1989/046

ARCHIVE:

PLEASE DO NOT DESTROY

Natural Environment Research Council

Effect of Climatic Change on Quantitative Aspects of United Kingdom Water Resources

M.A. Beran and N.W. Arnell

Contract report for Department of the Environment
Water Directorate

April 1989

CONTENTS

EXECUTIVE SUMMARY

1. The possible impact of climate change on quantitative aspects of water resources is investigated in this report. The report's main aim is to present and justify a research strategy for reducing the uncertainties in assessing the consequences of the greenhouse effect.

2. Water resource assessment rests on a foundation of hydrological science and the first step has been to review the state of knowledge about climate sensitivities of the component hydrological processes.

3. Water is of pervasive importance across many aspects of environmental response to climate change, not only to water supply. It is central to the partitioning of energy, and is an essential catalysing and transport medium for key processes of the greenhouse effect.

4. Evaporation will increase overall, possibly by five or six per cent per ^{o}C temperature rise. But in detail the changes will be much influenced by the changes to radiant energy, temperature, and the way in which plant water use reacts to increased carbon dioxide concentration.

5. Unlike runoff magnitude, runoff processes will be less influenced by the warmer environment. After reviewing the DOE core scenario and other sources of scenario information we speculate that the future runoff total will be greater, but also the amplitude of the seasonal cycle will increase, and the time series will be more variable. The necessary work to quantify this more precisely has yet to be done. Similar conclusions can probably be drawn regarding aquifer recharge, although even less is known quantitatively.

6. Changes to the frequency of fluvial flooding, and the hydrological consequences of sea level rise are of similar concern but, for the most part, lay outside DOE's remit so have not been included in the final summing up of priority research needs.

7. Research requirements have been classified according to (i) studies of causes of change; (ii) the measurement and detection of change; and (iii) impacts of change on water resources. It is recommended that DOE give most weight to area (iii) (60 per cent) and divide remaining funds equally among areas (i) and (ii).

8. The highest priority of research should go to evaluations of the consequences of climatic change on river abstractions and reservoir sources. DOE concerns in the coastal areas, and groundwater evaluations under the altered regime were two other high ranking activities in research area (iii).

9. Impact studies require the underpinning of a scenario for change and studies are advocated in area (ii) for extracting high resolution temporal and spatial information from GCM output. Continued data collection and flow naturalizeation are

also necessary to quantify past change and its climate sensitivity, and also to monitor for change. The paramount problem under research area (i) is the need for collaborative research, modelling and experiment, to solve the problem of vegetal response to higher temperatures and carbon enrichment. This is a general requirement across many impact sectors, not only water. Hydrologists should also be encouraged to contribute to GCM land phase development and validation.

10. A top priority subset has also been offered which is based upon water supply impacts on rivers and reservoirs, and the development of the hydrological scenarios required to drive them. This is best complemented by GCM validation studies from area (i).

NOTE ON UNITS AND RELATED TERMS

SI units are used throughout. The UK water industry uses Mld^{-1} for purposes of discharge measurement in water supply and waste control. 1 m^3s^{-1} (pronounced "cumec") is equivalent to 86.4 Mld^{-1}. In hydrological usage the term "specific" is taken to mean "per unit area", eg "specific discharge". It is often convenient to equivalence discharges or volumes per unit area or a rainfall depth. Thus 1 $m^3s^{-1}km^{-2}$ equates to 86.4 mm d^{-1}. Alternatively 1 mm a^{-1} over the land area of the UK would equate to 7.73 m^3s^{-1}.

Some useful areas and equivalences are:

Total area of continents	- 142×10^6 km^2
Total area of oceans	- 362×10^6 km^2
World area of freshwater lakes and reservoirs	- 0.8×10^6 km^2
World area of ice	- 1.6×10^6 km^2
Land Area of United Kingdom	- 244007 km^2
England	- 130360 km^2
Scotland	- 78765 km^2
Wales	- 20761 km^2
Northern Ireland	- 14133 km^2
GB area of freshwater lakes and reservoirs	- 1924.3 km^2
England	- 322.5 km^2
Scotland	- 1527.9 km^2
Wales	- 73.9 km^2

1. INTRODUCTION

1.1 Aims of the desk study

This desk study concerns the hydrological consequences of the greenhouse effect, and investigates the impact of climatic change on practical water-related issues such as water supply, flood control, and resource evaluation. Hydrology is somewhat unusual among the study areas covered by the series of desk studies in that it permeates all aspects of climate change work, scientific and operational. Inevitably with a topic at an early stage of scientific development many more questions will be asked than are answered. So a primary and unifying aim of this report is to identify those research areas most in need of immediate work; to reduce scientific uncertainties, to allow policy responses to be made by government and practical responses to be made by the water industry.

The questions that are most commonly asked by those with decision or policy making responsibilities are:

> What is the likely future climate during the next century?
>
> Do the changes in climatic mean values, variability, and incidence of extreme events lie outside our current experience?
>
> What is the level of certainty that can be attached to the predictions of climate conditions during the next century and of their hydrological and water resource consequences?
>
> What are the solutions; do they entail an adjustment to an inevitable change or can the threat be fought off at source?

They also sum to an all encompassing question of particular concern to the policy maker and others: what action, if any, needs to be taken now? An approach to the answer of this question is presented in chapter 8 which highlights a number of research priorities as well as broader policy issues of domestic and international interest.

1.2 Structure of the report

The heart of the report is chapter 5 in which the main perceived effects on water supply are raised. The main objectives of the report are fulfilled in chapter 8 which enumerates the most important research requirements drawn from the individual chapters.

Hydrology is not only an applied art; there are important scientific issues that underpin the water resource issues of chapter 5 and recommendations in chapter 8. Chapter 2 provides this background and at the same time reminds us of hydrology's wider involvement through the role played by water in atmospheric modelling, earth and plant sciences, and other aspects of the natural environment.

Chapters 3 and 4, like chapter 2, consists of background to the problem of quantifying the impact of the greenhouse effect. Some basic concepts are defined as well as sources of information for expressing the future environment, and the general framework of water and water resources in the UK.

Chapters 6 and 7 contain impacts of importance in the hydrological sphere, but which fall outside DOE's policy responsibilities. Chapter 6 concerns sea level rise, which will have as profound an impact on hydrology as it will on all other aspects. Chapter 7 includes a miscellany of water impacts such as flood control, navigation and power.

1.3 Parallel studies overseas

The greenhouse effect is a global concern and the UK is not alone in marshalling its scientific community to assess its impact on national life. The concluding statement from the Villach conference, organized jointly by UNEP and WMO, provided the necessary impetus for national and regional studies. In the United States the Department of Energy initiated a series of studies including one on information requirements for water resources impact evaluation (Callaway et al, 1985). The Environmental Protection Agency likewise have incorporated an assessment of hydrological impact into their recent report to Congress (EPA, 1988).

Recently the AAAS commenced a programme on Climatic Variability and U.S. Water Resources which brought together teams of experts from which contributory reports have already appeared. Environment Canada has funded a number of studies from universities under the umbrella of its Canadian Climate Centre. Many have focused on problems of the Great Lakes, navigation and hydropower in a warmer world. Australia has begun a climate programme within CSIRO which has published water related reports.

In Europe the Noordwijkerhout conference was a regional response to the call from the Villach conference for such meetings. Water resources was one of the main subject areas. This has spawned a number of follow-up meetings of which the September 1989 Helsinki conference on Climate and Water is the one closest to the subject of this report. The EEC is beginning its EPOCH programme in which climate change is the largest component.

International agencies are also active. WMO continues its World Climate Programme which includes WCP(Water) as a special topic.

The UK is heavily involved in this through IH; its most active area is the assembly and analysis of long time series and techniques for water resource impact evaluation. UNEP is the lead organization within the WCP for impacts and together with WMO created the Intergovernmental Panel on Climate Change in which the UK has the chair of the Scientific Assessment group. At the regional level RA VI has initiated a climate impact programme parallelling WCP(Water).

Other scientific agencies have climate change related programmes: Unesco and ICSU have the IGBP which is concerned with biospheric change, the latter organization through IAMAP also run ISLSCP. NATO are embarking on a programme related to global environmental change. In 1995 GEWEX will begin, this also is concerned with water and global change. IAHS is active through its involvement in these Unesco, WMO and ICSU programmes. It also has organized symposia around the subject, the most recent being at Vancouver in 1988. Again IH personnel have been involved as organizers and participants. IIASA has initiated a programme in which scenario development is central and water applications is one of the active area. Among the technical international organizations the IWRA is organizing a conference on Climatic Fluctuations and Water Management in December 1989 where the greenhouse effect will be discussed.

Explanation of acronyms

AAAS	American Association for the Advancement of Science
CSIRO	Commonwealth Scientific and Industrial Research Organization
EPOCH	European Programme on Climatic Hazards
GEWEX	Global Energy and Water Experiment
IIASA	International Institute for Applied Systems Analysis
IAHS	International Association for Hydrological Science
IAMAP	International Association for Meteorology and Atmospheric Physics
ICSU	International Council for Scientific Unions
IGBP	International Geosphere Biosphere Programme
ISLSCP	International Satellite Land Surface C Programme
IWRA	International Water Resources Association
NATO	North Atlantic Treaty Organization
Unesco	United Nations Education and Science Organization
UNEP	United Nations Environment Programme
WCP	World Climate Programme
WMO	World Meteorological Organization
RA VI	Regional Association VI (European area of WMO)

2. THE PROCESSES OF HYDROLOGY

2.1 Background on the Greenhouse Effect

This is not a textbook on hydrology nor is it a treatise on the greenhouse effect, but some introduction is useful in understanding why the world can be expected to warm, and to appreciate the need for research to reduce uncertainties in making predictions and setting scenarios for the future.

Greenhouse gases

The greenhouse effect is not specifically a hydrological problem; as a phenomenon it has been beneficial - without the heat-trapping capability of the atmosphere, the earth would be some 30 to 40 ^{o}C cooler than it is, and life would be impossible. The problem arises because man's activities have increased the sources and destroyed or impaired the sinks for greenhouse gases, especially carbon dioxide, and as a consequence atmospheric concentrations are rising. The Mauna Loa observatory has recently announced that the CO_2 concentration surpassed 350 ppmv in 1988 and that the annual increase was the largest on record; the current concentration has not been reached during this geological epoch, and is 30 per cent higher than the ambient pre-industrial level.

Carbon dioxide is only one of the anthropogenic gases responsible for the greenhouse effect, and might in due course be overtaken in its contribution by accumulations of methane, nitrous oxide, and CFCs. Man-made aerosols, deforestation and large scale basin transfers also have the potential to enhance global warming. The summation of their effects is expected to exceed the equivalent of a CO_2 doubling around the year 2030.

Temperature record

The Climatic Research Unit at the University of East Anglia maintains a global temperature data set which has shown 1988 to be the warmest year on record, globally speaking, and the 1980s to contain the six highest ranking years of the century. Although highly indicative this does not constitute proof of a strengthened greenhouse effect. However it is unreasonable to suppose that the global energy system is located at a turning point such that both increase and decrease of greenhouse gases in the atmosphere could lead to global cooling.

So the prudent and reasonable expectation is for the earth to warm by between $1^1/_2$ and $5^1/_2$ ^{o}C as a response to effective CO_2 doubling. The date of this rise is uncertain; it will not occur simultaneously with CO_2 doubling because of the thermal inertia of the oceans and the lag time has been estimated only within wide bands. A best "guesstimate" would be for a date in the last quarter of the 21st century, but it also has to be remembered that CO_2 doubling is itself only a "way-station" to higher concentrations unless steps are taken to halt the rise.

In the following sections we consider the individual components of the hydrological cycle in relation to their sensitivity to greenhouse warming and enhanced levels of carbon dioxide. For the total picture one needs to consider both the energy and the water cycles. Figures 2.1 and 2.2, redrawn from the recent NERC publication "Our Future World", illustrate the global magnitudes of the components of these two cycles.

2.2 Radiant energy and its partitioning

The earth receives from the sun an effectively constant stream of short wave radiation of 345 W m^{-2} at the top of the atmosphere. As shown on Figure 2.1, 31 per cent of this is backscattered and reflected but close to half is absorbed at the earth's surface (160 W m^{-2}). The warming of the surface and the air that this causes gives rise to long wave emission. Water vapour and many gases absorb long wave radiation strongly, and their effect in modifying this exchange is what is termed the "greenhouse effect". The effective doubling of the greenhouse gases will be responsible for radiative forcing equivalent to a 4 W m^{-2} enhancement of the long wave flux exchanged between the surface and the atmosphere.

Radiation can be regarded as a climatic variable in its own right as plants and some animals respond directly to radiation for physiological functioning. Of equal concern to hydrologists, glaciers and ice bodies react to the net radiation (incoming - outgoing long and short wave): because there is little surface warming most energy is used for melting. Oerlemans (1988) demonstrates that the world-wide retreat of glaciers (typically of the order of one kilometre per glacier since the early part of the nineteenth century) cannot be explained by the past moderate degree of warming, and the direct response to the enhanced radiation is required to account for the diminution of ice area.

In the UK context ice is not a significant water resource issue other than during rare occasions such as the 1947 flood disaster which was in part due to rapid snowmelt. Even on that occasion the major source of energy for snowmelt was from heavy coincident rainfall.

2.3 Evaporation and transpiration

General concepts

Net radiation, R_n, is the driving force for the evaporation process. R_n is the energy available for sensible heat flux - ie by convective transfer to the adjacent air via eddy and molecular diffusion, and as water vapour - ie after overcoming the latent heat of evaporation. As Figure 2.1 shows it is this latter pathway, involving soil physical and plant physiological processes, that is the more significant over land.

Figure 2.1 **Earth's radiant energy balance.** The diagram shows incoming radiation scaled to 100 per cent. In absolute terms the solar radiation is 1353 Wm^{-2} perpendicular to the sun's rays and on average 345 W m^{-2} normal to the surface of the earth. 69 per cent of this incoming short wave radiation is retained within the earth atmosphere system and converted to long wave radiation through the several routes. The portion of the balance of most concern to hydrologists is that at the land atmosphere interface; the evapotranspiration term is the latent heat flux.

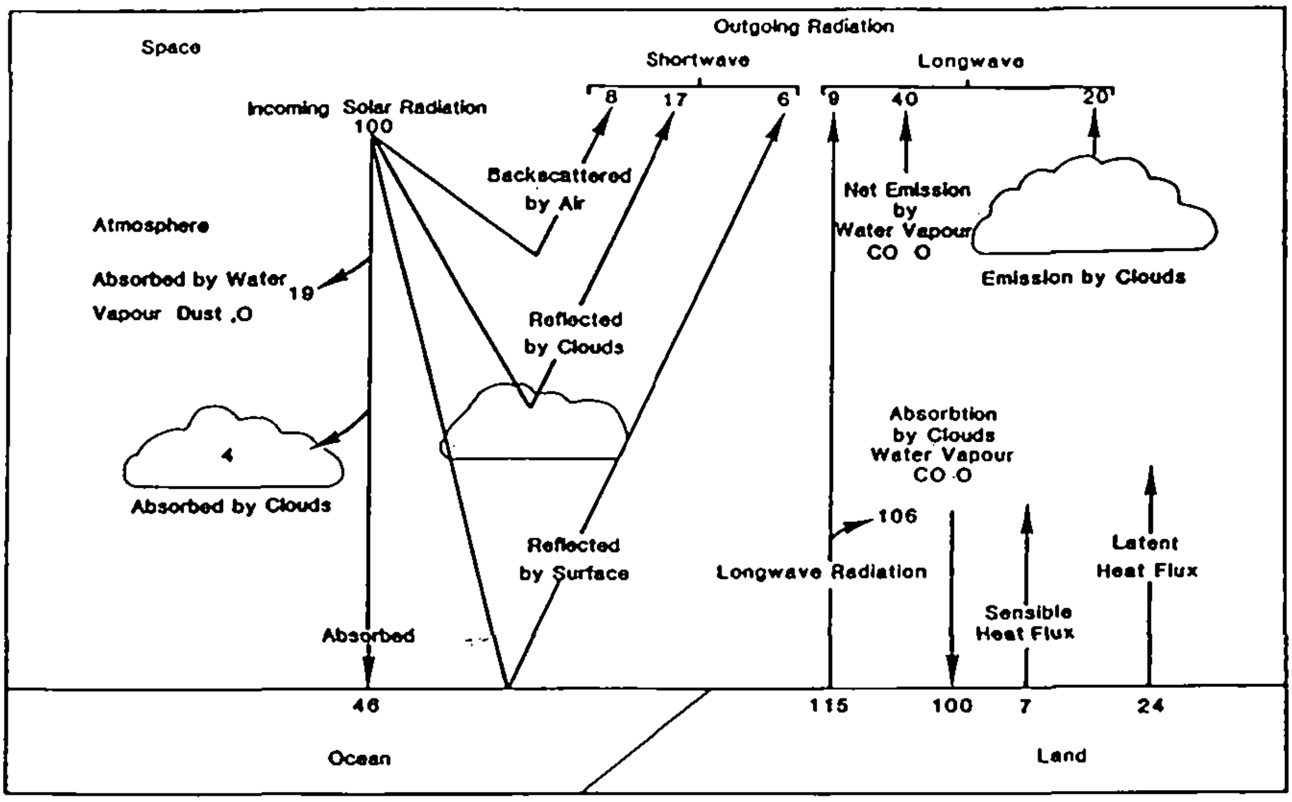
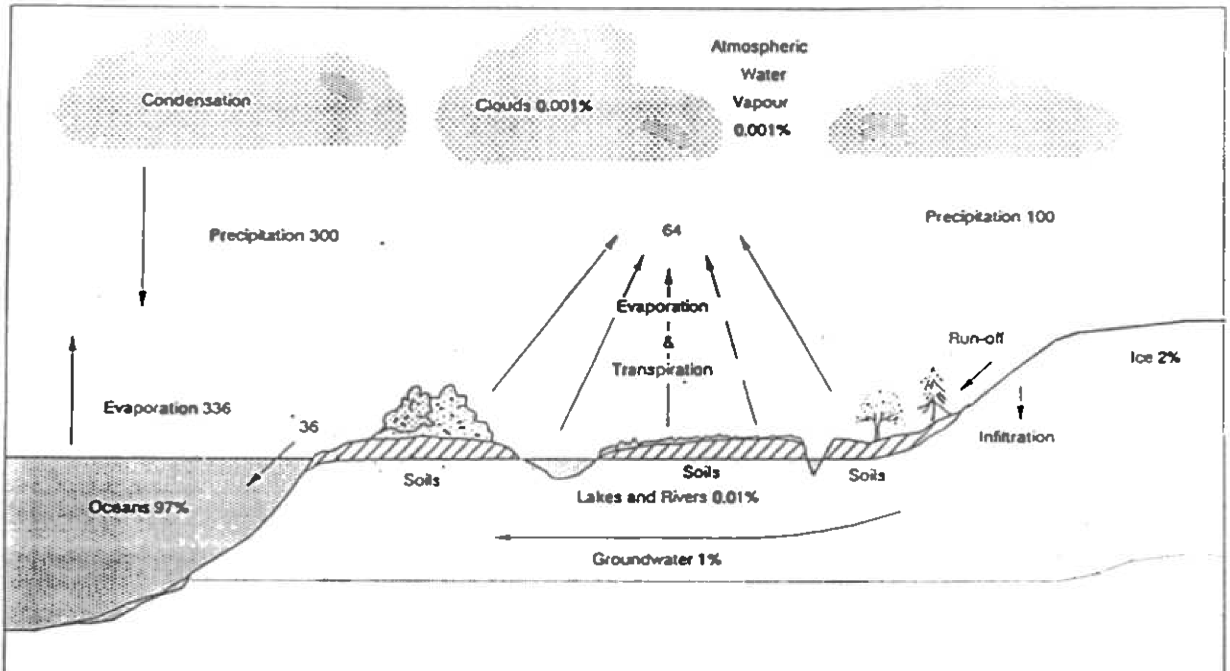


Figure 2.2 Main components of the hydrological cycle. The diagram illustrates the relative magnitude of reservoirs and the fluxes between them. Fluxes are given in gigatons per year and the relative unimportance in volumetric terms of the exploitable fraction (surface freshwater and river flow) is very noticeable. The runoff to the oceans is equivalent to 254 mm over the land area but less than 100 mm over the oceans.



Main Components of the Hydrological Cycle

Figure 2.2 compares the global magnitude of evaporation with the other components of the hydrological cycle; 64 Gta^{-1} is equivalent to 451 mm of annual evaporation over the land surface. Some two-thirds of this total occurs by the transpiration process in forests. Figures 2.3 and 2.4 illustrate the main processes involved in evapotranspiration in functional terms and after conceptualising as a set of resistances analogous to Ohm's Law of electric current. It is this latter form that investigators use when studying the effect of climatic change.

Global impact on evaporation

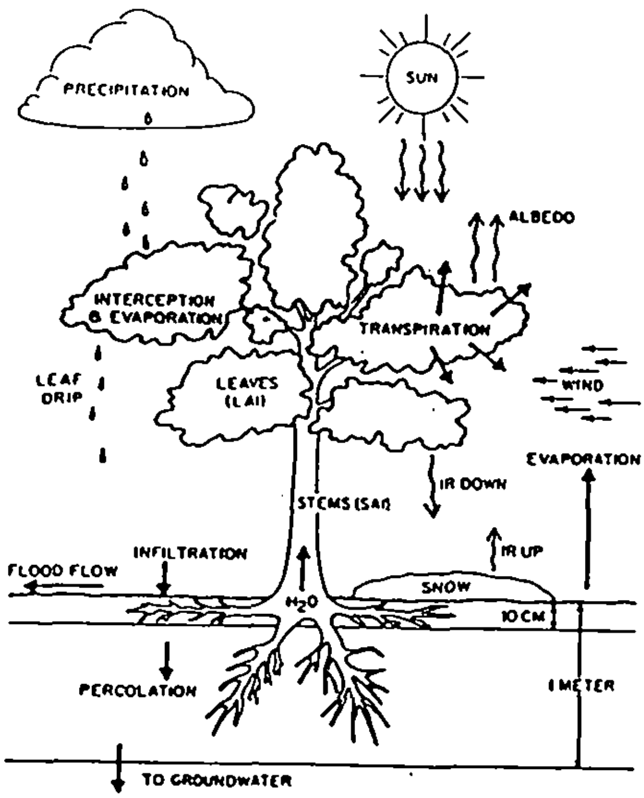
Figure 2.4 indicates that an important control on the rate of evaporation is the moisture content of the receiving atmosphere; the more saturated the atmosphere the less the evaporation. A warmer world will be capable of greater evaporation because the capacity of air to hold water vapour increases by about five or six per cent per degree temperature rise. Manabe et al (1985) adduced from this very fundamental property that the hydrological cycle will be strengthened (ie increased evaporation and precipitation) by about seven per cent for a doubling of carbon dioxide, and made a case for a general increase in extreme events.

The state of each of the elements of Figure 2.3 will influence the soil moisture status and demonstrates the difficulty of making deductions about changes. Any attempt to quantify the effect of climatic change must consider "supply-side" controls as well as the theoretical atmospheric capacity to retain moisture. Here only selected first order influences are discussed.

Most important is R_n which sets bounds on evaporation and will increase as a result of increasing concentrations of greenhouse gases quite independently of other climatic consequences. The water vapour pressure difference between the stomatal cavity and the local atmosphere (e_s-e_a) is linearly related to evaporation rate. By increasing leaf temperature atmospheric warming increases the vapour pressure gradient, and hence the rate of evaporation. The ultimate supply side constraint is the availability of moisture within the soil for evaporation. In vegetated regions evaporation therefore depends on the availability of soil moisture during the growing season. Elsewhere water held deeper than 20 cm below the surface will not be evaporated to a significant extent.

It is not correct to consider the influences as if the evaporating medium were decoupled from the weather system. The altered energy partitioning affects the climate which in turn alters temperature, cloudiness, windiness and ambient humidity. Another potentially important influence is the effect of carbon dioxide enrichment on vegetation. This problem has been referred to by Eamus et al (1988) and Unsworth et al (1988) in the UK context. In terms of Figure 2.4 it translates to an increase in canopy resistance r_c. Such climatic changes may alter plant morphology, leading for example to larger plants,

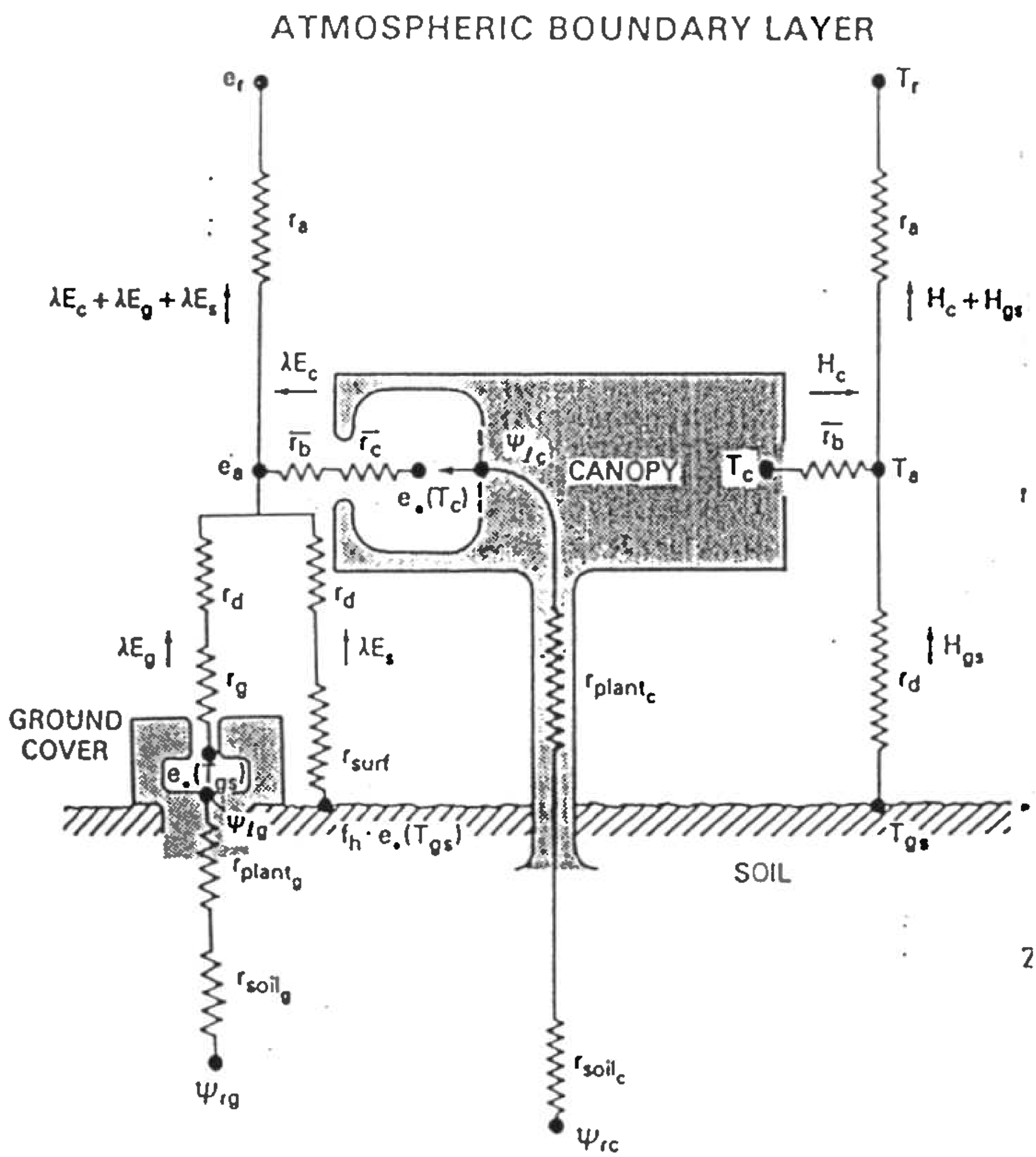
Figure 2.3	Illustration of canopy processes. Moisture and energy pathways in the canopy area and soil surface are the most complex part of the hydrological cycle, and also where the influence of warming and carbon enrichment are their most indeterminate. This complexity is magnified by the dynamic adjustments that takes place in this sub-system so that roots and canopy can exploit resources of light, nutrients, and moisture within biological constraints.



Presently land surface models seek a compromise

between realism and complexity

Figure 2.4 **Framework of Simple Biosphere (SiB) model.** The SiB model (Sellers et al, 1985) is a mathematical formulation of most of the processes illustrated in Figure 2.3 (although not the dynamic adjustment that takes place within the vegetative system). The transfer pathways for latent and sensible heat flux appear on the left and right hand sides of the diagram. The important terms that may change are the stomatal resistance, represented in SiB by a bulk canopy resistance, r_c, and the water vapour pressure e_r.



greater leaf area, changed rooting depth, and eventually to an altered biome.

Shuttleworth (1983) and Martin et al (1989) among others have reported on the sensitivity of evaporation to changes in climate inputs using mathematical simulation models of the process. Because most physical and plant physiological processes are reasonably well understood such an approach is less error prone here than for other land phase hydrological processes. Martin et al (1989) found that the dominant single variables were temperature, R_n and r_c for a forest biome in the USA. Their multifactor simulations tended to show a large impact with a temperature-only control run which reduced when other changes were included. For example, with a 2 x CO_2 climate change prediction a 28 per cent increase in evaporation for grass was reduced to a four per cent increase when direct CO_2 enrichment and leaf area changes were introduced.

Evaporation from the UK area

Figure 2.5 shows that in the UK actual evaporation varies from under 300 mm in the north of Scotland up to over 600 mm in the south-east of England. The physics of evaporation, of course, is identical in the UK and over the globe, but there are special circumstances which affect the relative importance of different pathways.

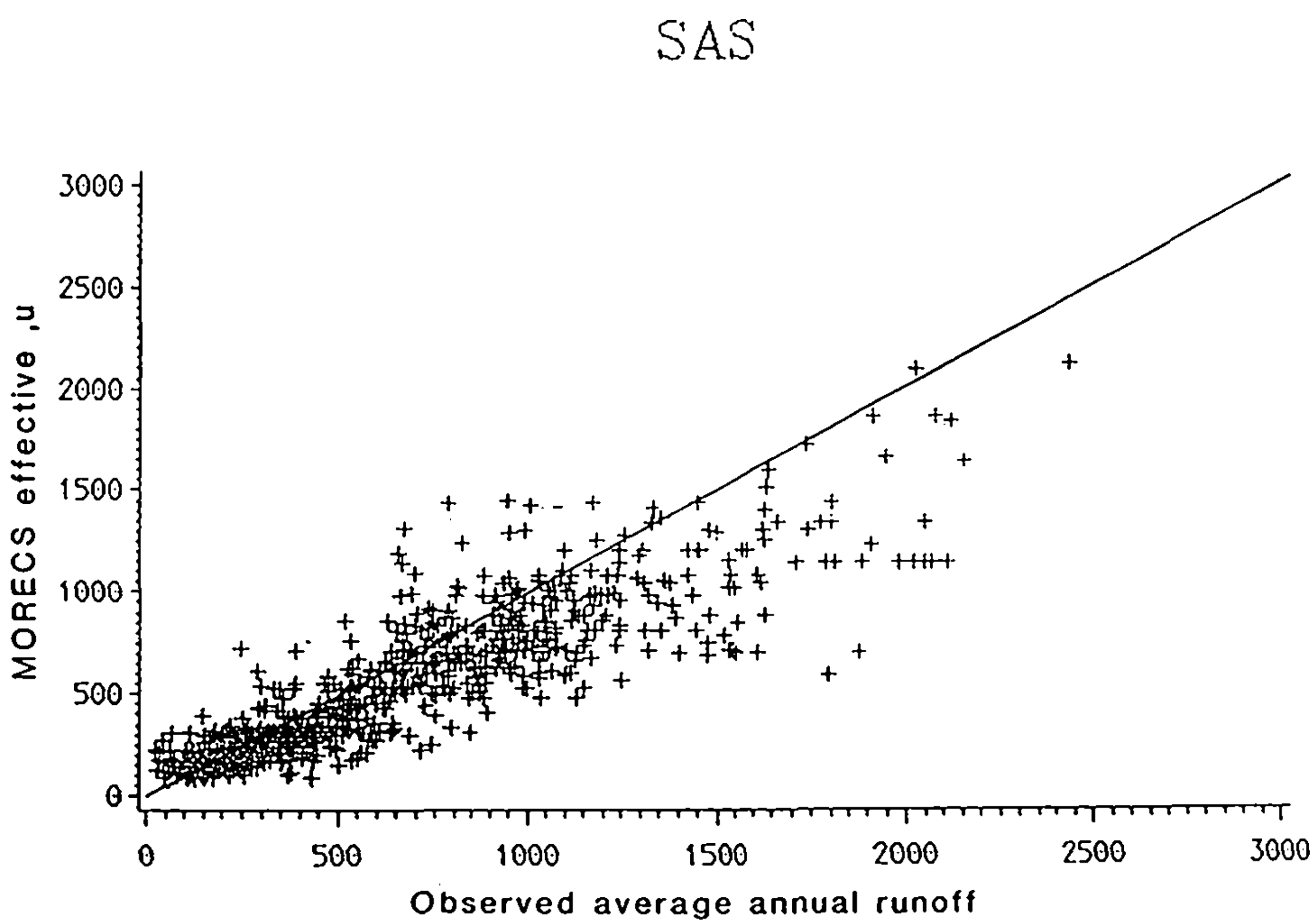
As elsewhere evaporation is limited by the availability of energy, R_n. However because of the UK's western continental situation this is enhanced by energy advected from adjacent oceans, and is responsible for the higher proportion which takes place from interception storage. Vegetation is seldom stressed under current climatic circumstances but a fine balance exists between biomass, soil and climate. It is thought that opportunity to increase biomass may be limited by nutrient supply and delivery rate as much as by energy or moisture supply.

The Meteorological Office's MORECS system (Thompson et al, 1981) employs a formulation of the evaporation and soil moisture processes and so could be used to investigate the sensitivity of evaporation to greenhouse warming over the entire country. Figure 2.6 shows a sample of how such a study may proceed. There is fair agreement in catchments in the high evaporation (low runoff) regions but the implication of the graph is that in upland areas the MORECS system overestimates observed evaporation.

Another alternative is to estimate actual evaporation from the difference between precipitation and runoff (see Fig 1.11b of Lewin, 1981 for a UK map based on this approach). Uncertainties are introduced by percolation to groundwater, error properties of the differencing operation, measurement errors, and spatial averaging errors in the individual terms. Though in common use for resource evaluation it is not suited to climate change studies.

Figure 2.5 Actual evaporation over the UK. This map has been produced from monthly averages of Morecs calculated actual evaporation over the period 1961 to 1985. Short root crop vegetation is assumed in this diagram. It differs markedly from maps produced from "P-Q" for the reasons given in the text. The Morecs method might provide one route for adjusting the map to how it might appear in a greenhouse-warmed world.

Figure 2.6 **Comparison of basin runoff.** The effective precipitation is that computed by the Morecs system, and is compared here with runoff records from stations in the same grid square. This bears on the same issue raised in Figure 2.5 of the disparity between evaporation inferred from runoff and precipitation data and that obtained by energy balance calculation. Further research is advocated to reconcile these differences.



2.4 Precipitation process

General

Viewed from the point of view of the global atmosphere evaporation and precipitation are almost inseparable. Precipitation occurs when the moisture retaining capacity of the atmosphere is exceeded. Nucleation is then necessary in order to allow this condensed moisture to precipitate. It has been discovered that there is a strong connection between the global sulphur cycle (see Figure 5 of Whitehead et al, 1989) and precipitation. Dimethyl Sulphide (DMS), which is derived from ocean algae, provides cloud condensation nuclei over sea and land. Changes to ocean processes induced by the greenhouse effect will certainly affect the production rate of DMS and hence global precipitation. However this is only one component of the "weather machine" and precipitation will respond to all changes in the general circulation, land surface and cryosphere caused by the greenhouse effect. Only a GCM can hope to quantify the net effect of all changes.

In GCMs precipitation is assumed to occur whenever super-saturation is indicated by the state of the system, and occurs as rain or snow according to the temperature near the surface. Reed (1986) and Wilson et al (1987) demonstrate that GCMs overestimate considerably the number of days on which precipitation occurs but at the same time underestimate the number of high rainfalls. This is due partly to the parameterization of the processes and partly to the large grid-scale at which GCM outputs are described.

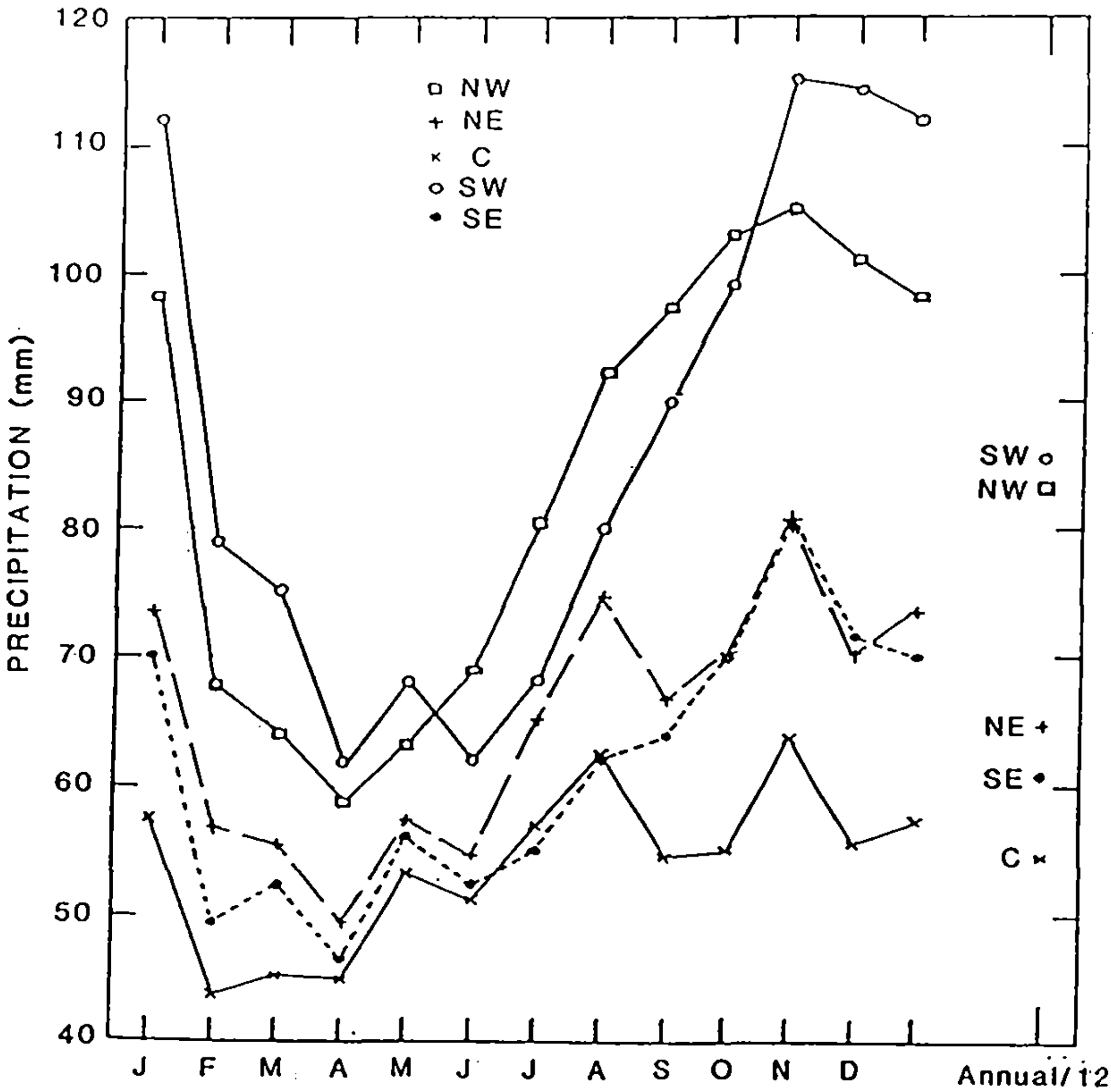
UK rainfall

Rainfall is the dominant form of precipitation in the British Isles, snowfall making up less than ten per cent of the total. However snowmelt can be responsible for extreme events, eg the 1947 floods. Other forms of precipitation, hail and dew, do not play important hydrological roles; although hail merits some attention in the context of climatic change due to its greater prevalence in countries to the south where it is responsible for crop and other damage.

Average annual precipitation over the UK is 900 mm with much of the most south and east receiving less than 700 mm. Rain occurs on average between 160 and 300 days per year, with a spatial variation following that of average rainfall. Interannual variability is low by world standards with a coefficient of variation of 11.3 per cent.

The pattern of precipitation under current climatic conditions reveals an approximate equality between the summer and winter half year. This traditional presentation of seasonal variation does however obscure a quite marked sinuosity in rainfall pattern around the year with a strong minimum near April - a month earlier in the centre and south-east, a month later in the west (Figure 2.7). This seasonal pattern is not at all well represented by GCMs (Wilson et al, 1987; Hulme et al, 1988).

Figure 2.7 Seasonal variation of UK rainfall. This diagram shows that the reputation for very little seasonal rainfall variation in the UK is not well founded. The climate change scenarios tend to enhance the amplitude of this variation. Increased summer evaporation will further increase the seasonal contrast.



Expected changes to the UK precipitation due to the greenhouse effect are discussed in Section 3.3 and mentioned in Section 4.2.

2.5 Soil moisture

The importance of water in the soil has been increasingly recognized by atmospheric modellers (Hunt, 1985; Brandyk et al, 1985). All GCMs now parameterize subsurface processes and there has been a simultaneous burgeoning of interest in remotely sensed soil moisture data and soil properties. The International Satellite Land Surface Climatology Project (ISLSCP) - a programme of the International Association for Meteorology and Atmospheric Physics (IAMAP) - is directed to these ends.

Feedbacks between the soil and climate systems proliferate. Wet soil leads to reduced albedo and reduced net radiation; drying and/or over exploitation leads to desertification (Jung et al, 1984), high albedo and reduced R_n; nutrient and trace gas exchange enters into the climate system via the carbon cycle. Because of the complexity of the system statements about global changes due to the greenhouse effect are possible only through GCMs.

Even the most complicated of these GCM soil process formulations are primitive by comparison with the description required for basin studies. The current view is that it is more accurate to compute soil moisture for hydrological purposes from more fundamental GCM outputs such as temperature and precipitation (WMO, 1987). One of the many problems with GCM soil moisture is the treatment of within grid-square variability in soil properties. The sensitivity of soil moisture prediction to alternative formulations has been investigated by Warrilow (1986). In his numerical experiment, precipitation depth and soil properties influencing evaporation were allowed to vary within a grid cell. While there were clear effects locally, from a global viewpoint evaporation and other climate fields were not much affected.

UK soil moisture estimation

There have been no national investigations of how climatic change and carbon enrichment may influence the soil moisture regime of the UK. As has been discussed above the MORECS model may well be suited to such a purpose although more complex models, eg SHE, will be required for locally critical problems such as radionuclide transport through the unsaturated zone.

2.6 Runoff formation processes

Runoff pathways

Despite many decades of hydrological science, and considerable successes in making predictions for practical aims, some basic hydrological processes remain a mystery. Foremost among these are the runoff formation pathways of moisture in the ground and at the surface. Modern theory, as illustrated in Figure 2.8, favours a combination of groundwater flow with very localized surface runoff. The greenhouse effect will affect this process largely by altering the magnitude of the climatic inputs. It is conceivable that a secondary response, arising from long term adjustments of vegetation and erosion processes to an altered pattern of inputs, may alter the pathways themselves; but this is speculative and long term.

As well as being of practical interest for water resources river runoff also plays a role in the global carbon cycle and hence the processes of climatic change. The transfer of organic carbon from the land to the sea via rivers is one of the major links within the cycle accounting for up to 1 Gt per year.

Modelling basin response

Although it appears from the preceeding paragraph that there will be few changes in the short term due to the runoff formation process itself, there still remains the major problem of modelling the response of a basin to its altered inputs: precipitation and evaporation. Runoff, like soil moisture, is part of a complex chain of interactions rendering intuitive deductions about change impossible, and reinforcing the need for predictive models.

Beran (1986) has categorized runoff impact studies according to the type of model that is employed: conceptual, empirical or water balance. Because conceptual and empirical models provide temporally detailed information they offer the best approach to water resource impact studies (section 5.2). The annual water balance has been used in more generalised investigations. In its most basic form

$$Q = P-E$$

it has been considered as applying to individual annual totals as well as to long term behaviour. Other more complex formulations are discussed in Wigley et al (1985), Beran (1986), and Dooge (1988) which recognize the interaction between P and E. A common object of these studies is the calculation of the magnification factor between the proportional change in inputs and proportional change in annual runoff.

$$r = (dQ/Q) \ / \ (dP/P)$$

The factor is very sensitive to the mathematical form, all values being possible from unity (for a multiplicative type of process, $Q=cP$) to infinity (for a low runoff subtractive process, $Q=P-E$).

As a general rule the magnification is greatest in areas of low runoff. This reveals a fundamental weakness in such an approach; its lack of regard for runoff formation processes. For example in arid and semi-arid regions, where much runoff occurs from a small number of intense falls as overland flow, the true magnification factor approaches unity, whereas most models predict much greater magnifications.

An important development of this approach, due to Eagleson (1982), endeavours to provide a rational basis for the long term water balance. His approach is based upon annual models for water consumption by vegetation in terms of soil moisture and plant productivity parameters. The model is "operated upon" by the probability densities of precipitation and potential evaporation in order to predict the actual to potential evaporation relation (hence runoff) as a function of soil and vegetation parameters. By postulating that in a water limited region vegetation will adjust to minimize water stress, and otherwise would maximize biomass, Eagleson was able to introduce canopy density as a dynamic term and so predict ecological as well as hydrological response. The form of the model is suited to climate change experiments but has not yet been applied in this way.

2.7 Research requirements

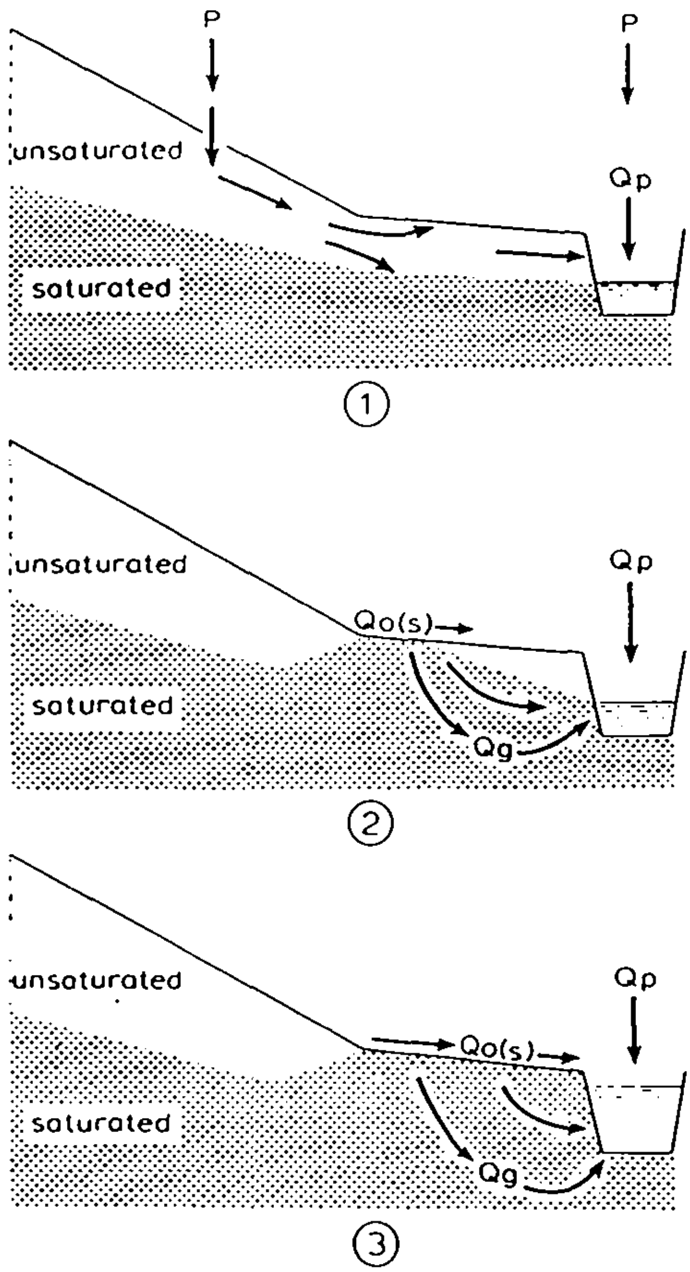
What is very apparent from this chapter, no less than from the other more biological desk studies, is that the strongly interacting components of the processes renders the single factor approach of little predictive value. Conceptual models need to be constructed which incorporate the individual and interacting effects and which also are based on a **good observational foundation.** In the context of evaporation this means controlled environment and field fumigation experiments at elevated temperature and carbon dioxide concentration in order to observe how vegetation reacts in its water use.

In the UK there exists the possibility for making use of the excellent hydrometric network and the operational MORECS system to provide first order impacts with the various provisos mentioned above in relation to interactions and the conceptual mismatch between climatologically defined evaporation, soil moisture and runoff and those same variables measured on the ground.

There is clearly a strong family resemblance between impact studies directed towards evaporation sensitivity and those concerned with crop productivity, soils, and plant community development. Joint studies should be funded which take advantage of the synergies at the system scale which tie together energy partitioning, the biosphere's water demand, and its productivity. Studies should also be conducted on the use of basin rainfall and runoff data to evaluate actual evaporation to validate other approaches. Much care is needed in the selection of data and the treatment of the storage term.

It is clear that we must protect the excellent hydrometric networks that have been built up in the UK. The apparently high

Figure 2.8 Development of runoff process theory. Runoff, from a process point of view, cannot be regarded simply as the residual of precipitation and evaporation. Indeed under the old-fashioned Hortonian view much runoff occurred only when the infiltration capacity of the soil is exceeded, and would therefore be controlled largely by hydraulic rather than thermodynamic processes. Though this view is largely discredited in the UK context, there is no fully adequate theory of "where runoff comes from". Much evidence points to the notion of a saturated mound adjacent to the channel network which is capable of both rapid response (including local surface saturation runoff, $Q_o(s)$) and of apparent long-memory processes.



density, by international standards, is fully justified by the diverse nature of the UK landscape, geology, land use, gradient from oceanic to continental conditions, and water utilization pattern.

Currently the average length of record on the national river flow archive held at IH is less than twenty years. Two rivers - the Thames and the Lea - have flow data extending back to 1883 but there is only a handful of additional gauging stations with fifty years of record. About seventy stations achieve the thirty year threshold, but this compares with approximately 300 in France and 500 in the Federal Republic of Germany.

Artificial influences on the flow regime, ie abstractions, returns and land use changes, represent a severe problem for the use of many of the long term UK records in climate change studies. However the problem, though difficult, is not insuperable but does require resources in order to perform the necessary "naturalization". Partial naturalization was previously performed as a matter of course, but has sharply declined since the mid-1970s reflecting the generally reducing resource available for hydrometric activities. As a measure of this decline, less than a dozen gauging stations nowadays forward naturalized flows to the national archive on a regular basis; the comparable figure was over one hundred a decade ago.

3. SCENARIO CONSTRUCTION FOR HYDROLOGICAL IMPACTS

3.1 The scenario concept

The term scenario is often misunderstood. It is not to be equated with a forecast - ie a statement about a future state of the system at a particular future time - so judgements about "correctness" or "inaccuracy" do not apply. Likewise it is not a prediction, which is somewhat weaker than a forecast being concerned with the statistical distribution followed by a variable, but nevertheless capable of validation retrospectively. A scenario is a weaker statement still and is about how a system might reasonably be expected to behave under certain circumstances. It is one version of the time evolution of a system and has equal force with a number of other equally feasible realisations

In this respect it is similar to a single Monte Carlo simulation run in which the core algorithm representing the way the system responds to its forcing variables is subjected to sucessive randomly assigned input values drawn from their probability distributions. Just as the Monte Carlo simulation obeys a strict set of rules, a scenario likewise has certain attributes which limit the freedom of the scenario builder. These are:

- It must be internally consistent
- It must not conflict with known facts
- It should be constructed in such a way that new facts as they are discovered can be incorporated.
- As a planning tool it must relate to variables and processes of practical interest.

Clearly in the current context it would be highly desirable to have a strict forecast, for example, of the UK climate in 2050. However the state of the art of climate modelling does not permit this, and we must be satisfied with much weaker statements about "what may be"; reasonable and supportable "fictions" that allow us to judge in broad terms the types of actions and responses that may prove necessary.

Because it does not have the force of a prediction or forecast it would not be correct to take specific action, eg reconstruct sea walls or extend reservoirs, on the basis of a scenario. However it would certainly be correct to develop policies to counter effects or to reduce uncertainties to a point where engineering actions could be taken. Chapter 8 outlines such actions in the context of water resources.

3.2 Sources of Scenario information for a 2 X CO_2 world

The tools that climatologists can call upon to develop scenarios for future climate have been enumerated by Hulme and Jones (1988). They include:

i. General circulation models simulating future conditions
ii. Palaeoclimatic analogues (the empirical approach)
iii. Spatial analogues - current climate at site B substituted for future climate at site A
iv. Synthesis or "committee scenarios" being a hybrid of other types
v. Arbitrary adjustments - eg upward or downward changes by fixed amounts of primary climatic variables (sensitivity analysis)
vi. Scenarios based on physical or statistical principles - used to supplement GCM scenarios and provide sub-grid information.

The core scenario recommended by DOE for the desk studies is of types i and vi and is derived from the GISS model results (Hansen et al, 1984) analysed by Bach (1987) for the 1987 Noordwijkerhout conference. Impact studies require scenarios that are expressed in terms which are relevant to the impact, for example in hydrology by using a rainfall runoff model to translate the climate scenario into a runoff scenario, possibly followed by a computer simulation of the water resource scheme.

The GCM approach is the most favoured one as it fulfils all the aims of Section 3.1. A drawback is the lack of spatial detail and it is not common for GC modellers to publish short time-step or extreme value data. This means that, as well as modelling the hydrological and water resource system, the impact investigator must also augment the climate scenario to include temporal variation or extreme values.

Empirical methods are much used in the USSR where the Holocene climatic optimum (5000-6000 BP) is equated with conditions to be met in the first decade of next century, and the last interglacial warming of c 125000 BP is used as an analogue for anticipated conditions at the end of the next century (Vinnikov and Lemeshko, 1987). The remoteness of these periods is indicative of the time that has elapsed since any comparable warming to that now envisaged. Problems of infilling spatially and temporally discriminated data and extreme values are no less severe with the empirical approach than with the GCM-based scenarios.

Instrumental methods, also termed "warm world scenarios", can provide necessary detail concerning local short term weather patterns, but for the reason stated above do not represent conditions expected far into the warming period. Spatial analogues are not independent of other methods because one of them must be used in order to identify the analogue region.

Once chosen then it is relatively direct to convert between the climate scenario and a hydrological scenario - eg one may use directly river flow data from the region. There are many problems with achieving a match and the error of factoring out locational differences, eg orography or distance from oceans, may exceed the stated advantages.

3.3 Climate change scenarios for the UK

GCM based scenarios

It is possible to derive scenarios for future conditions in the UK from several different GCMs. Unfortunately, these GCMs do not agree on the magnitude of change, and in some cases give different indications of the direction of change. The different models currently used for scenario development are described in detail by Schlesinger and Mitchell (1985) and Bach (1987). Whilst there are differences in model structure and parameterisation of various processes, all have very coarse grid intervals (typically several hundred kilometres square) making regional scenarios highly uncertain and very difficult to derive. Table 3.1 is taken from a comparison prepared by Hulme and Jones (1988) for IH, and shows the different estimates of change produced by different GCMs. None of the GCMs consider reproduce the current climate across the UK particularly well (the UK climate is heavily influenced by the seas surrounding the UK, which are not well represented at the scale of the various GCMs), and all have their own strengths and weaknesses.

The Core Scenario employed in the DoE Desk Studies is shown in Table 3.2, and is consistent in general terms with the simulated climates generated by the various GCMs. However, some parts of the scenario are too vague for hydrological applications: like most other areas of impact, estimates of hydrological impacts will be very dependent on the details of the change scenario, and in particular on seasonal changes in precipitation. An attempt was therefore made to refine the scenario, using several more recent reports including the review prepared by the Climatic Research Unit (Hulme and Jones, 1988) for IH.
The core scenario suggests a constant temperature increase of $3^{o}C$ throughout the year, but recent studies (e.g. Wilson and Mitchell, 1987) have suggested that temperatures in the UK will rise relatively more in winter than summer. Hulme and Jones (1988) looked at the spatial variation in temperature change across western Europe, using data from the UK Meteorological Office (UKMO) GCM, and suggested that the warming would be greatest in the east of the UK. By comparing several GCMs, they also suggested that the warming following a doubled concentration of greenhouse gases would be slightly higher than that in the DoE Core Scenario at between 4^{o} and $5^{o}C$. However, the effects of changes in temperature on hydrological characteristics are somewhat less than the effects of changes in precipitation (as indicated in Chapter 2 and shown again in

Table 3.1 Estimates from five GCMs of changes in temperature and precipitation with an equivalent doubling of atmospheric CO_2 at a point representing the UK

Source: Hulme and Jones (1988)

Table 3.1a Seasonal and annual temperature differences (^oC)

Model	Latitude	DJF	MAM	JJA	SON	ANN
UKMO	52.5°N	5.2	6.2	5.0	7.8	6.0
OSU	52.0°N	2.8	2.8	3.1	2.9	2.9
GFDL	51.1°N	5.8	4.8	5.9	5.4	5.5
NCAR	51.1°N	4.6	3.2	3.3	3.5	3.6
GISS	50.87°N	4.6	3.3	3.9	3.4	3.8
Average		4.6	4.1	4.2	4.6	4.4

Table 3.1b Seasonal and annual precipitation differences (mm/day)

Model	Latitude	DJF	MAM	JJA	SON	ANN
UKMO	52.5°N	0.19	0.70	0.86	0.58	0.58
OSU	52.0°N	0.18	0.01	-0.06	0.06	0.05
GFDL	51.1°N	0.50	0.26	-0.39	0.00	0.09
NCAR	51.1°N	0.82	1.37	0.22	0.75	0.51
GISS	50.87°N	0.53	0.09	-0.26	0.28	0.15
Average		0.44	0.49	0.07	0.33	0.33

Table 3.2 The DOE Core Scenario for the desk studies

Atmospheric concentration of CO_2:

2 x CO_2 (270 ppm to 540 ppm) by year 2050

Temperature:

Mean rise : 3 +/- 1.5°C by year 2050
Extremes : Highest season mean temperature (summer) in last century?
Lowest season mean temperature (winter) in last century?

Rainfall:

+/- 20 per cent on a seasonal basis by year 2050

Sea level rise:

80 cms (+85/-60) by year 2050

Extremes: +165 cms
+ 20 cms

Chapter 5); for simplicity the scenario considered in the present study incorporated a constant increase in mean temperatures of either 3° or $4^{\circ}C$.

Each GCM produces a different estimate of changes in precipitation across the UK. All appear to suggest an increase in annual precipitation across Britain, but the seasonal distributions of change differ. At the moment it would be wise to be sceptical of inferences as models lack any UK topography, however each model is fairly consistent in estimating wetter autumns and winters (to varying degrees), but estimates of the direction of summer changes vary. Hulme and Jones (1988) compared the estimated changes from five GCMs, and derived an average change, and from their figures it is possible to derive two scenarios for changes in precipitation in the UK:

i) "wet summers": an increase in rainfall of 40mm, 40mm, 30mm and 30mm respectively for winter, spring, summer and autumn;

ii) "dry summers": an increase in rainfall of 40mm in each of winter and spring, a reduction of 30mm in summer, and an increase of 30mm in autumn. Wilson and Mitchell's (1987) results imply drier summers in a warmer world.

These figures are most appropriate for southern Britain, and would need to be increased in proportion to changes in annual rainfall totals for wetter northern and western areas. The seasonal increases are of the order of 15 to 20%. Hulme and Jones (1988) suggested that the magnitude of the increase in precipitation would weaken from the southwest to the northeast across the UK, based on an analysis of UKMO data.

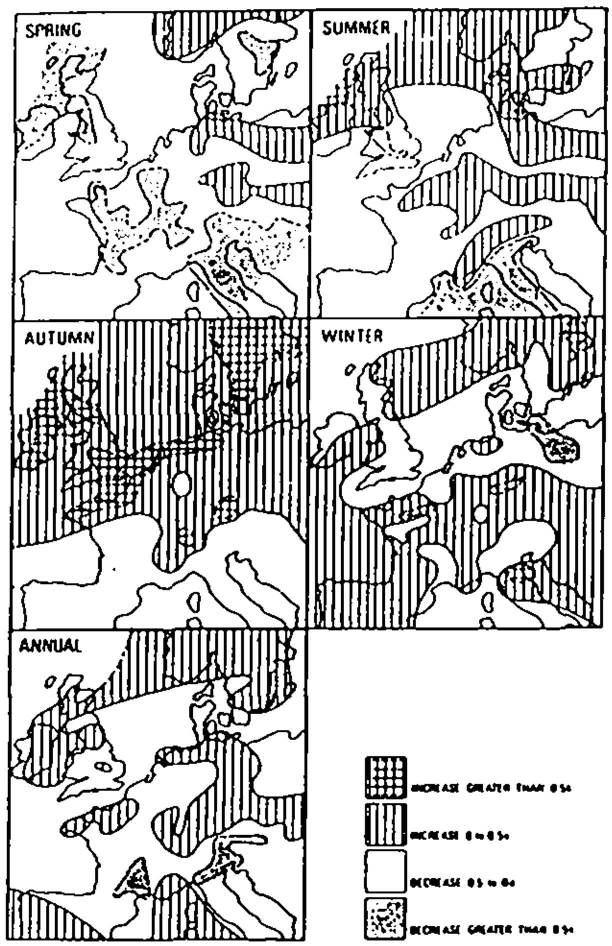
The scenarios used in this study are defined at the seasonal scale, and no suggestions are made about changes at shorter time scales. Wilson and Mitchell (1987) suggested that the number of "cold" days could reduce in a warmer world by more than implied by changes in mean temperatures, due to changes in variability, and that the number of days with "heavy" rain would increase. However, they emphasised that their UKMO GCM reproduced poorly current short term variability, and that estimates of changes in daily climate were to be treated with extreme caution.

Instrumental scenarios for the UK

It is possible to develop a scenario for a changed climate from past instrumental data. Lough et al (1983) followed such an approach to develop scenarios for a warmer Europe and North America from temperature data, and compared seasonal temperatures and precipitation in the coolest global twenty-year period on record (1901-1920) with the warmest (1934-1953). Figure 3.1 shows the changes in precipitation between the warm and cool periods across western Europe. However, a slightly different picture is produced if the "new" warmest period 1968-

Figure 3.1 Changes in precipitation between the warm and cool twenty-year periods, as multiples of the standard deviation

Source: Lough et al (1983)



1987 is used (Hulme and Jones, 1988), and it is difficult to decide whether to use global, hemispheric or even regional temperatures for selecting time periods. The degree of change between recent warm and cool periods is also less than the change possible with increased greenhouse gas concentrations. Nevertheless, instrumental scenarios can give insights into the direction of changes in climate.

3.4 Short time scale and sub-grid data

A brief survey is offered here of some of the techniques that can be used to obtain information for a specific location and to construct a high resolution time series in conformity with GCM grid square climate predictions. This has been termed the climate inversion problem.

Temporal adjustment

The simplest and most widely used method of deriving a time series suitable for impact studies is to adjust an observed climate series to conform to the revised means for the grid square. Normally a proportional adjustment is made to precipitation and an absolute addition or subtraction is made to temperature. Bultot et al (1988) have formalised this approach where a seasonal breakdown of climatology is available.

An alternative has recently been suggested by Karl et al (1989) which makes greater use of the GCM generated time sequencing. It consists of matching quantiles of the observed series and the GCM generated series from control climate runs (ie current or 1 x CO_2 climate). Having formed equivalences, eg of 5, 10, 20 etc percentiles between the observed and predicted values this same relationship is used to convert values from the perturbed climate runs of the GCM. This overcomes the common GCM problem of too many rain days and too few extreme events. Another approach has been described by Wilks (1988), who developed Markov chain models to generate stochastic daily data series from parameters based on monthly data.

Spatial infilling

Both methods described above serve also to adjust for the difference between a site of interest and the gridpoint value. A method due to Wigley et al (1989) is aimed specifically at the problem of providing a sub-grid scale climatology. The method entails establishing a regression relationship calibrated using local and regional meterological data. The variable to be predicted is regressed on grid scale areal averages of this and other meteorological variables. GCM versions of the predictor variables are then substituted into the regression equation in order to estimate the value at the site of interest. The equation is finally applied to both the control (1 x CO_2) and the perturbed (2 x CO_2) climates.

Extreme values

It is the extreme values, floods and droughts, which are often of most importance in water resource design, and hence climate change impact studies. However it is likely that it will not be possible in the foreseeable future to obtain extreme events directly from GCM output, so recourse must continue to be made to indirect approaches. At present there is no formalized indirect approach, and the statistics implied by the spatial and temporal infill methods are used without further amendment to the tail shape of the distribution.

An approach, which has been discussed but not applied in hydrological impact studies, makes use of storm track position and frequency; another is to interpret the GCM output as a synoptic chart and consider the statistical distribution of the main weather types. It can be speculated that such methods will prove more successful for droughts which are spatially extensive and, by definition, of long duration. Short term events such as rapid snowmelt, heavy rain and high winds will be more difficult to detect.

3.5 Research requirements for scenario development

The contribution that hydrologists can make to the improvement in GCM modelling is of course limited and has been mentioned in chapter 2. What is required is models of sufficient accuracy and temporal and spatial discrimination to be used for design calculations into the next century. Such a position is unattainable and for many years water resource impact work will depend on the various devices enumerated above for augmenting the output from the standard output.

Empirical scenarios should be explored with the aid of palaeo-hydrologists; which is not as developed a discipline in the UK as elsewhere. Temporal or warm world scenarios should be updated in the light of the warm run of years through the 1980s. A report would be very useful in which trial spatial analogues were presented, region by region, with supplementary notes on the GCM predictions, and on the scale of difference between their climatic controls and those operating in the British Isles.

Hydrologists should make more use of weather types as this will assist them in interpreting GCM output for extreme values. This is one aspect of the general problem of forming climate:water relations.

4. WATER RESOURCES IN THE UK: CURRENT PATTERNS AND PAST VARIABILITY

4.1 Introduction

Any attempt at an assessment of possible changes in a system must be based on an understanding of the current characteristics and recent history of that system. This chapter therefore provides a brief introduction to patterns and variations in water resource supply and demand in the UK.

4.2 Hydrological characteristics of the UK

Spatial variation of surface water

The UK has a humid temperate environment, characterised by moderation and generally abundant rainfall. In common with much of northern and western Europe, it experiences fewer extreme floods and droughts than other parts of the world (Arnell, in press), but in particular places and at certain times there may be very strong pressures on resources.

Data from the Surface Water Archive show that over the period 1961 to 1987 runoff from England and Wales averaged 458 mm in a year (nearly 70,000 million m^3), whilst an annual average of 1037mm (over 80,000 million m^3) ran off in Scottish rivers. Average annual runoff represented 50 per cent of average annual rainfall in England and Wales, but 73 per cent in Scotland (runoff is between 50 and 60 per cent of annual rainfall in Northern Ireland). These very generalised figures emphasise the variability in water resources across Britain, and even greater variability is experienced at the regional scale. Within England, average annual runoff varies from just 150mm in the Anglian Water area to 775mm in the North West Water area (as shown in Table 4.1). Higher runoff values are found in Wales and Scotland, with 1400mm a year on average in the Highland RPB area. Even greater variations are found between different catchments in the same region, reflecting differing climate, topography and geology.

Temporal variation of surface runoff

Annual runoff can vary considerably between years. The coefficient of variation (standard deviation divided by the mean) is a dimensionless measure of variability which can be used to compare variabilities of different time series, and varies between approximately 0.15 and 0.45 in catchments in the UK. Figure 4.1 shows the time series of total annual runoff from England, Scotland and Wales over the period 1961 to 1987, together with total annual rainfall. Strong correlation is apparent: variations in rainfall between years are greater than variations in evaporative losses, and flows therefore closely follow rainfall. Jones and Wigley (1988) have examined variations in annual and seasonal precipitation in England and Wales, finding a tendency in recent years for wetter springs and drier summers, and a close relationship between precipitation and circulation types (which indicate the

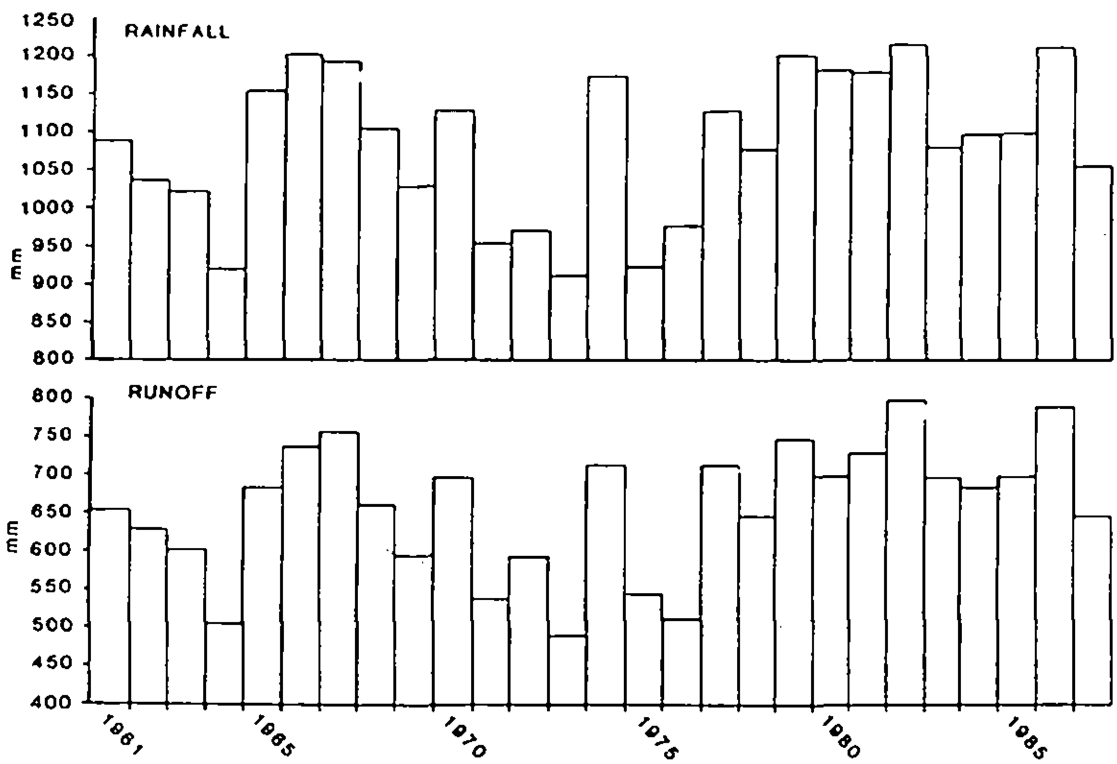
Table 4.1 Water resource availability in England and Wales, expressed as long term average annual runoff in millimetres and per capita.

Runoff data from the Surface Water Archive

	average annual runoff	
Water Authority	mm	per capita litres.day^{-1}
North West	775	4460
Northumbrian	460	4460
Severn-Trent	350	2490
Yorkshire	410	3280
Anglian	150	2180
Thames	215	670
Southern	360	2640
Wessex	368	4270
South West	740	15290
Wales	880	16810

Figure 4.1 Annual rainfall and runoff over Great Britain, 1961-1987

Data from the Surface Water Archive



overall pattern of weather over the country, and are expressed in such terms as "cyclonic" or "westerly").

At smaller spatial scales, stronger patterns of variation in flows over time are apparent. More local variations in rainfall are superimposed on catchments which respond differently to rainfall inputs. Figure 4.2 shows the variation in five-year mean annual runoff relative to the long term mean for a long record site on the River Severn: the mean annual runoff in the late 1960s was nearly 18 per cent higher than the long term mean, but was nearly 15 per cent lower in the late 1970s.

Maximum monthly flows in the UK tend to occur in autumn and winter in westerly parts of the UK, and in winter or spring in the east. Lowest flows are in June in western Britain but become later towards the east with minima in August and September. The magnitude of seasonal variability in flow is influenced not just by seasonal variations in effective rainfall but also by geological conditions. Flows in chalk catchments, for example, are much more consistent throughout the year and minimum flows occur later than in quicker-responding clay catchments. Changes in the distribution of flows through the year are currently being investigated at IH, in an attempt to see how closely variations in seasonal climate (as found by Jones and Wigley (1988)) are being reflected in river flows.

Catchment geology and topography also largely control the short-term variability in flows in a basin. Steep flow duration curves, representing rapid variations in flow, are characteristic of basins on relatively impermeable substrate that respond rapidly to rainfall and have little storage: flatter flow duration curves, indicating less variability through time, are typical of basins with more storage. The response of a basin to a change in climate will therefore depend to a large extent on basin geology and topography.

Groundwater

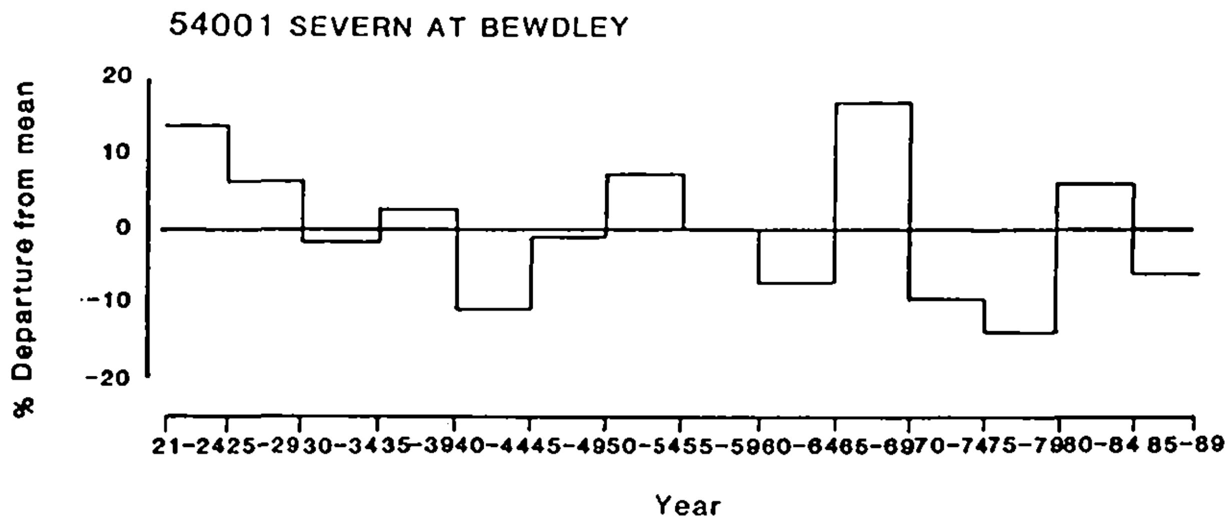
Groundwater is found in virtually all of the sedimentary deposits in the UK, but the Chalk and Upper Greensand, Permo-Triassic Sandstones and Magnesian Limestone are the most important aquifers. Most of these aquifers are in the south and east of England, and groundwater resources are limited - but occasionally locally important - in Scotland, Wales and Northern Ireland.

Monkhouse (1988) estimated the mean annual recharge into the more important aquifers in England and Wales over the period 1980 to 1985, and found a mean annual supply of 4630 million m^3 of water into the chalk and 1554 million m^3 into the Permo-Triassic Sandstones. Together, this constitutes just over 4 per cent of the total annual rainfall falling on England and Wales.

Aquifer recharge and groundwater levels are determined primarily by the total of winter rainfall which falls in the

Figure 4.2 The variation of the mean daily flow between five-year periods on the Severn at Bewdley

The mean daily flow for each five-year period is expressed as a percentage of the mean daily flow calculated over the entire period of record.



period, generally between October and March, when soil moisture deficits have been replenished. In dry winters soil moisture deficits may be replenished for only short periods of time, and hence recharge will be limited: in other years recharge may continue through into summer. The range in well levels in a year gives a general indication of relative recharge, and Figure 4.3 shows the annual range for the longest continuous well record in the UK at Chilgrove on the chalk in the Southern Water area. The amount of recharge determines the volume of river flow in many basins.

4.3 Water demand and use in the UK

Although the UK is on the whole blessed with apparently abundant water supplies, the areas with the greatest demands for water tend to be those with the least resources. Table 4.1 shows the annual average runoff per capita for each Water Authority in England and Wales, and it is apparent that the greatest pressures on resources are in the Thames and, to a lesser extent, Anglian Water areas. Furthermore, the demands for water tend to be highest in periods when flows are at their lowest. Relatively lower demands are made in both Scotland and Northern Ireland.

The total licensed abstractions in England and Wales for 1987 are given in Table 4.2 by Water Authority and sector, excluding CEGB withdrawals (all statistics in this section are taken from Water Facts 88 (WAA, 1988)). A total of 21,180 Mld^{-1} of abstractions was licensed, making an annual total of approximately 7,730 million m^3 (or over 10% of the average annual runoff) - although some water is of course abstracted and returned several times. The amounts abstracted vary as a proportion of the long-term average annual runoff, with the greatest relative abstractions in the Thames area. Abstractions for water supply dominate, and nearly 75 per cent of such abstractions are for domestic customers (from data in WAA, 1988). The rest goes to industrial, commercial and agricultural users to supplement the amount they withdraw directly. A further 4,578 Mld^{-1} are withdrawn by the CEGB for power station cooling, and 75 per cent of this is used in the Severn-Trent area.

Approximately 30 per cent of public water supply in England and Wales comes from groundwater, with the rest split equally between abstractions from rivers and storage reservoirs. However, the proportions vary between (and indeed within) Water Authorities: just over 50 per cent of the supply in Wessex derives from groundwater, whilst groundwater contributes only 4 per cent of the water supplied in Wales. Smaller proportions of demand are supplied from groundwater in Scotland and Northern Ireland.

The total amount of water abstracted for public supply in England and Wales rose by 17 per cent between 1976 and 1987/88 but the increase in supply to domestic consumers was nearly 30 per cent, reflecting increasing ownership of water-intensive

Figure 4.3 Annual range in levels in Chilgrove Well in the Chalk in Hampshire

The annual range gives an indication of the amount of recharge

Data from British Geological Survey Groundwater Archive

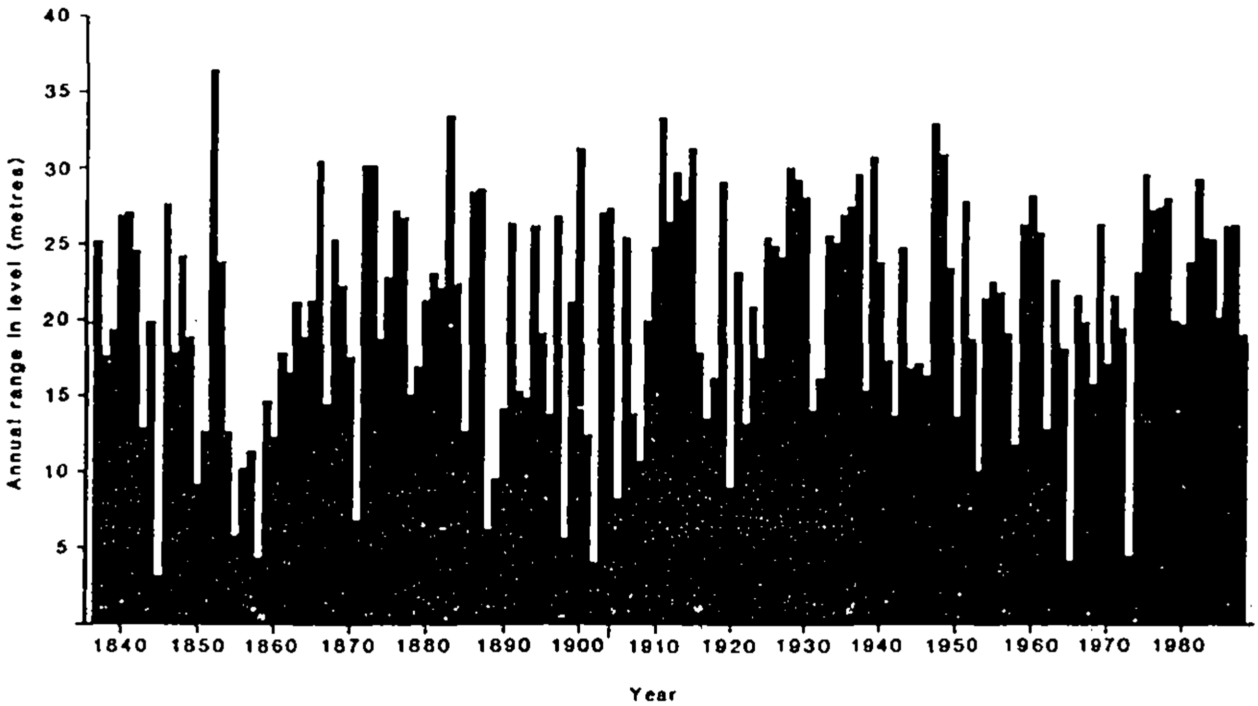


Table 4.2 Licensed water abstractions, 1987, in Mld^{-1}

Abstractions data from Water Facts 88 (WAA, 1988)

	Av. ann. runoff	Water supply	Industry	Spray irrig.	Agric.
	Mld^{-1}	Mld^{-1}	Mld^{-1}	Mld^{-1}	Mld^{-1}
North West	30,600	1819	1760	1	5
Northumbrian	11,700	1012	40	0	0
Severn-Trent	20,700	2374	495	25	7
Yorkshire	15,200	1593	376	9	12
Anglian	11,200	1725	244	43	15
Thames	7,700	4007	179	6	14
Southern	10,400	1280	114	3	11
Wessex	10,000	754	117	7	14
South West	22,000	531	110	4	29
Wales	51,200	2149	277	3	15

appliances. Direct industrial abstractions declined over the same period by over 50 per cent, due both to a reduction in traditional industries using large amounts of water and increases in the efficiency of water use (the decline in industrial abstractions has been cited as a contributing factor in the rising groundwater levels beneath many cities: Marsh and Davies (1983)). CEGB abstractions have fallen still further as power generation has been moved to coastal sites. Figure 4.4 shows the variation in abstractions in recent years.

The large amounts of abstractions and subsequent returns inevitably mean that flows in some rivers are very heavily altered from their "natural" state. Figure 4.5 shows a residual flow diagram for the River Tame in the Trent catchment (Pirt, 1989), indicating that over much of its course returns from abstractions in the Tame and other catchments dominate dry weather flows. Such influences will of course determine the response of the river to changes in climate.

In most years there is sufficient water to satisfy all demands, but occasionally resources are insufficient. The drought of 1975/76 led to major problems with responses including the ultimate action of rationing domestic customers. A more limited (though in some places more intense) drought in 1984 led to more restrictions on use in some areas, and it is possible that the dry winter of 1988/89 will lead to supply problems later in the year. Water suppliers in the UK have developed, largely since the 1976 drought, procedures for managing evolving drought problems, and many have defined acceptable levels of failure: hose pipe bans may be tolerated one year in ten, for example. Demand management is becoming increasingly important in the water industry (and experiments with metering domestic customers were begun in 1988). In recent years a flexible infrastructure has developed for managing water resources. This infrastructure will be put to the test if changes in climate have appreciable effects on water supply and demand.

Figure 4.4 Trends in water use over time in England and Wales by sector

Source: Water Facts '88 (WAA, 1988)

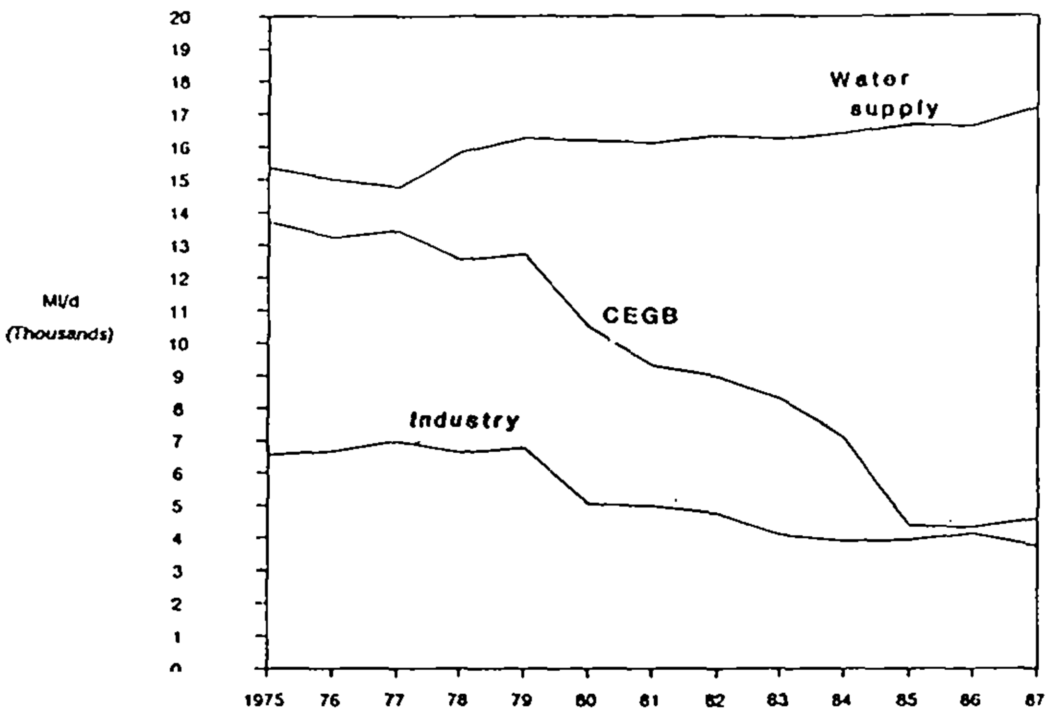
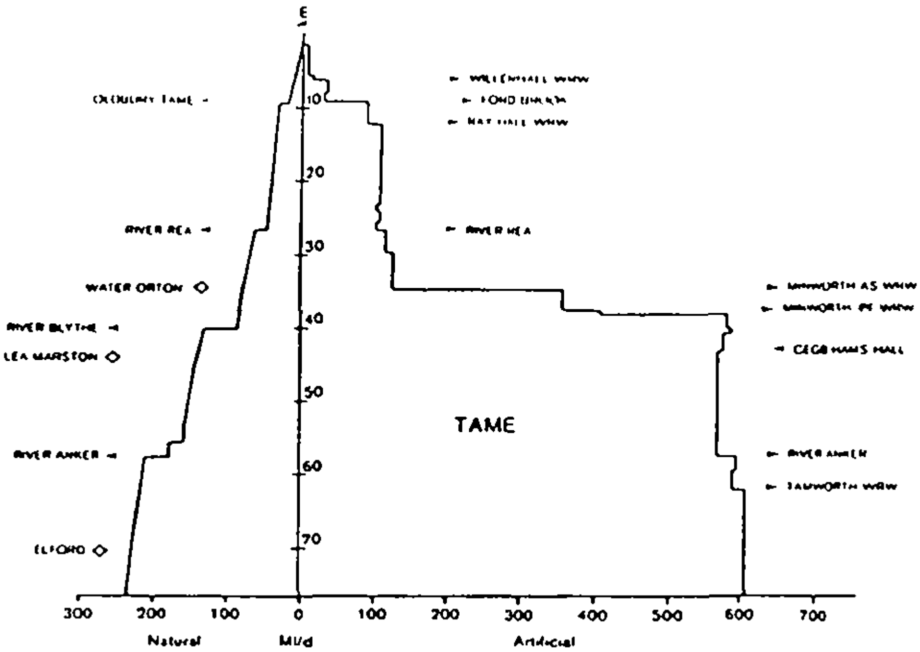


Figure 4.5 Residual flow diagram, showing the contribution of artificial influences to total dry weather flow along the River Tame

Source: Pirt (1989)



5. IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

5.1 An overview

Hydrology is the science of naturally occurring water, with emphasis on the land phase: water resource investigations use hydrological understanding and concepts to study and manage the exploitation of water. In essence, water resource management is a means of reducing water deficits and surpluses in both space and time, and is concerned with extreme events as well as average magnitudes. "Water resources" are defined both by the quantity and variability of water - either surface water or groundwater - of acceptable quality and by the demand for water from various, often competing, users. An assessment of the effects of climate change on water resource availiability must therefore consider both supply and demand. A simple framework for integrating supply and demand in assessments of changes in water resources is given in Figure 5.1. It is important to remember that variations in climate are but one influence on the evolution of resource availability, and that the effect of demographic and economic changes may be more significant, especially on the demand for water. Climate changes may also impact upon resource supply and demand through their effect on land use.

This chapter is divided into three sections, considering in turn the effects of climate change on surface water, groundwater and demand. A final section attempts an integration of the various effects of change on resource availability.

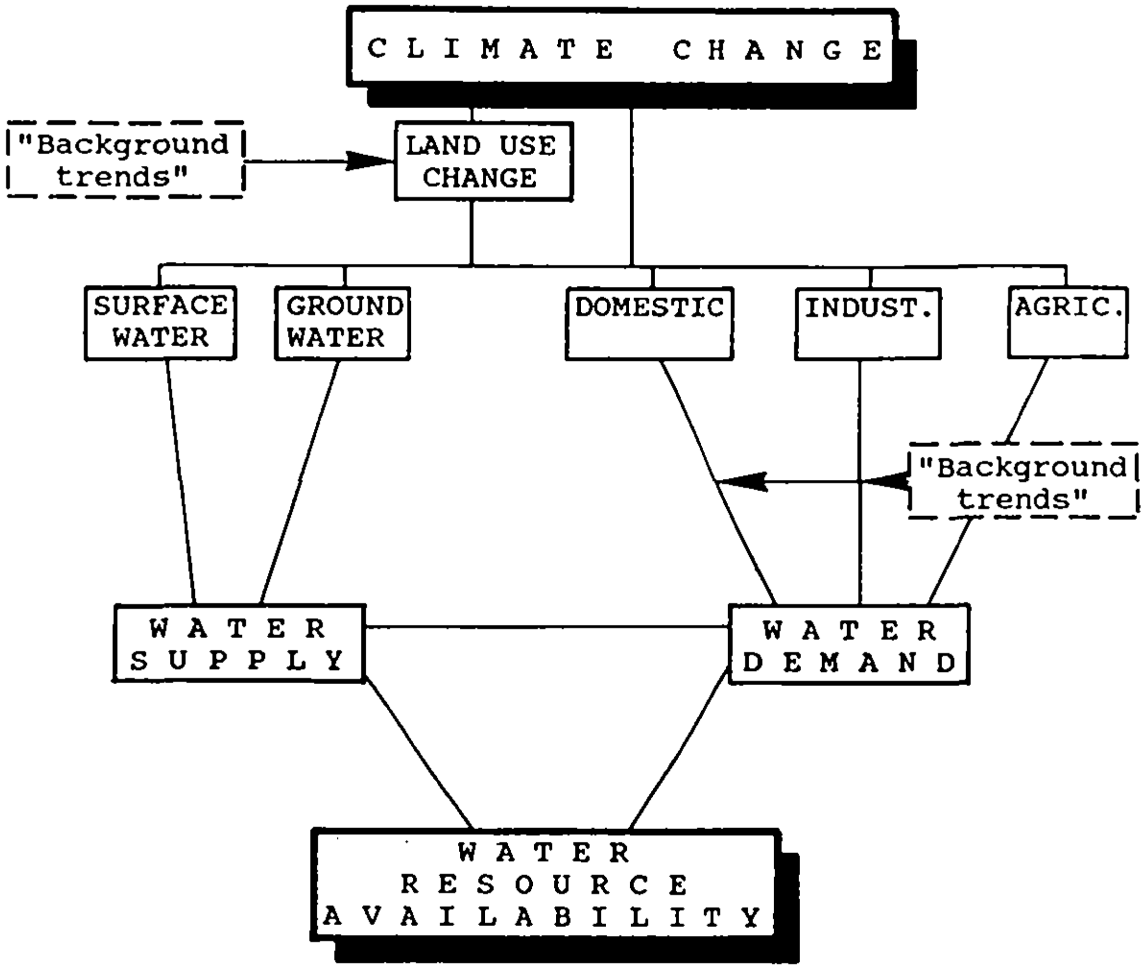
5.2 Effects of climate change on surface water supplies

Changes in climate can be expected to have consequences for both the mean and the variability in surface water resources, and such changes will have important implications for resource reliability and management. This section considers the possible effects of climate change on water resources in Britain, drawing on published work where available and appropriate and describing some new preliminary calculations. Four issues are discussed:

i) the effect of climate change on mean annual runoff;
ii) changes in the seasonal distribution of flows;
iii) changes in short-term variability in river flow;
iv) implications for reservoir reliability.

It is first useful to summarise the methods which are, or could be, used to estimate the effects of climate change on flows, and these methods basically fall into three groups (see Arnell and Beran, 1989 for more information on the strengths and weaknesses of the methods). Firstly, there are studies using "temporal analogues", which compare data from different periods in the past to estimate the direction, if not the magnitude, of possible changes in a warmer world. Secondly, it is possible to adopt a "spatial analogue" approach, and transfer information from one area to another predicted to have the same climate in

Figure 5.1 The inter-relationships between climate change and water supply, demand and resource availability



the future. The approach has been used in agricultural impact studies (e.g. Parry et al, 1988), but has not been applied with hydrological information. The final group of methods combines climate information with a hydrological model in an attempt to model the effects of changes in climate. Many such studies use GCMs to derive the climatic inputs (as described in Chapter 3), and hydrological models vary in complexity from simple regression-based models to complicated conceptual models of the rainfall-runoff process.

Effect of climate change on mean annual runoff

The mean annual runoff from a basin is probably the easiest hydrological variable to predict - because variations over time between years can be ignored - and is also a useful indication of resource availability. Several studies have considered the effect of changes in climate on mean annual runoff in various parts of the world, and although the results differ with locality and hypothesized change it appears that, in temperate environments at least, changes in precipitation are more important than changes in temperature and hence evapotranspiration. The following paragraphs summarise studies which have been conducted in the UK and continental Europe.

Schnell (1984) made some very general estimates of the effect of climate change on annual runoff in the European Community area, by combining estimates of change in precipitation and temperature derived from the UK Meteorological Office GCM with a biomass model; this deducts evapotranspiration and soil moisture replenishment from precipitation to produce potential runoff. The scenario assumed an increase in annual precipitation across Britain ranging up to 150mm (which is not inconsistent with the DoE core scenarios), and the results suggested that runoff potential would increase throughout Britain. The estimated increases in annual runoff potential ranged from close to zero in the south to over 100mm in Scotland.

A temporal analogue approach was used by Palutikof (1987) to estimate the direction of changes in annual runoff in Britain in a warmer world. She compared the mean annual runoff from ten basins in England and Wales in a cool period (1901-1920) and a warm period (1934-1953), where the runoff was reconstructed from recorded rainfall using a monthly regression model. Her results suggested that mean annual runoff would be lower in the south but higher in the north. If the reduced evapotranspiration expected in a CO_2-rich atmosphere was incorporated into the models predicting runoff from precipitation, annual runoff would increase throughout England and Wales. However, she also found that winter precipitation was lower in the warm period than the cool period, and this is at odds with scenarios derived from GCMs.

Two other studies have looked at the effect of climate change on annual runoff in western Europe. Jongman (1987) showed (but without explaining how) that the annual runoff of both the Maas and the Rhine as they entered the Netherlands would increase in a warmer world. More comprehensive studies of greater relevance to British conditions were undertaken by Bultot et al (1988), who used a scenario based on results from GCMs together with a conceptual rainfall-runoff model in three differing basins in Belgium. The results showed an increase in runoff in all three basins, ranging from 3 to 11 per cent. Annual precipitation was between 6 and 9 per cent higher under the change scenario, and in two of the three basins the proportional increase in runoff was less than the increase in precipitation: the greatest increase in runoff occurred in the basin with the most rapid response to rainfall.

There have so far been no studies in Britain using hydrological models to estimate the effect of climate change on annual runoff, but it may be possible to make some generalised statements using a simple water balance approach where changes in mean annual runoff are determined from changes in mean annual rainfall and mean annual evaporation. Evaporation, however, is dependent on several climatic attributes which vary together in a complex manner (as summarised in Section 2.2), and it is therefore necessary to resort in a general study to a simple empirical formula. One such formula which operates on the annual scale was developed by Turc (1954) from basins in several climatic environments:

$$E \qquad P \; (0.9 + (P/L)^2)^{-1/2}$$

E is mean annual evaporation in mm, P is mean annual precipitation in mm and L is a function of the mean annual temperature T in degrees celsius:

$$L \qquad 300 + 25\,T + 0.05\,T^3$$

Mean annual runoff is estimated by subtracting evaporation from precipitation. The method is widely used by French water resources engineers (occasionally with local modifications), but does not work particularly well in British conditions. Nevertheless, the Turc formula may give some indications of the rate of change in annual runoff under a changed climate, and Dooge (1988) has suggested using a modified version of the formula in climate change studies. The approach does not consider possible changes in transpiration rates with increased CO_2 (Idso and Brazel, 1984), which would alter the empirical relationship between temperature and evapotranspiration.

Table 5.1 shows the percentage change in runoff with given changes in temperature and precipitation, for three combinations of mean annual temperature and precipitation found in different parts of Britain. Tables 5.1a and 5.1b represent catchments with similar rainfall, but different mean annual temperature (one typical of eastern Scotland, the other of the English Midlands). The change in precipitation at a site is more significant than changes in temperature and, for a given change in precipitation, there is relatively little difference in effect on runoff between the "cool Scottish" and "mild English" sites. The tables imply that if temperatures were to

Table 5.1 Estimates of percentage change in mean annual runoff with changes in temperature and precipitation, using the Turc formula

Some caveats are outlined in the text.

a) Initial mean annual precipitation: 1000 mm
Initial mean annual temperature: 8 °C
Initial estimated mean annual runoff: 530 mm

Temp. change (°C)	Change in annual precipitation -10%	0%	10%	20%	30%	40%
1	-21.3	-4.8	12.3	29.7	47.4	65.3
2	-25.8	-9.6	7.1	24.2	41.7	59.4
3	-30.4	-14.7	1.7	18.5	35.8	53.3
4	-35.1	-19.8	-3.8	12.7	29.6	46.8
5	-39.8	-25.0	-9.5	6.6	23.2	40.1

b) Initial mean annual precipitation: 1000 mm
Initial mean annual temperature: 10 °C
Initial estimated mean annual runoff: 479 mm

Temp. change (°C)	Change in annual precipitation -10%	0%	10%	20%	30%	40%
1	-23.0	-5.6	12.6	31.2	50.2	69.6
2	-28.1	-11.2	6.4	24.7	43.4	62.5
3	-33.3	-17.0	0.2	18.0	36.3	55.1
4	-38.5	-22.8	-6.2	11.1	29.0	47.4
5	-43.7	-28.7	-12.7	4.1	21.5	39.5

c) Initial mean annual precipitation: 800 mm
Initial mean annual temperature: 10 °C
Initial estimated mean annual runoff: 311 mm

Temp. change (°C)	Change in annual precipitation -10%	0%	10%	20%	30%	40%
1	-26.1	-7.0	13.3	34.4	56.3	78.8
2	-32.2	-14.0	5.5	26.0	47.3	69.3
3	-38.3	-20.9	-2.3	17.4	38.1	59.5
4	-44.2	-27.8	-10.1	8.9	28.8	49.5
5	-49.9	-34.6	-17.8	0.3	19.4	39.4

increase by 3^{o}C, an increase in annual precipitation of 10 per cent or more would lead to an increase in annual runoff. For comparative purposes, the current scenario implies an increase in annual rainfall of 140mm (14 per cent on an initial value of 1000mm) if summers are wetter (as in Scotland and the north of England), but only 80mm (8 per cent) if summers are drier. Table 5.1c is more representative of the drier climates of southern and eastern England. Here annual precipitation would have to increase by over 10 per cent before annual runoff would increase: the scenario increase in precipitation of 80mm (10 per cent of 800mm) is just on this threshold value.

All three tables show that, with temperatures higher by 3^{o}C, an increase in annual precipitation of less than approximately 20 per cent gives a proportionately lesser increase in annual runoff. The form of the Turc formula means that, for some increases in temperature at least, actual evaporation changes in relative terms (if not absolute terms) by more than precipitation, thus reducing the increase in runoff. Some initial calculations reveal that the Turc formula gives a rather higher change in evaporation with increasing temperature than other, more accurate, procedures, implying that use of the Turc formula <u>overestimates</u> evaporation and hence <u>underestimates</u> changes in annual runoff.

The results and studies described in this section imply that mean annual runoff would increase over most of Britain in a warmer world, with the increase greater in the north. The actual increase in runoff is very sensitive to the estimated increase in precipitation (more so than to changes in evapotranspiration). It is important to note that alterations in annual runoff due to climate change may approach changes in runoff due to major land use change: Gross et al (1989) used a conceptual rainfall-runoff model to show, for example, that clearing the forest in a small basin in upland Wales could result in an increase of annual runoff of nearly 30 per cent.

Effect of change on seasonal distribution of flow

Changes in the seasonal distribution of flow could well be more significant in practice than changes in the total annual runoff. Several studies in various parts of the world have attempted to estimate such changes (see Gleick (1987) for an example from the Sacremento basin in California).

In her comparison of runoff in warm and cool periods, Palutikof (1987) found in the north of England higher flows in summer and autumn, but lower flows in winter and spring. This reflected lower winter precipitation totals, which is inconsistent with current GCM-based scenarios. Beran (1986) compared the same two time periods using data from the Thames at Teddington, finding that autumn and winter flows were higher in the warm period due to higher autumn precipitation.

In the absence of any detailed studies in Britain of changes in seasonal flows, it is possible to draw inferences from Bultot et al's (1988) experiments in Belgium. Their study used a similar change scenario to that considered here for southern Britain, with a temperature increase of approximately 3^{o}C (slightly higher in winter and lower in summer) but an annual increase in precipitation of just 54.3mm (with 7.7mm less rainfall between May and August). Winter and spring flows were found to increase in all three basins studied (Figure 5.2), but the effect on summer flows was depended on the hydrogeological characteristics of the catchment. Summer flows were little affected in the Zwalm and Semois catchments with little groundwater but increased in the Dyle catchment underlain by a sand aquifer, despite a reduction in summer rainfall. This was attributed to the storage and release of the higher winter rainfall, and a similar effect can be expected in chalk catchments in southern Britain. Indeed, Marsh and Lees (1985) have shown that flows on the chalk-fed Mimram in Hertfordshire were maintained during the 1975/76 drought by the high rainfall in the wet winter of 1974/75.

Although the evidence is limited, it can be supposed that the increased seasonality in rainfall (even under the "wet summer" scenario increases in summer precipitation are less than increases in winter precipitation) will be reflected in Britain in a stronger seasonal variation in flow. However, the effect will depend strongly on catchment geology, and it is possible that summer flows in catchments with high groundwater components will be maintained or even increased by higher winter and spring rainfalls.

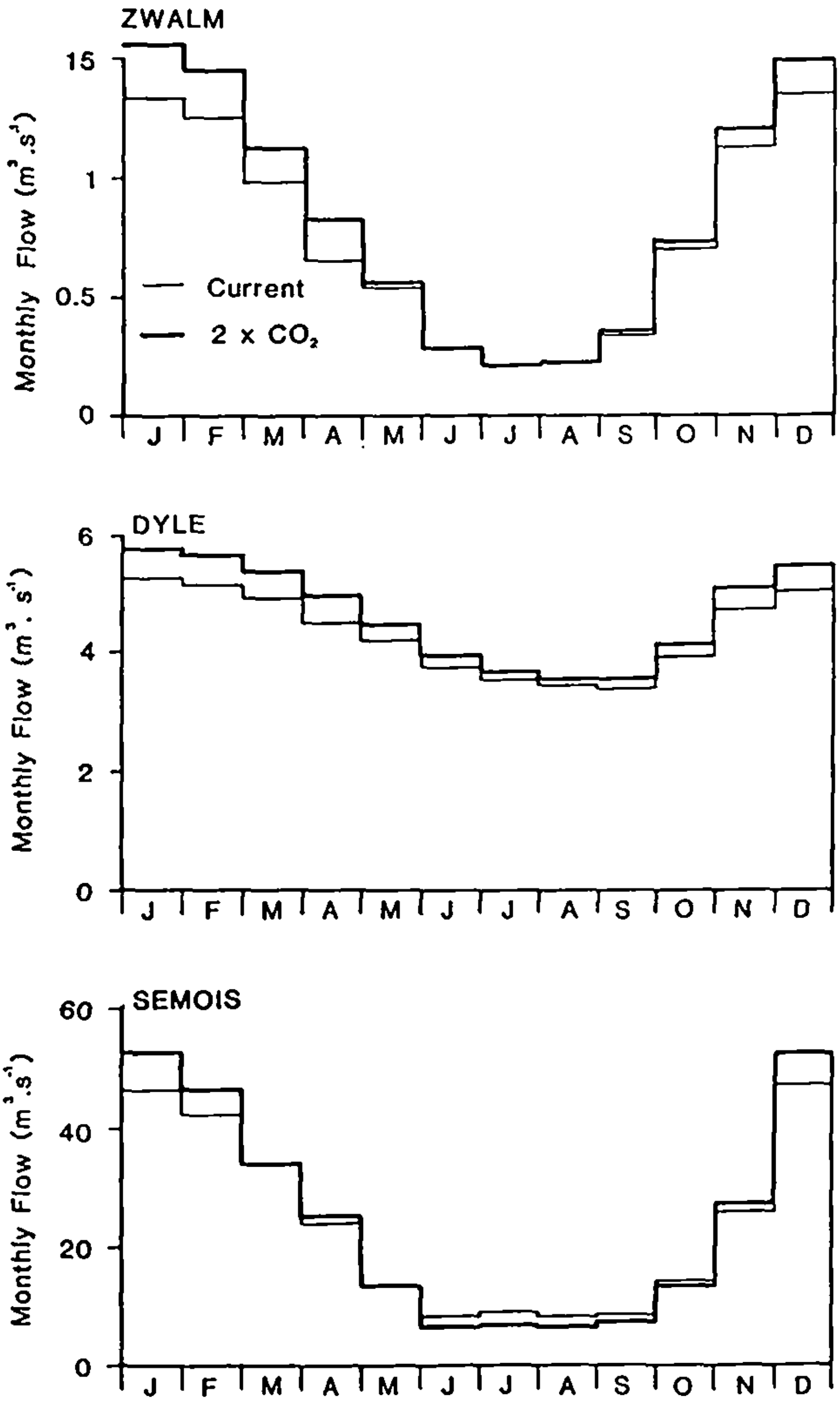
Effects on short-term flow variability

It is the short term variability in flow behaviour which defines a river's suitability for a wide range of uses. As a general guide, the more variable the flow in a river, the less suitable it is for uses such as water supply, power generation or waste dilution. Other things being equal, the more variable the flow the larger the storage necessary to maintain a particular yield at a desired level of reliability. Flow variability is generally characterised by the flow duration curve, showing flow against the proportion of time that flow is exceeded. A steep line indicates highly variable flows, whilst a more horizontal line indicates steady flows.

There have been few detailed studies of the effect of climate change on short-term variability in flow. To a large extent this reflects a lack of information about potential changes in short-term climate variability in a warmer world, and the studies that have been conducted have simply perturbed observed time series of temperature and precipitation by fixed amounts. Nemec and Schaake (1982), for example, examined the effect of changes in temperature and precipitation on flow variability in two rivers in the United States and one in Kenya by adjusting each day's climate data by constant factors and running their rainfall-runoff model again. Such an approach cannot represent possible changes in the duration of, for example, dry spells, and may result in a simple linear translation of flow variability along the "magnitude axis" (a linear shift in the

Figure 5.2 Simulated mean monthly flows under current and changed climates in three Belgian basins

Source: Bultot et al (1988)



flow duration curve, for example). Bultot et al (1988) managed to take a more subtle approach, changing the frequency distribution of rain days between current and future conditions. Although they did not publish detailed results, they concluded that the occurrence of low flows would increase in the Semois and Zwalm rivers but reduce in the Dyle basin, in close accordance with changes in seasonal flows.

One alternative approach to estimating changes in flow variability would be to use a temporal analogue, and compare flow duration curves from different periods in the past. However, there are few daily flow records in Britain covering the warm and cool periods used by Palutikof (1987), and another way of estimating changes in variability is simply to perturb an observed long-term flow duration curve. In Britain high flows occur in winter or spring, and the low flows occur in summer or early autumn. A flow duration curve can be adjusted by, for example, increasing the upper values by slightly more than the increase in precipitation - say by 15 per cent - and reducing the lower end by slightly more than the reduction in precipitation - by, for example, 15 per cent. Low flows would be increased if it is assumed that summer rainfall would increase. The approach is approximate, and is least appropriate in basins where storage is very important. Nevertheless, it can provide an indication of the possible magnitude of change. Figure 5.3 shows two such perturbed flow duration curves. The first - for the headwaters of the Severn - is simply shifted vertically, and there is little discernible difference in the frequency of occurrence of low flows. In the second case low flows are reduced, and the flow which is currently exceeded 95 per cent of the time would in the future be exceeded only 85 per cent of the time: in other words, flows would be below that discharge for three times as many days. The actual change at a site depends of course on both the change in short-term climate characteristics and catchment geology.

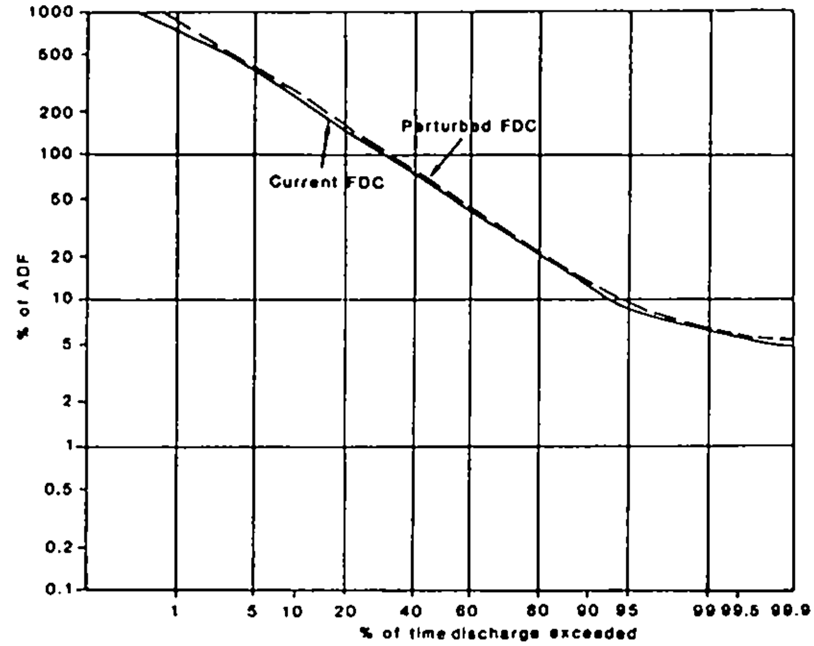
Effects on reservoir reliability

Whilst flow variability over time is interesting in itself and important for some practical uses, a better indication of changes in resource reliability can be gained by feeding hydrological information into a water resources model. Perhaps the simplest model is the reservoir storage-yield diagram, which shows the reservoir storage needed to maintain a particular yield with a specified degree of reliability: how big would a reservoir need to be to maintain a yield of $25Mld^{-1}$ with a probability of emptying (i.e. failure) in any one year of 0.01?

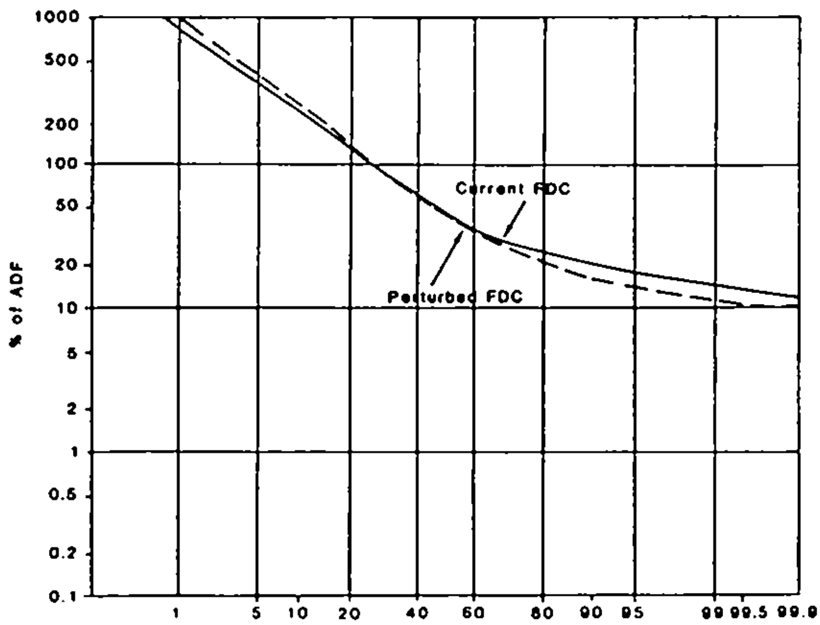
Nemec and Schaake (1982) calculated storage-yield diagrams from the time series of flows they had generated under current and possible future conditions, and compared the yield which could be derived, with 90 per cent reliability, from a reservoir with sufficient storage to yield under current conditions 10 per cent of the mean annual runoff. For the two US basins studied, a 1 per cent change in precipitation produced a 2 per cent

Figure 5.3 Flow duration curves under current climate, together with perturbed curves representing changed conditions

a) a catchment in mid-Wales



b) a catchment in eastern England



change in the yield, whilst in the more humid basin a 1 per cent change in potential evapotranspiration led to the same change in yield. They concluded that the effects on reliable yield (and also on storage reliability) depended more on changes in precipitation than in evapotranspiration.

Similar studies are underway at IH, but for now it is possible to make some educated guesses about effects on reservoir reliability using a generalised storage-yield diagram, where volumes are expressed as percentages of the mean annual runoff volume and yield is expressed as a percentile from the flow duration curve (Beran, 1984). Such standardized diagrams are relatively consistent across a large area, and indeed one diagram may be applicable for much of Britain (Figure 5.4).

If flows were to increase by a certain percentage, yield could increase too, with the shape of the flow duration curve influencing the change in reservoir reliability. Example calculations of the effect on reliability of a change in climate are shown in Table 5.2, for hypothetical reservoirs in northern England (where summer precipitation is assumed to increase) and the east Midlands (where summer precipitation is assumed to decrease). In both cases the desired yield is the flow exceeded 80 per cent of the time (approximately 23 per cent and 12 per cent of the average daily flow in the northern and midland sites respectively) and the reservoir has a storage equal to 4 per cent of the mean annual runoff volume, giving a 10 per cent chance of failure in any one year. The flow duration curves for the two sites were adjusted as described above, and the Table is used in conjunction with Figure 5.4. To summarise, under the scenarios adopted the chance of emptying for the reservoir in northern England would fall from one year in 10 to one in 25, whilst the reservoir in the east Midlands would fail more frequently, in approximately one year in seven.

These results apply of course to hypothetical reservoirs with a relatively high risk of emptying, and further studies are necessary to clarify the impacts of climate change on resource reliability under a wide range of conditions. The sensitivity of a reservoir depends on yield and storage relative to average flows. A small reservoir with a low level of regulation, for example, will be more sensitive to the duration of dry spells than average precipitation and evapotranspiration (Law, 1989).

5.3 Research needs for surface water resources impacts

Water resource availability and reliability are determined more by variability over time than mean conditions, except at high levels of reservoir regulation. At present only preliminary and approximate attempts can be made to estimate the effects of changes in climate on flow variability, and there is a clear need for more detailed studies in Britain. Such studies need to combine short-time scale input information (daily rainfall or temperature, for example) with conceptual models of the rainfall-runoff process. The characteristics of the input data will influence strongly the results obtained, and it is therefore necessary to attempt to understand and model the

Figure 5.4 A standardised storage-yield diagram for Britain
The graph shows reservoir yield as a flow exceeded a given proportion of the time, and reservoir size as a percentage of average annual runoff.

Based on Beran (1984)

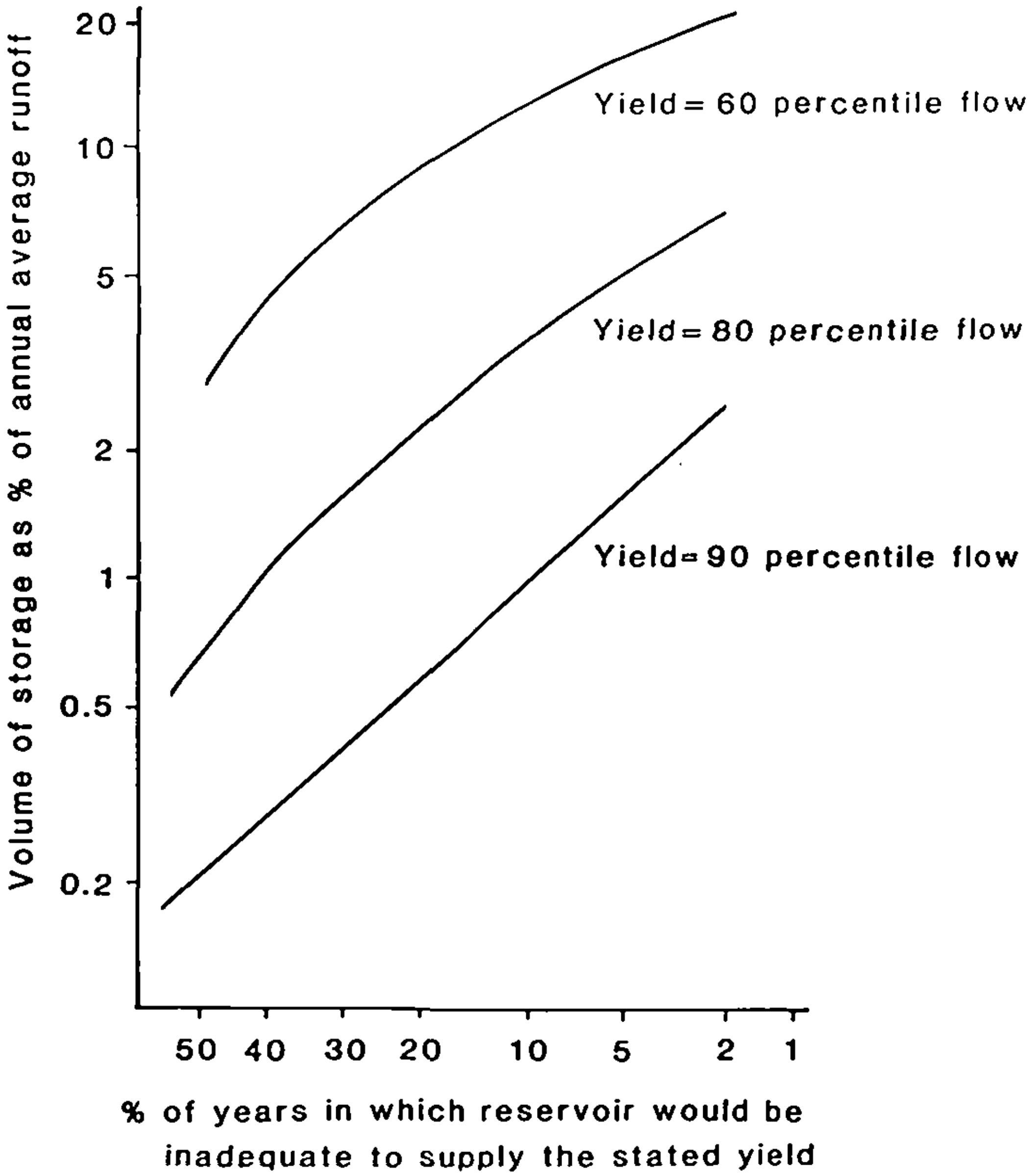


Table 5.2 Estimation of change in reservoir reliability using a standardised storage-yield diagram

Yield = flow exceeded 80% of the time (Q80)
Frequency of shortage = one failure in 10 years (10%)

Required volume of storage = 4% of annual runoff volume

"Northern England reservoir"

Average daily flow (ADF) = 10.7 m^3s^{-1}
Q80 = 22.8% ADF = 2.44 m^3s^{-1}
Annual runoff volume (ARV) = 338 x 10^6 m^3
Volume of storage = 13.5 x 10^6 m^3

Assume annual flow increases by 15%
New annual runoff volume = 390 x 10^6 m^3
Storage as % = 3.5% of ARV

Adjust flow duration curve by raising by 15% throughout
Q80 becomes Q84

New reservoir characteristics:
Yield = Q84 Volume = 3.5%
Reliability changes from 10% chance of failure to 4% failure rate

"Midland England reservoir"

Average daily flow (ADF) = 0.02 m^3s^{-1}
Q80 = 11.9% ADF = 0.0024 m^3s^{-1}
Annual runoff volume (ARV) = 0.631 x 10^6 m^3
Volume of storage = 0.025 x 10^6 m^3

Assume annual flow increases by 7%
New annual runoff volume = 0.675 x 10^6 m^3
Storage as % = 3.7% of ARV

Adjust flow duration curve by raising high flows by 15% and reducing low flows by 15%
Q80 becomes Q76

New reservoir characteristics:
Yield = Q76 Volume = 3.7%
Reliability changes from 10% chance of failure to 15% failure rate

potential future changes in climatic variability. The key characteristics of the catchment (and reservoir, where appropriate) which determine sensitivity to climate change need to be identified, and attempts must be made to learn how to generalise results from site-specific studies using catchment characteristics. The study of generalised flow duration curves and storage-yield diagrams will both help understanding of important controls on sensitivity to change and enable some generalised estimates of impact to be made. It is also necessary to run some comparative experiments to compare the relative effects of climate change and land use change, to place climate change in context.

5.4 Effects of climate change on groundwater resources

Groundwater makes a very important contribution to water resources in many parts of the world - not least Britain, as indicated in Chapter 4 - and it is somewhat surprising that there have been very few studies into the possible effects of climate change on recharge and groundwater levels. Only Bultot et al (1988) appear to have considered changes in groundwater storage, during their study of three small Belgian basins.

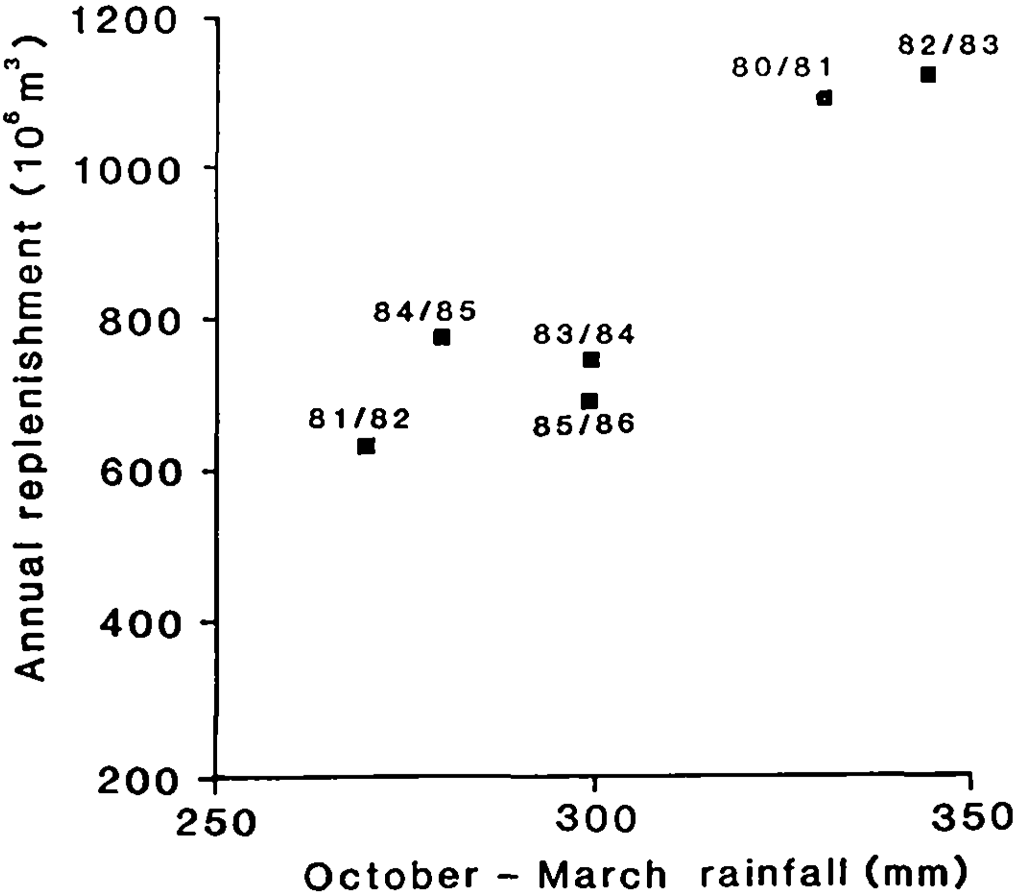
As a general rule, groundwater recharge in Britain takes place in winter once the summer soil moisture deficits have been replenished, and ceases in late spring when soil moisture deficits reappear. The actual recharge period varies between years, however, and sometimes recharge occurs in summer (in the Permo-Triassic aquifers in the Eden Valley in Cumbria, for example) or is limited in winter (as in the winter of 1975/76). Nevertheless, an increase in winter effective rainfall should lead to an increase in groundwater recharge and hence groundwater levels.

It is difficult to estimate the magnitude of the effect, because of the lack of a simple relationship between winter rainfall summed over a fixed time period and recharge, but diagrams such as Figure 5.5 provide the basis for some crude estimates. Annual replenishment in the chalk in the Anglian Water area (taken from Hydrological Data UK Yearbooks) is plotted against the October to March rainfall over the whole of the region, and it is possible to infer that for each increase in winter rainfall of 10mm, recharge increases by approximately 70 million m^3. This crude estimate applies of course only to East Anglian chalk, and very different effects could be noticeable elsewhere. An increase in groundwater recharge would mean not only increased groundwater resources in summer but also, in some areas, higher summer river flows (as described in Section 5.2).

There are, however, qualifications to this simple impression of increased resource availability. Infiltration to groundwater is influenced by infiltrations capacity, which may impose an upper bound on the amount of the extra winter rainfall that can actually be accepted into the aquifer. Surplus rainfall would simply run off, and groundwater recharge would not rise by as

Figure 5.5 Annual recharge to the chalk in the Anglian Water area in relation to winter precipitation

Data from Hydrological Data UK Yearbooks



much as the increase in winter rainfall would imply. In Britain this is most likely to occur with the Permo-Triassic sandstones, which have lower infiltration capacities and hydraulic conductivities than the chalk and upper greensand aquifers. Bultot et al's (1988) conceptual model predicted a reduction in groundwater levels in one of their study catchments, where streamflow generation was dominated by surface processes (such as saturation overland flow). They attributed the lower groundwater levels to improvements in the conditions necessary for surface or near-surface flow, and hence a reduction in the amount of water available for infiltrating all the way down through the soil profile: this perhaps reflects the low infiltration capacities and conductivities of the catchment soils and geology.

One of the most sensitive British ecosystems to react to change may be the chalk (or indeed other limestone) bourne. Many are already seeing normal headwater positions moving downstream under the effect of well pumping. It is very possible that some redress would occur in a warmer wetter winter scenario, particularly as an accompanying move to less frequently frozen ground could assist infiltration.

In summary, it appears that higher winter rainfalls, were they to occur, would lead to increased groundwater recharge and hence higher groundwater levels - possibly throughout the year - but that in some areas this increase may be limited by the constraints of aquifer properties. The effects of a sea level rise on coastal aquifers is considered in Section 6.3.

5.5 Research needs for groundwater effects of climate change

The importance of groundwater as a resource in Britain requires that studies are undertaken on the potential effects of increased winter rainfall on groundwater recharge. Such studies must be based on the analysis of past recharge data and an understanding of the hydraulic characteristics of aquifers, together with predictions of the effects of climate change on soil moisture variations over time.

5.6 Impacts of climate change on demand for water

Estimates of future demand for water are as difficult to make as estimates of water supply following climate change. Some studies have considered the effect of climate change on demand for water, and Callaway and Currie (1985) concluded that "The location, timing and magnitude of many different types of demand for water may be quite sensitive to the effects of CO_2 build-up on temperature and vegetation". However, many non-climatic factors also influence demand for water:

i) Demography factors: demand for water will increase as population increases. This is likely to be less significant in the UK than in other parts of the world;

ii) Socio-economic factors: as economies and social attitudes towards water change, so will water demand;

iii) Policy and institutional factors: demand for water may be influenced by institutional policies towards water. Water recycling and re-use may be improved, for example, or alternative pricing structures aimed at managing demand may be introduced. Losses from mains leakage may be reduced.

Climate change aside, most forecasts predict an increase in demand for water at a range of scales (Gardiner and Herrington, 1986; MacDonald and Kay, 1988). With a change in climate, these forecasts may need to be dramatically revised. Unlike many commododities, demand for and abstractions of water are to a large extent determined by its supply, and the most significant effect of climate change on water use may be through its impact on water supplies.

It is convenient to consider the impact of climate change on water demand in the UK by the three main sectors, agriculture, industry and domestic.

Changes in agricultural demand for water

Agriculture in all its forms is a major user of water in Britain, and the one most influenced by climatic variability and change. Much of the rainfall intercepted and evaporated from vegetation in Britain can of course be considered to be agricultural use, but agriculturalists also draw heavily on surface and groundwater resources with consequent implications for other water users.

The Advisory Council for Agriculture and Horticulture predicted in 1980 (ACAH, 1980) a four-fold increase in agricultural demand by the end of the century, due mainly to increases in abstractions for irrigation. Most of this is used for "sub-irrigation", or the watering of crops by seepage from watercourses, and summer flows in many lowland rivers are significantly reduced by such consumption. Evans (1983) estimated that the amount consumed in sub-irrigation in the Fens area in a 1 in 20 year dry summer is approximately equivalent to a half of the volume of the Grafham Water reservoir. Demand for sub-irrigation can be expected to change considerably in a warmer, CO_2-rich world, as crop water requirements increase and transpiration rates reduce. This will have consequences for flows in many lowland areas.

The amount of water in Britain withdrawn for spray-irrigation has increased in recent years, and is closely linked to summer soil moisture deficits (Evans, 1983). Spray irrigation is required to maintain yields of certain crops in eastern England in eight or nine years out of ten at present, and if summers become drier as well as warmer this need can be expected to increase. Set against this increase, however, are possible changes in the efficiency of irrigation water use and, in a more complicated way, possible changes in agricultural practices as a result in changing economic and policy conditions.

At present, the abstraction for general use with livestock represents the largest component of direct agricultural demand (approximately 170 million m^3 - 465 Mld^{-1} - and mostly from public supplies: ACAH (1980)). However, whilst this is an important element in demand for good quality water, it is believed to be relatively insensitive to changes in climate.

Changes in agricultural demand can have an indirect effect on the water resources available to other sectors by altering river flows and groundwater recharge, and can have a direct influence through changes in managed abstractions (for spray irrigation, for example). Estimation of the impacts of such changes requires information on changing crop-water requirements in a changing climate.

Changes in industrial demand for water

Much of the industrial demand for water (excluding water for cooling - see Chapter 7) is not directly sensitive to changes in climate, and climate change can be expected to influence industrial abstractions only through its effect on supply reliability. Changes in industrial demand and abstractions will reflect general economic health, changes in industrial structure and changes in attitudes and policies towards water use, and these effects may be greater than those of climate change. Since the drought of 1976 many industries have improved their efficiency of water use, in order to limit disruption in dry years (Parker et al, 1986).

Changes in domestic demand for water

Household demand in Britain currently accounts for approximately a quarter of total demand, and is predicted to increase in absolute terms. This increase will reflect changes in water use rather than increases in population totals, and estimates of future demands are therefore dependent to a degree on assessments of changes in, for example, ownership of washing machines. Hall et al (1988) describe a detailed study of water use in the South West Water area, and whilst they do not consider explicitly the effect of possible climate change, it can be inferred from the areas of demand itemised that domestic water use per capita is probably insensitive to changes in climate. Garden sprinkler usage will probably increase, but this constitutes only a small proportion of domestic demand (less than 3 per cent at present: WAA, 1988). However, total domestic demand in some areas may be expected to increase in a warmer world. If warmer summers encourage greater tourism in South West England, for example, total summer demand will rise: the supply infrastructure in the South West is currently geared towards meeting peak summer demand. In 1985/86 the average daily supply in the South West rose from 412 Mld^{-1} in the lowest week to 506 Mld^{-1} in the peak of the summer season (South West Water, 1987).

5.7 The effect of climate change on demand for water: research needs

The links between climate and demand for water are currently less clear than the links between climate and water supply, and more research is needed into both the direct sensitivity of demand to climate and the effects of supply changes on demand. It is important to understand also the consequences of changing non-climatic influences on demand and abstractions. The timing and spatial distribution of demand may be very different in a changed climate, and studies of the possible increases in peak summer demand due to increased tourism in, for example, the South West would help with long-term resource planning. Regional-scale studies of changes in demand and supply are needed in order to ascertain the relative importance of the many potential changes in the water resources of the UK (Chen and Parry (1987) summarise a regional scale study in the western US, showing changed ratios of demand to supply with changes in supply). Finally, case studies of the impacts of recent climatic effects on water demand and management response (Glantz and Wigley, 1987; Riebsame, 1988) will help understanding of possible future changes and consequences.

It is quite possible that the evolution of water resource availability in the UK over the next 100 years will be conditioned as much by changes in demand as by climatically-induced changes in supply.

6. HYDROLOGICAL CONSEQUENCES OF SEA LEVEL RISE

6.1 Magnitude of the rise

Sea level rise is probably the most worrying of the consequences of the greenhouse effect in the mind of the public. The DOE core scenario for sea level rise is that given by Jelgersma et al (1987) which in turn was taken from the work of Robin (1986). Robin derived his forecast of 80 cm (+85,-60) largely by forward projection of the trend of the recent past although with some consideration for the components which make up the change. These three components are:

Thermal expansion of the ocean
Meltwater from major ice sheets
Meltwater following glacier retreat

to which could be added the more speculative and much larger consequences of the collapse of unstable ice sheets. At given localities one must also consider isostatic and other local adjustments which will continue independently of the greenhouse effect.

Since the publication of the Scope 29 report, scientists investigating the problem of sea level rise, eg Warrick (1989) and Oerleman (1989) have tended to base estimates on the summation of the three individual components listed above. In the early stages of greenhouse warming it is now thought that increased precipitation over ice cap regions will diminish the cryospheric contribution to sea level rise. Also there has been an increasing appreciation of the role of thermal inertia in slowing the rate of warming. The upshot of these recent evaluations is to reduce the earlier projections to within Robin's low to medium range. A revised working estimate of 50 cm rise by the middle of next century may now be favoured as more likely than the earlier estimate.

6.2 Hydrological aspects

Sea level rise has many critical technical and social consequences among which are a number of concern to hydrologists:

Impeded drainage from low lying coastal plains.
Flooding in estuaries where the joint action with fluvial discharges is also important
Groundwater level rise on the coastal plain
Saline intrusion into the coastal groundwater
Urban drainage and sewage outfalls in littoral settlements
Pumping and sea-wall protection to low lying fenlands and similar areas
Saline intrusion into estuaries affecting freshwater intakes

Regime changes in lower stream courses due to outfall siltation and change.

There has been no concerted research yet published that has attempted to address these issues worldwide or in the UK. Local and regional authorities are aware of the extent of sea defence works under the current climate and sea level regime but the identification of future risk areas at a national scale has not begun. The Durham University Quaternary Research Laboratory have prepared maps at the scale of 1:2.5M (Figure 6.1) and MAFF have digitized areas below the 5 m contour. A major session at the 1989 River and Coastal Engineers conference will tackle an overview of some of the topic listed above.

6.3 Technical problems

Given a particular scenario for sea level rise there still remain difficulties demanding research before the hydrological consequences can be evaluated. The following paragraphs illustrate these for some of the section 6.2 list.

Urban and land drainage on the coastal plain

Some estuaries are of considerable length, eg Yorkshire Ouse and Severn, and so the potential impact length and number of influenced tributaries is accordingly high. The level of economic and agricultural activity is frequently very great and such terrain may contain important trunk routes. While 50 cm may not appear to be a large figure it has to be recalled that many arterial drainage scheme designs turn on level differences of a few centimetres. In the riparian zone 20 cm can make the difference between a water meadow and an agriculturally productive field. An extra hour of tidelocking can impose a need for expensive extra storage or pumping in urban areas. The greenhouse scenario for additional winter rainfall is an aggravating factor in evaluating the impact of climatic change on land drainage.

Pumped fenland drainage

There are some 15,000 km^2 of land in the UK where free gravity drainage is restricted, of which some 9,000 km^2 requires partial or total pumping (Beran, 1982). Much of this land lies in the East Anglian fenland and includes some of the most productive agricultural land in the country. Sea level rise will affect this area in several ways. The head against which pumps will operate will increase. Current design principles adopt a duty point for pumps in the upper part of the expected working range but the addition of 50 cm or 1 m would certainly require considerable adjustment for efficient working. The change in the runoff to the pumped area remains indeterminate and is already complicated by the interplay between inflow rate, tide or river level into which the pump discharges, and electricity tarrif or pump operation routine (Figure 6.2).

Figure 6.1 General indication of areas at risk from sea level rise in the UK. The map shows the major coastal lowlands that lie below an altitude of 5 m AOD.

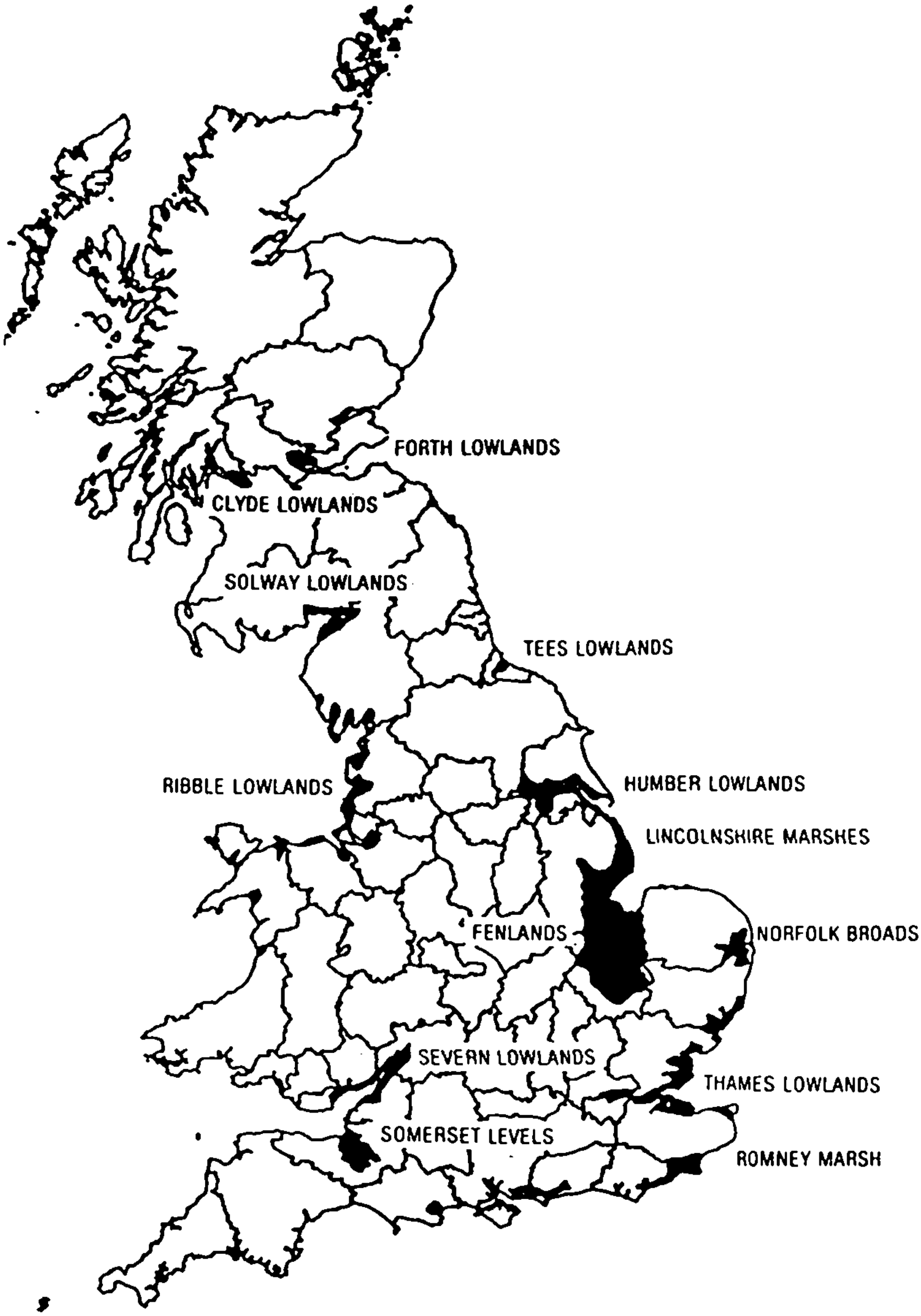
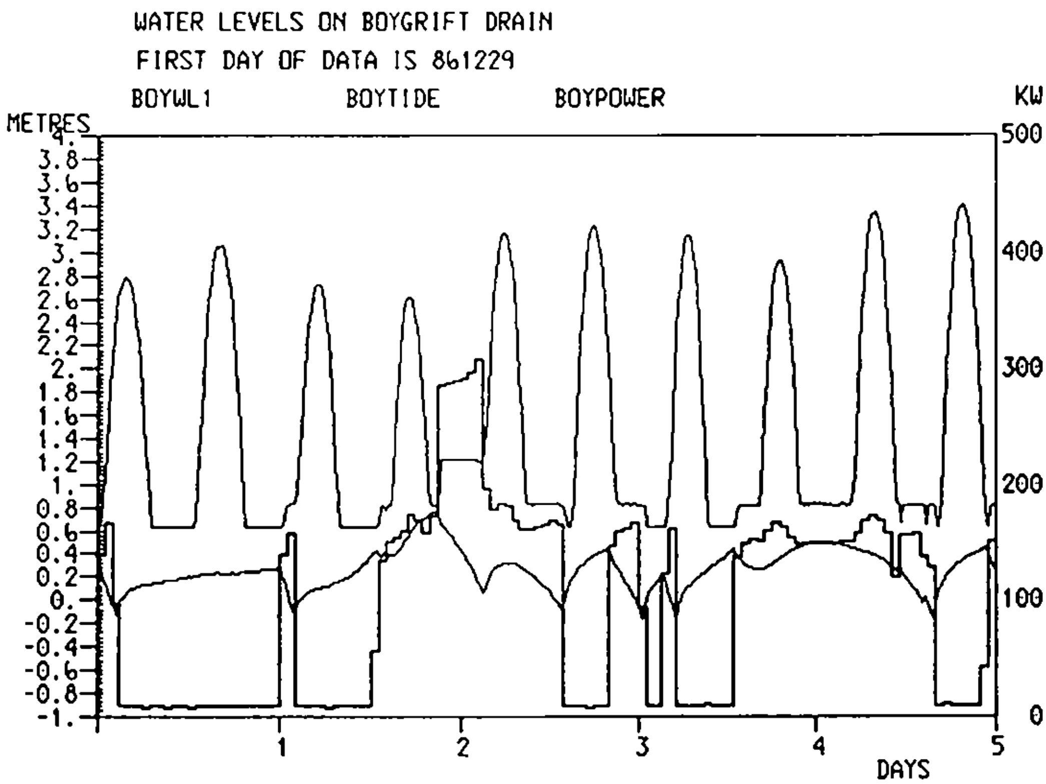


Figure 6.2 Water levels and pump output from a Lincolnshire fenland catchment. The diagram illustrates the complex management and design problems faced at the interface between land systems and the sea which will be exacerbated by sea level rise. The tidal signal can clearly be seen as can the tendency for drain level to rise through the tidal peak due to the avoidance of pumping where possible against a high head.



The increased head against sea and river levees will increase seepage considerably and hence increase saltwater incursion and overall pumping costs. However these are minor considerations when set against the larger problem of maintaining the integrity of the levee bank itself (which is of course a soil mechanics rather than a hydrological problem).

River training and regime problems

It is important for navigation, and effluent and intake design that rivers have a free and stable outfall to the sea. Sea level rise will reduce gradients and induce instability in lower courses. It is not possible to generalise about estuarial stability and its upstream consequences because of the role of interacting processes such as the acretion and erosion cycle, wave action and longshore drift. Also episodic flood events are important in determining river geometry so assumptions must be made about changes in storm frequency and joint probability with fluvial flooding. Similar matters have been raised in Boorman et al (1988). Dutch work reported by Hekstra (1989) indicates increases in tidal range, and changes to currents wave climatology in the North Sea as a result of sea level rise.

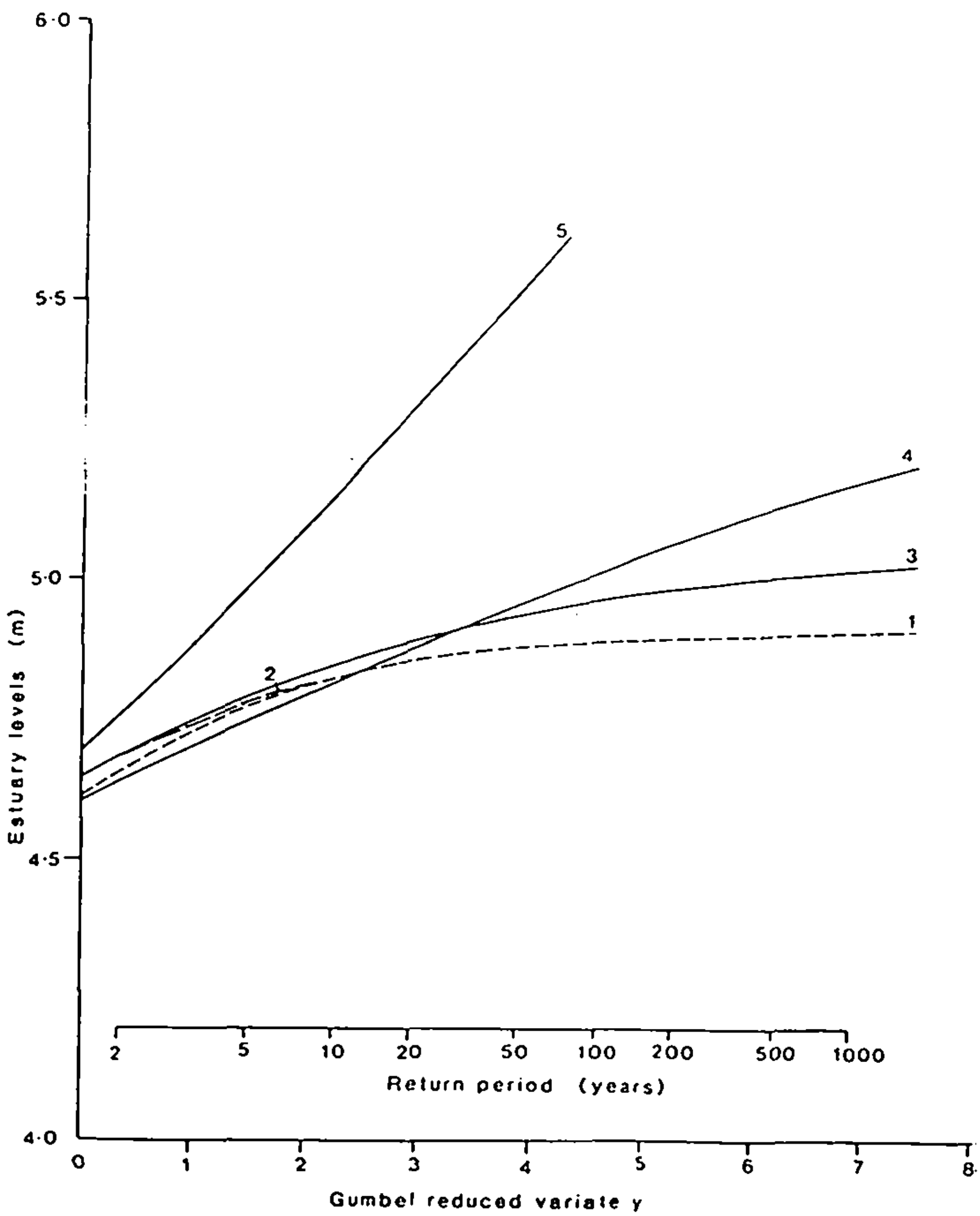
Flood protection along estuaries

This problem becomes one of acute interest to hydrologists where there is a risk of flooding both from high tides and surges from the seaward side and also from fluvial flooding from upstream. This is of very widespread occurrence around British coasts due to our high tidal range and mature landscape with associated shallow-graded lower rivers courses. In some cases, notably the Thames, Great Ouse and Yorkshire Derwent, barrages have been built to exclude sea water from the upper estuary. Clearly sea level rise will bring an altered pattern of tide and surge wave propogation and some barriers may prove inadequate ultimately.

The Thames barrier and downstream coastal protection works were constructed to a standard which allowed for a sea level rise of 76 cm per century up to the year 2030; the rate of rise was computed from previous trends. Upstream of the Thames barrier flood protection presents a particularly complicated picture because the closure operation must be complete soon after the preceeding low tide in order to provide upstream flood storage. In consequence the decision to close has to be based on a forecast of the subsequent high tide and surge (Figure 6.3). The CEC report (reported in Warrick, 1989) will contain simulations of estuary response to historic surge events such as that of February 1953.

Even rivers with barriers may experience residual problems due to sea level rise. Lincoln lies on the River Witham and due to the restricted channel it is provided with extensive controlled flood storage upstream of the city. Although the Grand Sluice at Boston seals the Witham from the sea there is a clear tidal signal visible well upstream due to the storage of floodwater during the tidelocked period. Were the effect of sea level rise

Figure 6.3 Level frequency relationship for the Thames estuary. Line 5 shows the return period of different levels at Tower Pier without the Thames barrier. Line 1 indicates perfect barrier operation, ie no forecast error of North Sea surge so a total guarantee that the barrier will always close as planned. Line 4 shows the effect of a practical response to surge forecast uncertainty with an element of built-in safety that leads to line 4 falling below line 1 at low return periods. The diagram also illustrates how flood protection must consider the effect of sea level rise on extreme events, not on the mean sea level.



to lengthen the tidelocked period and decrease the channel capacity through Lincoln even marginally, say from 60 down to 50 m^3s^{-1}, the strong non-linearity in the storage frequency relationship would reduce the effective return period - eg from 100 years to near 60 years - of protection afforded by the upstream storages (Institute of Hydrology, 1982).

Groundwater

The problem of saline intrusion into coastal aquifers is very serious on the world scale - eg 1.2 million ha within the Ganges Brahmaputra delta - but not hitherto of note in the UK except in isolated instances. However it will be more than a theoretical problem following any sea level rise. Many coastal towns on the south and east coast withdraw water from aquifers, particularly Chalk and Crag, close to the sea level limit and these will suffer some restriction.

The precise form of the interface between fresh groundwater and the sea is very dependent on local surface and subsurface conditions and has not been made the subject of a general study in the sea level rise context. The problem is exacerbated by the near horizontal interface with the sea water that will permit a disproportionate ingress of sea water. Theoretically a wedge will form with the freshwater depressing the salt water but an ideal form will not in general develop due to variations in permeability. Mean sea level exercises a fixed control on the equilibrium height of the water table adjacent to the coast and at this point a rise may be expected to be reflected in total. However the form of the phraeatic surface inland from the coast will appear "damped" and approach asymptotically the pre-rise surface.

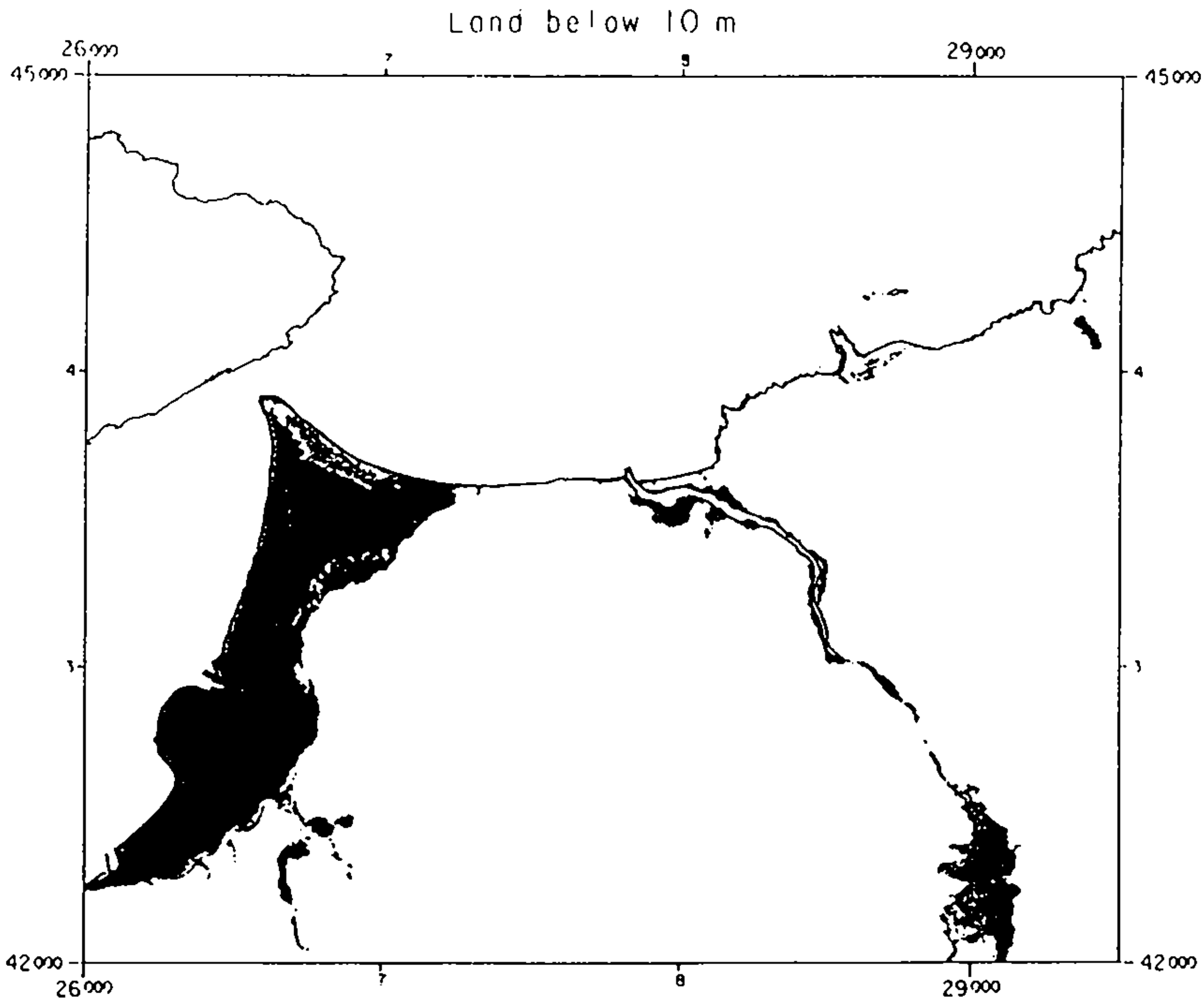
As well as deep wells some limited use is made of shallow aquifers on the coastal plain for domestic and horticultural purposes. These will be at risk. However there is almost no exploitation of dune supply as in the Netherlands where salinization is a major concern (Goemans, 1986).

Definition of zones at risk from flooding

Any socio-economic study of the consequences of sea level rise requires a definition of areas which are at risk. This is based on maps, contours and spot heights. The problem of scale has been referred to with preliminary studies at very large (Figure 6.1) and very small scales underway. Here we consider the technical means for the strategically important medium scale (eg 1:100,000) of identification.

Digital terrain models, which show land surface elevations on a regular grid, are now becoming available. At the Institute of Hydrology we work with a 50 m grid derived from the 1:50000 series contour and spot height information. As Figure 6.4 shows this produces a believable impression of coastal morphology but more work is necessary to evaluate the absolute accuracy of interpolations. Problems which have been identified are that the source data consists of the coastline (nominally mean high water springs), the 10 m contour and a sparse network of spot

Figure 6.4 The use of Digital Terrain data to identify risk areas. The map is prepared by interpolating contour and spot height data to a regular 50 m grid and plotting values within required bands. The dark shading relates to land at risk from high sea levels of 8 m, and the light shading indicates the increased areas at risk from 10 m sea level. As in Figure 6.2 the levels of land at risk relate not to mean sea level but to high tide + surge + run-up + (in some circumstances) wave height.



heights. The disposition of these latter heights exercise considerable influence on the resultant interpolated value and can make the difference between a naive and a realistic ground model.

Research should be pursued to introduce locally defined data on the altitude of the mapped coastline, to superimpose the channel information on the surface shape, and to investigate the properties of alternative trend surfaces.

7. OTHER IMPACTS ON HYDROLOGY AND WATER MANAGEMENT

7.1 Introduction

Chapters 5 and 6 have summarised some of the potential effects of climate change on hydrology and water resources, but there are many more possible areas of impact. These have generally been less well studied, and it is frequently possible to make only educated guesses about sensitivities and impacts. This chapter attempts to itemise these additional consequences of climate change.

7.2 Fluvial flooding

The possible increases in coastal flooding due to climate change have been well publicised and studied, but it is probable that patterns of inland fluvial flooding will change. Most fluvial floods in the UK occur in winter or spring, and are associated with prolonged heavy rainfall generating saturated ground conditions. There are exceptions to this general pattern, and some of the most damaging floods have occurred following heavy summer rainfalls (at Lynmouth in 1952, to take but one example).

There have been very few studies into the effect of climate change on flood frequencies (although Bultot et al (1988) found in their simulation studies that floods became more frequent). However, there is an increasing number of studies into the relationships between climate and flood generation (see Arnell (1989) for a regional study in western Europe, for example), and these studies may provide the basis for some suggestions about future patterns of flood occurrence following climatic change.

Increased winter and spring rainfall is likely to lead to an increased frequency of flooding. Not only are heavy short-period rainfalls likely to become more frequent (as suggested by Wilson and Mitchell, 1987) but in a generally wetter world catchments are more likely to be saturated for longer periods. An assessment of possible changes in soil moisture contents awaits improvements in the representation of hydrological processes at the sub-grid scale in GCMs (as discussed in Section 2.5).

Higgs (1987) has related flood magnitude and frequency in each year in the upper Severn basin to the frequency of occurrence of different Lamb Weather Types, showing that years with a greater frequency of westerly air-flows tend to experience more floods. If information on changes in weather types can be obtained from GCMs, it may be possible to draw inferences about future flood occurrence.

Although snowmelt floods are currently not frequent in the UK, in some years large floods are caused by a combination of melting snow and heavy rain (in 1947, for example). As winters become warmer it can be expected that the amount of precipitation falling as snow would decrease, on average, and that there would be fewer snowmelt-based floods. However, estimates of the effect of climate change on snowfall are currently very uncertain, and the links between snowfall and snowmelt floods are complex (depending on the amount of associated rainfall, the rate of change in temperature and the delivery of radiant energy).

Increased summer temperatures can be expected to increase convective activity and hence might trigger more frequent thunderstorms and associated flooding if enough moisture were available. The generation of thunderstorms is dependent on the interaction between temperature and moisture in the atmosphere, however, so is not easy to predict: there are no published studies of possible changes in the propensity to generate thunderstorms. In a drier summer it is probable that soil moisture contents will be lower, and that a greater amount of the event rainfall would be needed to raise soil moisture contents before a flood could develop. Finally, many of the largest summer floods in recent years have been caused by thunderstorm cells associated with intense and prolonged depressions tracking across the UK from the west. The frequency of occurrence of such summer depressions may change in a warmer world.

7.3 Reservoir safety

Reservoir safety issues are receiving much attention at present, following the implementation of the 1978 Reservoir Safety Act, which requires each reservoir to be inspected and its design standard evaluated. The design standard for reservoir spillway design varies from the one in 150 year flood for small reservoirs to the probable maximum flood (PMF) for large reservoirs in high risk areas. The calculation of design floods involves an estimation of both extreme rainfall frequencies and windspeeds (which influence wave build-up). Research is currently underway at the Institute of Hydrology into improved techniques for estimating extreme rainfalls (Dales and Reed, 1989), but information on joint probabilities of heavy rain, snowmelt and wind is not available.

Climate change will have an influence on reservoir safety through changes in both the occurrence of extreme rainfalls and maximum wind velocities. However, it is difficult to estimate the consequences because, as has been repeatedly emphasised, the present state of GCM modelling does not allow the estimation with confidence of changes in short-duration effects. Reservoir design flood calculations frequently use design rainfalls with durations of less than 24 hours as the median reservoired catchment is less than $5km^2$. Nevertheless, estimates of sensitivities in risk could possibly be made by adjusting current rainfall frequency curves according to best scenario estimates of change.

7.4 Hydropower generation

Hydroelectric power schemes provide under 3 per cent of the total electricity generated in the UK, but their use is primarily to meet peak power demand. Schemes are concentrated in Scotland and upland Wales, and whilst most consist of a simple reservoir, some are pumped storage schemes where cheap electricity is used to pump water back up into a reservoir to be released at times of peak electricity demand. Climate change can affect hydroelectric power generation both through changes in power demand (e.g. the possible shift of some winter demand to summer due to the substitution of air conditioning for heating) as well as through changes in the water available for power generation.

Hydropower production is determined by the volume of water stored, the head of water and turbine efficiency. As volumes of storage increase due to higher winter rainfalls the potential for power generation increases too, but the increase would be limited by reservoir capacity. Changes in the volume of reservoir storage over time are related to flow variability as well as reservoir size, and changes in variability will therefore affect the ability to meet particular power demands. Finally, changes in flood potential in winter may lead to alterations in reservoir operating rules: for example, it is conceivable that an increased risk of high winter flows would require reservoirs to be maintained at lower levels during winter.

While it would be relatively straightforward to determine the possible effects of climate change on hydropower generation for a given scenario condition, such a study has not been done in the UK. Studies in the Great Lakes Basin have examined the potential for increased power generation under a changed climate (Singh, 1987; Cohen, 1986).

There are at present very few "run-of-river" hydropower schemes in the UK. Such schemes cannot store water, and the potential for, and reliability of, power generation is dependent on flow variability, and hence the shape of the flow duration curve. An increase in river flows would mean that run-of-river schemes become more viable, although an increase in variability giving more frequent low flows would work in the opposite direction.

7.5 Water for cooling

Abstractions for power station cooling are a major withdrawal in the UK (as indicated in Chapter 4), although have been decreasing as power generation has tended to be located at coastal sites. The demand for cooling water will possibly alter as demand for power changes, but the greatest impact of climate change may be on the potential supply of cooling water. An increase in total runoff implies a greater availability of cooling water, while changes in variability may mean a reduction in availability in certain times of the year. The temperature of the cooling water is also important, and as river temperatures rise in a warmer world (George, 1988) more water will be demanded to achieve the same amount of cooling. The consequences of climate change for power station cooling depend also, of course, on the degree to which current demands are constrained by resource availability. In the Trent basin, for example, changes in the use of water for cooling would have significant downstream resource consequences.

7.6 Navigation

Inland waterways are in many areas of the world important transport routes, and changes in climate could have significant economic consequences. Sanderson et al (1988), for example, estimated that lower levels in the Great Lakes Basin could lead to increases in transport costs of some 30 per cent. In the UK, however, only 1600 km of the 2400 km of navigable inland waterways are used at present for freight (Brandon, 1987), and flows in these waterways are heavily controlled. It is therefore very difficult to estimate the effect of climate change on navigability, although it is possible that the suggested increase in annual runoff volumes would both allow greater traffic and pose additional operational complications on waterway managers.

Recreational use of waterways has increased considerably in recent years, and currently more than 70 waterway restoration schemes are in hand (Brandon, 1987). This increased use will impose additional pressures on rivers and water resources regardless of any changes in climate. It is important to note that canals are supplied from reservoirs, many of which are old, and that these reservoirs will be affected by changed hydrological conditions.

Any assessment of the effect of climate change must take into account both changes in hydrological inputs and operational responses.

7.7 Water-based recreation

One recreational use of water was introduced in the previous section. Much recreation takes place around water (as described by Tanner (1973) and Parker and Penning-Rowsell (1980)), but for many uses the amount of water is not critical. Water-based recreation is probably, therefore, relatively insensitive to changes in flow patterns induced by climate change, although changes in water quality (Jenkins and Whitehead, 1989) will affect both fishing and bathing.

7.8 Urban drainage

Urban storm sewer drains are designed to cope with rainfall events with relatively low return periods, typically of the order of one in five years. An increase in the frequency of such rainfalls can be expected if the hypothesised strengthening of the hydrological cycle occurs, and this will have obvious consequences. It is possible that many current drains will be found to surcharge more frequently. Further studies on possible changes in short-period rainfall will help in the quantitative assessments of changes in risk.

7.9 Morphological consequences of hydrological change

The relationships between river basin morphology and hydrology have been well studied, and geomorphology textbooks contain many examples of morphological changes following sometimes minor hydrological changes. These morphological changes in turn can have implications for water resources and water users. Perhaps the most obvious are change in river channel form, leading to increased maintenance costs, and altered sedimentation due to changes in both surface and channel erosion. The relationships between changes in climate and morphological changes which influence water resources are, however, complex, and there are many feedback loops. Verhoog (1987), for example, describes how changes in vegetation associated with changes in climate may alter the resulting changes in hydrological and geomorphological response. Studies into the relationships between climate, morphology and hydrology have a long history, but only recently have models been developed which can be used to predict the consequences of change in one or more of the inputs (Kirkby (1989), for example)

7.10 Research requirements

The previous sections have itemised some of the possible effects of changes in climate on water resources and water users, and it is clear that there are still a great many unknowns. In particular, research into the historical associations between "flood propensity" and climate and circulation characteristics needs to be enhanced, the sensitivity of hydropower demand to water availability (given hydropowers' role in peak periods) needs to be examined, and the control of river temperature on cooling potential must be investigated. Underpinning several areas of impact are studies into the possible changes in the occurrence of short-period rainfalls. Scenarios for such changes may be based on spatial analogues or through association with weather types.

Finally, it is difficult to undertake generalised investigations into many of the impacts of climate change on the sectors summarised above. The consequences of climate change are best studied by individual analysis of particular examples.

8 FUTURE REQUIREMENTS

8.1 Policy issues

Policy deals with ultimate aims and enabling strategies within which activities to achieve these aims can flourish. In the water field one needs to be concerned with scientific and with practical activities. The pervasiveness and importance of hydrological and water resource studies may be summed up in the following guiding principles:

> Water plays a central role in energy partitioning within the atmosphere and at the surface.
>
> Water acts as an essential catalysing and transporting medium in the biosphere and geosphere allowing cycling of trace gases, nutrients and organic materials within and between the land, ocean and atmosphere.
>
> The transfer function between climate and hydrology involves threshold processes which sometimes amplify and aggravate water resource consequences.
>
> Because engineering works transfer water resources from periods and locations of excess to periods and locations of deficit, increases in the temporal and spatial variability tend to have strongly non-linear consequences to the reliability of such works.
>
> The planning, design, construction and lifetime of major water resource works is substantial, even by comparison with climatic change. This means that incremental adjustment to change is seldom a viable; the ability to accommodate change must be thought about and, if necessary, built in at the outset.

UK water design engineers in government, industry, and private practice need to be made more aware of the non-stationarity that exists in the environment, and to be aware of the possible unidirectional changes flowing from global warming and climatic change. This is largely a matter of education and information but needs to be nurtured by educators and professional bodies. This is quite a wrench from past established practice which is predicated on the understanding that the past is our surest indicator of the future.

Policies that permit ready response to extreme climatic and hazardous events have to be set in train; indeed the lessons of the 1976 and 1984 droughts have left the UK in a relatively good position to deal with episodic events. Sustained or regularly repeated events of a similar order will need to be institutionalized so that, for example, drought orders and consent waivers, can be more even more responsively set in place.

Scientific hydrology was able to assist with those events by informing managers of forward projections of resources, linkages between surface and subsurface resources, and cross-basin linkages. The scientific background to inform policy makers on the greenhouse future is discussed in the following section.

8.2 PRIORITY RESEARCH FOR DOE REQUIREMENTS

Research requirements within each subject area have been included in individual chapters. A strategy for research is set out in this section which concentrates on priority topics within DOE's policy remit.

Hydrological and water resource studies can be categorized as follows:

i) **Causes of change:** which includes process oriented studies on water in its atmospheric and land phases and which are directed to an understanding of the direction and magnitude of the greenhouse effect.

ii) **Measurement and detection of change:** which include analyses of past variability, especially through long time series of hydrological and climate data; and also the maintenance of suitable data sets for detecting the signal of ongoing change.

iii) **Impact studies:** in which scenarios for change are used to investigate the consequences of the greenhouse effect on water supply and other water sensitive systems.

It is considered that the third area is the one of most concern to DOE. A division of effort of 20, 20 and 60 per cent between them would represent this emphasis. The lists that follow have been set out in diminshing prioirity order within each subject area, although all topics are ultimately essential to the evaluation of climate change consequences and should be pursued in time.

Causes of change

The twenty per cent of DOE supported effort to be directed towrds process studies is needed to assist with the better understanding of water and energy partitioning processes within and from vegetation and the soil profile.

The most pressing unknown concerns the water use of vegetation in the changed environment, though this is of a scale that demands community collaboration for experimental and modelling work. DOE involvement in any future consortium would be welcomed.

One specific area for DOE support is the MITRE collaboration in which IH is improving the description of land phase processes within the UK Meteorological Office GCM.

GCM validation at all levels is important. One where DOE support would be appropriate is the comparison of GCM runoff with observed runoff. A pilot project over Europe has shown the technical feasibility but the comparison needs to be made for the UK area too.

Soil moisture processes have received very little attention. In the initial stages this could take the form of a desk study to identify possible sensitivities.

Evaluation of change

It is considered that equal emphasis and funding be given to studies that set the scene for the future and studies that concern instrumental records (past and current), ie ten per cent of climate change expenditure on each.

Development of secenarios of the future climate underpins all impact studies. While a task for climatologists and atmospheric modellers in the early stage, it is hydrologists who provide the necessary high temporal and spatial resolution and the information on extreme values, from the "broad brush" data provided by the modellers. DOE funding is required for studies in this area.

Concerning instrumental records it is most important to maintain a runoff record comparable with the national rainfall record. Support for flow naturalization activities should therefore be funded and DOE is the appropriate body.

The report of the Working Group on Long Term Reference Sites has recommended setting up a national network for the study of global environmental change (which includes climatic change). Many of these sites require hydrological measurements to be made and it would be appropriate for DOE to support an IH involvement in this activity.

Policy response can learn from past extreme events. The lessons of earlier droughts and floods should be assembled and analysed.

Impact on water resources

Climate change impacts can be subdivided into those concerned with supply and those related to demand. The major emphasis by DOE should be placed on the former, eg 55 of the 60 per cent allowed. Water supply issues can be further subdivided into those concerned with water availability for use, and those concerned with public safety.

The impact on water availability for public supply involves scenarios for low flow conditions and technically divides into storage and non-storage cases. Management and whole-basin issues also arise and should be supported by DOE.

There are several hydrological aspects of sea level rise which lie within DOE's responsibility including urban drainage and surface and subsurface water supply in the coastal zone. Other areas which use IH's cartographic manipulation skills for definition of risk zones impinge on both DOE and MAFF areas of responsibility, and DOE support would assist necessary development.

Groundwater resources in the UK will increase in importance under the suggested scenario and a renewed inventory of resources under an altered climate is a necessary precursor to planning. There may also be a requirement for process studies and local survey, eg at coastal locations.

The principle public safety issue of concern to DOE is that of reservoir safety. The impact on design standards of certain scenario climates would be a useful subject for a desk study and would consider rainfall, runoff and wind.

A desk study into the sensitivity of the demand for water to climate is needed in order to list the relevant issues for the UK.

8.3 Priorities with a limited budget

It is considered that a timetable could be set up so that, within a period of five years, DOE could be provided with useful contributions in all these areas but would cost a minimum of £300,000 per annum - more if substantial monitoring and experimental work was supported.

With a budget of, say, £50,000 per annum, it would not be possible to carry out tasks in parallel as several of the minority tasks (in terms of effort) would fall below the threshold that would justify a start being made. It is considered important to maintain an involvement in all three areas so the suggested percentage still pertains; £10,000 for prediction studies, £10,000 for data analyses and £30,000 for impact studies.

Area (i) is the hardest hit financial limitations as it is only the initially lower priority tasks that are attainable within the limits. Therefore GCM validation for the UK and a short term desk study on soil moisture implications should be favoured. It is considered that the two high priority tasks are equally justifiably funded from Air Quality Directorate funds.

At the outset all area (ii) effort should be concentrated in scenario studies where procedures for extracting basin scale information can be developed. In subsequent years the problem of naturalization of flows should be addressed, the other topics as resources permit.

A piecemeal approach to area (iii) is not viable so topics should proceed mostly in series. Water supply impacts should occupy £20,000 of the £30,000 as an ongoing commitment to this fundamental area of DOE interest. The remaining sum would be split among desk studies for individual topics; groundwater resource evaluation is the most important one for early treatment.

9. REFERENCES

ACAH, 1981. Water for agriculture: future needs. Advisory Council for Agriculture and Horticulture in England and Wales, London.

Arnell, N.W. in press. Hydrology of humid temperate areas. In Falkenmark, M. and Chapman, T.G. (eds) Comparative Hydrology. UNESCO.

Arnell, N.W. 1989. Changing frequency of extreme events in Northern and Western Europe. In FRIENDS in Hydrology IAHS Publ. 187, 237-249.

Arnell, N.W. and Beran, M.A. 1989. Climatic change scenarios for water resource impact studies. IIASA Workshop on Development of Regional Climate Scenarios for Impact Assessment. IIASA, Feb. 1989.

Bach, W. 1987. Scenario Analysis. European Workshop on Interrelated Bioclimatic and Land Use Changes. Noordwijkerhout, The Netherlands, Oct. 1987.

Beran, M.A. 1982. Aspects of flood hydrology of the pumped fenland catchments of Britain. Proc. Symp. Polders of the World. Lelystad. Vol. 1, p643.

Beran, M.A. 1984. Climate change : New problems for water resources and hydrology. In Proc. International Conference on Hydrology and Scientific Bases for the Rational Management of Water Resources, pp. 3-22, Paris,1982, Unesco/WMO/IAHS. SC-84/WS/53.

Beran, M.A. 1986. The water resource impact of future climate change and variability. In Titus, J. (ed.) Effects of changes in stratospheric ozone and global climate. USEPA/UNEP. Washington, pp 299-330.

Boorman, L.A., Goss-Custard, J. and McGrorty, S. 1988. Effects of sea level rise on coastal ecosystems of conservation and amenity interest in the UK. Institute of Terrestrial Ecology, Monks Wood. Report to DOE.

Brandon, W. (ed). 1987. River Engineering - Part 1, Design Principles. Institution of Water and Environmental Management. 316p.

Brandyk, T., Dooge, J.C.I. and O'Kane, J.P.J. 1985. Soil moisture in general circulation models. Report of University College Dublin for EEC. 62p.

Bultot, F., Coppens, A., Dupriez, G.L., Gellens, D. and Meulenberghs, F. 1988. Repercussions of a CO_2 doubling on the water cycle and on the water balance - a case study for Belgium. J. Hydrology, 99, 319-347.

Callaway, J.M. and Currie, J.W. 1985. Water resource systems and changes in climate and vegetation. In Characterisation of information requirements from studies of CO2 effects. DOE/ER-0236, Washington, 23-67.

Chen, R.S. and Parry, M.L. (eds) Climate Impacts and Public Policy. UNEP/IIASA.

Cohen, S.J. 1986. Impacts of CO_2-induced climatic change on water resources in the Great Lakes Basin. Climatic Change, 8, 135-153.

Dales, M.Y. and Reed, D.W. 1989. Regional flood and storm hazard assessment. Institute of Hydrology, Wallingford, Oxon. Report no. 102. Report to DOE.

Dooge, J.C.I. 1988. The role of the hydrological cycle. Proc. symp. on Climate and the Geo-sciences. Louvain-la-Neuve, 22-27 May 1988. (to be published by Reidel).

Eagleson, P.S. 1982. Ecological optimality in water-limited natural soil vegetation systems. Water Resources Research 18, 325-340.

Eamus, D. and Jarvis, P.G. 1988. Direct effects of CO_2 increases on trees and forests in the UK. Report to DOE. Institute of Terrestrial Ecology, Edinburgh.

Environmental Protection Agency 1988. The potential effects of global climate change on the United States. Draft Report to Congress. US EPA Oct. 1988

Evans, D. 1983. Agricultural demand for water. J. Institution of Water Engineers and Scientists, 37, no. 6, 513-520.

Gardiner, V. and Herrington, P. (eds.) 1986. Water Demand Forecasting. Geobooks: Norwich.

George, P.G. 1988. Impact of climate change on freshwater ecosystems. Report to DOE. Freshwater Biological Association.

Glantz, M.H. and Wigley, T.M.L. 1987. Climatic variations and their effects on water resources. In McLaren, D.J. and Skinner, B.J. (eds) Resources and World Development. Wiley: Chichester pp625-641

Gleick, P.H. 1987. Regional hydrologic consequences of increases in atmospheric CO_2 and other trace gases. Climatic Change, 10, 137-161.

Goemans, T. 1986. The sea also rises: the ongoing dialogue of the Dutch with the sea. In Titus, J.G. (ed) Effects of changes in stratospheric ozone and global climate, Vol. 4: Sea level rise. UNEP/USEPA.

Gross, R., Eeles, C.W.O. and Gustard, A. 1989. Application of a lumped conceptual model to FREND catchments. In FRIENDS in Hydrology. IAHS Publ. 187, 309-320.

Hall, M.J., Hooper, B.D. and Postle, S.M. 1988. Domestic per capita water consumption in South West England. J. Institution of Water and Environmental Management. 2, 626-631.

Hansen, J., Russell, G., Rind, D., Stone, P., Fung, I., Reudy, R. and Lerner, J. 1984. Climate sensitivity: analysis of feedback mechanisms. In Hansen, J. and Takahashi, T. (eds) Climate Processes and Climate Sensitivity. American Geophysical Union, Washington D.C.

Hekstra, G.P. 1989. Regional consequences and responses to sea level rise. In N. J. Rosenberg, E. Easterling, P. Crosson and J. Darmaster (eds) Greenhouse Warming: Abatement and Adaptation. Washington, Resources for the Future.

Higgs, G. 1987. Environmental change and hydrological response : flooding in the upper Severn catchment. In Gregory, K.J., Lewin, J. and Thornes, J.B. (eds.) Palaeohydrology in Practice. Wiley: Chichester pp133-161.

Hulme, M. and Jones, P.D. 1988. Climatic change scenarios for the UK. Climatic Research Unit Report for IH. Nov 1988. 48p.

Hunt, B.G. 1985. A model study of some aspects of soil hydrology relevant to climate modelling. Q. J. Roy. Met. Soc. 111, 1071-1085.

Idso, S.B. and Brazel, A.J. 1984. Rising atmospheric carbon dioxide concentrations may increase streamflow. Nature 312, 51-53.

Institute of Hydrology. 1982. River Witham system scheme. Lincoln flood alleviation - Hydrological studies. Report to Anglian Water Authority. 29p.

Jelgersma, S., Tooley, M.J. and Shennan, I. 1987. The impacts of a future rise in sea-level on the European coastal lowlands. European Workshop on Interrelated Bioclimatic and Land Use Changes. Noordwijkerhout, The Netherlands, Oct. 1987.

Jenkins, A. and Whitehead, P.G. 1989. Climate change and UK water quality. Report to DOE. Institute of Hydrology.

Jones, P.D. and Wigley, T.M.L. 1988. Recent changes in precipitation and precipitation variability in England and Wales: an update to 1988. Climatic Research Unit report for WRc. August 1988, 55p.

Jongman, R.H.G. 1987. The Rhine-Maas megalopolis and its watercourses: consequences of climate-induced hydrological changes. European Workshop on Interrelated Bioclimatic and Land Use Changes. Noordwijkerhout, The Netherlands, Oct. 1987.

Jung, H.J. and Bach, W. 1984. The effects of model-generated climatic changes due to a CO_2 doubling on desertification processes in the Mediterranean area. In Fantechi,R. and Margaris, N.S. (eds) Desertification in Europe 231p.

Karl, T.R., Schlesinger, M.E. and Wang, W.C. 1989, A method of relating General Circulation Model simulated climate to the observed local climate. Part I: Central tendencies and dispersion. IIASA Workshop on Development of Regional Climate Scenarios for Impact Assessment. IIASA, Feb. 1989.

Kirkby, M. 1989. A model to estimate the impact of climate change on hillslope and regolith form. Working paper no. 522. School of Geography, University of Leeds.

Law, F.M. 1989. Identifying the climate sensitive segment of British reservoir yield. Proc. Conf. on Climate and Water, Helsinki, September 1989.

Lewin, J. (ed.) 1981. British Rivers. Allen and Unwin: London.

Lofting, E.M. and Davis, H.C. 1977. Methods for estimating and projecting water demands for water resources planning. In Climate, Climatic Change and Water Supply. National Research Council, Washington.

Lough, J.M., Wigley, T.M.L. and Palutikof, J.P. 1983. Climate and climate impact scenarios for Europe in a warmer world. J. Climate and Applied Meteorology 22, 1673-1684.

MacDonald, A.T., and Kay, D. 1988. Water Resources Management: Issues and Strategies. Blackwell: Oxford.

Manabe, S. and Wetherald, R.T. 1985. CO_2 and hydrology. Advances in Geophysics. 28A, 131-155.

Marsh, T.J. and Davies, P.A. 1983. The decline and partial recovery of groundwater levels below London. Proc. Instn. Civil Eng. Part 1, 74, 263-276.

Marsh, T.J. and Lees, M.L. 1985. The 1984 Drought. Hydrological Data UK. Institute of Hydrology/British Geological Survey, Wallingford, Oxon.

Martin, P., Rosenberg, N.J., and McKenney, M.S. 1989. Sensitivity of evapotranspiration in a wheat field, a forest, and a grassland to changes in climate and direct effects of carbon dioxide. Climate Change. (in press).

Monkhouse, R. 1988. Groundwater fluctuations and the areal estimation of recharge. In Hydrometric Register and Statistics 1981-1985. Hydrological Data UK. Institute of Hydrology/British Geological Survey, Wallingford, Oxon.

Nemec, J. and Schaake, J. 1982. Sensitivity of water resource systems to climate variations. Hydrological Sciences Journal. 27, 327-343.

Oerlemans, J. 1988 Simulation of historic glacier variations with a simple climate-glacier model. Journal of Glaciology, 34, No 118, 333-341.

Oerlemans, J. 1989. A projection of future sea level. Climatic Change. In press.

Palutikof, J.P. 1987. Some possible impacts of greenhouse gas induced climatic change on water resources in England and Wales. In The influence of climate change and climatic variability on the hydrologic regime and water resources. IAHS Publ. 168, 585-596.

Parker, D.J. and Penning-Rowsell, E.C. 1980. Water Planning in Britain. Allen and Unwin: London.

Parker, K.T., Lord, W.B.H., Read, N.J. and Parsons, J. 1986. Social and economic responses to climatic variability in the U.K. Technical Change Centre, London.

Parry, M.L., Carter, T.R., Konijn, N.T. 1988. The impact of climatic variations on agriculture. Vol 1, Assessments in cool temperate and cold regions. Kluwer, Dordrecht.

Pirt, J. 1989. The estimation of river flows with particular reference to natural and artificial components. In FRIENDS in Hydrology. IAHS Publ. 187, 361-371.

Reed, D.N. 1986. Simulation of time series of temperature and precipitation over eastern England by an atmospheric General Circulation Model. J. Climatol, 6, 233-253.

Riebsame, W. 1988. Adjusting water resources management to climate change. Climate Change 13, 69-97.

Robin, G. de Q. 1986 Changing the sea level. In B Bolin, B.R.Doos, J.Jager, and R.A.Warrick (eds). The Greenhouse Effect, Climatic Change and Ecosystems. SCOPE 29. Chichester, Wiley.

Rodda, J.C. 1976. Facets of Hydrology. Wiley, London. 368p.

Sanderson, D., Marchand, M., Howe, D. and Alpaugh, C. 1988. Climatic change and Great Lake levels : The impact on shipping. Climatic Change, 12, p.107-133.

Schlesinger, M.E. and Mitchell, J.F.B. 1985. Model projections of the equilibrium climatic response to increased carbon dioxide. In MacCracken, M.C. and Luther, F.M. (eds) Projecting the climatic effects of increasing carbon dioxide. US Dept. of Energy, DOE/ER-0237. Washington D.C.

Schnell, C. 1984. Socio-economic impacts of climate change due to a doubling of atmospheric CO_2 content. In A. Ghazi and R. Fantechi (eds) Current Issues in Climate Research Reidel: Dordrecht Reidel 270-287.

Sellers, P.J., Mintz, Y. and Sud, Y.C. 1986. A brief description of the simple biosphere model (SiB). Proc. ISLCP Conference, Rome 2-6 Dec. 1985. ESA Paris SP-245 (May 1986) pp91-107.

Shuttleworth, W.J. 1983. Evaporation models in the global water budget. In Street-Perrott, F.A., Beran, M.A. and Ratcliffe, R. (eds) Variations in the Global Water Budget. Dordrecht: Reidel.

Singh, B. 1987. The impacts CO2-induced climate change on hydr-electric generation potential in James' Bay territory of Quebec. In The influence of climate change and climatic variability on the hydrologic regime and water resources. IAHS Publ. 168, 403-418.

South West Water 1987. Report and Accounts, 1986/1987. South West Water.

Squire, G.R. and Unsworth, M.H. 1988. Effects of CO_2 and climatic change on agriculture. Report for DOE. Institute of Terrestrial Ecology.

Tanner, M.F. 1973. Water resources and recreation. Sports Council Water Recreation Series, Study 3.

Thompson, M., Barrie, I.A. and Ayles, M. 1981. The Meteorological Office Rainfall and Evaporation Calculation System MORECS (July 1981). Met. Office 8, Hydrological Memorandum 45.

Turc, L. 1954. Calcul du bilan de l'eau evaluation en fonction des precipitations et des temperatures. IAHS Rome Symposium. IAHS Publ. 38, 188-202.

Verhoog, F.H. 1987. Impact of climate change on the morphology of river basins. In The influence of climate change and climatic variability on the hydrologic regime and water resources. IAHS Publ. 168, 315-326.

Vinnikov, K.Y. and Lemeshko, N.A. 1987. Soil moisture content and runoff in the USSR territory with global warming. Meteorology and Hydrology. 12, 96-103.

Warrick, R.A. 1989. Personal communication, based on Investigation of past and future European sea level changes and their impacts (CEC Contract EV4C.0048.UK(H)). Annual report October 1987-September 1988.

Warrilow, D.A. 1986. The sensitivity of the UK Meteorological Office atmospheric General Circulation Model to recent changes to the parameterization of hydrology. Proc. ISLSCP Conference, Rome, 2-6 December 1985. ESA Paris. pp 143-149.

Water Authorities Association, 1988. Water Facts 88. London.

Wigley, T.M.L. and Jones, P.D. 1985. Influences of precipitation changes and direct CO2 effects on streamflow. Nature 314, 149-152.

Wigley, T.M.L., Jones, P.D., Briffa, K.R. and Smith, G. 1989. Obtaining sub-grid-scale information from coarse resolution GCM output. J. Geophys. Res. In press.

Wilks, D.S. 1988. Estimating the consequences of CO_2-induced climatic change on North American grain agriculture using General Circulation Model information. Climatic Change 13, 19-42.

Wilson, C.A. and Mitchell, J.F.B. 1987. Simulated climate and CO_2 - induced climate change over western Europe. Climate Change 10, 11-42.

WMO. 1987. Water resources and climate change: Sensitivity of water resource systems to climate change and variability. Proc. Norwich meeting, November 1987. WCAP-4. Geneva, 50p.