of suggestions have been made: higher temperatures 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 shrink and crack, whilst increased waterlogging would encourage the development of gleyed profiles (CCIRG, 1991).

Figure 3.2 shows the percentage change in average annual runoff across the UK by 2050 assuming (i) no change in summer rainfall but an 8% increase in winter rainfall (CCIRG scenario from Table 2.3) and (ii) two different changes in potential evaporation. Figure 3.2a assumes an annual increase in potential evaporation of around 15%, whilst Figure 3.2b assumes an increase of 7% (Arnell et al, 1990). The changes were estimated by applying a very simple monthly water balance model to monthly rainfall and potential evaporation data from MORECS (the Meteorological Office Rainfall and Evaporation Calculation System: Thompson et al, 1981) averaged over the period 1961 to 1980. There are two important points to note from Figure 3.2. Firstly, there is a very large difference between the two different assumptions about evaporation. Figure 3.2a shows a *reduction* in average annual runoff across all but the north west, whilst Figure 3.2b indicates an *increase* in runoff across the whole country. Secondly, there is a large difference in impact across the UK, with the south east showing the greatest relative reduction (Figure 3.2a) and the smallest relative increase (Figure 3.2b). Figure 3.3 illustrates further the difference between different climate change scenarios, for a group of several MORECS cells in south east England. The shaded area defines the region 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 2.3) with an increase in evaporation of just 7%, whilst the lower line shows the effect of the driest CCIRG rainfall scenario with a 15% 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 that catchment and the catchment geology (Arnell et al, 1990). Figure 3.4 shows changes in monthly runoff - as a percentage departure from the current mean - for three different catchments, assuming the climate change scenario presented in Figure 3.2b (*the actual numbers are not to be taken too seriously here; the point of Figure 3.4 is to show the relative behaviour of different catchments*). Catchment A is a lowland catchment in eastern England. Summer rainfall is not very effective at generating runoff because potential evaporation is much higher than rainfall. Changes in summer rainfall or potential evaporation therefore have relatively little effect on summer flows, but have a greater effect of course on flows in autumn, because they determine the time when soil moisture deficits are replenished. Catchment B, however, is an upland catchment in north east England. Here summer evaporation is very close to summer rainfall, and a change in either sends the catchment into a water surplus (more summer rainfall) or a deficit (less rain or higher evaporation). There is therefore a very large percentage change in summer runoff, although the absolute amount may be quite small. The river flow regime in Catchment C is dominated by drainage from a chalk aquifer, and summer flows are totally dependent on the amount of winter recharge; river flows could be higher even during a warmer, drier summer, if groundwater recharge were to increase (Section 3.3). Although the actual numbers shown in Figure 3.4 are conditional on the climate change scenarios used and the form of runoff simulation model, it is expected that the relative behaviour of the different catchments is well represented.

There have been far fewer studies of the effects of climate change on reservoir reliability and the implications for the reliability of an entire water system. Cole et al (1991) ran some daily flow sequences representing current and future conditions through a reservoir storage-yield analysis, and 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 annual runoff of 8% in the south east, for example, led to a reduction in reliable yield of a hypothetical reservoir of between 8 and 25%. 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. Smithers and Bunch (1991) went further, and ran a number of climate change scenarios through a model of the water supply system operated by North West Water Services. They looked at the reliability of this "real" interconnected water supply system, and showed that the operational costs of climate change varied between X and Y according to the scenario used.

Although there have been very few studies of potential changes in water supply systems, it is already possible to conclude that 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 3.5 shows the stages in the simulation of the effects of climate change on water supply system reliability. Between each stage is a "filter", which may amplify the change being passed through the chain or possible dampen it down. Different catchments will respond in different ways to changes in climate inputs. The response of a water supply system will depend on how it is configured and the pressures it 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 than a system with a greater amount of buffering capacity. The more inter-connected the system, the better it will be able to cope with changes in climatic inputs.

3.3 Changes in groundwater resources

Approximately one third of all public water supplies in the UK derive from groundwater, and in large parts of the south east groundwater is the dominant source. There have, however, been no studies of the potential implications of climate change for groundwater recharge 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 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 only recharged 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 possibly drier summers - is compensated by an *increase in rainfall* during winter. A reduction in 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 it is better to have 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 groundwaters than short period intense rainfall, so if winter rainfall in the future were to be concentrated into shorter periods, recharge would be reduced.

3.4 Effects of rising sea level

A rising sea level would have two potential consequences for water resources; saline intrusion into coastal aquifers and a threat to surface water abstractions close to the tidal limit.

3.4.1 Saline intrusion into coastal aquifers

The Water Research Centre has, under contract to the NRA, surveyed coastal aquifers potentially at risk from saline intrusion. All ten 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 (Clark and Morgan, 1991). At the national scale, the effect of sea level rise on groundwater resources will be minimal, but local problems might arise. The WRc is currently modelling the impact of sea level rise on saline intrusion in a number of case study aquifers (results??).

3.4.2 Sea level rise and surface water abstraction points

Approximately 35 public supply abstraction points are located close to the tidal limits of a river (Clark and Morgan, 1991). NRA policy is to favour abstractions near the tidal limit (NRA, 1992), because upstream abstractions remove water along the whole length of the river.

The Water Research Centre, again under contract to the NRA, is reviewing the risk to low-lying public water abstractions in a number of estuaries, and has concluded (?) that the effects of sea level rise would be slight. The effect of sea level rise on the tidal limit would, of course, depend on estuary geometry, and estuaries which amplify sea level rise by the largest amount will be most affected.

3.5 Climate change and demand for water

It was noted in Section 3.1 that demand for public water supplies in England and Wales is projected to rise by 18%, or nearly 3200ml/day, by 2021. This increase is independent of climate change, and it is possible that global warming will lead to further increases. The implications of climate change for demand for water are currently being studied at the Department of Economics of the University of Leicester under contract to the Water Directorate of the Department of the Environment. The project is scheduled to finish in March 1993. Some conclusions, however, can already be drawn.

The greatest impact of climate change is likely to be on the demands for garden watering and the demand for summer spray irrigation.

Domestic garden watering by hosepipe can consume up to 30l/day, and is the major contribution to peak demands in southern and eastern England. Demand is highest on a warm late spring evening after a few dry days (and can be particularly high on a Friday). Demand for garden watering can represent around 5% of the total volume of water supplied to domestic customers during a year, so an increase of, say, 10% due to higher temperatures would only produce an increase in *annual* domestic demand of 0.5%. However, the contribution to domestic demand from garden watering is concentrated in the summer season, and an increase 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 awaits further study.

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 in 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 greater influenced by economic factors such as the price of vegetables and, also, the price of water. 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.

The major contribution to peak demands in northern and western England comes from burst pipes following a freeze and a thaw. In a warmer world, burst pipes might be expected to occur less frequently, but cold "pipe-bursting" events are still likely to occur. There is too little information on potential changes in the frequency of extreme frosts to estimate future losses from busrt pipes.

The remaining area which might be influenced by climate change is the demand for cooling water. Higher river water temperatures (Chapter 4) 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 cooling water requirements.

The instream demands of aquatic ecosystems and water quality maintenance might also be expected to change as river flow regimes alter and water temperatures increase; these demands are considered further in Chapters 4 and 6.

3.6 Effect on NRA water resources activities

Climate change is likely to have implications for operational NRA water resources activities and for design and resource planning.

3.6.1 Operational implications of climate change

The potential operational implications of climate change for the NRA water resources function include (i) dealing with requests for new or revised licences, (ii) responding to drought conditions and preparing or reviewing Drought Orders and (iii) increased monitoring to ensure that licence conditions are both being met and remain appropriate. Under current rules, compensation would need to be paid if licences were revoked or revised.

Increasing demands and possible reductions in supplies from established sources mean that abstractors will be seeking new water supplies and therefore applying for new licences. Abstractors may also want to revise existing licences to, for example, reduce compensation flow requirements or abstract larger volumes. Reviews of licence applications already consume a large proportion (xx%??) of NRA water resource staff time, and an increase in applications would add further pressure.

Staff time is also under heavy pressure during drought conditions. Resources need to be assessed, supplementary sources located, abstractors and public liaised with, 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. This 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.

The NRA currently monitors compliance with licence requirements (both routinely and occasionally). 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 licenced amounts would need to be reduced; in other cases, an increased availability of water might mean that larger volumes could be abstracted.

It would be difficult for the NRA to change licence conditions on the basis of predicted future flows or groundwater availability, even if climate change were widely accepted or even "government approved", because the actual numerical estimate of change in a particular catchment will remain uncertain for many years. Individual predictions would therefore be open to legal and technical challenge, except in the unlikely event that a single climate change scenario became accepted as "best possible professional practice" (*note that predicted future change in sea level is more likely to be accepted - Chapter 5 - because there are no specific affected parties ready to appeal*). Any revision to licence conditions would therefore need to be based on recent experience, backed up with the justification that this recent experience is not just an unusual occurrence which will be followed by a return to "normality". This important issue appears again in Chapter 4, and is considered in more detail in Chapter 9. Revocation or revision of licences, of course, also means that compensation may need to be paid to licence-holders. This would be an additional revenue cost which, under current NRA rules, would need to be covered from abstractors; an increase in the rate of revocation of licences would therefore lead to an increase in abstraction charges.

The possibility that climate is evolving and that conditions on current abstraction licences may not remain appropriate implies that the NRA should require that licences are reviewed periodically (HOW MUCH IS THIS DONE AT PRESENT??). This would enable greater flexibility in coping with climate change - but would of course entail additional work.

3.6.2 Design and planning

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, and by then temperature could be 1oC higher than at present (Table 2.3).

One approach would be for a regional resource assessment to include four different sets of figures. One would show resources during a defined baseline standard period (1961 to 1990, for example). The other three would be based on three "approved" climate change scenarios; a "best guess", a "driest" estimate and a "wettest" estimate.

The differences between these scenarios at present would be rather large (Section 3.2), but would indicate the degree of sensitivity of water resources in a region to possible change. It may be that the effects of changes in resource availability will be considerably less than the effects of (also uncertain) changes in demand, and can be ignored. In some regions even the "driest" climate change scenario might lead to few resource problems; in other cases, it might be appropriate to play safe and base assessments of future water resource potential on the worst case scenario.

Climate change implies that regional resource assessments need to be periodically reviewed given evolving experience and improving predictions of future conditions.

3.7 Information needed by the NRA

The NRA needs a number of tools and pieces of information in order to cope effectively with the implications of climate change for water resources. In particular, the NRA requires:

1. Models which are capable of simulating river flows and groundwater recharge under future climate conditions. A review of models used in the NRA has recently been completed (NRA, 1991 "Fawthrop").

2. Advice on whether climate really *is* changing - based on the interpretation of global, not local, data. This advice could take the form of a policy directive, stating for example that the NRA should accept IPCC and Department of the Environment statements about climate change: the issue is discussed further in Chapter 9.

3. A set of "approved" climate change scenarios, showing changes in *daily rainfall* and *potential evaporation* (although some applications could get away with weekly scale data). The Link Project at the Climatic Research Unit (Chapter 2) should provide the technical support for these scenarios.

4. Methodological advice on (i) expressing resource availability against an evolving background (does the concept of the 1 in 50 year effective rainfall remain useful? Would it be appropriate to reference all reliability predictions to a common standard period, such as 1961-1990?) and (ii) how to use both observed data - validated but possibly less relevant in the future - and predicted climate data - which will be both speculative and highly uncertain.

The recent, current and proposed research projects relevant to water resources are listed in Annex B. To summarise, current projects are looking at (i) the effects of climate change on river flow regimes, (ii) the sensitivity of demand for water to climate change, and (iii) the implications of sea level rise for water resources. A proposal is currently being considered by MAFF for an investigation into possible changes in demand for summer spray irrigation.

3.8 Key sensitivities and uncertainties

Table 3.1 shows seven potentially important implications of climate change for water resources, together with the climate parameters of relevance.

1. Low winter recharge of surface and groundwater resources: this is most affected by changes in winter rainfall and the duration of the recharge season as influenced by soil moisture deficit periods. It is currently very difficult to make precise predictions of changes in resource potential, because climate model predictions of rainfall are very uncertain. The difference between different scenarios are very large (as indicated in Figure 3.3). The "worst-case" effect of climate change would be to increase the frequency of "dry" winters, although climate model predictions tend to be pointing towards winters that are wetter on average. *The possibility of experiencing drier winters (or winters with shorter periods of more intense rainfall) needs to be explicitly considered during the analysis of climate model predictions.*

2. Increased demands for spray irrigation: this would be affected by summer soil moisture deficits, but the effects of agricultural prices might also be very important. NRA policy of encouraging abstractors to irrigate using water stored during winter should help to mitigate the effects of increased demand (as long as there is enough winter water available).

3. Increased demands for garden watering: this will be affected not only by changed temperatures, but also by the ownership of hosepipes and sprinklers and, perhaps most important, by the price charged for water. Economic factors may be more important than climatic influences.

4. Pipe bursts during thaw: it is unlikely that there will be no extreme freezes in the future, so it is possible that losses in pipe bursts might not be reduced. More information is needed on the climatic conditions associated with pipe bursts, however, before it will be possible to predict changes in their frequency.

5. Saline intrusion: current indications are that this will be relatively unimportant, although NRA policy of encouraging abstractions as close to the tidal limit needs to take sea level rise into account.

6. Increases in demand for water: it is probable that increases in the demand for water due to population growth and economic development will in many regions be of equal or greater importance than the effects of climate change (although like climate change projections, forecasts of future demand are uncertain). It is an unfortunate geographical coincidence that the areas expected to have the greatest growth are also those regions showing the greatest sensitivity to change in climate and where there is the greatest difference between different climate change scenarios.

7. Deterioration in water quality: this might be affected by climate change - as will be considered in Chapter 4 - but will also be affected by developments in the use of agro-chemicals and water treatment. Locally these trends may also be rather more important than the direct effects of climate change on water resources.

Critical activity	Relevant climatic parameters	Other relevant parameters
Low winter recharge of resources	1. Amount of winter rainfall 2. Duration of winter recharge season: spring and autumn soil moisture deficits 3. Potential evaporation	
High summer irrigation demand	1. Summer soil moisture deficits 2. Summer evaporation	1. Increased interest in irrigation by farmers
High demands for domestic garden watering	1. Peak temperatures in spring and summer 2. Evaporation in spring and summer	1. Increased ownership of garden sprinklers 2. Price of water
Pipe bursts during thaw	1. Frequency of freeze and thaw: minimum temperatures	
Saline intrusion into aquifers and river intakes	1. Sea level rise	
Increasing demands for public water supplies		1. Rate of economic development 2. Population change 3. Water efficiency use of domestic appliances and industry 4. Price of water
Declining water quality	1. Increased temperature 2. Changes in flow and recharge regimes	1. Application of agricultural chemicals 2. Trends in water treatment

Table 3.1: Critical water resources activities, and relevant climatic parameters.

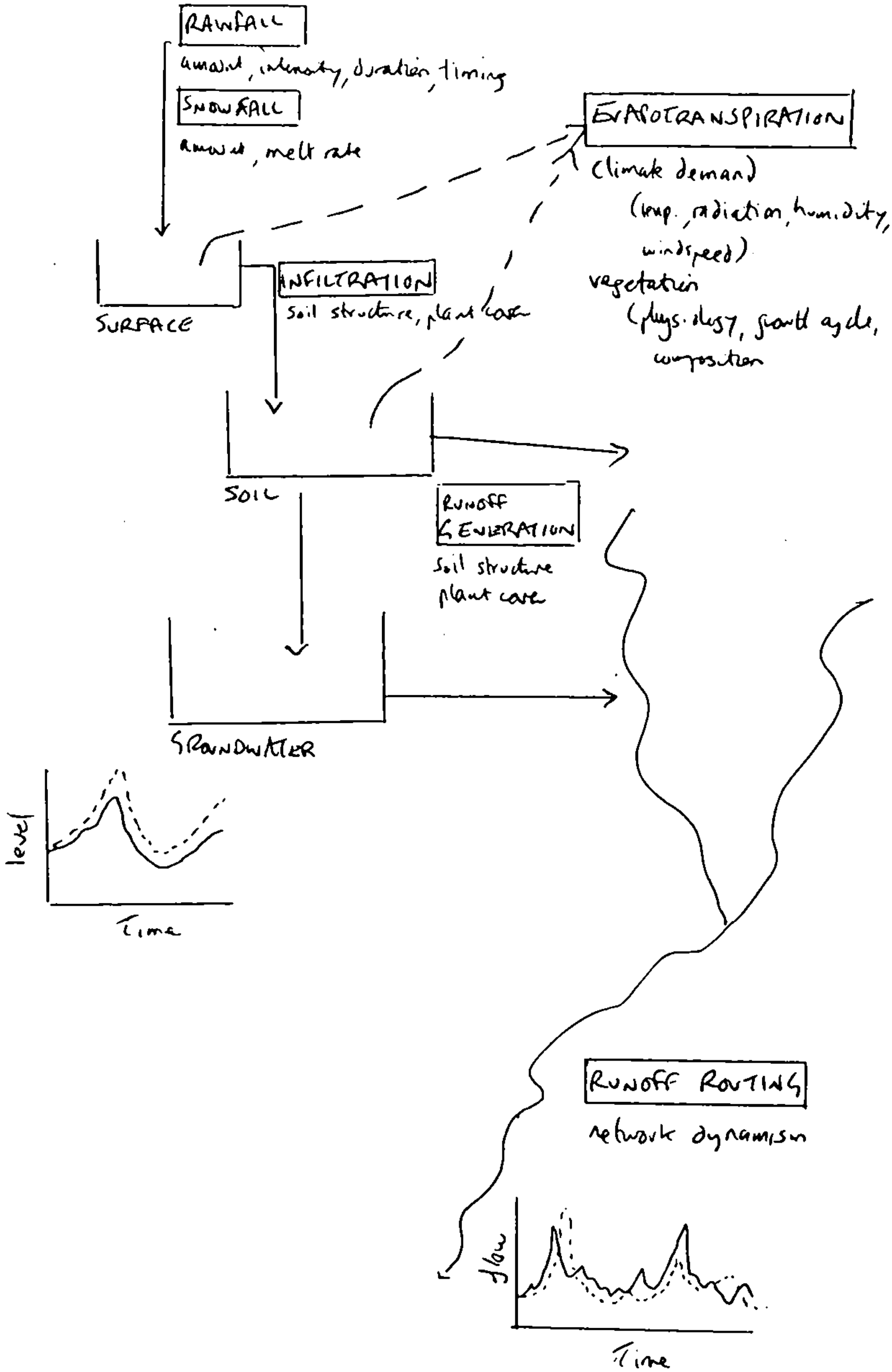
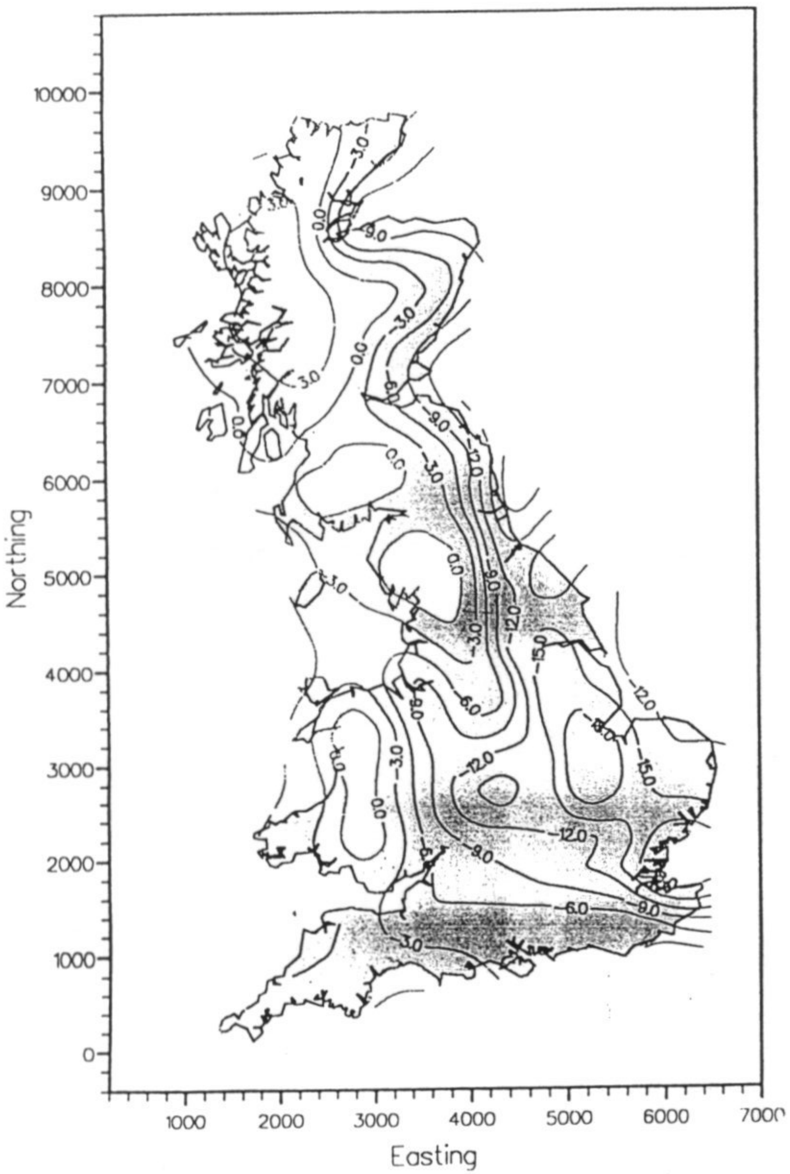
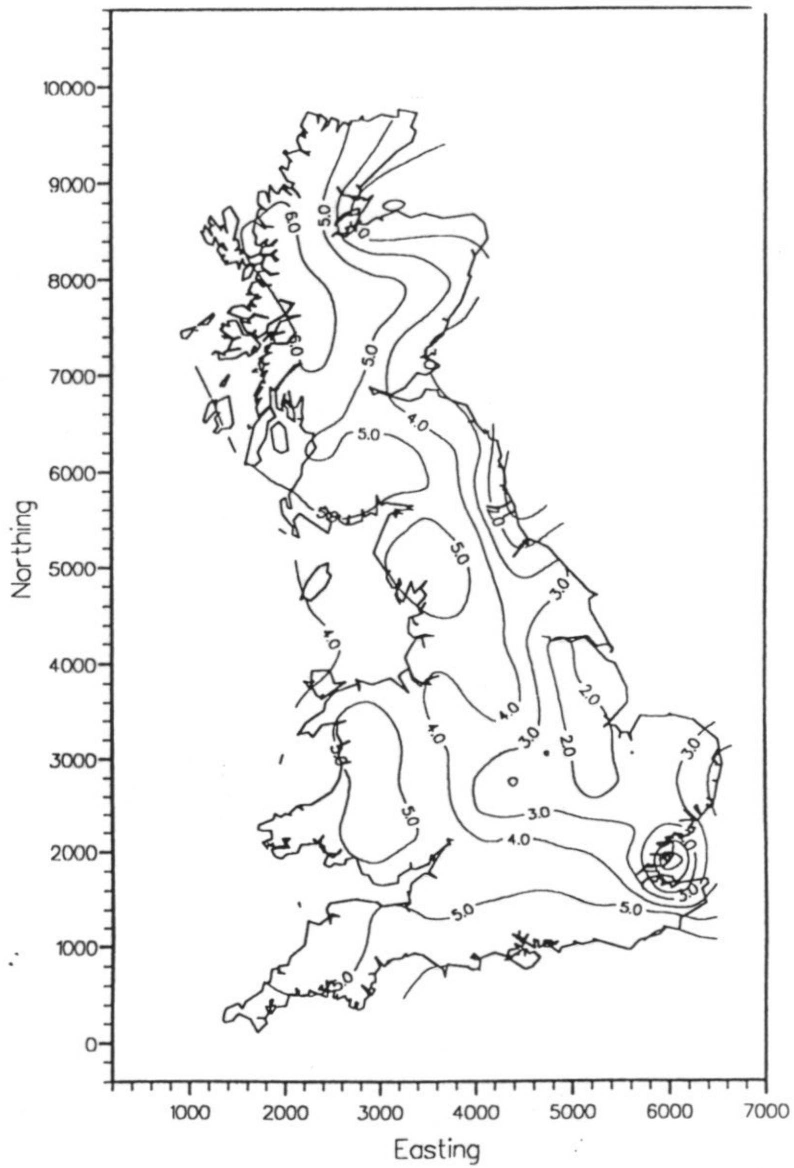


Figure 3.1 The hydrological system, and potential changes due to climate change



a) the "most feasible" CCIRG rainfall scenario, plus a 15% increase in potential evaporation



b) the "most feasible" CCIRG rainfall scenario, plus a 7% increase in potential evaporation

Figure 3.2 Simulated percentage change in average annual runoff by 2050.

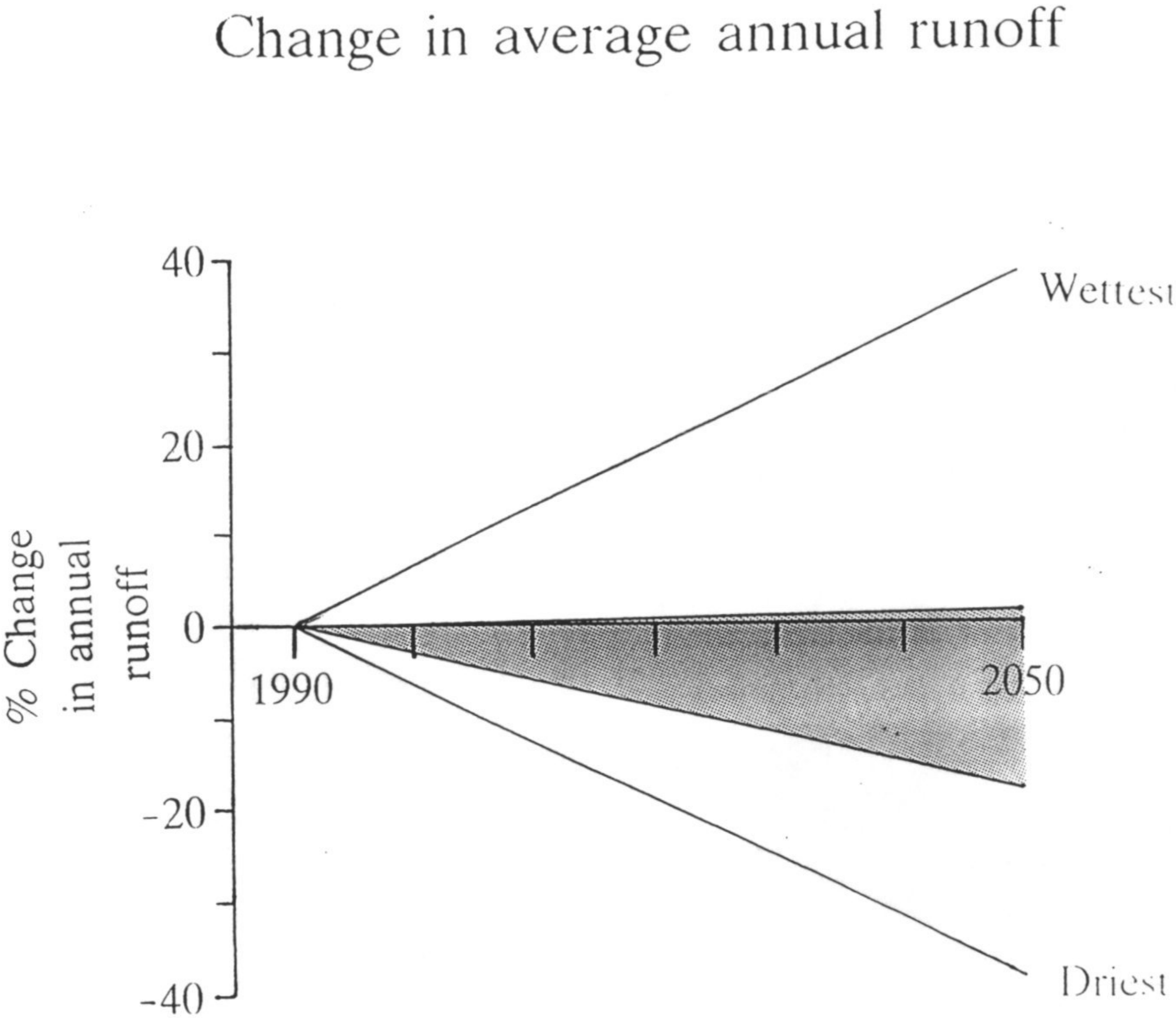


Figure 3.3 Effect of different climate change scenarios on average annual runoff by 2050 for a portion of south east England.

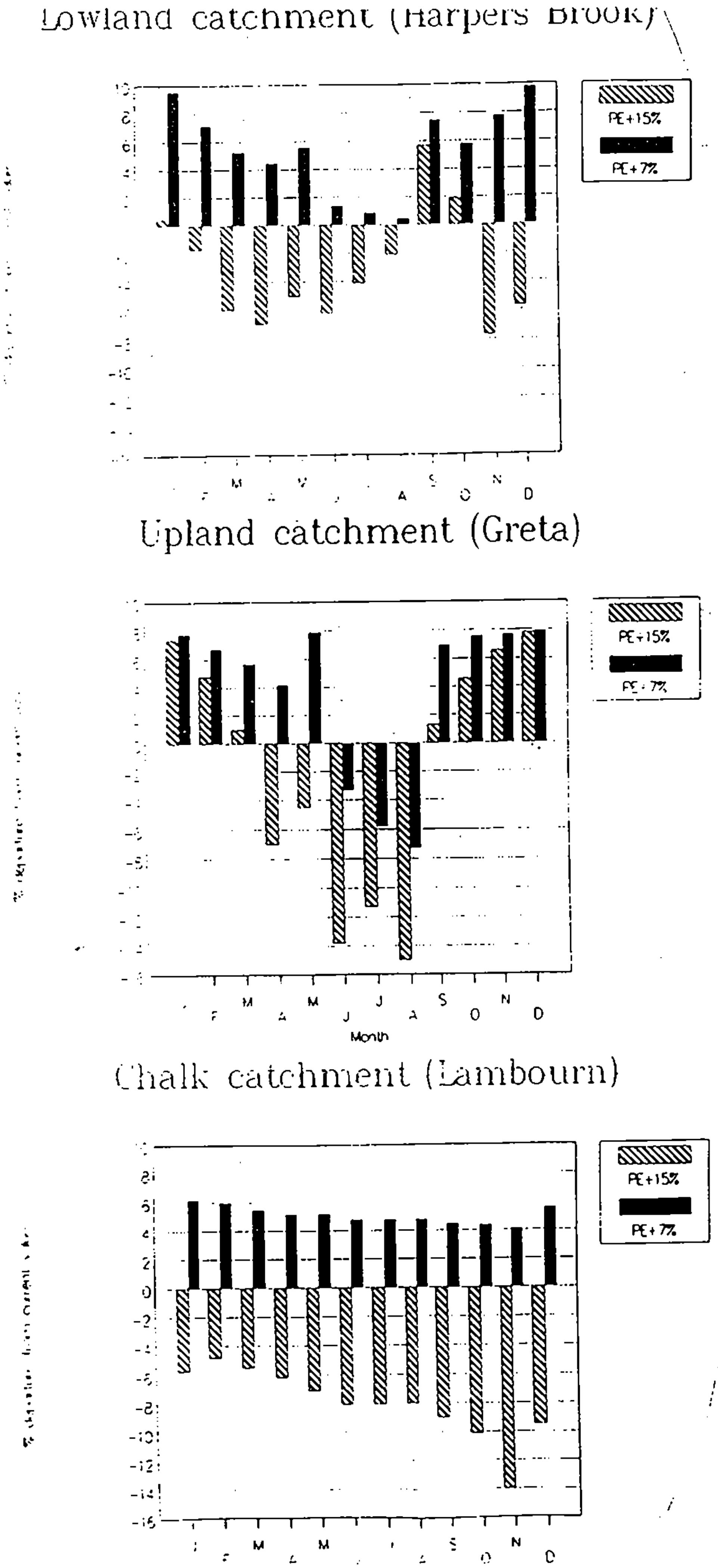


Figure 3.4 Effect of a climate change scenario on average monthly runoff in three catchments. The "most feasible" CCIRG rainfall scenario, plus a 7% increase in potential evaporation.

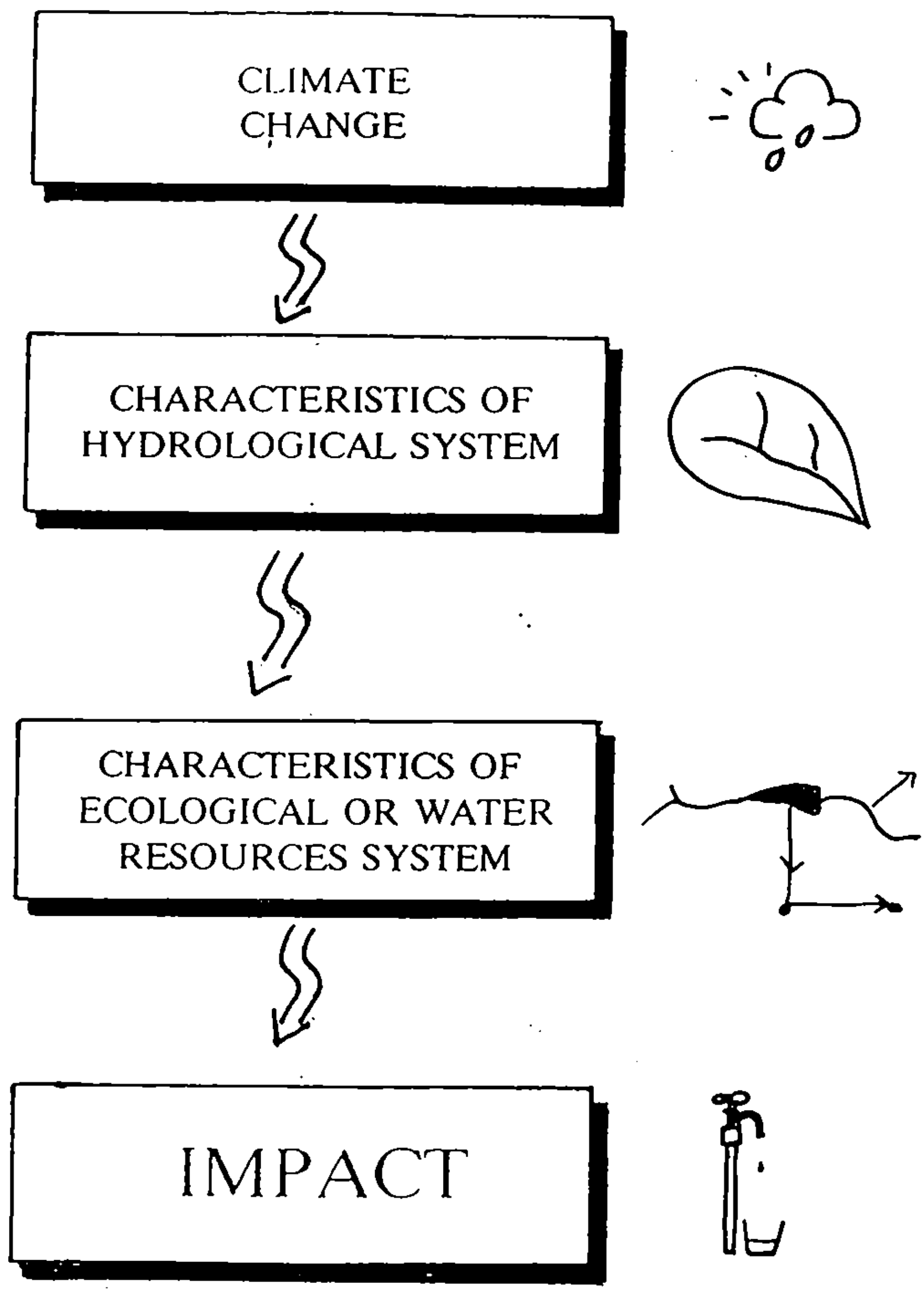


Figure 3.5 A climate change passes through several systems before resulting in impacts on water resource availability.

4. POLLUTION CONTROL

4.1 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 wish to discharge to NRA-controlled waters (it currently has around 139,000 discharge consents). It will impose conditions on the consents which depend on the characteristics of the receiving waters.

The major difficulty with water quality management has been the lack of formal water quality objectives against which standards and consents can be determined. European Community directives covering bathing water quality and drinking water quality have been in force since 19xx (others?), and in 1991 the NRA began preparing proposals for a set of statutory water quality objectives (SWQOs) and associated water quality standards (NRA Water Quality Report No. 5, 1991). 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.

It is useful to distinguish between "natural" background water quality and "man-made" quality, or pollution. The "background" water quality of a river or aquifer is defined by the natural chemical and biological constituents of the water, and tends to be controlled by catchment soil, rock type and natural vegetation. It is not often a management issue, except where some components of the background water quality need to be removed before the water goes to public supply. Sediment, for example, has to be settled out, and hard water from chalk aquifers is often softened. Water draining from upland peat bogs may have a discolouration which needs to be removed (Naden...).

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 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. 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 feedbacks and responses to both climatic and non-climatic controls (Figure 4.1) 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 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 EC, the NRA and the public.

Consideration of the effects of climate change on water quality are conveniently split into two distinct areas, the uplands and the lowlands. Upland streams tend to be fast flowing, oligotrophic streams and high in dissolved oxygen and with catchments wholly, or significantly, draining land which is not under intensive agricultural production systems. In such systems the water quality reflects dominantly 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 well mixed due to the high precipitation input and short residence times and so although thermal stratification is not uncommon in summer, eutrophication is not presently a problem. 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.

From the point of view of operational water quality management, upland waters are relatively simple to manage as a resource since they are used predominantly for supply and recreation. Lowland rivers, on the other hand have to suffer a duplicity of function in that they not only provide water for abstraction but also a transport pathway for removal of effluents.

4.2 Changes in 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. For example, the concentrations of toxic chemicals will be directly effected by changing flow conditions. An increased flow producing a dilution and a decreased flow a concentration effect, providing the input flux remains constant. High temperatures alone might, for example, lengthen the survival time of pathogenic bacteria although water concentrations will be further modified by changes in flow. Indirectly, changes in land use will also complicate the pollutant response in that climatic change might lead to increased pesticide and fertiliser usage, thereby increasing the loading to surface waters and, a change in the runoff pathway, through different cropping patterns, soil moisture conditions and land management strategies. Overall, the impact on water quality must be carefully considered for each pollutant and generalities are difficult. It is, however, useful to consider in more detail the likely response of nitrate and Dissolved Oxygen as examples of the complex system of feedbacks and processes requiring consideration.

Nitrate and dissolved oxygen concentrations are determined through a complex series of mechanisms, involving chemical reactions, bacterial transformations and flow. In simple terms, assuming no inputs, nitrate concentration in a river reach is the product of the initial concentration minus losses from denitrification 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 but, since nitrate concentrations are usually higher in proportion to ammonium concentrations, denitrification is the dominant process and consequently, nitrate concentration decreases. Lowered flow in the reach increases the water residence time allowing more time for the microbial breakdown to occur and so should also reduce nitrate concentrations. Assuming a hotter and drier scenario for much of the south-east these relationships indicate that lower nitrate concentrations can be expected in lowland rivers. Running this lower flow scenario through a more complex river quality simulation model, however, indicates that nitrate concentrations will generally increase (Figure 4.2). This results from unchanged effluent inputs, and so effectively higher initial concentrations since flow is lower, which overwhelm microbial effects. Although the increase is relatively small, discharge consents may need adjusting to maintain the river quality objective. Furthermore, the changed flow distribution has a potential effect on the distribution of water chemistry concentrations. This has implications for the setting of effluent discharge consents given that SWQOs will be set at 95 percentile levels. Warmer and drier summers may also cause autumnal flushing of nitrates into the water course, as occurred following the break of the drought in 1976 (Figure 4.2).

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A change to lower flows in summer would have a direct effect on dissolved oxygen concentrations through reduced dilution and this would combine with a temperature effect as warmer water is able to hold less oxygen. In a stream with a single large BOD point source, the interaction between de-oxidation and reaeration produces the characteristic downstream oxygen sag. The effect of the warmer, drier climate will be to pull the sag curve lower (Figure 4.3).

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 are thus "natural"), 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.

4.3 Changes in 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. Present water quality problems stem mainly from increased acidity in response to deposition of anthropogenic sulphur and nitrogen compounds. Here the indirect effects of climate change will probably be limited to marginal areas which have become economically viable for land improvement with a subsequent increase in stocking density and fertiliser or pesticide application. 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 undoubtedly be an increase in surface water acidity and might cause lake productivity to increase although eutrophication is unlikely to be a major problem.

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Future responses in upland water quality to long range transboundary air pollution are a main consideration with respect to climate change. Increased rainfall may concentrate flow through the upper soils with low acid neutralisation capacity and so will increase the frequency and magnitude of acid episodes. In upland areas, deposition of acidic compounds is increased through cloud, or occult, deposition whereby plant and ground surfaces filter moisture droplets directly from the atmosphere. This is a particular problem in areas under commercial conifer plantation. If cloud cover increases as a result of increased temperature and rainfall, the pollutant loading would be enhanced in sensitive upland areas, and again particularly to upland forests. Increased drying of soils under a more seasonal rainfall regime with higher evapotranspiration will cause sulphur and nitrate mineralisation and promote increased acidification. All of these effects must be considered in the light of possible future decreases in pollutant emissions which will tend to reduce their impact. 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.

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, coupled with slightly 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, while removal of the resulting discoloured water is directly proportional to the rate of water throughflow. Increased winter rainfalls will, therefore, exacerbate the washout of these coloured waters. Thus, what is envisaged is 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.

4.4 Changes in phytoplankton

Most species of planktonic algae can survive and grow at temperatures well in excess of those predicted for a warmer world. Hawkes (1969) has examined the temperature tolerance of different groups of algae and suggested that diatoms grow best at temperatures below 25°C and blue-green algae at temperatures above 30°C. There are, however, notable exceptions, such as the diatom *Acnanthes marginulata* which can tolerate temperatures up to 41°C (Patrick, 1969) and the blue-green alga *Oscillatoria rubescens* which is commonly described as a cold water form. 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. Global measurements of phytoplankton primary production (Westlake et al, 1980) certainly demonstrate that annual net production is not strongly correlated with latitude. Lakes at high latitudes and high altitudes, nevertheless, tend to have lower production rates unless they are particularly rich in nutrients. 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 most U.K. 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°C and only begins to decline at temperatures above 25°C. Winter temperatures in the U.K. are predicted to increase by 2 or 2.5°C in a warmer world. 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 innocculum which so often provides the `springboard' for subsequent summer blooms.

In recent years, several species of bloom forming algae have clearly benefited from a succession of mild winters. In the South Basin of Windermere, for example, blooms of the blue-green alga *Oscillatoria agardhi* have tended to appear in warm summers that were preceded by mild winters. Figure 4.4 shows the effect of a series of mild winter on the average summer crop of *Oscillatoria* in this mesotrophic lake. Note that strong summer growths (Figure 4.4a) are only recorded in the late 1980s when warm summers are combined with mild winters (Figure 4.4b).

Current atmospheric circulation models suggest that global warming will fundamentally alter the distribution of pressure belts across Central Europe. The seasonal succession of phytoplankton in lakes is now known to be influenced by the timing as well as the strength of wind-induced mixing (Reynolds, 1987; Steinberg & Hartmann, 1988; George et al, 1990). Reynolds (1984) has developed a suite of models that can be used to predict patterns of seasonal succession and these are now being linked to a physical model of lake stability. In most temperate lake, the first species to appear are the diatoms that can grow when the 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. Long-term studies of phytoplankton succession in the South Basin of Windermere (Talling, 1989) certainly demonstrate that the growth of the blue-green alga *Oscillatoria agardhi* is strongly influenced by the wind. This buoyant alga grows well in a stable water column but growth can be suppressed by quite short periods of intense mixing. Figure 4.5 contrasts the summer phytoplankton of Winderemere in an unusually calm year (1989) and an unusually windy year (1985). In 1989 (Figure 4.5a) the late summer plankton was dominated by *Oscillatoria* but in 1985 (Figure 4.5b) 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 U.K. 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 & Walters, 1983). Experimental and remote sensing studies (Reynolds & Carling, 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 twenty-five 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 we can expect these `seed' populations to grow and have a more pronounced effect on downstream water quality. Abstraction schemes that transfer water between catchments will also have a pronounced effect the the dynamics of our river plankton. Algal `bloom' problems are most likely to arise where water is abstracted from the lower reaches of a river and then transferred by canal to another river system. *

4.5 Changes in estuarine and coastal water quality

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.

Salinity, sediment and "freshwater-based" pollution in an estuary may all be affected by climate change. A *higher sea level* would mean that the salt front would 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 3. 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). A *change in freshwater inflows* 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. *Increased temperatures and insolation* would mean that biogeochemical processes would operate at a faster rate, and might contribute to a lessening of water quality problems. HR Wallingford are currently investigating the implications of climate change for estuarine water quality, under contract to the Department of the Environment.

Increased temperatures and insolation can also be expected to improve the quality of coastal bathing waters. (information on sensitivity of biogeochemical activity in salt water to temperature and sunshine?).

4.6 Changes in the performance of water quality management systems

Urban storm drains are designed to remove storm runoff from urban surfaces. This water is often extremely dirty, and contains in particular heavy metals and hydrocarbon-based pollutants. Storm events can therefore result in a pulse of very poor quality water reaching a water course. A sizeable proportion of the storm sewer system in old urban areas is combined with the foul sewerage system. Surcharging of these systems therefore means that untreated sewerage is also discharged into the receiving watercourse, along with runoff from the urban surface. 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 biogeochemical 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-imposed water quality objectives.

4.7 Effect on NRA pollution control activities

The NRA's pollution control activities can broadly be divided into three areas; operational, design and planning, and emergency response.

4.7.1 Operational activities

The largest part of the NRA's pollution control work is taken up by responding to applications for consents to discharge into watercourses. There is unlikely to be a climate-induced change in *demand* for such 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 Q95 flow value. Lower stream discharges might mean that absolute discharge consents would need to be reduced. Discharge consents expressed in terms of the quality of the receiving water will not be affected.

Discharge consents are currently reviewed periodically, so can be changed to suit altered hydrological conditions. It would, 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.

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

4.7.2 Design and planning

The NRA does not itself get involved in the design and planning of water quality management systems, but long-term planning work involves setting water quality objectives and identifying source protection zones. The proposed system of SWQO's will be independent of climatic conditions since "water quality" of a river is determined as the chemical characteristics of a sample derived from the water body. As such, the water quality objective is determined as an acceptable level of chemical constituents within the water sample, irrespective of flow although clearly, flow conditions play a major role in achieving that critical chemistry.

The NRA is at present beginning to identify a number of groundwater protection zones, and is considering how best to define consistently zone boundaries. 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 be affected by climate change. In general, it appears that the NRA's long-term water quality planning work will be largely unaffected by climate change.

4.7.3 Emergency response

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

Man-made pollution events are not necessarily going to increase in a warmer world (except to the extent that changes in agricultural practice might lead to alterations in the potential for farm-based pollution). The effect of a given polluting event, however, might vary in a warmer world. 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 peak 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.

Need for research on (i) potential ~~[illegible]~~ impact on urban drainage system, (ii) microbiology of water → biol monitoring/classific" techniques + need to expand ecotoxicological data base

4.8 Information needed by the NRA

The NRA needs information in the following areas:

1. Changes in the parameters (→ processes) controlling water quality - primarily water temperatures, climate inputs, river flows and land use and, to a lesser extent, soil structure.

2. Potential changes in specific systems currently experiencing water quality problems. These include catchments suffering from excess nitrate concentrations and acid precipitation; how would climate change exacerbate (or ameliorate) current problems?. It would also be necessary to identify situations most sensitive to climate change (which requires information on factors controlling sensitivity to change), in order to locate rivers or aquifers at particular risk.

3. Critical values need to be determined for specific water quality parameters in particular locations - beyond which action is necessary - and efforts made to determine the likelihood that climate change would cause these critical values to be exceeded.

4. Information is needed on means of calculating water quality statistics against a background of an evolving climate. How meaningful will the Q95 value be, for example? How can historical information be combined with predictions of future conditions?

5. Experience from recent extreme events - such as the 1976 and 1988-1992 droughts - can provide very valuable insights into the behaviour of the water quality system under stress.

6. Do recent extreme events represent changed conditions, or are they simply rare events which can be discounted? This applies to the 1988-1992 droughts, and will also apply in the future: how will it be possible to tell when an "unusual" event marks a significant departure from the long-term average?

Research projects into climate change and water quality are listed in Annex B. All the current projects are funded by the Department of the Environment.

4.9 Key sensitivities and uncertainties

Table 4.1 shows three potentially important implications of climate change for water quality, together with the climate parameters of relevance.

1. 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.

2. Increased magnitude of autumnal flushing: This may cause operational concern in both the

How will climate Δ affect flow regime? → ∴ the assimilative capacity of rivers for point Q's → the effects on urban drainage system.
Climatic induced Δ's to the requirements for abstract's may affect flow regimes (operational strategy Δ) ∴ impact on ecol. → fisheries may require reappraisal of some env'l qual standards

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 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.

3. 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 recent trend in surface water acidification should reverse even under changed climatic conditions. Afforestation will probably continue to exert a significant influence on surface water chemistry.

Critical activity	Relevant climatic parameters	Other relevant parameters
Change in flow/water quality relationships	1. Annual and spatial rainfall and temperature distribution 2. Changes in flow regimes	1. Potential change in land use 2. Changes in applications of agrochemicals 3. Changes in discharge/abstraction strategy
Increased magnitude of autumnal flushing	1. Seasonality of flow regime	1. Agrochemical application 2. Anthropogenic pollutant deposition flux
Changes upland water quality	1. Change in soil moisture deficit 2. Periodicity of rainfall 3. Change in summer temperature and rainfall	1. Future land use policy 2. Future acidic emissions strategy
Increased frequency of algal blooms	1. Change in air and water temperatures 2. Change in windspeeds	1. Change in phosphate inputs

Table 4.1: Critical pollution control activities, and relevant climatic parameters

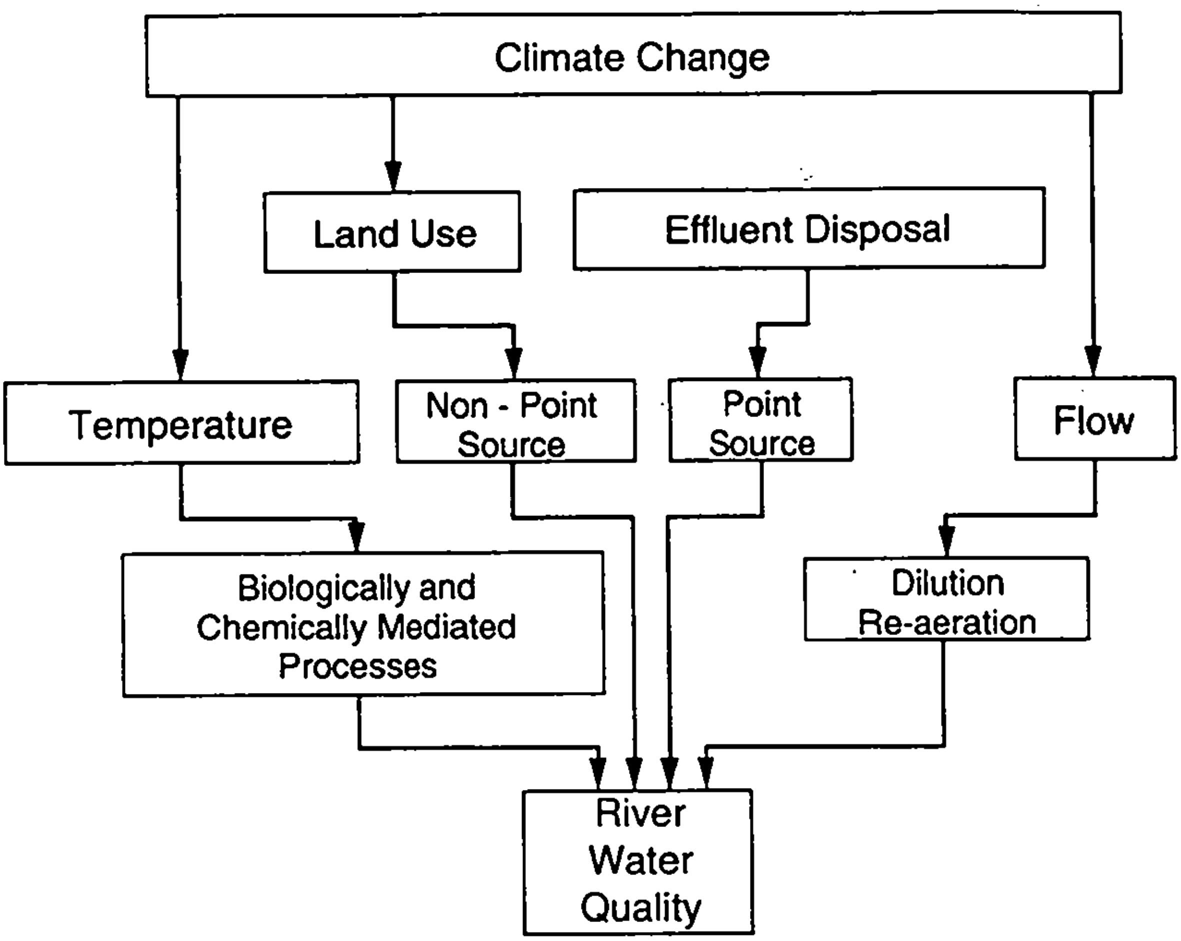

Figure 4.1. The major climatic and non-climatic factors controlling water quality.

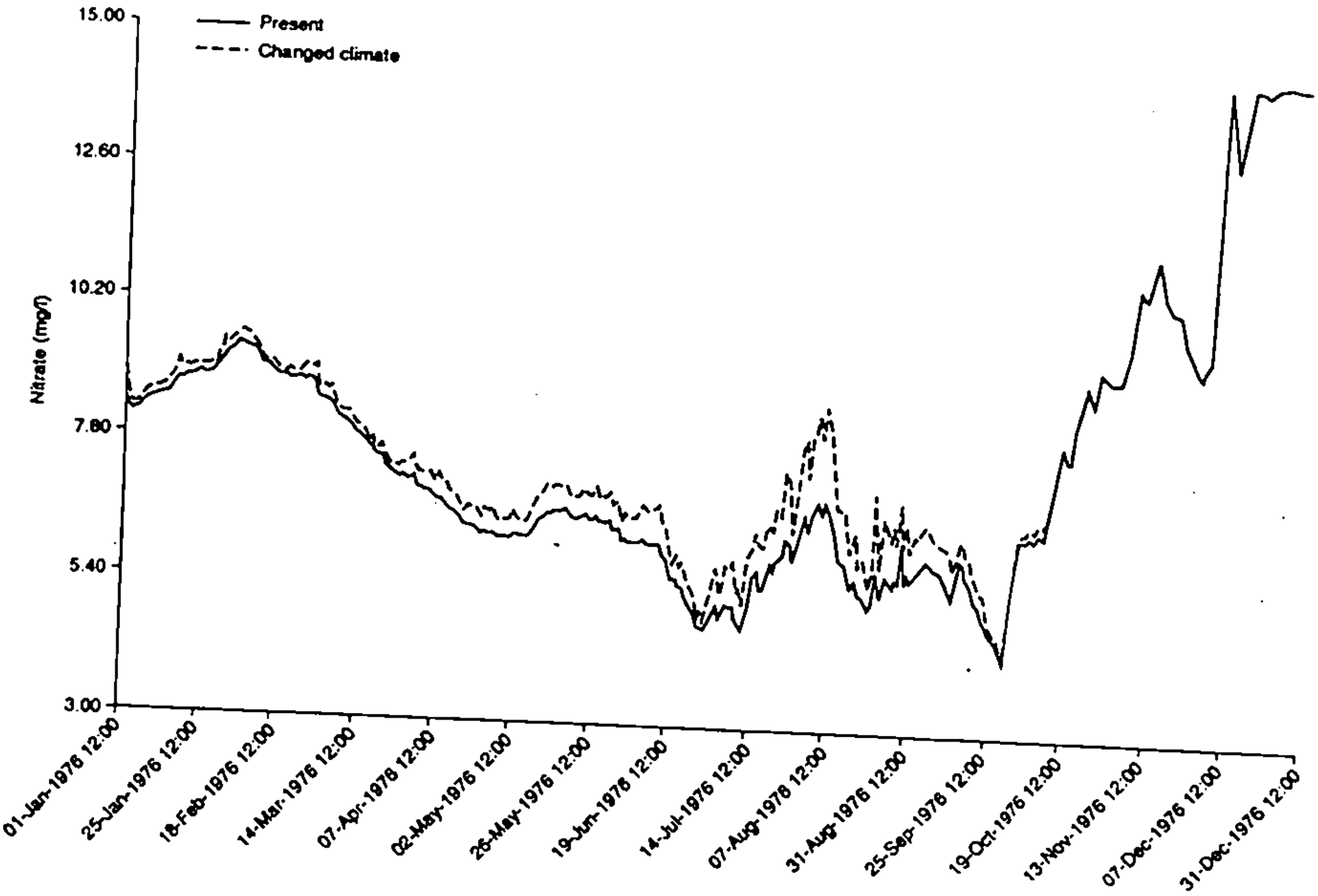

Figure 4.2. Observed nitrate concentrations in the River Thames at Romney during 1976 compared with those predicted for a more seasonal flow regime using a water quality model.

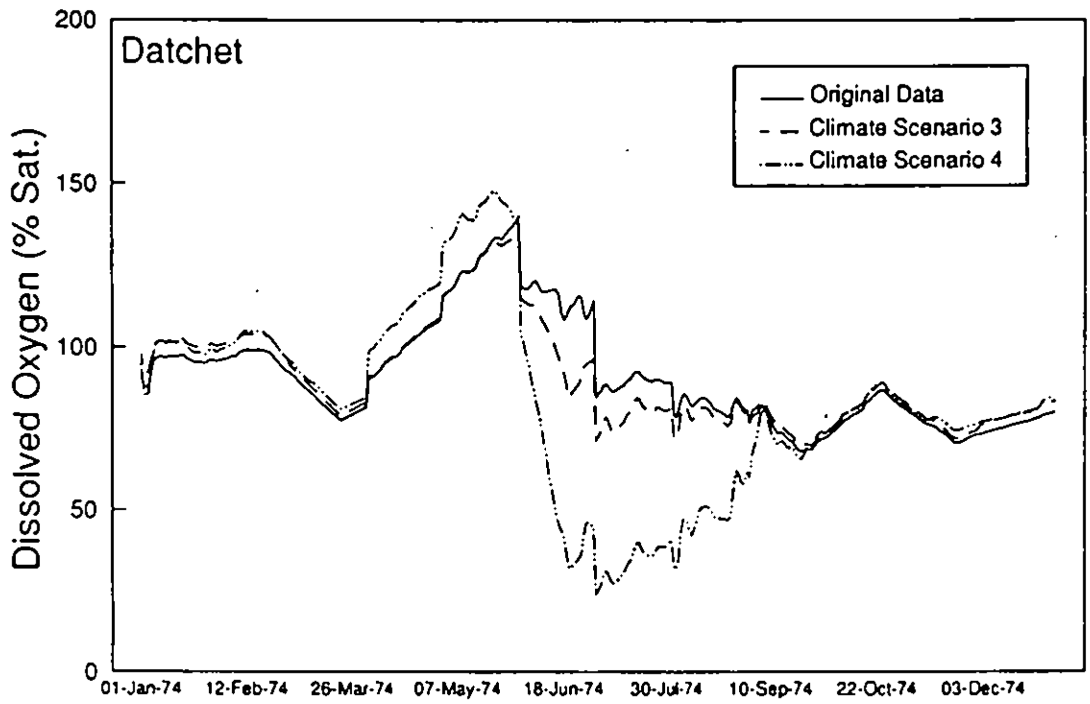

Figure 4.3. Observed dissolved oxygen concentrations in the River Thames at Datchet during 1974 compared with those for a wetter climate (scenario 3) and a drier climate (scenario 4) using a water quality model.

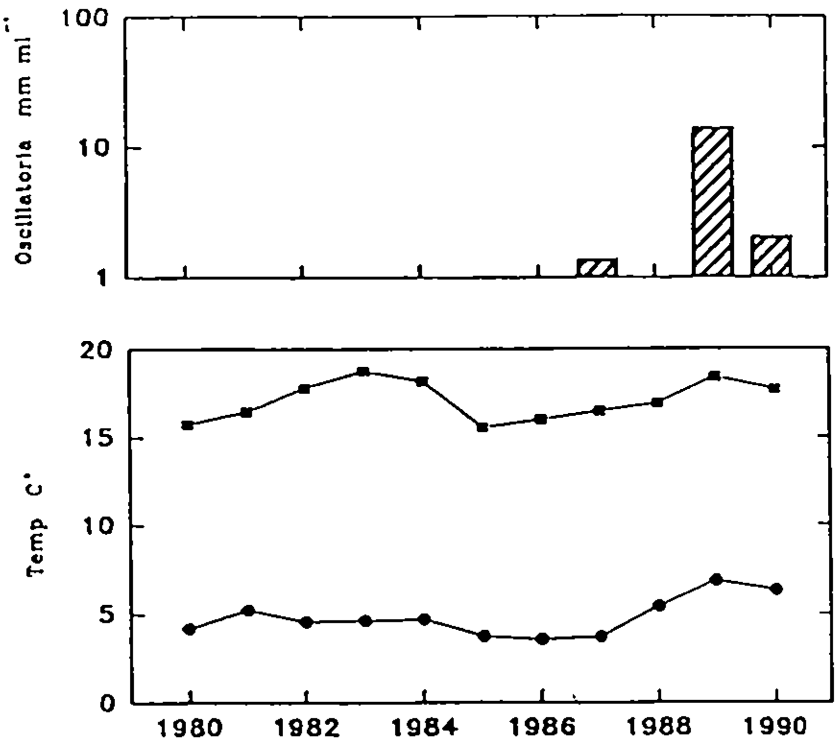

Figure 4.4: Factors influencing the growth of the blue-green alga *Oscillatoria agardhi* in the south basin of Windermere between 1980 and 1990.
(a) The year to year changes in the average summer crop of *O. agardhi*.
(b) The year to year variations in the average winter (bottom) and summer (top) temperatures.

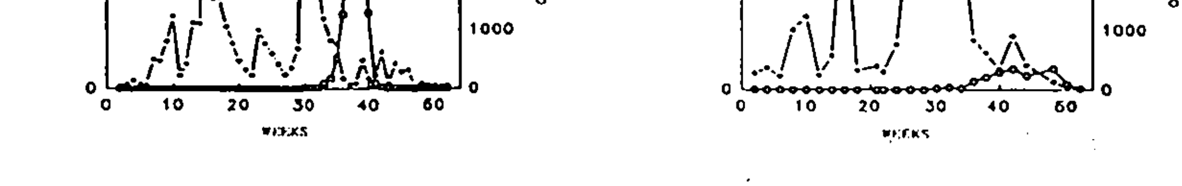

Figure 4.5: The seasonal succession of phytoplankton in the south basin of Windermere in (a) 1989, and unusually calm year and (b) 1985, an unusually windy year.o *Oscillatoria* filaments per ml; • microalgae cells per ml (unpublished data supplied by S.I.Heaney).

5. FLOOD DEFENCE

5.1 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 responds to flood emergencies. In 1991/92, £XX million was spent on capital programmes along the coast, and a further £YY 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 flooding are quite different. Coastal and fluvial flooding are also affected by different climate change parameters.

5.2 Changes in coastal flooding

There have been several studies in the UK into the effects of climate change and associated sea level rise on coastal flooding. Some of these projects (Annex B) have been funded by the NRA, and explicit reference to sea level rise was made as far back as the 1990/91 Corporate Plan (NRA, 1991). Figure 5.1 summarises the effects of climate change on flood risk in the coastal zone.

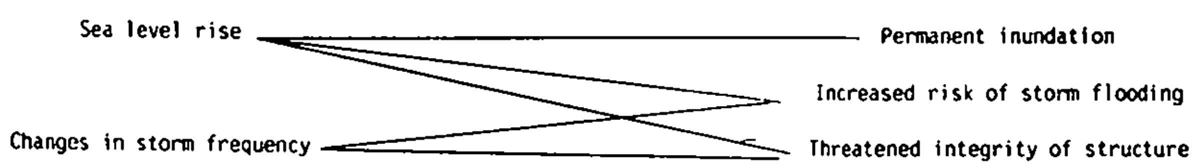

Figure 5.1: Impacts of climate change on coastal flooding

The Climate Change Impacts Review Group estimated that mean sea level would be between 90 and 290 mm higher than present by 2030, with a best estimate of 190 mm. The local effect, 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 5.1 (these values will be used in scheme design and planning - see Section 5.4).

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

Table 5.1: Assumed rise in sea level by NRA region (NRA, 1991)

Although these assumed changes in mean sea level are uncertain, there is even greater uncertainty about possible changes in the frequency of occurrence of storms and their associated high winds and storm tide surges. 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, 1990). Current climate models do not simulate small-scale disturbances such as storm systems at all well, so both the IPCC and the CCIRG stated that it was impossible at present to create feasible scenarios of changes in storm frequency (IPCC, 1990; CCIRG, 1991). Holt (1991), however, attempted (under contract to the NRA) to use climate model simulations to assess possible changes in storm frequency in the North Sea. He found a slight increase over the next century, but the increase was well within the natural variability that has occurred over the last 100 years. *At present, therefore, it can be assumed that the change in mean sea level will have a greater effect on coastal flood frequencies than a change in the rate of occurrence of storms.*

Figure 5.1 indicates that there are three potential impacts of climate change along the coast. The first - permanent flooding of land currently above sea level - is likely to be of limited economic importance, 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 might also increase pumping costs for the drainage of low-lying land.

The second impact of climate change listed in Figure 5.1 is far more important. An increase in mean sea level implies that the risk of storm waves overtopping sea defences would increase. Figure 5.2 shows the hypothetical effect of an increase in mean sea level of 200 mm on the estimated return period for a given flood level (CCIRG, 1991). A level of 3.2m has, according to this example, a return period of 100 years; if sea level were to rise by 200 mm then the return period between exceedances of 3.2m falls to 25 years and 5 years for curves A and B. A relatively small increase in sea level can therefore have a very large impact on the frequency of structure overtopping, and the impact is dependent on the slope of the level-frequency curve. The flatter the curve, the greater the increase in frequency for a given rise in sea level. Curve A in Figure 5.2 - the flatter curve - is typical of conditions along the south coast of England, whilst the east coast tends to have rather steeper curves such as Curve B. In practice, a rise in sea level will not simply mean that the level-frequency curve shifts by an amount equal to the change in sea level. Wave patterns may also change because of the altered depth profile in the run up to the shore, and therefore the slope of the level-frequency curve might also change. Finally, the effect of a rise in sea level on the height of wave crests as they reach the shore depends on the form of the shoreline. Other things being equal, the gentler the beach gradient the greater the increase in wave height for a given increase in mean sea level (reference...).

An increase in sea level would not only increase the risk of a structure being overtopped, but could also threaten the structural integrity of the coastal defence system. 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.

It is very difficult to generalise the impact of higher sea levels on coastal flooding because of the importance of local shoreline geography and beach form on the extent to which both storm still water levels and wave heights are affected.

The economic consequences of a rise in sea level have not been directly quantified, but are likely to be very large. Flood losses during the 1953 East Coast floods reached £30 million (at 1953 prices: £xx million at 1991 prices), and since then there has been considerable development in coastal flood risk areas. The GeoData Institute (1991) 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.

5.3 Changes in fluvial flooding

Far less attention has been paid to the implications of climate change for fluvial flooding in the UK (or indeed anywhere in the world). In the most general terms, there are three types of fluvial flood 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 often enhanced by rainfall. Snowmelt floods are rare across central, southern and eastern England, but 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.

Increased temperatures should mean that volumes stored in snow packs would decrease - thus lessening the potential for large volume snow-melt floods - but there have been no studies conducted in the UK to investigate the effects of a 1.5 to 2.1°C increase in temperature (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.

As is the case with longer-duration river flow regimes (Chapter 3), 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) and the channel slope. 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 hypothesise that the effects of climate change on flood peaks will be greatest in steep, responsive catchments.

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, as is the case with sea levels, a relatively small change in the magnitudes of floods would have a very large effect on the frequency of flood damage, with the greatest effect again where flood frequency curves have a small slope.

Most fluvial flood defence schemes are less exposed to erosion than coastal defence schemes; they take the form of embankments set back from the main river channel or, more rarely, bypass channels. Some schemes, however, may be affected by increased erosion if river flow regimes change and flood frequencies increase. River sedimentation affects the capacity of channels to transmit flood discharges, and any change in sedimentation would have implications for scheme efficiency.

5.4 Effect on NRA flood defence activities

NRA flood defence activities can be grouped under four headings; maintenance and scheme review, development control, capital works design and construction, and emergencies.

5.4.1 Maintenance and scheme review

Activities under this heading include day-to-day operational tasks and more general asset management. Operational tasks include weed cutting in rivers and remedial works to rectify localised erosion. Dredging may also be needed in some rivers. Changes in river flows and sea levels might be expected to increase the monitoring and maintenance requirements for flood defence structures, whilst weed growth might be increased by higher temperatures and increased insolation (Chapters 4 and 7).

Asset management involves the review of the ability of flood defence schemes to meet their design standards. The NRA is currently reviewing sea defences, and is looking in particular at the standard of service provided by each scheme, the current maintenance costs and the likely rate of deterioration of the asset. Both maintenance costs and the rate of deterioration will change under climate change, and in different ways for different schemes. Information on likely changes is needed when assessing the costs and benefits of maintaining a particular asset; climate change might alter priorities or encourage different attitudes to some assets. The benefits of improving some assets may be less than the costs of the necessary work - where low value land was being protected - implying that the assets would need to be abandoned. This could of course lead to local political problems, although Treasury rules preventing the allocation of central government grants to schemes that are not cost-effective would make it very difficult for the NRA to actually undertake uneconomic work.

The University of East Anglia (Turner et al, 1991) estimated the costs and benefits of three alternative responses to four sea level rise scenarios imposed on the east coast from Hunstanton to Felixstowe, under contract to MAFF. The responses were (i) to abandon the defences, (ii) to maintain the defences as they are and accept a lower standard of protection and (iii) to improve the defences to take account of sea level rise. The coastal region was divided into 115 flood units, and for each unit the costs and benefits of the three responses were evaluated using a cost-benefit analysis; for the coastal strip as a whole, it would be more cost-effective to maintain or improve the defences than to abandon them. The study was necessarily very generalised.

5.4.2 Development control

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 very costly, and would represent a major effort).

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

5.4.3 Design and construction of capital works

Capital works for flood defence are eligible for grants from MAFF if the benefits of the proposed scheme can be shown to exceed the scheme costs. 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 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. In practice, some flood defence schemes were built to a lower design standards because a larger scheme was not cost-effective. Design standards for coastal flood defences have tended to be higher than for river flood defence because of the risk of loss of life, and schemes implemented after the 1953 East Coast floods had a nominal design return period of one in 1000 years. 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") should be protected to a standard of at least one in 50 years. The actual level of protection provided by a new scheme will be dependent upon costs and benefits; Treasury grants are only available for cost-effective schemes (quite what happens when no standard of protection within the class limits is economically feasible has yet to be determined).

At present, therefore, every floodplain reach is either meeting its particular level of service, or is not (although reviews have not yet been completed). It is unlikely that climate change would cause many reaches to change status - because the acceptable range of level of service for a class is very wide - although reaches with a design standard close to the limit for that class might shift (urban areas with nominal design standards of one in 50 years are most likely to change status).

Changes in climate will have greater effects on the estimation of scheme design standard and capacity, the justification of the scheme, and the actual physical design of the scheme.

The estimation of scheme capacity generally involves a statistical flood frequency analysis: how large is the 100-year flood, for example? Frequency analysis, however, assumes a stable climate, which will obviously be inappropriate in the face of climate change. The NRA has prepared a Policy Implementation Guidance Note (TE/FD/001) concerning climate change, which presents allowances which should be added to estimates of design still water levels to show the effects of sea level rise. The estimates are shown in Table 5.1. Nothing similar has been prepared for river flood frequencies, although it is not feasible simply to recommend adding a standard amount to estimates from present data: it was suggested in Section 5.3 that the effects of climate change on river flood frequency will vary between catchments. How relevant is the Flood Studies Report (NERC, 1975) under an assumption of a changing climate? The unit hydrograph procedure will probably be more robust, because it would "only" be necessary to provide revised rainfall frequency inputs representing different climate change scenarios (although the equations for estimating unit hydrograph parameters at ungauged sites are calibrated on past data). The regional flood frequency curves would need to be revised in their entirety. One approach would be to calculate frequency analyses using data from a standard period.

The evaluation of flood alleviation scheme benefits combines the frequency distribution of flood magnitudes with a site magnitude-damage relationship. As currently applied, therefore, the approach assumes a stable climate. If flood risk is increasing - as is likely along the coast in particular - then the benefits of flood alleviation will be underestimated.

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". Schemes should be designed now so that they can be revised as sea level rises or better predictions of change are made. In particular, the note suggests that foundations are designed and constructed so that defences can be readily raised, but adds the important qualification that this would be subject to the scheme still being economically-effective. A report from HR Wallingford (1992) has reviewed alternative coastal defence designs (both embankments and vertical sea walls) and made some suggestions for flexible design. A similar approach is necessary with fluvial flood defence.

5.4.4 Emergencies

This area covers emergency action during a flood and flood warning. Climate change would not have a big 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.

5.5 Information needed by the NRA

Information and tools are needed in the following areas:

1. Advice on whether climate really is changing, and whether it should be considered in flood management. To an extent the NRA has already accepted climate change along the coast.

2. "Approved" scenarios for changes in the frequency of flood-producing rainfall, the frequency of storms and surges, and sea level rise; the third is much the easiest of the three.

3. Information on the relative sensitivity of different catchment types to changes in rainfall characteristics. This would help identify catchments - and floodplains - at the greatest risk due to climate change.

4. A procedure to estimate the effects on flood characteristics of different rainfall scenarios. This will require some form of physically-based model which can simulate flood characteristics reasonably accurately, but which can be readily applied in ungauged catchments. Such a model might lie at the heart of a future revision to the Flood Studies Report.

5. Methodological recommendations on estimating flood risk against a changing climate. How useful are recent data? How useful is the concept of the 100-year flood? How can scheme benefits be assessed against a changing flood risk?

6. Information on flexible design techniques for river flood defence.

7. Information on the possible effects of changed river flows on erosion, sedimentation and the subsequent integrity of flood defence works.

Annex B lists current and recent projects concerned with climate change and flood defence. All focus on the coastal zone, and a considerable amount of progress on estimating changes in risk and developing flexible designs has been made. Much of this work has been funded by the NRA.

5.6 Key sensitivities and uncertainties

Table 5.2 shows a number of flood defence issues sensitive to climate change, together with the relevant climate parameters.

Critical activity	Relevant climatic parameters	Other relevant parameters
Increased overtopping of coastal defences / reduced standard of service	1. Sea level rise 2. Storm frequency change 3. Change in wind directions	
Integrity of coastal defences	1. Sea level rise (and associated tidal changes) 2. Storm frequency changes	1. Sediment supply
Frequency of floodplain inundation / standards of service	1. Frequency of flood-producing rainfall 2. Duration of saturated conditions	1. Channel improvements 2. Land use change?
Maintenance / integrity of river defences	1. Frequency of flood-producing rainfall 2. Duration of saturated conditions 3. Increased water temperatures	1. Land use changes (sedimentation)
Storm sewer flooding	1. Intense short-duration events	

Table 5.2: Critical flood defence issues, and relevant climate parameters.

1. Increased overtopping of coastal defences: this is the most "catastrophic" effect of climate change for the UK, and has attracted a great deal of attention within and outside the NRA. Small changes in mean sea level can produce very large changes in risk, with changes in the frequency of overtopping dependent on local shoreline and beach gradients. The gentler the gradient, the greater the relative effect of sea level rise on storm water levels and wave heights. Rising sea levels will mean that it will become increasingly expensive to protect coastal flood-prone land to a given standard of service; reviews of coastal flood defence provision are likely to provide the NRA with its greatest political and community problems.

2. Integrity of coastal defences: rising sea levels mean changing patterns of wave erosion and deposition, with consequent implications for the maintenance of coastal flood defences. Losses of salt marshes would have particularly significant effects on some coastal defence systems.

3. Frequency of floodplain inundation: it is unlikely that climate change will produce as large a change in flood risk in inland rivers as along the coast (and could, of course, result in a *reduced* flood risk). Impacts will vary between catchments, with responsive, steep or highly-urbanised catchments catchments showing the greatest sensitivity to changes in short-duration rainfall characteristics.

4. Maintenance and integrity of river flood defences: river defences will be affected by changed patterns of erosion and deposition following changes in river flow regimes and sediment supplies. Increased temperatures and insolation would mean greater weed growth, with a consequent increase in the need for stream clearance.

5. Storm sewer flooding: increased high-intensity short-duration rainfalls would cause storm sewer surcharge, with implications both for "off-river" flooding nuisances and for receiving channels.

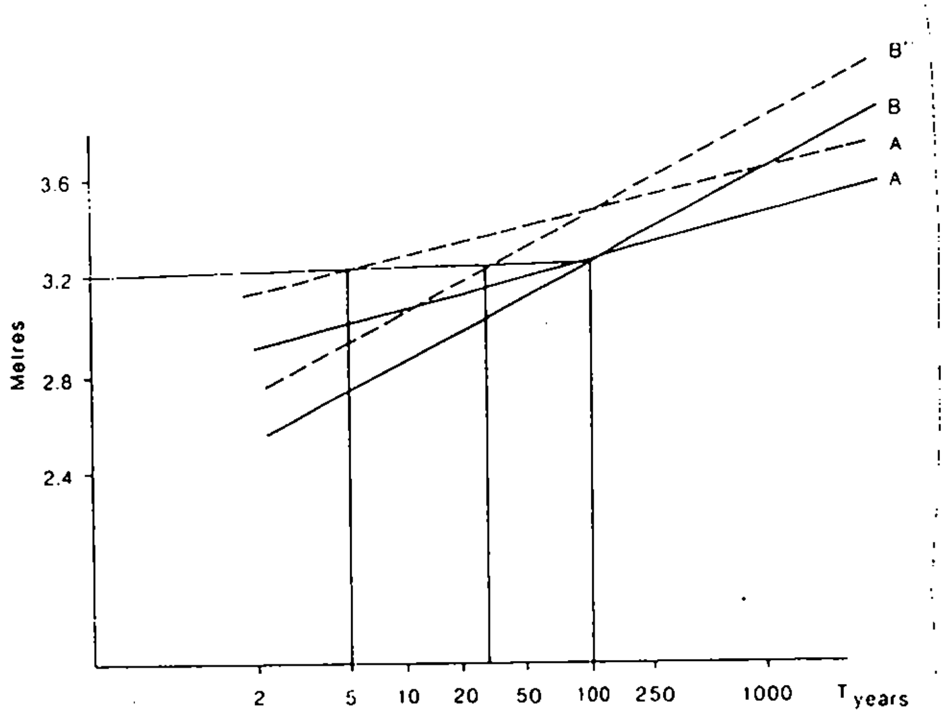

Figure 5.2 Showing how a change of 0.2m in mean sea level affects return periods for different probability curves. The 3.2m level (solid lines A, B) has a 'return period' of 100 years at both sites at present. However, for a 0.2m sea level rise the return period falls to 25 years and 5 years at B and A respectively (broken lines A', and B'). The examples are hypothetical, but B is characteristic of the east coast of England, and A is more representative of the south coast. (Pugh, in CCIRG, 1991)

6. FISHERIES

6.1 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 wildlife resource in need of conservation, secondly it is a managed resource exploited commercially, and thirdly it is a resource exploited for recreation. 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, they have the greatest relative importance in the south, east and centre.

The NRA is responsible for licencing commercial fish farms (generally off-river) and the commercial netting of eels and elvers, and also sells angling licences for recreational fishing. Most of the 1.2 million licences sold each year are taken up by coarse fishermen.

Figure 6.1 summarises the effect of climate change on freshwater fish. Fish *physiology* 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 ocean circulation and freshwater flows might lead to changes in salmon *migration* patterns.

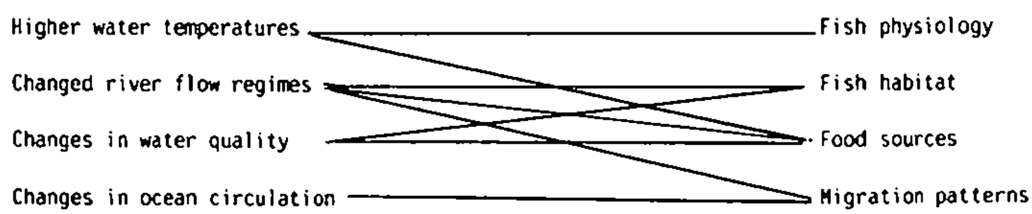

Figure 6.1: Impacts of climate change on fish

6.2 Changes in fish physiology and habitat

6.2.1 Fish physiology

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

Table 6.1 summarises the documented range of spawning temperatures for fourteen common species of freshwater fish and notes the upper lethal limits quoted for their eggs. The most temperature sensitive fish in the U.K. 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. Most of the lakes in which they thrive today are cool, deep lakes in the west and north. In a warmer world, the winter temperatures in many of these lakes could come perilously close to 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 would, however, stimulate early emergence and the newly hatched larvae would be smaller in size and might not be able to find enough food to survive. Most of the other species listed in Table 6.1 spawn much later in the year. 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.

Species	Spawning temperatures	Lethal temperatures
Coregonus lavaretus	0 - 4	> 8
Salvelinus alpinus	3 - 15	> 8
Thymallus thymallus	6 - 10	> 14
Salmo trutta	1 - 10	> 13
Salmo salar	0 - 8	> 16
Salmo gairdneri	4 - 19	> 20
Perca fluviatilis	5 - 19	> 16
Barbus barbus	14 - 20	> 20
Esox lucius	4 - 17	> 23
Cyprinus carpio	12 - 30	> 26
Rutilus rutilus	5 - 22	> 27
Abramis brama	8 - 24	> 28
Tinca tinca	18 - 27	> 31
Alburnus alburnus	14 - 28	> 31

Table 6.1: Range of spawning and lethal temperatures for the eggs of a number of common freshwater fish (all values to nearest °C).

The fish that spawn in the colder months of the year are also the ones most likely to suffer from an increase in summer temperatures. Table 6.2 lists the optimum and upper critical range of temperatures commonly quoted for the more temperature sensitive fish in the U.K. The most vulnerable lake fish are 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. The numbers of charr in the South Basin of Winderemere have declined steadily throughout the 1980s (Mills et al, 1990). This decline follows an extended period of enrichment and coincides with a marked decrease in the summer concentrations of oxygen in deep water. To date the lowest oxygen deficits have, fortuitously, been recorded when the summers have not been exceptionally warm (Figure 6.2). In a warmer world high surface temperatures and low deep water oxygen concentrations are certain to coincide. The charr would then be confined to very narrow range of depths and would probably not be able to feed efficiently.

The most vulnerable river fish is our native brown trout (Salmo trutta). Most trout populations in the U.K. should be able to survive, but their growth rate would be very much slower than it is today. Elliott (1976 a, b and c) has published a series of papers that quantify the thermal limits for growth and survival in brown trout. Figure 6.3 shows how the energy available for growth at a given temperature decreases progressively as the food supply is reduced. 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.

Species	Optimum range	Upper critical range
Coregonus lavaretus	8 - 15	20 - 25
Salvelinus alpinus	5 - 16	22 - 27
Thymallus thymallus	4 - 18	18 - 24
Salmo trutta	4 - 19	19 - 30
Salmo salar	6 - 20	20 - 34
Salmo gairdneri	10 - 22	19 - 30

Table 6.2: The optimum and upper critical limits for the more temperature sensitive species of fish in the U.K. (all values to the nearest °C).

Figure 6.4 shows a family of growth curves calculated using `full ration´ rates incremented for every fifteen days. The curves cover the growth of the trout for the first two years of their life (ie. up to the time where they become smolts and migrate to the sea). The `normal´ curve is based on actual 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. Current `climate change´ scenarios suggest that winter temperatures in the U.K. could increase by 4°C and summer temperatures by 2°C. These growth curves demonstrate 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.

6.2.2 Fish habitat

The basic controls on fish habitat are water velocity and depth, channel substrate, in-channel vegetation, bank characteristics and vegetation, and water quality. Different fish species, however, 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 has involved the development of relationships between habitat suitability and, so far, 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 U.K. climate becomes progressively warmer, summer droughts will become relatively common. Lake fish are relatively well buffered against these climatic extremes, but river fish are very susceptible to prolonged droughts. Black Brows is a small stream in central Cumbria that normally has a relatively equable flow regime. Long-term studies of the trout populations in this stream (Elliott, 1985), nevertheless, demonstrate that severe droughts can kill large numbers of young trout. Figure 6.5 summarises the average yearly losses recorded from the parr stages of trout in this over a twenty year period (1969-1989). Annual losses have been calculated using the well established method of `key factor analysis´ (Varley, Gradwell & Hassel, 1973). In this method, population density is expressed on a logarithmic scale and loss rates (k factors) calculated for successive stages in the life cycle. 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.

6.2.3 Fish migration

Droughts that threaten the survival of young fish in the upper reaches of a river may also discourage migratory fish from moving upstream. The FBA (now the IFE) has operated a salmon counter on the River Frome in Dorset since 1971. An analysis of the monthly returns from this counter demonstrates that there are usually two `runs' of salmon in the year, one in the summer and one in the autumn. In summer, the number of fish moving upstream is not closely related to the mean flow but very low flows usually stop the fish from moving upstream. Figure 6.6 shows the effect that the dry summers of 1976 and 1989 had on the movement of salmon in the Frome. In 1976, very few fish moved upstream but the number of potential migrants was also very low. In 1989, the stock of fish in the river was very much higher so the limiting effect of the low summer flow was much more obvious. In a warm world, the summer runs of salmon in many U.K. rivers could well disappear. The number of salmon moving upstream in the autumn could, however, increase if summer droughts were followed by heavy rains.

Changes in ocean circulation patterns might also affect migratory routes, and hence the abundance of salmon in rivers (reference?).

6.2.4 Food sources

A change in river flow regime and water quality will also of course 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 in Section 6.2.3. The invertebrate community at a site is a dynamic complex of interactions (Armitage and Ladle, 1991), and it will therefore be difficult to model the detailed effects of climate change. The most likely affect 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 quite 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.

6.3 <u>Effect on NRA fisheries activities</u>

The NRA will not be able to do very much to prevent fish populations changing as water temperature increases, flow regimes change and water quality alters. It might, however, need to reconsider stocking policies and specific management activities as "natural" species composition changes.

Increased water temperatures might mean that a given amount of pollution would have a greater chance of causing significant fish kills. This would mean more frequent response to fish kill emergencies, and would encourage greater efforts to prevent pollution incidents.

Increased water temperatures might also result in a change in the incidence of fish diseases, with subsequent implications for the management of disease outbreaks.

6.4 Information needed by the NRA

The NRA needs information on:

1. Potential changes in water temperature: the University of Exeter is currently estimating changes in the thermal regimes of rivers following climate change, under contract to the Department of the Environment.

2. The effects of changes in river flow regime and water quality on habitat suitability and hence fish populations. The work currently being undertaken in order to derive ecologically acceptable low flows is directly relevant.

3. The effects of changes in water temperature on fish physiology and disease.

4. The changed sensitivity of fish to pollution, with higher water temperatures.

6.5 Key sensitivities and uncertainties

Table 6.3 shows the aspects of the NRA's fisheries function most affected by climate change, together with the relevant climate parameters.

Critical activity	Relevant climatic parameters	Other relevant parameters
Change in fish populations	1. Water temperature 2. River flow regime changes 3. Changes in water quality	
Sensitivity to pollution incidents	1. Water temperature	
Fish disease	1. Water temperature	

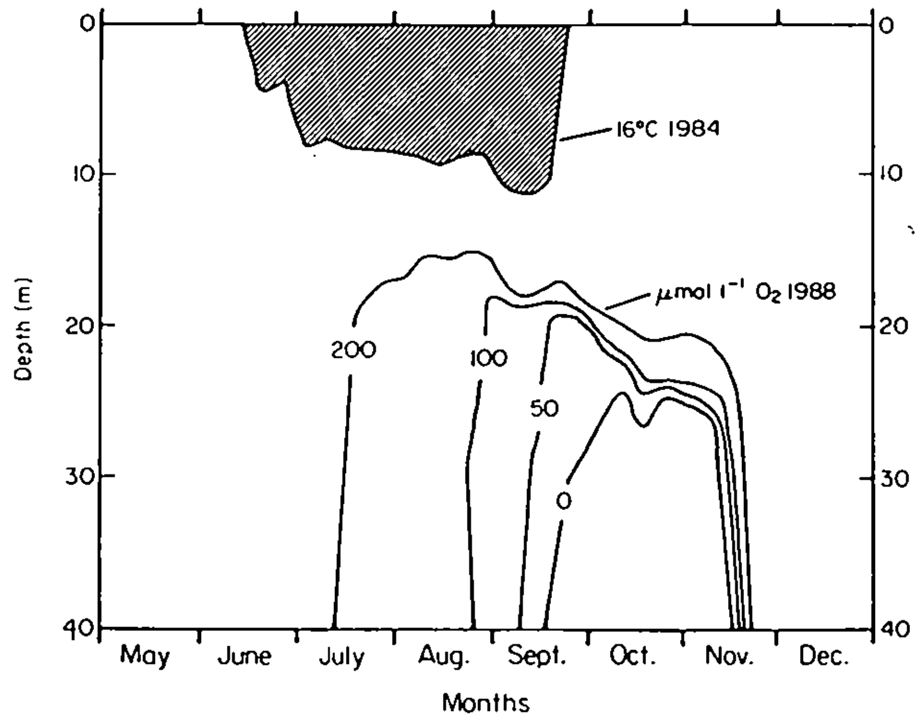

Figure 6.1: Distribution, in depth and time, of dissolved oxygen (μmol O_2l^{-1}) in the hypolimnion during 1988 and temperature (^oC) in the epilimnion during 1984, for the south basin of Windermere. The hatched area indicates the extent to which temperature exceeded the preferred maximum for charr (16^oC) in a recent warm year, and the isopleths for oxygen show the extent of a recent substantial deoxygenation in the hypolimnion. If both phenomena occur in the same summer, charr would be restricted to a layer of water between 10 and 20m depth, for periods of 1-4 months.

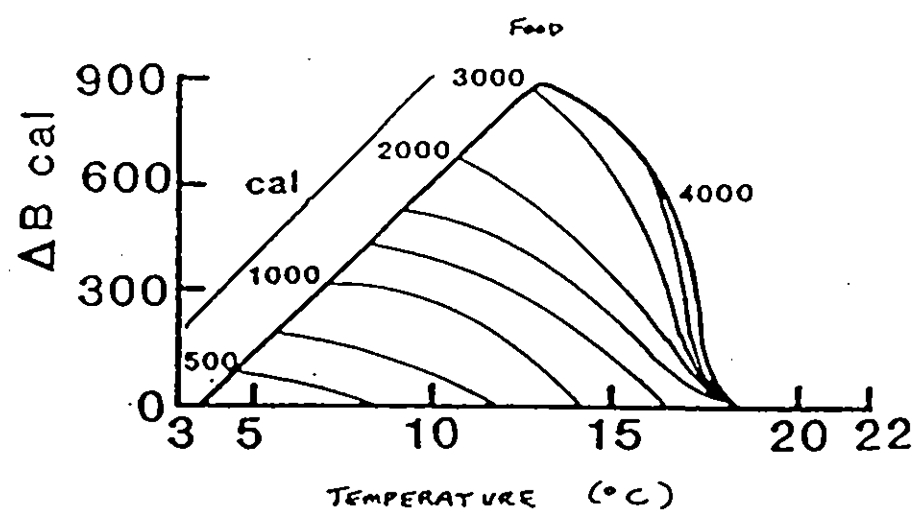

Figure 6.2: Energy available for growth at different temperatures and different feeding regimes.

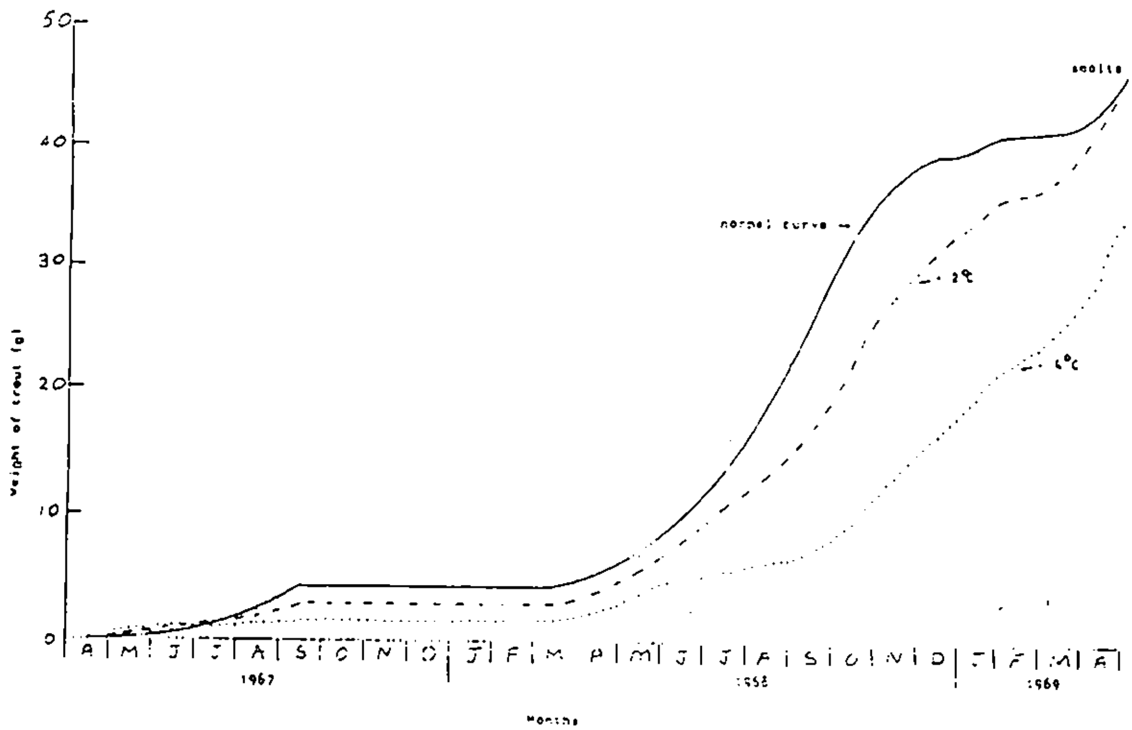

Figure 6.3: The predicted effects of increased temperature on the growth of brown trout (Elliot, unpublished data).

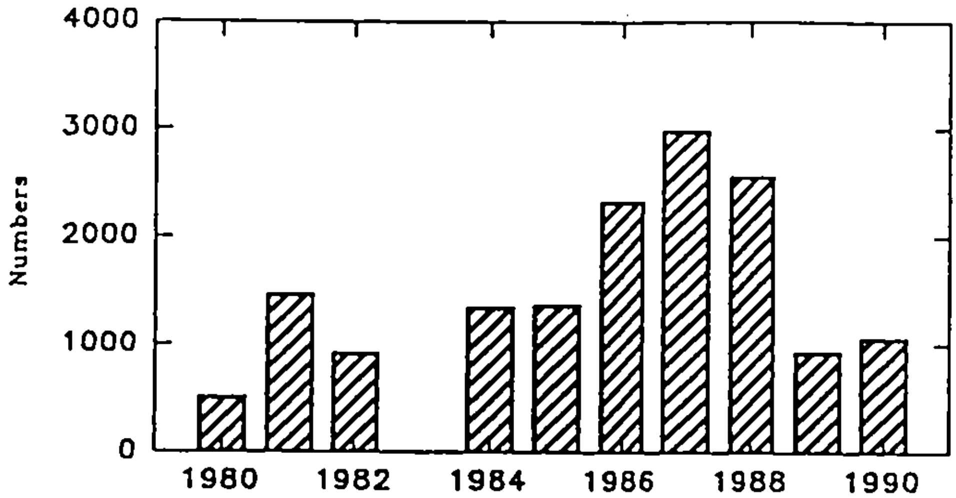

Figure 6.4: The year to year variation in the number of salmon moving up the River Frome in summer. The numbers are numbers logged on a resistivity counter positioned in a gauging weir. The counter was not operating in 1985.

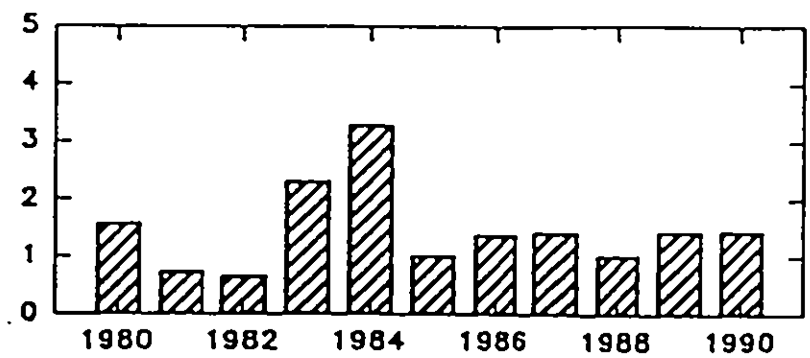

Figure 6.5: The year to year variation in the number of trout lost between the parr stages in May/June and the parr stages in August/September. The loss rates have been calculated by key factor analysis.

*

7. CONSERVATION

7.1 Introduction

The NRA aims to conserve and enhance wildlife, landscapes and archaeological features associated with waters under NRA control. In practice, this means that the NRA is involved in conservation along river corridors and the coastal fringe. The NRA undertakes conservation work both generally to improve the environment 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.

It is important to distinguish between changes in inland riverine ecosystems and coastal ecosystems.

7.2 Changes in freshwater wetland and river corridor ecosystems

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

Firstly, a change in temperature and patterns of soil moisture deficit would lead to changes in the species composition of ecosystems. Cannell (in CCIRG, 1991) estimated that an increase in temperature of 1°C 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 riverine ecosystems, although Cannell (1991) noted that a 1°C rise in temperatures would enable many dragonfly species to spread to northern England and that higher temperatures could affect adversely the hibernation patterns of amphibians. 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. 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.

Secondly, 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.

7.3 Changes in coastal ecosystems

Approximately 10% of the notified nature reserves of the UK occur near sea level on the coast (Cannell, 1991), and salt marshes extend along XX% of the coastline of England and Wales.

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 deplaced 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 80cm in sea level would lead to the elimination of the "general salt marsh" zone (the zone covered only in higher spring tides) along a 12km 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.

Sand dune habitats would be attacked by erosion, and would where possible respond by migrating inshore. Given the freedom to move, large dune sites are therefore 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).

(mention Posford-Duvivier report..what is in it?)

7.4 Effect on NRA conservation activities

The NRA aims generally to improve the environment in and around watercourses and along the coast, and to ensure that conservation issues are considered when water management schemes are designed and implemented.

It is impractical to attempt to maintain a particular ecosystem against a background of a changing climate, so the NRA would need to develop strategies for dealing with particularly exposed communities. The NRA (and the public) would have to accept that some systems would evolve into a different structure, but might be able to encourage the development of corridors linking some sites to allow migration.

Changes in the emphasis of river and coastal management activities due to climate change might also lead to changed pressures on conservation. An increasing interest in "soft defences", for example, might mean that conservation becomes even more intimately connected with coastal defence.

7.5 Information needed by the NRA

The NRA requires information on:

1. Elements of wetland, riverine and coastal ecosystems showing the greatest sensitivity to change in climate, and the sites at the greatest risk of significant change.

2. The sensitivity to change of individually important species or communities (such as otters).

3. The *rate of change* in climate (particularly of temperature and sea level rise).

4. The relative importance of climate change and other changes, such as an alteration in land use.

The NRA may need scientific information to backup alleged "impotence" in the face of a changing ecosystem.

7.6 Key sensitivities and uncertainties

Table 7.1 shows the aspects of the NRA's conservation function most sensitive to climate change, and indicates the relevant climate parameters. The *rate of change* is particularly important.

Critical activity	Relevant climate parameters	Other relevant parameters
Loss of coastal marshes and mudflats	1. Sea level rise (amount and rate)	
Loss of coastal bird habitat	1. Sea level rise (amount)	
Change in riverine/wetland ecosystem composition	1. Temperature (amount and rate) 2. Soil moisture deficit	1. Land use change 2. Local availability of invading species
Change in "important" species	1. Temperature	1. Land use change

Table 7.1: Critical conservation activities, and relevant climate parameters.

8. RECREATION AND NAVIGATION

8.1 Introduction

The NRA's recreation and navigation functions are very closely related, because much navigation is for recreational purposes. In general, the role of the NRA is to (i) develop the amenity and recreation potential of waters and lands under NRA control and (ii) improve and maintain inland waterways where the NRA is the navigation authority.

Common to both activities is a requirement to maintain water levels in rivers and to conserve water.

8.2 Changes in recreation

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 main role of the NRA is to ensure a clean water environment for recreation; increasingly, this means ensuring that water meets certain objective 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).

The *demand* for tourism and recreation generally is very dependent on economic, social and technological changes, and is generally increasing. The NRA plans, for example, to manage an increase in the number of visitors to NRA facilities of 45% between 1989/90 and 1993/94 (NRA, 1991). 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 (Smith, 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.

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.

8.3 Changes in navigation

The NRA is the navigation authority for a number of rivers in the Anglian, Southern and Thames regions, and in these rivers 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 British

Waterways Board is responsible for the UK's canal network and for other navigable rivers.

The vast majority of the navigation on rivers for which the NRA is the navigation authority is recreational, and commercial navigation on NRA rivers is largely limited to the few harbours which come under NRA control and tidal portions of some rivers (such as the Thames).

The main impact of climate change on navigation concerns 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 the recently-renovated Kennet and Avon canal in Berkshire could not open in 1990 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 3). Supplies to a canal often come from a number of small, independent, reservoirs, and these are likely to be particularly sensitive to climate change. (How much water does an "average canal system" use in a year? Water used in each lock operation?). Changed river flows would also affect sedimentation patterns within a navigable waterway.

8.4 Effects on NRA recreation and navigation activities

NRA recreation managers will find it difficult to plan for any effects of climate change on the demand for recreation, and will be concerned much more with maintaining water quality standards for different water-based activities (see Chapter 4 for a discussion of the effects of climate change on NRA water quality activities). The NRA would need to be particularly concerned about minimising the outbreak of toxic algal blooms.

There are three main areas in which climate change would affect the navigation function:

1. The operational management of river levels in rivers where the NRA is the navigation authority. It may be necessary to develop new operational strategies to conserve water.

2. Maintenance activities in rivers where the NRA is the navigation authority; changes in sedimentation patterns might necessitate alterations to dredging regimes.

3. Review of licences for the supply of water to navigation systems. Although demand from the navigation authorities might not increase (except to the extent that increased evaporation might increase losses from supply reservoirs and rivers), the supply of water might be altered and the NRA might need to reconcile a number of competing demands for a reducing resource.

8.5 Information needed by the NRA

The NRA requires:

1. Information on the future rate of exceedance of water quality standards specified for particular water-based activities (see Chapter 4).

2. Information on the ability of water supply systems to provide enough water to maintain navigation in rivers and canals (see Chapter 3). Navigation systems relying on large numbers of small supplies may be particularly at risk.

3. Techniques for optimising navigation potential (by maintaining river levels) whilst minimising use of water.

4. Information on changed sedimentation patterns in those rivers for which it is the navigation authority.

8.6 Key sensitivities and uncertainties

Table 8.1 summarises the effects of climate change on recreation and navigation, and lists the relevant climatic and non-climatic parameters. The recreation and navigation functions are most influenced by changes in water quantity and water quality, which are summarised in Chapters 3 and 4 respectively.

Critical activity	Relevant climatic parameters	Other relevant parameters
Demand for water-based recreation	1. Temperature 2. Factors affecting water levels (Table 3.1) 3. Climate "comfort" factors (cloudiness, windspeed)	1. Social, economic and technological changes
Water-course recreation potential	1. Water temperature 2. Factors affecting water quality (Table 4.1)	
Water supply for navigation systems	1. Rainfall 2. Factors affecting water quantity (Table 3.1)	1. Competing demands
Sedimentation in river channels	1. Factors affecting water quantity (Table 3.1)	1. Land use change

Table 8.1: Critical recreation and navigation activities, and relevant climate parameters.

9. SENSITIVITY OF NRA ACTIVITIES TO CLIMATE CHANGE

9.1 Areas of greatest sensitivity

Different amounts of information are available for different spheres of the NRA's interest. In general, this can be characterised as "quite a lot is known about sea level rise and its implications, a fair amount is known about changes in water resources, less is known about changes in water quality, and nothing numerical is known about anything else". Many of the impact assessments made in previous chapters have had to resort to rather vague guesswork and generalisations.

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. In some areas these relationships are well-defined - in rainfall-runoff modelling, for example - whilst in others very little is known, and sometimes the relevant climate parameters are not even known. Where the climate-response relationships are known and can be modelled, it is possible to estimate quantitatively the implications of different climate change scenarios, even if there may be considerable uncertainty surrounding the scenarios themselves.

Each of the preceding chapters finishes with a summary of sensitive activities and relevant climate parameters. Table 9.1 lists all the identified sensitive activities, and indicates (i) the degree of uncertainty surrounding the relevant climate parameters and (ii) whether the links between climate and response are well-known at present. 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 very poor understanding of these links in the conservation and recreation areas in particular. Table 9.1 also gives a subjective assessment of the relative importance of each area of impact to the NRA.

9.2 Coping with climate change

The different NRA functions will need to respond differently to climate change, due to the different degrees of sensitivity and uncertainty about climate change and system response. There are, however, a number of themes common to all or many NRA functions.

1. It is important that some competent body - the NRA or the Department of the Environment, for example - issue a policy statement asserting that climate change is a problem and requiring it to be considered where appropriate. Such a statement already exists within the coastal defence sphere. Furthermore, the statement ought to make reference to a set of "approved" climate change scenarios indicating changes in at least monthly temperature, rainfall and potential evaporation, as well as changes in the frequency of occurrence of high-intensity rainfall. At present the CCIRG scenarios should be used as a consistent starting-point, but over the next few years the scenarios developed by the DoE-funded link project at the Climatic Research Unit should become the standard.

Sensitive activity	Degree of certainty in controlling climate parameters	Understanding of climate-response relationship	Importance to NRA
lack of winter recharge	**	***	*****
high summer irrigation demand	*	*	***
high demand for garden watering	*	*	****
reduced frequency of pipe bursts	**	*	*
saline intrusion along estuaries and into aquifers	**	***	**
lack of water for effluent dilution	*	**	***
increased agricultural pollution	*	*	***
flushes after dry spells	*	*	**
mobilisation of soil minerals	*	-	*
increased frequency of algal blooms	**	*	***
increased overtopping of coastal defences	***	***	*****
integrity of coastal defences	**	**	****
changed frequency of floodplain inundation	*	*	****
maintenance/integrity of fluvial flood defences	*	-	**
flooding from storm sewers	*	*	**
change in fish population	*	*	*
sensitivity of fisheries to pollution incidents	**	*	**
incidence of fish disease	**	*	*
loss of coastal mudflats and habitat	***	*	*****
change in composition of river corridor ecosystems	**	-	***
loss of important species	**	-	***
changed demand for water-based recreation	*	-	**
changed potential for water-based recreation	**	-	**
altered supply of water for navigation	**	*	**
sedimentation in navigable channels	*	-	*
KEY	* bad ** poor *** good **** very good	- not at all * badly ** can be quantified *** good	* low ***** high

Table 9.1: Activities sensitive to climate change, and degree of uncertainty.

2. It is necessary to identify critical values for each function and location, and determine the risk that these values are exceeded as a result of climate change, in order to identify both sensitive areas and at-risk activities.

3. An evolving climate background necessitates a flexible 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.

4. It is important to monitor changes in water systems, 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.

5. Catchment plans can provide a framework for considering explicitly the effects of climate change in a consistent and coordinated way across all functional activities.

6. It is becoming increasingly important to calculate and specify hydrological characteristics over a common standard period.

10. PRIORITY AREAS FOR RESEARCH

10.1 Research issues

Annex B summarises the relevant research projects that have recently been completed or are underway. Effort so far has concentrated very much on the coastal flooding problem - much funded by the NRA - and, to a lesser extent, on possible changes in river flow regimes and water resources. Some work has also been done on possible changes in streamwater quality and coastal ecosystems.

Tables 10.1 and 10.2 suggest a number of priority areas for research, indicating the potential benefits to the NRA from the project (note that the projects are not ranked within each priority class). Some of the proposed projects are of value to organisations other than the NRA, and joint funding may be appropriate. Note that some areas of research do not appear in the Tables, because research is already underway (Annex B); this is particularly true of coastal flooding.

Research area		Benefits of project
1.	Impacts of climate change on catchment potential evaporation	Essential element in estimating possible changes in surface and groundwater resources
2.	Potential changes in groundwater recharge	Potential changes in groundwater resources are unknown; the areas most reliant on groundwater are those likely to be most sensitive to climate change, and have the fastest growth in demand
3.	Implications of climate change for operation of an integrated water management system	How can the characteristics of a water management system mitigate or exaggerate the effects of climate change? Would changes in operating rules be sufficient? Use an example system from the south east?
4.	Is the 1988-1992 drought a sign of climate change?	Results would help managers assessing licence requirements (but it is unlikely to be conclusive)
5.	Combined and relative effects of changes in climate inputs, land use and river flows on streamwater quality in sensitive catchments	Enable identification of relative importance of different factors affecting streamwater quality; results could be used to identify more generally sensitive catchments
6.	Critical thresholds for specific systems	The project would consider how to identify critical thresholds for specific water management systems, and how to assess likelihood that the thresholds are crossed.
7.	Impact of climate change on fluvial flood characteristics	Information on degree of potential change in flood frequency curves, and sensitivity of different types of catchment
8.	Combining historical information with scenarios of future climate	Methodological advice on how to actually use climate change scenarios in scheme design and planning.
9.	Changes in agricultural practice, with implications for agricultural pollution	Important for pollution control function
10.	Changes in algal blooms	Important for pollution control and recreation functions
11.	Sensitivity of important river ecosystems to climate change	Information on response of ecosystems/key species to climatic variability and change

Table 10.1: High priority subjects for research

Research area		Benefits of project
1.	Expressing hydrological characteristics against an evolving climatic background	The project would enable the more accurate presentation of information on averages and risks.
2.	Changes in fluvial geomorphology	Information on changes in sedimentation and erosion of value to flood defence and navigation functions
3.	Effects of climate change on recreation-potential of a water-course	Information on factors affecting ability of a system to sustain/attract recreation, and therefore on sensitivity of recreation to climate change
* 4.	Sensitivity of fish to pollution incidents	Important for pollution control function *

Table 10.2: Medium priority subjects for research

Annex A

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NAVIGATION

Published or freely-available reports

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Annex B

Relevant research projects

Function: "Climate change scenarios for the UK"

Title	Funding agency	Contracting organisation	Status	Duration	Comments
Climate change scenarios for the UK	DoE (Global Atmospheres Division)	Climatic Research Unit	in progress	1991-1993	Hadley Centre - Impacts community LINK project
Transient climate change scenarios	MAFF	Climatic Research Unit	in progress	1991-1993	input to agricultural impact studies

Function: 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 B009	Water Research Centre	Complete	1989-1990	Inherited from NW Water Authority
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 on demand for water	DoE (Water Directorate)	Dept. of Economics, Univ. of Leicester	in progress	1991-1993	Part of DoE Water Directorate "umbrella" project
Possible effects of sea level rise on water resources	NRA B05.2	Water Research Centre	in progress	1990-1992	

Function: Pollution control

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 Atmospheres Division)	Institute of Hydrology	in progress	1990-1994	DoE "Core Modelling" programme, with ecological parts by ITE

Function: Flood defence

Title	Funding agency	Contracting organisation	Status	Duration	Comments
Impact of climate change on sea defences	NRA C07	Water Research Centre	complete	1990-1991	?
Economic appraisal of the consequences of climatic-induced sea level rise (1)	MAFF	University of East Anglia	complete	1990-1991	
Economic appraisal of the consequences of climatic-induced sea level rise (2)	NRA C07.1	Halcrow	complete	1990-1991	NRA Anglian extension to above MAFF project
Sensitivity of sea defence structures to greenhouse effect	NRA C07.2	HR Wallingford	complete	1990-1991	
Beach development due to climatic change	NRA C07.3	HR Wallingford	in progress	1990-1992	
Climate change, sea level rise and associated impacts in Europe	EC DGXI	Dept. of Geography, Coventry Poly.	in progress	1991-1993	Part of EC-scale study and consortium
Impact of sea level rise on coastal lowlands	EC / NRPB and others	Environmental Research Centre, Univ. of Durham	in progress	?	several linked projects
The economic impact of predicted sea level rise on the central southern coast of England	MAFF	GeoData Institute, Univ. of Southampton	complete	1990-1991	
Evaluation of tidal return periods - changes due to climate change	NRA C07(91).1	..to go to tender	not started	1992-?	PROPOSED project

Function: Conservation

Title	Funding agency	Contracting organisation	Status	Duration	Comments
Environmental opportunities under a scenario of sea level rise	NRA F01.41	Posford-Duvivier	in progress	1990-1992	
Climate change, rising sea levels and the British coast	DoE Air Quality Division	Institute of Terrestrial Ecology	complete	1989	

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