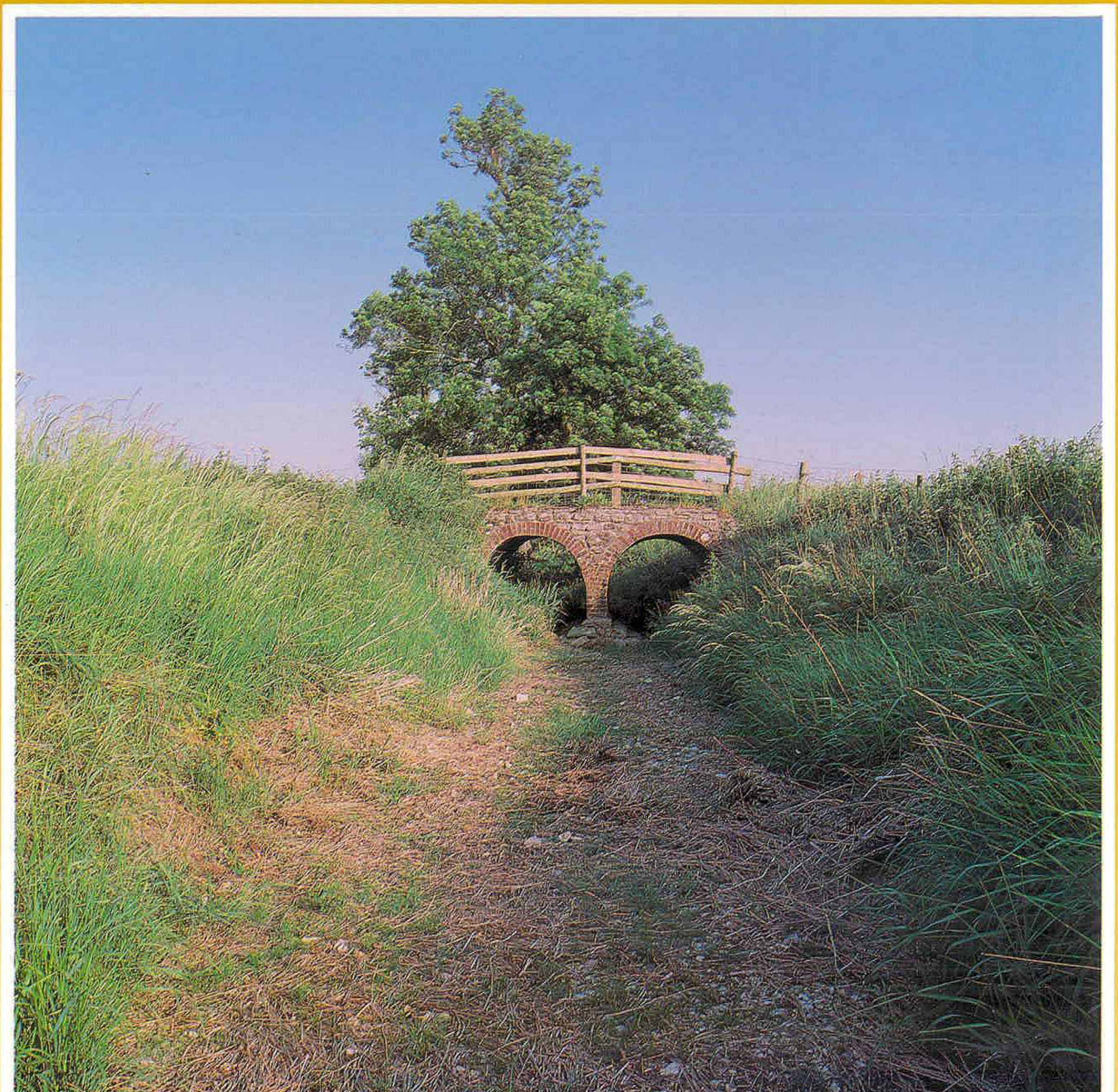
Hydrological data UK



The 1988-92 Drought

INSTITUTE OF HYDROLOGY • BRITISH GEOLOGICAL SURVEY

THE 1988-92 DROUGHT

An occasional report in the
Hydrological data: UK series which
reviews the drought within a hydrological
and water resources framework

THE 1988-92 DROUGHT

by

T.J. Marsh, R.A. Monkhouse, N.W. Arnell, M.L. Lees & N.S. Reynard

with additional contributions from S.C. Loader, S. Green & P. Doorgakant

Financial assistance towards the preparation and production
of this publication was provided by:

The Department of the Environment

The National Rivers Authority

Institute of Hydrology British Geological Survey

Published by the Institute of Hydrology,
Wallingford, Oxon OX10 8BB

ISBN 0948540 59 1

Editor Hydrological data UK series: T.J. Marsh

Printed and bound by Bourne Press Ltd.
on chlorine free environmentally friendly paper.

Graphics: J. J. Carr

Cover: The River Kennet near Avebury
Photograph: Neil Campbell-Sharp

FOREWORD

The climate of the United Kingdom is noted for its short-term variability; sustained periods of very wet or very dry weather are relatively rare. Human and animal communities tend to adjust to the climate's capricious nature and only when the normal range of variation is exceeded does any real threat to economic activity or the aquatic environment become a possibility. Droughts in the UK do not pose the very real threat to lives and livelihoods that persistent rainfall deficiencies do in many parts of the world. Nonetheless, fuelled in part by speculation concerning the effect of global warming on United Kingdom rainfall patterns, scientific, media and public interest in the 1988-92 drought and its effects remained at a high level in England for much of the recent past.

Society now places a higher premium on the amenity and environmental benefits of rivers and wetlands whilst continuing to query the cost and justification for the range of water conservation measures developed to mitigate the impact of extended periods of rainfall deficiency. The recent drought provided a reminder of the conflicting demands on the water industry and the vulnerability of the UK to unusual climate conditions. It also demonstrated the ongoing need to develop improved water management practices to withstand the twin stresses imposed by increasing water demand and lengthy periods of low rainfall.

The drought which, at one time or another, embraced much of Europe can be traced back to the spring of 1988 in much of the English lowlands. It was punctuated by a number of wet interludes but by early-1992 had become exceptionally protracted and, in groundwater terms, more severe than any this century. The 1988-92 period stimulated reviews of water management policies in a number of countries at a time when the search for practical and scientifically-based sustainable development options is intensifying. Fortunately, the drought helped to provide many useful insights into both the scale and scope of the water resources and environmental problems caused by long-term rainfall deficiencies and the strategies needed to combat them. This, of course, will be of particular significance if the extra-ordinary weather patterns recently experienced become a more familiar feature of our climate in the future.

This review of the 1988-92 drought is the latest publication in the *Hydrological data UK* series. A principal function of the series is to disseminate information relating to contemporary hydrological conditions and to provide a perspective within which to examine the effects of exceptional weather patterns. Publications in the *Hydrological data UK* series are prepared under the aegis of a steering committee which includes representatives of Government departments, the National Rivers Authority, the Met. Office and the water industry in England, Wales, Scotland and Northern Ireland.

Professor W. B. Wilkinson
Director, Institute of Hydrology

National Rivers Authority region or River Purification Board boundary
Hydrometric area number and boundary
HIGHLAND R.P.B.
NORTH EAST R.P.B.
TAY R.P.B.
FORTH R.P.B.
CLYDE R.P.B.
TWEED R.P.B.
SOLWAY R.P.B.
NORTHERN IRELAND
NORTHUMBRIA/ YORKSHIRE
NORTH WEST
SEVERN-TRENT
ANGLIAN
WELSH
THAMES
SOUTH WESTERN
SOUTHERN

CONTENTS

APPENDICES

The 1988-92 drought report

The objective of this report is to provide comprehensive documentation of the 1988-92 drought within a hydrological framework and to establish a benchmark against which future periods of severe rainfall deficiency may be compared. The spatial and temporal variations in the drought's intensity are examined and its severity assessed within the perspective provided by long-term rainfall and hydrometric records. An introductory hydrological overview of the United Kingdom is given to help place the conditions experienced during 1988-92 in a suitable context. The synoptic backcloth to the drought's development is also reviewed and the European perspective is examined using selected rainfall and river flow records to index drought severity. Additionally, a short review of water resource variability in Great Britain over the featured five years - and the water industry's response to the actual and projected deficiencies - is included to help explain the often complex linkages between hydrological stress and water supply impacts on the community.

For reference purposes a map is provided on page 73 to help locate the principal rivers, reservoirs and monitoring sites mentioned in the report.

What is a drought?

Droughts are multifaceted both in their character and range of impacts. Whilst in broad terms the concept of a drought is readily recognised by the public at large, translating this intuitive understanding into an objective procedure for indexing or assessing drought severity is far from straightforward. In part, this reflects the difficulties involved in quantifying a phenomenon which varies in its extent, duration and intensity both regionally and locally. Thus the 1975/76 drought, for example, achieved a remarkable intensity in central southern England over a 16-month timespan[1,2]. By contrast, the 1984 drought was largely restricted to the spring and summer and was most severe in the normally wetter northern and western parts of Britain[3]. Both these droughts featured a sequence of dry months bracketed by very wet conditions which clearly delineated the drought's duration. The 1988-92 drought was a more complex event separated into a number of more, or less, severe phases. Though less intense than the 1976 drought, the 1988-92 drought was remarkably protracted in the eastern lowlands where large rainfall deficiencies extending well beyond four years could be recognised.

Perhaps of equal importance in attempting to index drought severity are the differing impacts associated with meteorological droughts - defined essentially on the basis of rainfall deficiency, hydrological droughts - where accumulated shortfalls in runoff and recharge are of primary importance, and agricultural droughts - where the availability of soil water through the growing season is the critical factor. The impact on the community during most periods of large rainfall deficiency is likely to be very uneven and dependent on a number of features of the drought. Hot weather and dry soils may generate heavy water demand in the spring, for irrigation and garden watering in particular. This can overstretch the water distribution systems and trigger hosepipe bans at a time when overall water resources may be relatively healthy. Conversely a wet summer, as in 1992, may suppress demand and greatly moderate restrictions on water use when resources are at historically very depressed levels.

An additional factor is the public perception of drought severity which may vary considerably from individual to individual. A very hot, dry summer, for instance, is likely to be viewed in a more relaxed manner by the holiday-maker than the farmer or industrialist reliant on river abstractions, especially if reservoir or groundwater stocks are sufficient to provide continuity of domestic supplies. In such circumstances, the environmental stress resulting from drought conditions may be of considerably greater importance than the water supply impact.

The water industry has developed a range of storage mechanisms and operational strategies, linked to the probabilities of various drought intensities, in order to maintain water supplies. The development of new gravity-fed or pumped storage reservoirs together with the increased networking of supply sources, often involving cross-basin transfers or the further integration of surface and groundwater supply schemes in a regional grid, provide a large measure of flexibility in combating local or regional shortages. The complexity of water resource systems and water utilisation patterns can be such as to make the link between shortages of rainfall and water supply problems appear rather tenuous. This is particularly true where supply zones relying on surface water sources and groundwater sources are closely juxtaposed. The fragility of the water supply outlook can vary appreciably from neighbourhood to neighbourhood and present a considerable public relations challenge to the water industry (see page 60). It will be appreciated therefore that no single methodology for assessing drought severity is likely to be able to accommodate all the relevant variables and to reflect regional and temporal differences in the attitude to the inconvenience associated with restrictions on water use introduced to combat a developing drought.

Data and information sources

This report is based largely on data assembled as part of a national hydrological monitoring programme maintained jointly by the Institute of Hydrology (IH) and the British Geological Survey (BGS) on behalf of the Department of the Environment and the National Rivers Authority (NRA). Hydrological data are routinely provided by a number of measuring authorities - principally the regional divisions of the NRA in England and Wales and the River Purification Boards in Scotland.

The bulk of the required meteorological data for the UK were purchased from the Meteorological Office. For the purpose of historical comparisons the long time series of homogenised monthly rainfalls for England and Wales compiled by the Climatic Research Unit (University of East Anglia) was used. The CRU also provided updates for the Central England Temperature series[4].

The European precipitation datasets derive largely from those developed by the Climatic Research Unit and held on the World Climate Disc - in some cases these data were augmented by recent figures purchased from the Meteorological Office.

The great majority of the historical British river flow and groundwater level data featured in this report were extracted from the National River Flow Archive (maintained by IH) and the National Groundwater Level Archive (maintained by BGS). The European data derives from several sources: French, Norwegian, Danish and Russian flow data were extracted from the FRIEND archive at the Institute of Hydrology[5]; German data were provided by the Bundesanstalt fur Gewasserkunde, Koblenz; Spanish data were obtained through CEDEX, Madrid, and Romanian information was supplied by the National Institute of Meteorology and Hydrology in Bucharest. Some published European data sets have also been utilised.

The following report - published at the same time as *The 1988-92 Drought* - provides important, and complementary, additional material concerning the methods available to index drought severity:

Mawdsley, J.A., Petts, G.E. & Walker, S. (1994) *Assessment of Drought Severity*. BHS Occasional Paper No.3.

Administrative framework for hydrometry in the UK water industry

The regional divisions of the NRA undertake the great majority of the hydrometric monitoring activity in England and Wales. The monitoring of river flows in Scotland is largely undertaken by the seven River Purification Boards. In Northern Ireland responsibility for hydrometric data acquisition and processing is shared between the Departments of Environment and Agriculture.

The boundaries of the NRA and RPB regions follow the catchment divides between major river basins (see Frontispiece). Although a number of strategically important reservoirs export water to neighbouring regions, water demands are largely met from sources within each authority region. The administrative divisions of the water industry thus form a suitable basis for an initial assessment of the spatial variation in drought severity across Great Britain. To retain a greater measure of spatial differentiation, and for consistency with much of the historical rainfall data featured, the original ten regions of the NRA have been used for data presentation purposes in this publication; in 1993 the Northumbria and Yorkshire regions and the South-West and Wessex regions were amalgamated.

Acknowledgments

A report of this type could not have been prepared without the active cooperation of a wide range of organisations and individuals. The credibility of any drought review is heavily dependent on both the availability and quality of hydrological, and related, datasets. The assistance of all involved in the data acquisition and archiving of the data exploited in this report is gratefully acknowledged. Particular mention should be made of the late John Couling (NRA Southern Region) whose expertise and advice will be greatly missed. It is hoped that this record of the 1988-92 Drought stands as a suitable testament to the endeavours of all hydrometric personnel.

The report benefited from many valuable suggestions and comments made at the draft stage. Particular thanks are due to Mr C. E. Wright (Dept. of the Environment) for his advice and guidance.

Many of the analyses, tables and figures presented in this report reflect more than a decade of national archive system development under the supervision of D.G. Morris; the software development undertaken by O. Swain and R. W. Flavin in particular, is gratefully acknowledged. R. A. Monkhouse, recently retired, was responsible for the software development associated with the majority of the groundwater material in the report. K. M. Irving provided valuable software support and user guidance in relation to the analysis of low flows. The bibliography of major English droughts was compiled by F.M. Law.

The authors are grateful to S. Green and F. J. Sanderson for the preparation and checking of much of the technical material featured in the report. S. Black was responsible for the preparation of the draft report and supervises the sale and distribution of Hydrological data UK publications through the National Water Archive Office at the Institute of Hydrology. The editorial and production management of the 1998-92 Drought report was undertaken by H.K. Arnell and J.H. Griffin of the Information Services section at the Institute of Hydrology.

THE 1988-92 UNITED KINGDOM DROUGHT IN SUMMARY

Rainfall for Great Britain over the four-year period beginning in the spring of 1988 was very close to the long-term average but for much of that time many rain-bearing weather systems followed a relatively northerly track remote from the English lowlands[6]. As a result, the normal north-west/south-east rainfall gradient across Britain was greatly accentuated: north-west Scotland being very wet whilst eastern and southern England were exceptionally dry. This unusual and very persistent disturbance to the normal rainfall distribution, together with the abnormally high temperatures which have characterised much of the recent past (and encouraged high rates of evaporative loss), provide the setting for the drought conditions experienced throughout most of the 1989-92 period.

Rainfall

In a few places close to the east coast the drought remained severe for most of the four years ending in the summer of 1992. Elsewhere, several wet episodes, notably the winter of 1989/90[7], served to partition the drought into relatively distinct meteorological phases. A significant reduction in long-term rainfall deficiencies occurred in the first half of 1991, and again in the spring of 1992, but whilst in rainfall terms terminations in the drought could be identified, the amelioration in drought severity with respect to river runoff and groundwater levels in the east was barely noticeable prior to the autumn of 1992.

Intense drought conditions characterised parts of the North-East in late 1989, but for England and Wales as a whole the drought achieved its greatest severity over the period beginning in March 1990. Notwithstanding a relatively wet spring in 1992, the 28-month rainfall total up to and including June 1992 is eclipsed only by the minima established during the prolonged droughts of the mid-1850s and late 1780s. Similarly, in the 44-48 month timeframes, rainfall totals from the latter half of 1988 were the lowest in 130 years, although closely approached by the dry period ending in August 1976. Over the longest timespans the drought was markedly more severe in the eastern lowlands of England. Rainfall totals over the 28-months to June 1992 were more than 20% below average over the greater part of England southeast of a line from Humberside to Dorset, and the persistence of the drought has only one or two parallels since the turn of the century. In some parts of East Anglia, and a few localities to the north, both 1990 and 1991 rank amongst the three driest years this century and accumulated deficiencies over the four years from the spring of 1988 were the equivalent of a full year's rainfall.

Temperature and evaporation

Although temperatures during 1991 fell well short of the exceptional figures registered for the two preceding years, they remained appreciably above average and the 1988-92 period is the warmest five-year sequence in the 332-year Central England Temperature series. Consequently, evaporation rates remained well above average for lengthy periods, especially in 1989 and 1990 when potential evaporation losses in the English lowlands were more typical of parts of southern Europe. Throughout much of southern and eastern Britain the record evaporation demands produced persistently dry lowland soils which, by robbing the rainfall of much of its effectiveness, served to significantly exacerbate drought conditions.

In the English lowlands a relatively modest shortage of rainfall can produce very substantial reductions in river flows and aquifer recharge. The effect of elevated evaporation losses over the 1988-92 period was, in broad terms, to translate a 20% decrease in rainfall into a halving of overall runoff and recharge rates.

River flows

Notably low river flows were recorded over wide areas in the latter half of both 1989 and 1990 and, by the winter of 1991/92, runoff rates were the lowest on record in eastern, central and southern England; late-winter flows in the lowlands were similar to those normally associated with the summer. By the late summer of 1992 monthly flows in some eastern rivers had remained below average for almost four years. Over the latter half of this period monthly runoff totals for many spring-fed rivers remained close to the long-term minimum. The hydrological severity of the drought emerges most clearly when accumulated runoff totals are examined. For the two-year period beginning in July 1990 runoff totals for many lowland rivers (and a few others) fell below any previous 24-month accumulation.

The low flow statistics for many rivers in eastern and southern England have been largely redefined since early 1988. In part this reflects the limited length of most UK gauging station records - relatively few exceed forty years. A longer historical perspective is provided by the flow record for the River Thames (at Kingston). This suggests that only during the 1901-03 and 1933-35 droughts have lower 24-month flows occurred this century and the significance of these historical minima may well be exaggerated by the tendency of low flows to be underestimated prior to the major refurbishment of Teddington Weir in 1951.

Depressed runoff rates over an extended period were associated with a shrinkage in the stream network that is without modern parallel; the corresponding loss of amenity and aquatic habitat was considerable. The environmental impact was exacerbated in those catchments where groundwater pumping, often over many years, has steadily reduced river flows and caused the headwater sources to migrate downstream.

Groundwater

The regions where the long-term drought achieved its greatest severity coincide broadly with those areas where groundwater is the major source of water supply. In much of the eastern lowlands of England a cluster of three or four winters with modest aquifer replenishment separated by extended groundwater recessions provide the background to the very depressed water-tables in the summer of 1992. From the Yorkshire Wolds to the eastern Chilterns - and probably over a more extensive area - there is no close precedent this century for the inordinately low accumulated recharge over the four winters ending with 1991/92.

For much of the 12-month period beginning in the summer of 1990, water-tables, in the Chalk especially, remained close to, or below, the lowest level on record. The heavy and prolonged recharge required to restore water-tables to within their normal range did not materialise over the 1991/92 winter[8] and groundwater levels in southern Britain remained depressed entering 1992. A hot, dry spell in mid-May signalled a general end to a very modest winter recovery and the onset of the 1992 recession in the lowlands. Commonly, spring levels were below the seasonal average by the equivalent of around twice the normal winter replenishment. The spring recession was gentle but water-tables had declined to unprecedented levels over wide areas by the summer.

Evidence of the singular character of the drought is provided by groundwater levels at a number of long-term observation boreholes. At the Dalton Holme well in the Yorkshire Wolds, where records commence in 1889, February 1992 levels were below all previous minima. Near the southern boundary of the zone of maximum groundwater depletion, the Therfield Rectory observation well (in Hertfordshire) dried-up in January - for the first time in seventy years.

Throughout much of the eastern Chalk, early summer 1992 groundwater levels were the lowest on record and water-tables were also exceptionally depressed in the majority of the Permo-Triassic sandstone aquifers. On the basis of a sparse monitoring network (for the pre-1950 period), it appears that in the summer of 1992 overall groundwater resources for England and Wales were at their lowest since at least the turn of the century.

Overview

Data from a number of long established raingauges indicate that the 1988-92 rainfall deficiency, whilst close to the extreme range of normal variability, is not entirely without precedent; four or five broadly comparable episodes may be identified over the last 250 years. River flow and groundwater level records are generally much shorter and, partly as a consequence, may appear to exaggerate the drought's severity. However, temperature data allied to the limited hydrometric information extending back into the last century support the contention that the 1988-92 drought is, in hydrological terms, outstanding in magnitude over a large proportion of the English lowlands.

Direct comparisons between British droughts are hampered by the distinct character of each major period of rainfall deficiency. One common thread has been the increasing influence of the pattern of water use in determining the drought's impact on the community. The integration of water supply networks, regionally and locally, and the development of new resources has greatly enhanced our ability to withstand even severe drought conditions. However, water demand in England and Wales, which increased by around two percent a year over the 30 years to 1990, is a countervailing influence. Climate change may prove to be another, at a time when the margin between demand and existing resources is already narrow in parts of south-eastern Britain.

The coincidence between the regions of maximum drought intensity over the 1989-92 period and the greatest increases in water demand has important implications for the future development and management of water resources. As significant perhaps is the recognition that rising water demand coupled with protracted shortages of rainfall pose a real threat to the aquatic environment; the role of groundwater especially in sustaining lowland rivers and wetland ecology is now receiving much greater attention. The water industry faces a considerable challenge in developing and implementing improved, more environmentally sympathetic, management techniques to help reconcile the needs of the human and wildlife communities.

Geology

The drainage pattern in Great Britain is largely a response to regional contrasts in geology. The principal upland areas - mostly in the west - are developed on the oldest rocks. These are generally impermeable and promote a rapid river flow response to rainfall. The associated relief affords opportunities for natural or artificial impoundments to exploit abundant rainfall in the headwaters as part of strategically important reservoir systems. Lowland Britain, on the other hand, is mostly founded on relatively young strata. The occurrence of extensive porous and fractured rocks interleaved between beds of impermeable clays is a major feature of much of southern and eastern England. Groundwater from these aquifers - of which the Chalk is the most important - is the major supply source throughout most of the lowlands and, via springs and seepages, is a major component in the discharge of many lowland rivers.

Hydrology

The United Kingdom is one of the wettest countries in Europe but, importantly, it is characterised by large regional variations in rainfall. The higher precipitation totals are associated with the maritime west - average annual rainfall exceeds 4000 mm in the mountains of the Scottish Highlands, Lake District and Snowdonia. The east - much of which is within the rain-shadow of the western hills and less frequently in the path of rain-bearing depressions - becomes progressively drier with decreasing elevation. Average annual rainfall totals of less than 600 mm characterise large parts of the English lowlands, with totals of below 500 mm around the Thames estuary. This represents very modest rainfall in a European context; appreciably drier regions are confined to southern Spain and parts of eastern Europe. A guide to the dryness of south-eastern England is provided by the listing of average rainfall for a selection of European cities presented in Table 1.

Whilst in global terms rainfall in the UK may be considered to be evenly distributed throughout the year, seasonal contrasts are appreciable, especially in the west where a tendency towards a late autumn/early winter maximum may be recognised. Partly as a result of convective rainfall over the summer half-year, the contrasts are less strong in the drier areas - August or November are typically the wettest months and spring the driest season.

A substantial proportion of the rainfall is accounted for by evaporative losses; around half on a nationwide basis. Evaporation may occur directly from the soil, from open water surfaces or as transpiration from plants. Knowledge of the soil moisture status and evaporation rates are essential factors in any evaluation of water resources. Potential evaporation (PE) is the maximum evaporation which would occur from a continuous vegetative cover amply supplied with moisture. PE is primarily a function of solar radiation, temperature, windspeed and humidity. It exhibits a strong annual cyclicity, peaking normally in June or July; typically, only 10-20% of the annual evaporative loss occurs during the winter half-year (October-March). In an average year PE totals range from less than 400 mm up to 600 mm, being greatest in the south and east of the country, especially in coastal areas where windspeed is an important factor. A decrease is seen northwards and with increasing altitude, 350 mm being typical over the Scottish mountains although substantially higher annual totals are known to occur where aspect and land use favour higher rates of evaporative loss.

From the early spring, the ability of transpiration to proceed at its potential rate is reduced as a result of drying soil conditions, the ability of vegetation to take up water and the measures plants take to restrict transpiration under such conditions. Thus in the absence of favourable soil moisture conditions actual evaporation (AE) rates will fall below PE, appreciably so in dry years. Given normal rainfall, the accelerating evaporation demand during the spring leads to a progressive drying of the soil profile and the creation of what is termed a Soil Moisture Deficit (SMD), consequently surface runoff and infiltration to aquifers is greatly reduced. Following a particularly warm and dry summer, the SMD may be equivalent to about three months average rainfall in the eastern lowlands. When plant activity and evaporation slackens in the autumn, rainfall wets-up the soil profile (reaching 'field capacity' when saturated) and subsequently runoff rates increase and aquifer replenishment commences once again.

As a result of evaporation losses, the north-west to south-east gradient in runoff is markedly steeper than that for rainfall. For example, whilst rainfall for the Anglian region is, on average, a little over a third of that for the Highland RPB region, the corresponding ratio for runoff is around one eighth (Figure 1). In large parts of the English lowlands average potential evaporation losses are equivalent to over three-quarters of the available rainfall; the residue serves to sustain river flows, replenish reservoirs and infiltrate through the soils to recharge aquifers. The variation in evaporation rates through the year also imposes a marked seasonality upon rates of river runoff and aquifer recharge although where groundwater makes a substantial contribution to river flow, the contrast between winter and

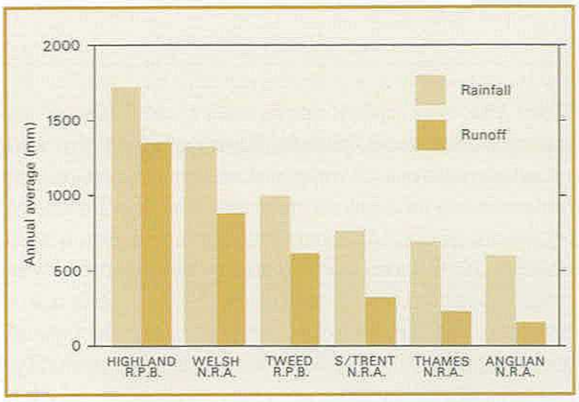


Figure 1 Average annual rainfall and runoff (in millimetres) for selected regions of Great Britain

summer flows is considerably moderated. In the lowlands minimum flows usually occur in the autumn, whereas in the more maritime, and more impervious, western catchments flows on average are lowest in the summer. During freezing conditions notably low flows may also occur in the winter.

Groundwater levels tend to rise from late-autumn through winter into spring, and then to fall from spring through summer into autumn. Generally, the water-table reflects the topography in muted form with very modest seasonal variations in lowland valleys. The temporal and spatial patterns of aquifer replenishment (or recharge) may vary considerably though. Recharge is affected by the nature of the deposits through which water must pass to reach the water-table. Where the deposits have low permeabilities there will be a consequent reduction in the amount of replenishment and an increase in the time before the water levels begin to rise. Similarly, where the unsaturated zone is of considerable thickness, the lag between the commencement of infiltration and water-table response may be several months. Conversely, in some limestone and sandstone aquifers, where recharge is principally via fissures, the rise and fall in the water-table may be rapid. Finally, where the natural drainage of groundwater (appearing as springs, seepage lines or 'risings') is rapid, water levels rise more slowly during recharge periods because large quantities are simultaneously being discharged.

As a consequence of geographical contrasts, regional susceptibility to drought varies considerably. In the west, dry conditions for two or three months encourage steep recessions and lead to very low river flows. Large rainfall deficiencies over longer periods of, say, five to seven months starting in the spring, put stress upon the smaller reservoir systems (usually full at the end of the winter). In the east, such deficiencies may normally be borne more easily although the associated high soil moisture deficits may be expected to inhibit plant growth and generate heavy local demand for irrigation. A substantial reduction in winter recharge can provoke greater water resources stress leading to depressed groundwater levels, reduced baseflows during the following summer and a lower base to commence the next recharge cycle. Such a winter drought could also be a problem in the west but as winter rainfall depths are considerable even in a dry year, reservoirs are still likely to fill to acceptable levels which should secure supplies through all but the most severe spring and summer droughts.

The international context

In relation to the needs of the community in its widest sense, water availability and drought susceptibility depend on many factors apart from local precipitation totals. Nonetheless rainfall - its amount and variability - provides the essential starting point for any general appraisal. Britain appears fortunate in this regard, ranking as one of the wettest countries in Europe (see Table 2). When allowance is made - on a countrywide basis - for evaporative losses the available runoff is approximately double that for France and Germany. Using a global scale of reference and employing the rather crude yardstick of per capita water availability, a somewhat different perspective emerges with Great Britain - England even more so - clearly falling within the 'water-poor' nations of the world. Nationwide comparisons are, however, of rather limited value for countries like the UK where spatial variations in annual precipitation totals can range beyond an order of magnitude. This point is emphasised in Table 3 which confirms that water demand accounts for a substantial proportion of total runoff throughout much of the English lowlands. The exceptionally high percentage quoted for the Thames region needs to be interpreted with caution - there is extensive re-use of water - but it does underline the basic fragility of water resources in the South-East.

The concentrations of population, industry and intensive agriculture, together with the associated heavy demand for water, in the driest parts of the UK provide the key to many of the water problems which have attracted considerable attention in recent years. Regions with high population density and limited rainfall may be found elsewhere in Europe but most benefit directly, via major international river systems, from the high rainfall in, often remote, headwaters. Such is the case in the Netherlands, the Ruhr region of Germany and the North Italian Plain where rivers flowing from the Alps provide a very substantial supplement to the local resources. The drainage pattern in southern Britain is less favourably disposed as regards the natural augmentation of water resources in the eastern lowlands. However, since early Victorian times regional water transfer schemes have been developed to allow the drier regions of England and Wales to benefit, albeit to a moderate degree, from the more abundant rainfall in the west and north. Nonetheless, the concentration of more than 25 million people in the English lowlands, an area of around 50,000 km^2 with an average annual rainfall of less than 700 mm per year, presents - uniquely on this scale in Europe - a margin of indigenous resources relative to demand that is both limited and inherently vulnerable to year-on-year variations in runoff and recharge.

TABLE 1 EUROPE - AVERAGE ANNUAL RAINFALL FOR A SELECTION OF EUROPEAN CITIES

City	Average annual rainfall (mm)
Zürich	1090
Brussels	850
Utrecht (De Bilt)	770
Dublin	760
Rome	740
Oslo	730
Lisbon	710
Vienna	660
Paris	620
Budapest	610
Copenhagen	600
Berlin	540
London	530
Madrid	440
Athens	400

TABLE 2 EUROPE - AVERAGE ANNUAL PRECIPITATION (RANKED) AND RUNOFF

Country	Precipitation (mm)	Runoff (mm)
Switzerland	1500	1000
Norway	1450	1250
Iceland	1200	1750*
Austria	1200	670
Great Britain	**1090**	**550**
Italy	1000	600
Portugal	900	220
Belgium	850	360
France	750	300
Germany	750	260
Netherlands	750	250
Czechoslovakia	720	220
Romania	700	190
Cyprus	500	<50

The annual averages have been rounded.
Source: Water Resources of the World[9]
* This estimate may make too large an allowance for the contribution from glaciers.

TABLE 3 GREAT BRITAIN - WATER RESOURCES

	Annual rainfall (mm) (1941-70 average)	Annual runoff (mm) (long-term average)	PWS (1987/88) (as % of runoff)
Great Britain	1089	660	4.7
Scotland	1431	1040	1.1
England and Wales	912	460	9.0
NRA Regions:*			
North West	1217	810	7.8
Northumbria	879	490	8.3
Yorkshire	833	420	9.1
Severn-Trent	773	330	12
Anglian	610	170	14
Thames	704	240	47
Southern	794	320	14
Wessex	869	370	8.9
South West	1194	740	2.2
Welsh	1334	850	2.4

Data Sources: Surface Water Archive, Meteorological Office, Water Facts 1988[10]
PWS = Public Water Supply *as in 1992

A REVIEW OF WEATHER PATTERNS OVER WESTERN EUROPE 1988-92

Background

This chapter provides an introduction to the basic synoptic climatology of western Europe and a brief review of some of the particular weather patterns associated with the very unusual hydrological conditions experienced over the period November 1988 to April 1992. Particular attention is directed to the winter of 1988/89 which instigated the drought conditions in many areas.

The northern hemisphere Polar Front marks the area of convergence between warm tropical air from the south and cold Arctic air from the north. This zone of convergence between air masses results in a strong, mid-latitude westerly air flow that largely determines the climate of northern and western Europe. The movement of high and low pressure systems along this convergence zone is generally attributed to steering by high level winds known as the polar 'jet'. At the surface, the influence of these systems may only last for a matter of days but is responsible for the inherent variability in the weather. The recurrent stream of westerlies and surface fronts is broken largely by the development of surface high pressure areas, which either block or deflect the 'jet' stream and the westerly air flow. These blocking anticyclones can last a considerable length of time, up to several weeks. In the winter they tend to produce still, cold and often foggy periods, while in the summer they produce still and warm conditions.

The normal situation for the British Isles and north-western Europe sees the prevailing westerlies carry a succession of frontal disturbances throughout most of the year. During the summer, a large high pressure cell centred on, or near, the Azores builds northwards, and as a consequence the number and severity of these depressions tends to decrease. High pressure is even more dominant in central and eastern areas of Europe which enjoy a distinctly continental climate; the majority of summer rainfall results from convective activity. During the winter an extensive anticyclone over Siberia produces very cold conditions and any frontal disturbances tend to bring snow. The typical Mediterranean climate is somewhat different; the summer tends to be long with an extension of the Azores high pressure cell dominating from March or April through to October, breaking down first in the west. In some European regions the settled conditions are punctuated by weather conditions determined in large part by local winds such as the Mistral or the Artesian. During the winter the western Mediterranean is often influenced by the southern sections of Atlantic depressions on the Polar Front. Other parts, such as the Gulf of Genoa, are well known for the generation of local low pressure systems; a substantial proportion of the rainfall in Italy and Greece, for instance, is actually generated within the basin itself.

Relative to much of Europe, a higher proportion of United Kingdom's rainfall is frontal in character. Therefore, despite its maritime location, the UK can be more vulnerable to droughts resulting from a shift in the preferred tracks of Atlantic low pressure systems.

1988-92

The recent past has been a period of notable warmth at the global scale[11] and this is fully reflected in the temperature records for western Europe. Figure 2 shows the ten-year running mean of the Central England Temperature (CET) series which starts in 1659. The smoothing effect of the averaging disguises a marked year to year variability: the annual average may be anything between 7.5°C and 10.5°C. Arguably, the variability is less and the minima consistently higher in the 20th Century than in the 19th. The warmth of the 1940s is clearly apparent but the five-year period ending in 1992, during which temperatures were about 1.2°C above average, is the warmest on record by an appreciable margin - 1990 and 1989 ranking first and second respectively in the 334-year series.

An impression of the degree to which weather patterns during 1988/92 diverged from the normal range may be gained by examining Figure 3. This shows the anomalies in temperature - relative to the Central England Temperature series average for 1961-80, and rainfall - relative to the 1941-70 England and Wales average, for each of the 40-month periods beginning in November since 1767. With such a lengthy averaging period the anomalies tend to cluster around zero far more than for individual

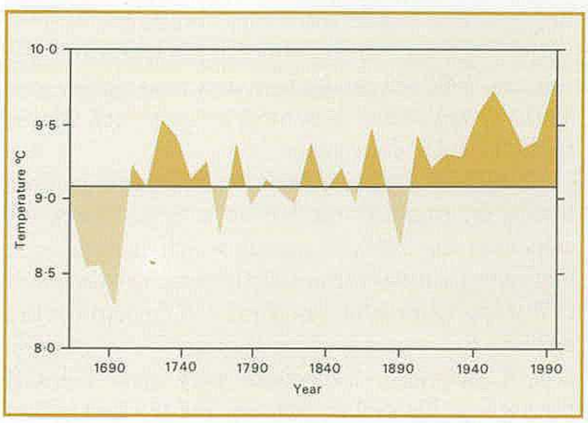


Figure 2 Central England Temperature series (ten-year running mean), 1659-1992

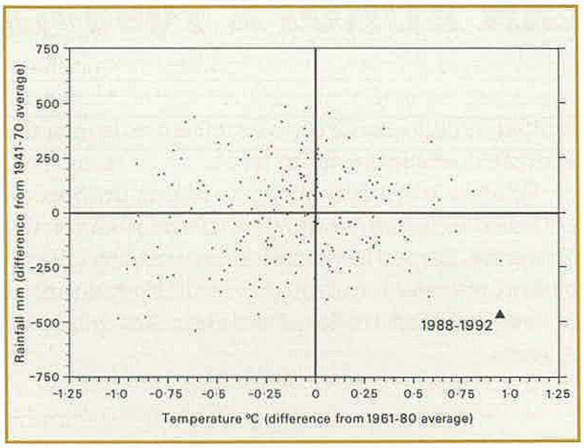


Figure 3 England and Wales rainfall and temperature anomalies (for 40-month periods beginning in November), 1767-1992

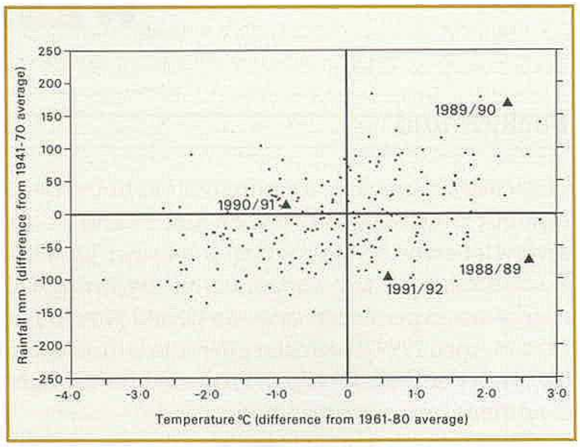


Figure 4 England and Wales rainfall and temperature anomalies for the winter (Dec-Feb), 1767-1992

seasons or years but the plotting position for the 1988-92 period occupies an isolated position in the warm, dry quadrant. November 1988 to February 1992 is the fourth driest such period on record, and also the second warmest. There is no close precedent for this combination of elevated temperatures and low rainfall.

Although, overall, the 1988-92 period was singular in character, weather patterns still displayed considerable temporal variability. The winter of 1988/89 over much of northern Europe was particularly unusual[13]. The Azores High maintained both its strength and a very northerly position well into the winter. This in turn meant that the polar 'jet' was deflected to the north, and most of western Europe and southern England remained under the northern edge of a high pressure cell for much of the winter. This abnormal synoptic picture - persistent anticyclonic conditions and a consistent 'jet' pathway - meant that the depressions on the Polar front were continually tracking across Scotland and Scandinavia. By contrast, England and western Europe experienced a rare combination of mild, dry conditions. Figure 4 shows the winter (December-February) temperature and rainfall anomalies for England and Wales since 1767. While the normal pattern varies around cold and dry or warm and wet winters, 1988/89 can be seen as a clear outlier and 1991/92 registered a second notably low winter rainfall total in four years.

Table 4 provides a broader European context, listing the monthly rainfall for selected European sites over the 1988/89 winter which signalled the beginning of notable rainfall deficiencies over much of Europe. (A breakdown of rainfall throughout the ensuing four years is given on page 70). Within the UK, Cambridge recorded very low rainfall throughout December, January and the first half of February, and the winter rainfall total was only 84% of the long-term average. By contrast Fort William, in western Scotland, received the full force of the Atlantic systems deflected north around the Azores High. Each of the three winter months recorded well above normal rainfall and the winter total substantially exceeded the 1941-70 average (for some areas of Scotland this excess was over 300%). Tromso, in Norway, was also notably wet and other sites on the western coast of Scandinavia recorded anomalies as high as those found in Scotland. As in the UK, however, spatial variations in precipitation totals were large across most of Europe. The rainfall totals for Nuremburg in Germany have been included to show how the particular weather systems tended to influence western Europe, while the more eastern and central regions recorded nearer average rainfalls.

Throughout most of the British Isles much of the remainder of 1989 was drier than normal right into December. There was a distinct east/west split with the western regions recording close to average rainfall for the period March to November 1989, but some eastern areas, from northern Scotland to southern England recording totals well below average.

In rainfall terms the winter of 1989/90 began very late in England and Wales. The anticyclone over Siberia had extended its influence west and covered most of northern and western Europe. Some areas, including large parts of Britain, recorded no rainfall over a five-week period beginning in November. Only when the high pressure broke down in mid-December 1989 could the Atlantic depressions re-exert their influence. The change in synoptic conditions was dramatic and a run of vigorous low pressure systems crossed the UK very rapidly. A record central low pressure, for a December Atlantic depression, of 936 millibars was recorded over Iceland on the 24th and, despite the dry start to the month, the December rainfall total was around twice the average throughout a substantial proportion of the UK. January and February 1990 continued this pattern. With the exception of the eastern seaboard, all areas remained wet; regional rainfall totals were mostly 50% or more above the seasonal average for the winter three months. Equally remarkable, the first three months of 1990 were each at least 2.8°C warmer than the 1961-80 average and, taken together, constituted the warmest start to any year as indexed by the Central England Temperature series[14]. The 1989/90 winter was also very windy with a high frequency of gales. This mild and notably unsettled weather regime accounts for the 1989/90 winter outlier in the warm and wet quadrant illustrated in Figure 4.

The exceptional rainfall of the 1989/90 winter stopped as suddenly as it had started as a northern extension of the Azores high pressure built, once again, from the south and west to dominate the synoptic situation in late March. Although there was considerable day-to-day variation, most of western Europe maintained fairly high pressure throughout May, which was particularly dry and warm. The summer too remained hot and dry with record high temperatures recorded across much of southern Britain in early August[15,16]. Heat wave conditions were also experienced throughout much of Europe. Most regions then experienced a dry and very mild autumn. For the year as a whole, mean temperatures were outstanding, the warmest on record in England and the warmest since the eighteenth century in Paris.

Over the winter of 1990/91 rainfall varied relatively little from the long-term average and, in contrast to the recent past, it was a little cooler than normal. A very dry May and a wet June in 1991 followed the same pattern as the previous year, but the summer as a whole (April to September) was dry and warm. The winter of 1991/92 exhibited many of the features of 1988/89 but, in Britain was less extreme (see Figure 4); parts of the continent experienced a sharper intensification of the drought over this mild winter period - see page 66. From the spring, weather patterns were largely determined by the return of Atlantic frontal systems which brought persistently unsettled conditions and, in the autumn, substantial rainfall to the UK; this wet phase began somewhat later on the continent.

Convectional rainfall in Great Britain

With higher than average temperatures over the period 1988-92 thunder-producing weather patterns might have been expected to be more prevalent in the UK. Mild winters tend to be wet and hence have more frontal activity with embedded thundery outbreaks (although this was not the case during the winter of 1988/89) and warmer summers may have more periods of anticyclonic activity and hence produce more convective thunderstorms. In the event, statistics relating to thundery activity during 1988-92 are not consistent with such an assumption and the incidence of thunder during the period was generally quite low.

The *Weather* magazine's Weather Log has monitored the monthly totals of days with thunder at selected UK sites since 1966. From these data a 20-year (1966-85) average has been calculated for comparison with the 1988-92 period. The results appear in Table 5. At both Heathrow and Eskdalemuir the number of days with thunder in each of these five years was below the 1966-85 average. The 16 days recorded for Heathrow in 1992 relate principally to the period when the drought was rapidly declining in severity (see page 15).

Snow

The extraordinary warmth of the period 1988-92 meant that snowfall became relatively rare (with the exception of the Scottish Highlands where the peaks certainly received abundant precipitation). Since 1981 the Weather Log has routinely published the number of days in a month that snowfall (and snow lying at 0900 hrs) was recorded. The four winter seasons since 1988/89 in southern England have produced the lowest number of days with snow in the twelve-year record. This is given greater significance by the notable warmth of the 1980s (see Figure 2) which also manifested itself in limited snow accumulations in the Alps. Considering only the December to February totals, the 1981/82 to 1987/88 average at Heathrow is 17 days with snowfall, the four-year average between 1988/89 and 1991/92 is only 4 days.

In Scotland the picture is similar. The average for the initial six years at Eskdalemuir is 40 days, compared to the four-year average between 1988/89 and 1991/92 of 26 days; a comparable reduction in snow was recorded for Abbotsinch on the west coast.

TABLE 4 RAINFALL FOR SELECTED EUROPEAN SITES FOR THE WINTER OF 1988/89

Site	Dec '88 (mm)	Jan '89 (mm)	Feb '89 (mm)	Total for winter (mm)	Average for Dec-Feb (mm)	1988/89 as % of average
Cambridge	23	28	47	98	116	84
Fort William	307	470	709	1486	631	235
Dijon	42	15	36	93	179	52
Tromso	161	163	140	464	295	157
De Bilt	70	29	47	146	193	76
Madrid	0	10	20	30	148	20
Nuremburg	81	25	32	138	132	105

TABLE 5 DAYS WITH THUNDER

	Heathrow (No. of days)	Eskdalemuir (No. of days)
1966-85 Average	17	11
1988	12	10
1989	11	6
1990	11	4
1991	10	6
1992	16	4

RAINFALL

Background

Rainfall in the United Kingdom has been measured for over 300 years, although during the pre-1850 period particularly the network was sparse and raingauge design and exposure were not subject to the rigorous standards now maintained. Currently there are around 5000 raingauges in the UK but coverage in some, mostly mountainous, areas is relatively thin and problems remain in accurately assessing areal rainfall totals particularly where snow constitutes a significant proportion of the overall precipitation. Notwithstanding the imprecision of some early records, long-term rainfall series generally provide no firm evidence of any overall trend although significant perturbations with extended periods below, or above, the long-term average are characteristic of many lengthy rainfall time series. Figure 5 shows that for England and Wales as a whole, persistently dry periods were rather more common in the 150 years preceding the First World War; notably protracted rainfall deficiencies occurred in the 1780s, 1810s, 1850s and, especially within the 25 years commencing around 1885. The latter two periods were dry at Kew also but generally the pre-1850 rainfall totals were marginally greater than those recorded over the last 50 years. Such perturbations in UK rainfall time series - together with seasonal changes in the distribution of rainfall[17] - although modest by comparison with those identified in parts of Africa, for example, provide a stimulus for continuing research at the Institute of Hydrology and elsewhere into the global and regional climatological factors which determine hydro-meteorological variations in western Europe.

Overture to the drought - the 1980s

United Kingdom rainfall in the 1980s was the highest for any decade this century: only 1987 and 1989

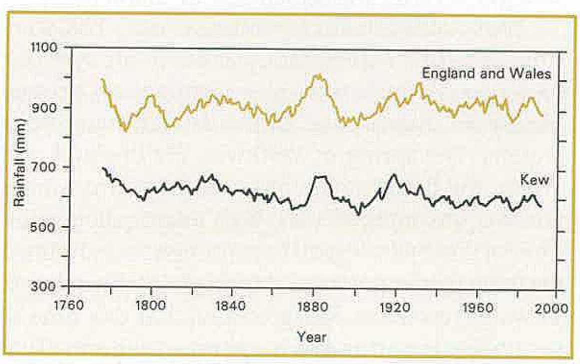


Figure 5 Ten-year running mean annual rainfall totals

recorded below average annual totals relative to the twentieth-century mean. Despite this preponderance of wet years, the average rainfall over the decade remained less than five per cent greater than the preceding mean - testimony to the limited variability of rainfall within this timeframe. The positive anomaly for the 1980-89 period is associated with an increased frequency of cyclonic weather patterns which can be traced back over 40 years[18,19]. In the recent past this tendency is reflected in the abundant precipitation in Scotland where the 1980s is the wettest decade on record by an appreciable margin. In south-eastern England the rainfall anomaly was generally positive but only marginally so over wide areas, and in some localities, eastern Kent for example, rainfall was below average in most years.

A modest tendency for the west-to-east rainfall gradient across Britain to be accentuated was a feature of the 1980s as a whole. This is particularly true of Scotland where the western Highlands were persistently wet and the eastern lowlands somewhat drier than in the preceding decades. Also of significance in relation to water resources was the tendency for a greater proportion of the overall rainfall to be concentrated within the winter half-year. This was most obvious in some Highland areas where, over the ten years, winter rainfall was around 30% greater than the average whereas the 1980-89 April-September rainfall was somewhat below the long-term mean. As a consequence the mild seasonality which characterises much of the UK was reinforced in the 1980s with some of the more maritime and mountainous districts (mostly in Scotland) registering up to two-thirds of their rainfall over the winter half-year. For England and Wales, seasonal contrasts were much less exaggerated but relatively low rainfall in the summer half-year, especially over the July-September period, together with above average winter rainfall strengthened the normally subdued seasonal contrasts in most regions.

Over the period 1979/80 to 1988/89 the ratio of winter half-year (October-March) rainfall for England and Wales to that of the ensuing summer half-year was 1.34; substantially greater than the long-term average and the highest for any decade in the England and Wales series. In the 19th century, decadal values close to unity were typical but the limited raingauge coverage of mountainous sites, may have exerted an influence. The 12-year sequence, beginning with 1977, of years with winter rainfall in excess of that for the summer half-year is without precedent (see Figure 6) and culminated in an extreme winter/summer contrast in 1989/90. The greater hydrological effectiveness implied by such a pronounced tendency for precipitation to occur at times of low evaporative loss is reflected in the

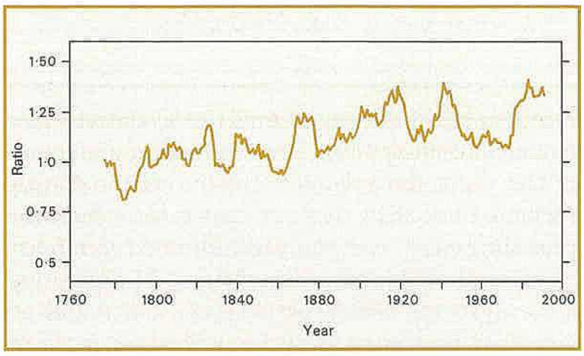


Figure 6 The ratio of winter to summer half-year rainfall for England and Wales (ten-year running mean)

elevated runoff totals which typified large parts of northern Britain in the 1980s (see page 33). By contrast, in much of lowland Britain - where the potential benefits of increased winter rainfall to water resources are considerable - little departure from the normal half-yearly partitioning of annual rainfall was evident for the 1980s as a whole.

Drought episodes were generally only a very minor feature of the 1980s although a notable spring and summer drought afflicted much of western and northern Britain in 1984. This was of limited duration however and the considerable concern for water resources generated by the extreme drought of 1975/76 was largely dissipated over the ensuing twelve years.

Development of the drought

Although the rainfall total for the United Kingdom over the five years beginning in August 1988 was marginally above the 1941-70 average, large negative anomalies characterised south-eastern Britain and exceptional positive anomalies typified much of western Scotland (see Tables 6 and 9). Notwithstanding a significant drought in some eastern areas (see below), the four-year period ending in the spring of 1992 was, for Scotland, significantly wetter than any 48-month sequence ending prior to 1989, in a record from 1869. The contrast with the English lowlands was remarkable.

In common with several earlier very protracted droughts, the 1988-92 rainfall deficiency developed in an uneven manner in most areas. At the country-wide scale a number of notable sequences of both dry and wet months could be identified (see Table 7). Broadly, the drought achieved its greatest severity in north-eastern Britain during late 1989. From the spring of 1990 however, it became increasingly focused on the English lowlands although a number of relatively short-term rainfall deficiencies afflicted much of southern Britain over the ensuing two years.

The seeds of the drought were sown in the late spring of 1988 in the lowlands, but, for England and Wales as a whole, the rainfall deficiency beginning in August 1988 was more significant. By the autumn, an incipient drought could be widely recognised and a general intensification occurred through the early winter. The November 1988 to January 1989 rainfall total for England and Wales was the lowest since 1879 and notable rainfall deficiencies extended throughout the English lowlands. The drought moderated during the February to April period - the wettest for eight years - then re-intensified through the latter half of the year. The five-month period ending in September was the driest on record for Haweswater in the Lake District and triggered requests for a number of Drought Orders (see page 61) in the North-West. A sequence of 30-35 rainless days, beginning around early November and embracing much of the UK, resulted in a rapid growth in the geographical extent of the drought[20]. By the late autumn of 1989 much of central, southern and eastern Britain was affected.

In most regions, the 1988-92 drought was punctuated by a number of wet interludes and, away from the eastern seaboard, a distinguishing feature of the drought was the rapidity with which substantial changes in severity occurred. Sustained sequences of very wet or very dry weather served to alter the drought's complexion over periods of as little as six weeks. Such changes were especially dramatic over the seven months beginning in November 1989.

1990

Heavy and sustained rainfall from mid-December 1989 produced a brisk amelioration in drought conditions and the transformation continued into 1990. Several damaging storms in late January 1990 heralded a remarkably wet February which concluded the wettest winter (December-February) on record for Great Britain. This exceptionally unsettled episode partitioned the drought into two distinct phases in most of the English lowlands. In a few eastern areas however, rain-shadow effects limited the winter rainfall and the reduction in drought severity was much less substantial.

The volatile climatic conditions of early 1990 were superseded by a dominantly anticyclonic synoptic pattern and the late-winter termination proved merely an interruption in the drought over most regions. The spring of 1990 was, for England and Wales, the driest since 1893 and the warm, sunny weather encouraged very high evaporation rates. This further hydrological transformation underlined the particular importance of spring rainfall in relation to water resources. Meagre rainfall at this time of year, when runoff and recharge rates are normally at a maximum in the lowlands, can make for a rapidly deteriorating water resources outlook.

Whilst in most areas the summer of 1990 was not especially dry, by late-September a notable seven-month drought extended across much of southern Britain. Large parts of central, southern and eastern England recorded less than half the average rainfall over this period and the water resources outlook was particularly fragile where this short-term drought overlaid significant deficiencies in the 24-30 month timeframes.

1991-92

By the end of 1990 many districts in East Anglia had registered ten successive months with below average rainfall (see Figure 7) and the regional dimension to the drought had become greatly accentuated. The dry sequence of months continued in much of the lowlands until the late-spring or early-summer of 1991. For the 15-month period ending in May 1991, rainfall totals were the lowest on record in many lowland districts and long-term regional deficiencies had, once again, built to a very substantial magnitude. A wet June served to arrest the drought's progress and limit water demand at a vulnerable time. Subsequently, the familiar pattern became re-established and many lowland areas registered below average rainfall in each of the last five months of 1991. At year-end, very severe drought conditions extended across much of eastern, central and southern England and large rainfall deficiencies again reached well beyond the eastern lowlands - several raingauges to the south of Manchester, for example, recorded their lowest annual rainfall total since 1887. Rainfall deficiencies in timeframes greater than 18 months were largest in a broad zone from the Humber to the North Downs. January and February 1992 saw a further intensification in the lowland drought and the accumulated deficiencies since the spring of 1988 were the equivalent of a year's average rainfall in a significant proportion of eastern England[21].

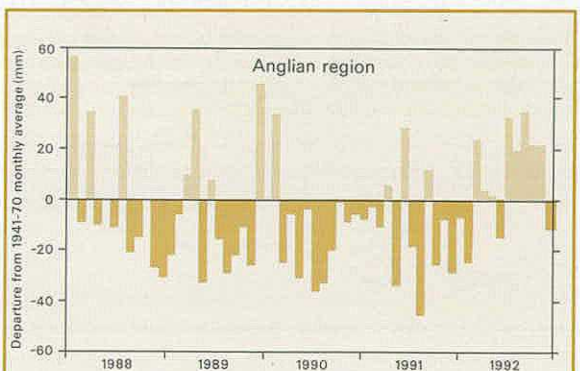


Figure 7 Monthly rainfall anomalies for the Anglian region, 1988-1992

Termination of the drought

A number of recent droughts, for example those of 1959, 1976 and 1984, have ended dramatically as a result of heavy and sustained autumn/early winter rainfall. By contrast, the 1988-92 event had no sharply defined termination, the final phase extending beyond 12 months in some areas. In part, this reflects the timing of the onset of wet conditions. The spring of 1992 was wet over much of the drought-affected area but rainfall deficiencies continued to build in parts of southern England - by June notable short-term (6-10 months) droughts stretched from Cornwall to Kent. Where, as in East Anglia, the spring rainfall was more abundant its hydrological impact was greatly moderated by the accelerating evaporation rates. Thus groundwater levels continued to decline as the meteorological drought abated (see page 53).

A relatively wet summer in 1992 did, however, allow aquifer replenishment to re-commence early in the autumn. Particular impetus to the post-drought recovery was provided by a thunderstorm on the 22nd September which produced over 50 mm of rainfall throughout a substantial part of the English lowlands, some localities recording in excess of 100 mm[21]. Unsettled conditions continued throughout most of the autumn, and the six-month period ending in January 1993 was the wettest such sequence this century for Britain as a whole. Although less heavy than over much of Scotland, rainfall in the English lowlands was generally sufficient to bring the drought to an end. By early 1993 the passage of a sequence of active low pressure systems had shifted the national focus of hydrological concern from drought to the risk of flooding. Nonetheless, a few pockets remained with substantial rainfall deficiencies, e.g. close to the Thames Estuary and extending into north Kent. An extremely dry eight-week period beginning in early February 1993 rekindled local concern for the water resources outlook. However, a wet late spring ensured that, at the regional scale, 12-monthly rainfall totals throughout England and Wales were close to, or above, average and runoff rates and groundwater recharge levels were relatively healthy.

The spatial extent of the drought

In its most severe manifestations the drought bore principally on the English lowlands but Figure 8 confirms that, over its full compass, the drought extended throughout most of eastern Britain. The 70% isopleth delineates the zones of greatest drought intensity - a few districts in a band from Northumbria to Lincolnshire registered very extreme intensities in rainfall terms. The exaggeration in the west-to-east rainfall gradient in Scotland is remarkable but is clearly apparent also in southern Britain.

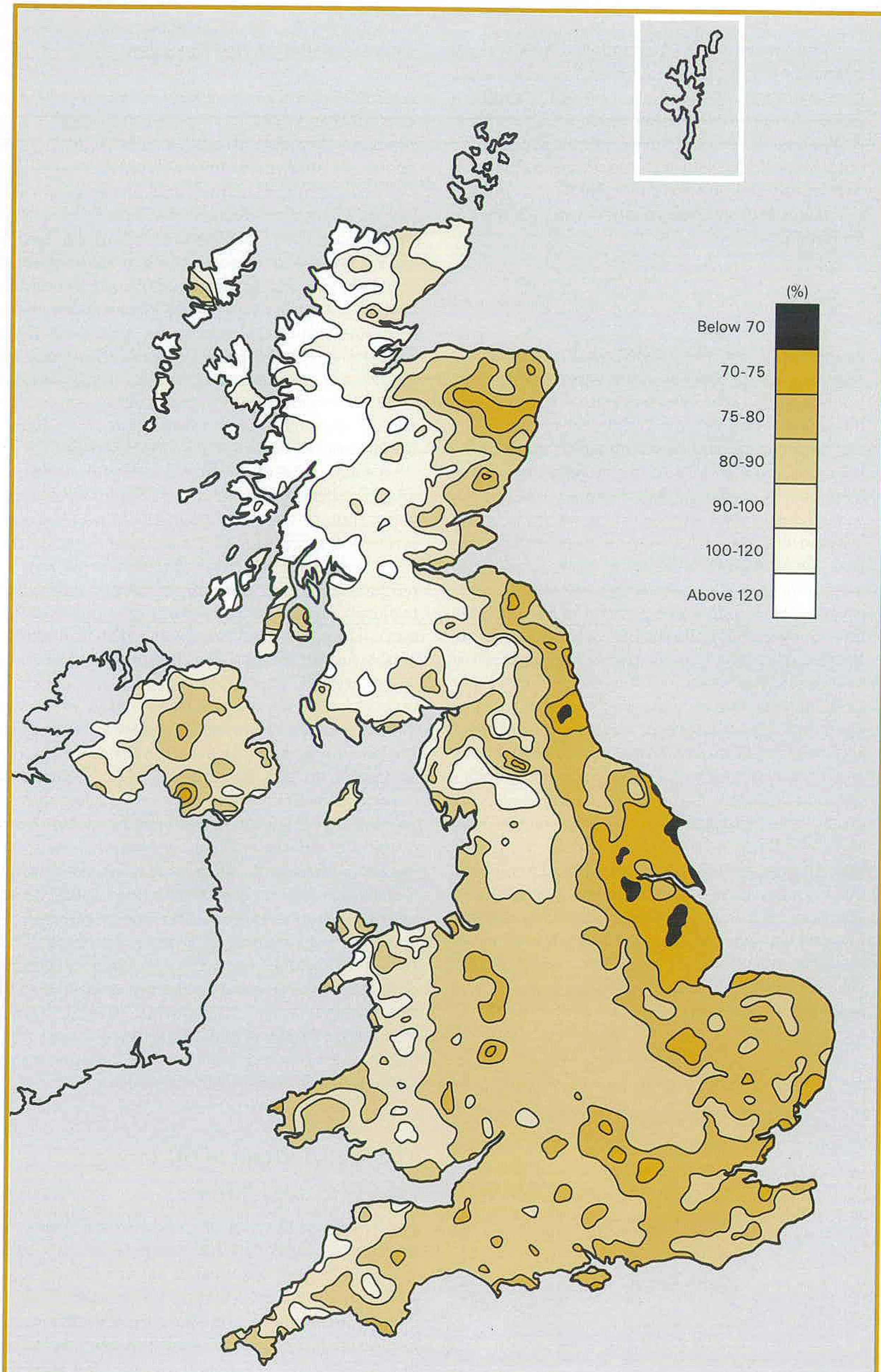


Figure 8 August 1988- February 1992 rainfall as a percentage of the 1941-70 average (Source: Met. Office)

Within the 1988-92 period, spatial variations in drought intensity were substantial with few regions - western Scotland excepted - escaping at least a limited period of rainfall deficiency. Figures 9 and 10 illustrate the two major phases of the drought and the maps on page 18 highlight significant periods in its development. The first of these (Figure 11) illustrates the percentage rainfall for the period November 1988 to January 1989. Over these three months the majority of eastern and southern Britain recorded less than 60% of average rainfall with areas south of a line from Exeter to London registering barely a third. Some striking similarities, especially in the South-East, may be identified between Figure 11 and the percentage rainfall map for the three months beginning in December 1991 (Figure 12) which marked the final intense phase of the drought.

The 12-month period ending in November 1989 produced drought conditions in almost all regions of England and Wales, with notable severities in parts of the Northumbrian and Southern regions, and the North-East River Purification Board area. The second phase of the drought impacted most severely on lowland England but significant secondary droughts may be recognised for example on the Cheshire Plain and, more locally, in central districts of the Grampian region.

In a water supply context, dry winters create concern for the water resources outlook but the community and environmental impact can be greatly exacerbated if the ensuing summer is hot and dry. Such was the case over the May-November period in 1989 (Figure 13) but the accompanying map - showing percentage rainfall over the spring and summer of 1990 (Figure 14) - documents an even more extreme rainfall deficiency which stressed water supplies even though resources were generally healthy at the end of the preceding winter.

The severity of the drought

National scale

Droughts rarely display anything approaching a uniform severity at the national scale but the 225-year England and Wales rainfall series does provide a means of setting the 1988-92 period in a suitable historical context. On a countrywide basis the most notable rainfall deficiencies occurred - broadly - over the two and four-year timeframes. For sequences starting in March the twenty-four months ending in February 1992 were the driest on record, and considering sequences starting in any month, only

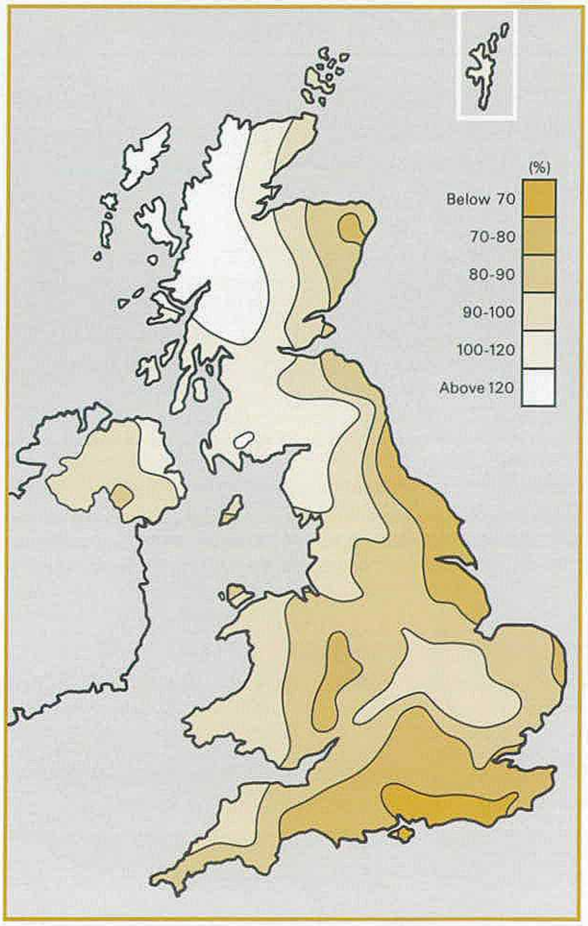


Figure 9 Apr.1988 - Nov. 1989 rainfall as % of the 1941-70 average (Source: Met. Office)

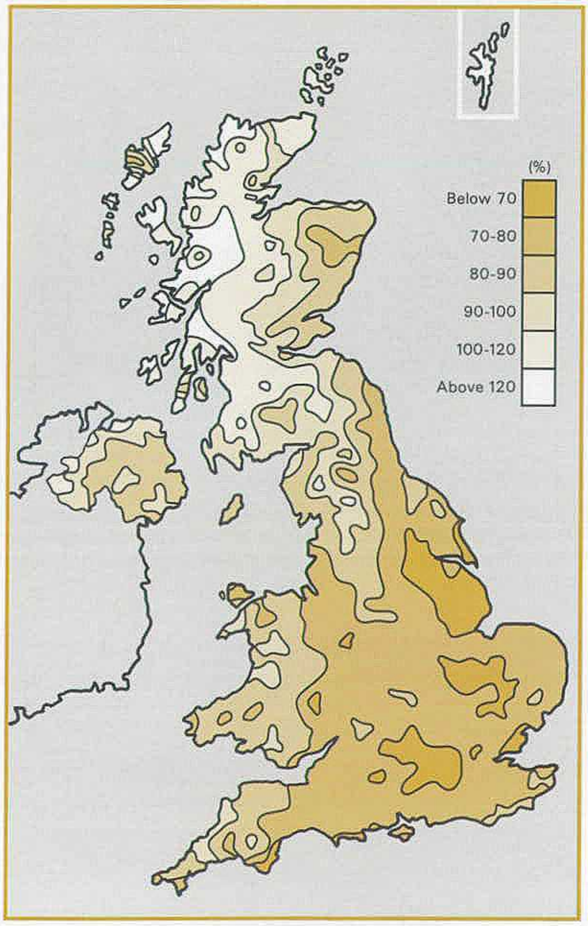


Figure 10 March 1990 - Feb. 1992 rainfall as % of the 1941-70 average (Source: Met. Office)

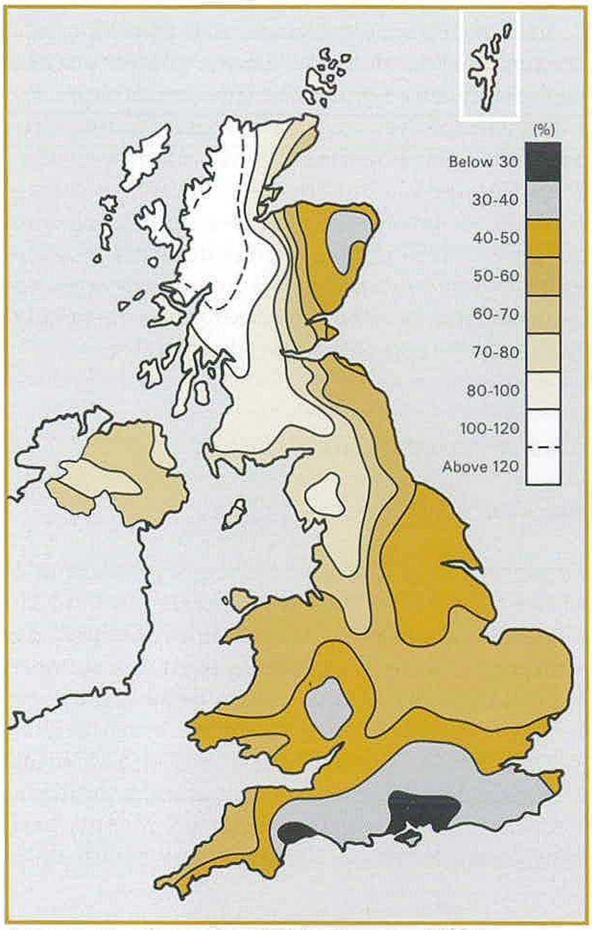


Figure 11 November 1988 - January 1989

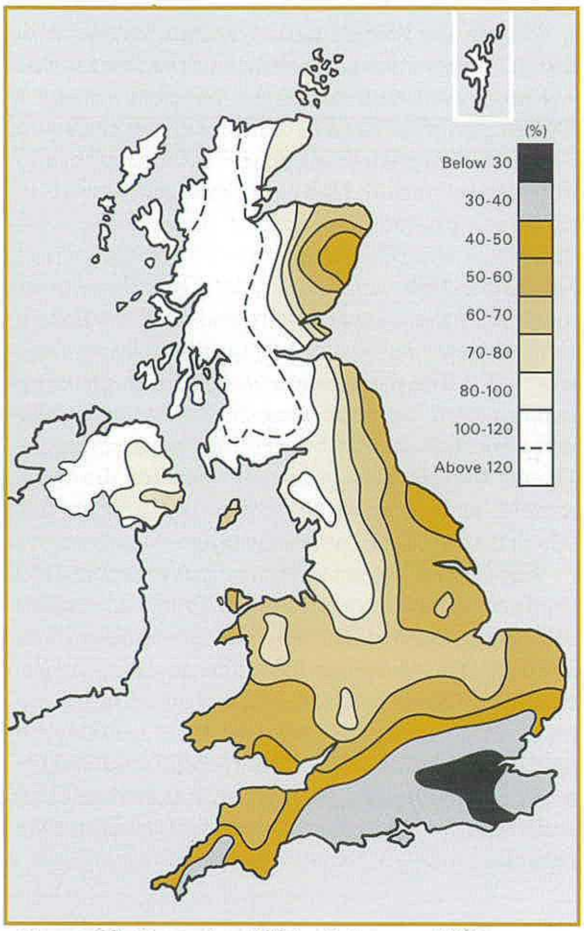


Figure 12 December 1991 - February 1992

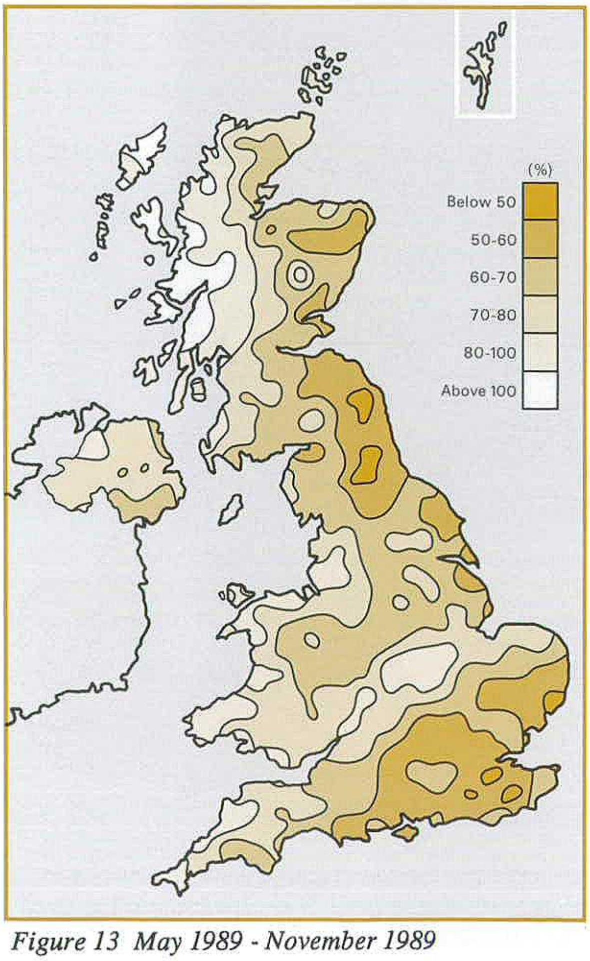


Figure 13 May 1989 - November 1989

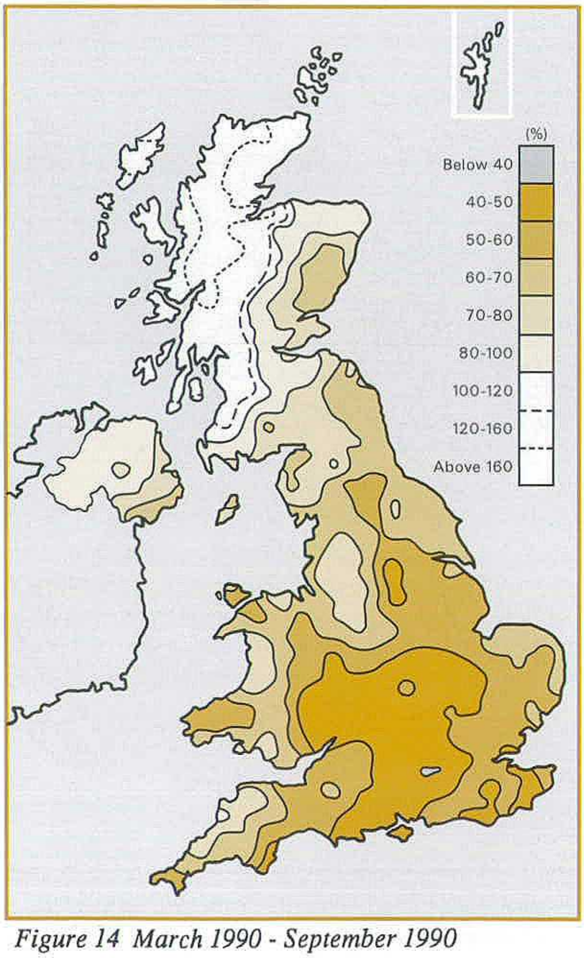


Figure 14 March 1990 - September 1990

Each map shows rainfall as a percentage of the 1941-70 average (Source: Met. Office) in the 1930s, 1850s and, more conjecturally, the 1780s have appreciably lower 24-month rainfall accumulations been registered (see Table 8). Since the 1850s, only the rainfall deficiency ending in August 1976 was as severe as those registered to February 1992 in the 40-45 month timeframe.

Regional and catchment scale

For a large proportion of the English lowlands rainfall deficiencies over the 1988-92 period were notable over a wide range of timeframes - from three to more than 50 months in some areas. Table 9 provides an assessment of regional drought severity for three timespans which, generally, serve to identify the most extreme rainfall deficiencies; two particularly intense shorter term drought episodes are also featured. The spatial dimension to the drought is readily apparent with the most severe conditions experienced in the Anglian, Thames and Southern regions. However, the figures serve to obscure some important intra-regional contrasts in drought severity. For example, in the Severn-Trent region rainfall deficiencies increased markedly from west to east; this is also true of the Southern NRA region. In Yorkshire, over the full compass of the drought, rainfall deficiencies in the Wolds and Humberside were as great as any registered elsewhere but drought conditions in the Pennines were sporadic and much reduced in overall magnitude.

The return periods quoted in Table 9 derive from tables provided by the Meteorological Office[22]. The tables assume a sensibly stable climate and are based upon n-month regional rainfall figures over the 1911-70 period. The incorporation of data for the sustained rainfall deficiencies around the turn of the century and in the 1970s, as well as the recent event itself, would be expected to moderate the quoted return periods somewhat. Though the return periods provide a useful index for the purposes of regional comparisons, they should be interpreted with caution as they relate to durations which start in a given month[23]. Such analyses would be appropriate, for example, if river flows are being projected during a drought on the basis of rainfall probabilities associated with the forecast period.

When examining the severity of droughts in retrospect, a random (or 'any') month analysis is normally more suitable since the start date is then less relevant. For a start in any month there are more opportunities for lower accumulations to be identified and thus the event rarity would be moderated. This disparity is most marked at short durations when differences between the two estimates may be around an order of magnitude. For example, whilst the Thames Valley rainfall total for the 12 months ending in February 1991 is the lowest (for a March start) in a record from 1883, appreciably lower 12-month accumulations were registered during the 1975/76, 1921/22 and 1933/34 droughts - around twenty 12-month sequences in all. At the longest durations the 'given' start month estimates show a tendency to converge with those relating to 'any' start month.

Table 9 provides a guide to the important temporal variations in drought severity over the four years from late-1988. Their significance emerges more clearly in Figure 15 which charts the growth and decline in the drought - as indexed by the return periods associated with the rainfall deficiencies in the Anglian and South West regions. Both regions registered comparable drought severities in 1989 but the ensuing wet winter in the South-West greatly moderated long-term rainfall deficiencies thereafter. By contrast, after a brief wet interlude, the drought continued to intensify in the Anglian region and return periods exceeded 50 years for much of the 28-month period up to June 1992. In the South-West accumulated deficiencies were of a lesser magnitude but, as the nine-month running totals indicate, a number of important short to medium-term deficiencies developed following the end of the 1989/90 winter.

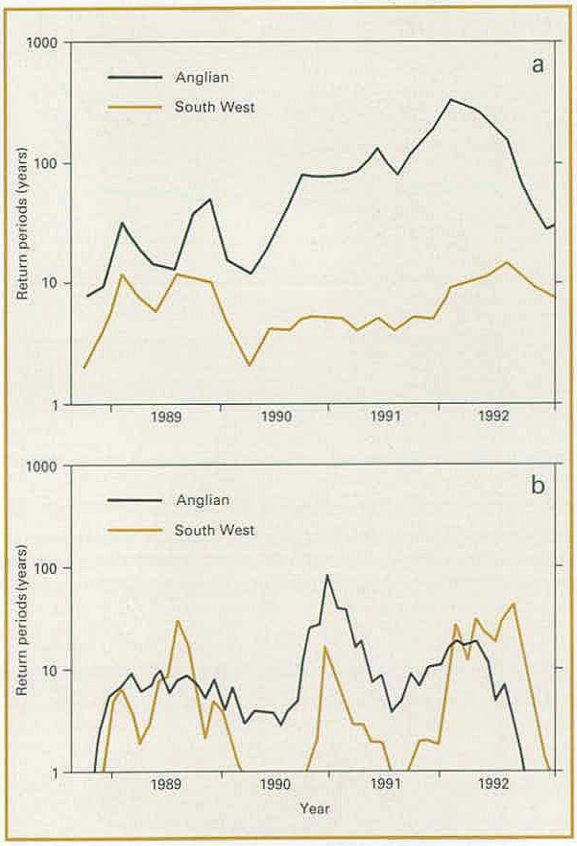


Figure 15 Estimated return periods for rainfall deficiencies in the Anglian and South-West regions: a) based on accumulated rainfall totals from Aug. 1988 b) based on running nine-month accumulations

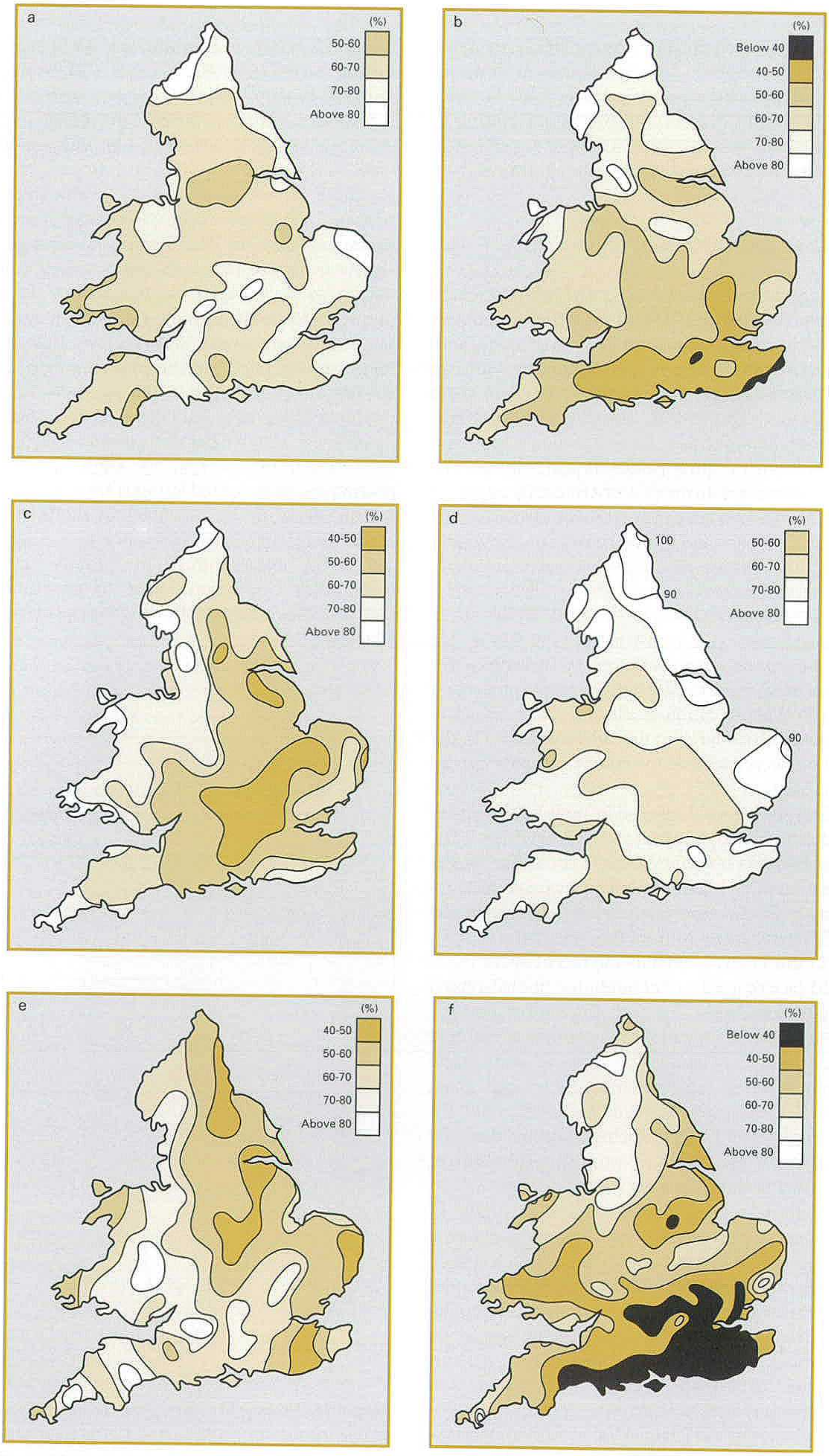


Figure 16 Spatial variation in rainfall (% of long-term average) for six drought episodes: a) Feb - Oct 1887; b) Feb - Nov 1921; c) Feb - Sept 1929; d) Apr -Sept 1934; e) Feb - Sept 1959; f) Jan-Aug 1976

Individual raingauges

Rainfall data for individual raingauges show significantly greater variability than figures aggregated over a region and many new rainfall records were established over the 1988-92 period. During the drought's initial phase some exceptionally rare accumulations were registered in the North-East. For example, in 1989 the Durham University and Whittle Dean Reservoir raingauges registered their lowest annual rainfall totals in records extending back to 1850. At Sunderland, where measurements began nine years later, the previous lowest was eclipsed by a wide margin: the return period associated with the 1989 total is well in excess of 200 years[24].

Exceptionally low annual rainfall totals characterised the following two years in much of eastern England. For some localities the 1990 and 1991 totals rank behind only 1921 this century. Understandably, the most outstanding deficiencies occurred over the longer timespans. This is confirmed by Table 10 which ranks n-month rainfall accumulations over a range of durations for six lengthy rainfall series.

The intensity of the spring/summer rainfall deficiencies in 1990 is confirmed by the rankings of the lowest six-month accumulations at Norwich, Oxford and Kew. The latter two sites have rainfall records exceeding 200 and 300 years in length respectively. The 1976 drought dominates the entries in the 12-month category but the 1988-92 event features increasingly for longer durations. At Oxford, and for the East Midlands site, the minimum 24-month totals recorded during the recent drought are unparalleled in at least 190 years. In the 48-month timeframe the Exeter deficiency ranks among the four most severe droughts whereas, for the other featured raingauges, there has been no closely comparable deficiency since the turn of the century. A discussion of the suitability of the timeframes used in Table 10 for objective comparisons between droughts is included in the following section.

A comparison with historical droughts

No two droughts are alike in terms of their spatial extent and temporal variations in intensity. The associated difficulties in making objective comparisons may be appreciated by examining the regional contrasts in drought severity shown in Figure 16 which illustrates six notable within-year periods of rainfall deficiency for England and Wales[23].

By the selective use of rainfall, or other hydrological data, it is possible to over- or underestimate the relative severity of individual deficiencies. This can be especially important in relation to water supplies. As stress on resources increases during a drought, emphasis may understandably be placed on the severest extreme arising from a wide-ranging analysis encompassing many target sites and a broad spread of durations. This may be done without regard for the fact that the stressed resource is not uniquely sensitive to the particular duration which is associated with the longest return period.

Analyses presented on pages 25 and 26 testify to the exceptional nature of the 1988-92 drought within the timeframes considered; one objective of this section is to provide a context within which comparisons with historical rainfall deficiencies may be made. Few protracted droughts fail to exhibit substantial, and sometimes abrupt, changes in

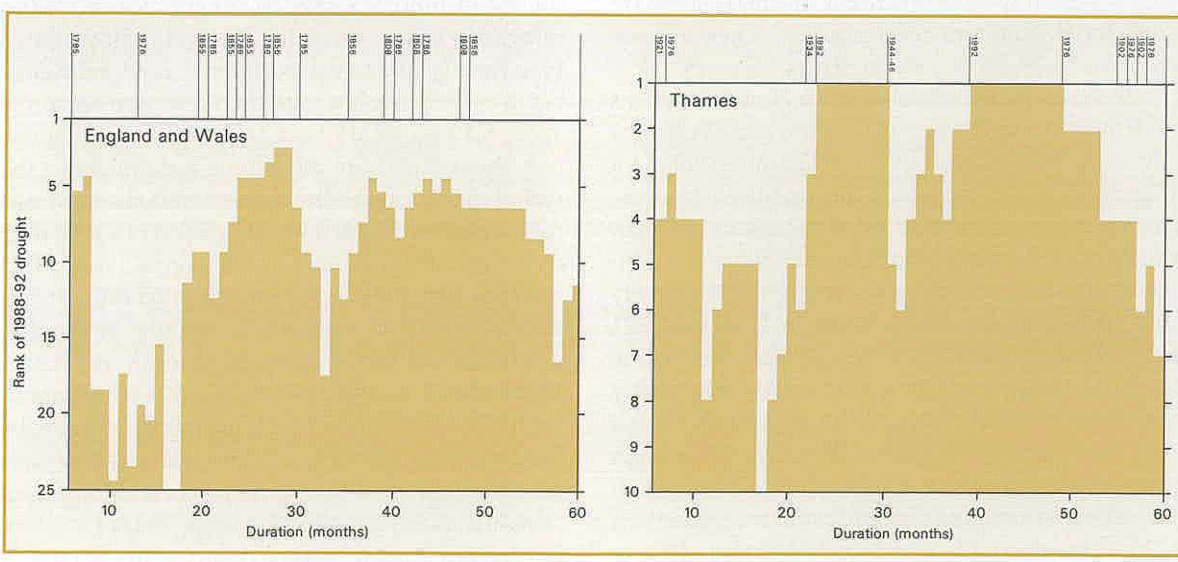


Figure 17 Rankings of the1988-1992 rainfall deficiencies (over 6-54 months) relative to other drought events in the rainfall records for a) England & Wales (from 1767) and b) the Thames catchment (from 1883)

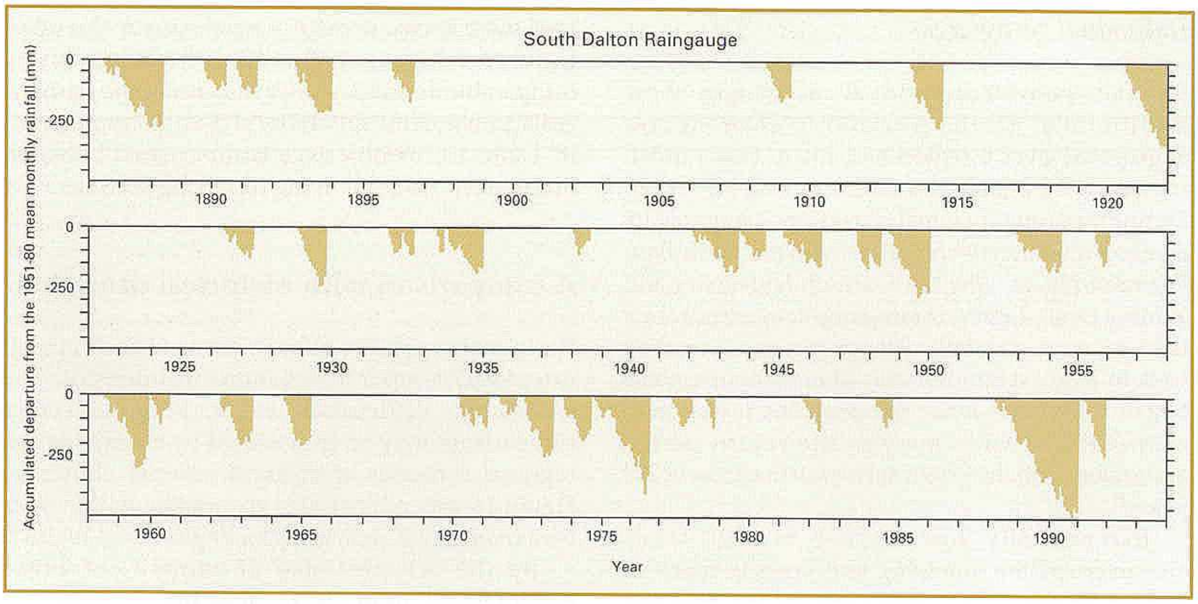


Figure 18 Rainfall deficiency index for the South Dalton raingauge

intensity through time. Thus as the duration examined changes so the relative importance of particular events change also. Figure 17a charts the ranking of the 1988-92 rainfall deficiency for England and Wales, over a wide range of durations, within the context of the twenty-five most severe deficiencies registered in the full historical rainfall series. The rankings relate to non-overlapping events and the year corresponding to the end of the first-ranked deficiency is given at the head of the diagram. The droughts of 1784-88, 1855-58 and 1975-76 are pre-eminent in most of the timeframes, and for periods in excess of 36 months the 1805-08 drought also ranks consistently amongst the most severe three or four. Within the 24-56 month timeframes the 1988-92 event generally ranks as slightly wetter than the earlier long-term deficiencies; for accumulations less than about 30 months the 1933-35 event was also comparably severe. If twentieth century droughts alone are considered, the recent event established new minima over the 26-29, 38 and 46-month timeframes.

Because of the relatively large regional variations in drought intensity across England and Wales, the corresponding diagram for the Thames catchment (Figure 17b) is rather more informative. Here, the catchment rainfall record extends back to 1883 and the short- and medium-term deficiencies are dominated by the 1975/76 drought, although the extremely dry three- and six-month spells in 1938 and 1921 were both important in water resources terms. Within the two- to three-year timespan the 1990-92 deficiency is without parallel although the 1944-46 event was only moderately less severe. The 1988-92 drought also eclipsed previous minima in the 40-49 month range but over longer durations ranks second or third behind the droughts which ended around 1976 or 1902.

Drought indices

Developing precise and serviceable drought indices to facilitate objective comparisons between droughts remains a considerable scientific challenge[25]. In large part, this reflects the difficulty of indexing a phenomenon which exhibits large spatial and temporal variability. Assessing the scale of the impact on the community introduces further difficulties as droughts affect different groups in different ways. Farmers are particularly adverse to dry soil conditions in the spring whereas water managers are especially concerned by low winter rainfall which limits replenishment to surface and groundwater resources. Notwithstanding these limitations, simple rainfall deficiency indices do at least permit broad historical comparisons to be made[3,26].

Figure 18 shows accumulated departures from the mean monthly rainfall for the South Dalton raingauge in Humberside. Drought indices of this type readily identify periods of rainfall deficiency but they require cautious interpretation since the apparent magnitude of each low rainfall event can be rather sensitive to the criteria used to define the end of each drought. In this instance a drought was considered terminated when a period of six months registered above average total rainfall; using this methodology substantial accumulated deficiencies may still exist at termination. Whilst somewhat arbitrary, the termination criterion helps direct attention to the longer-term droughts which are of particular relevance to groundwater resources. Unfortunately the South Dalton series is incomplete around the turn of the century - several long-term rainfall deficiencies affecting large parts of western Europe are known to have occurred in the twenty years beginning in the mid-1880s (see page 65).

Nonetheless, in the context of the last 85 years the pre-eminence of the recent event is clear. Similar analyses for other long-term raingauges inland from the Humber estuary confirm the outstanding nature of the drought in this timeframe[27].

Throughout most of the English lowlands south of Humberside, rainfall over the 1990/91 winter was insufficient to trigger a similar termination to that exhibited by the South Dalton deficiency index. Generally, the meteorological drought did not end until the summer of 1992 but over much of central and southern England peak rainfall deficiency scores were constrained by the impact of heavy rainfall over the December 1989 to February 1990 period. Nonetheless, areal rainfall figures for the Thames Valley demonstrate that a comparable maximum intensity was achieved to that registered during the 1975/76 drought and, if the 1988/89 event is included, a duration similar to the very extended droughts around the turn of the century.

TABLE 6 RAINFALL AUGUST 1988 - MAY 1992

Region	Rainfall (mm)	% of 1941-70 average
Great Britain	4280	102
England and Wales	3080	95
Anglian NRA region	1890	80
Scotland	6340	115
Clyde RPB region	7740	120

NRA = National Rivers Authority
RPB = River Purification Board

TABLE 7 NOTABLE N-MONTH RAINFALL TOTALS FOR ENGLAND AND WALES

Period	% of 1941-70 average	Estimated return period (years)	Comment
Oct 87 - Mar 88	137.9	40-50	7th wettest this century
Apr 88 - Jun 88	74.7	5-10	5th driest since 1957
Nov 88 - Jan 89	52.0	40-50	Driest this century
Feb 89 - Apr 89	145.1	15-30	11th wettest this century
May 89 - Nov 89	67.0	40-60	Driest since 1947
Dec 89 - Feb 90	169.3	150-200	Wettest since 1915
Mar 90 - May 90	46.7	70-90	Driest this century
Jul 90 - Sep 90	54.5	30-40	Driest since 1972
Mar 90 - Sep 90	59.5	150-200	Driest on record
Dec 90 - Apr 92	131.3	10-20	Wet winters/early springs common in last 20 years
Aug 91 - Feb 92	68.9	30-40	Driest since 1934
Mar 92 - Apr 92	135.0	2-5	5th wettest since 1965
Jul 92 - Nov 92	124.0	5-10	3rd wettest since 1960

Note: The return periods for wet episodes are underlined

TABLE 8 MINIMUM RAINFALL TOTALS FOR ENGLAND AND WALES (1767-1992)

	24-month rainfall				43-month rainfall			
Rank	End year	Month	mm	%	End year	Month	mm	%
1	1786	07	1387	76.4	1808	06	2723	85.5
2	1855	09	1396	76.9	1857	05	2734	85.1
3	1934	10	1432	78.9	1786	04	2742	84.5
4	1781	12	1435	78.8	1976	08	2785	87.2
5	1992	02	1448	79.6	1781	05	2830	88.1
6	1803	10	1453	80.1	1992	06	2831	88.9
7	1808	03	1489	81.8	1907	09	2851	88.8
8	1922	07	1508	83.0	1965	08	2873	89.9
9	1976	09	1518	83.6	1890	07	2873	90.0
10	1845	10	1520	83.8	1816	06	2892	90.8
11	1864	10	1526	84.1	1944	08	2893	90.6
12	1949	07	1536	84.6	1935	08	2898	90.7
13	1906	09	1539	84.8	1852	05	2898	90.2
14	1974	07	1542	24.9	1847	09	2901	90.4
15	1806	05	1544	84.9	1804	09	2905	90.5

Notes: Non-overlapping events only are featured in this table. The percentages relate to the long-term average for the particular 24-month or 43-month sequence featured.

TABLE 9 NATIONAL AND REGIONAL RAINFALL ACCUMULATIONS FOR SELECTED DURATIONS WITH ESTIMATES OF RETURN PERIODS

		8/88-2/92	R.P. (yrs)	11/88-11/89	R.P. (yrs)	3/90-2/92	R.P. (yrs)	3/90-9/90	R.P. (yrs)	8/91-2/92	R.P. (yrs)
England and Wales	mm	2870	35-50	777	20-50	1448	60-80	292	150-190	409	30-50
	%L	86		77		79		59		69	
NRA Regions											
North West	mm	4160	5-10	1160	5-10	2134	1	467	20-35	704	2-5
	%L	93		87		88		70		88	
Northumbria	mm	2718	50-70	659	140-180	1502	15-20	323	35-50	418	10-15
	%L	85		68		85		66		73	
Severn Trent	mm	2396	25-45	663	15-20	1207	50-80	240	100-150	327	15-25
	%L	86		78		78		55		68	
Yorkshire	mm	2536	60-90	669	25-45	1310	60-90	279	50-70	369	10-15
	%L	84		73		79		61		69	
Anglian	mm	1734	>200	500	20-40	877	>200	194	100-150	247	20-40
	%L	79		74		72		56		66	
Thames	mm	2062	80-120	548	30-50	1002	>200	187	>200	241	70-100
	%L	81		71		71		48		54	
Southern	mm	2347	80-120	576	100-140	1196	80-120	209	>200	272	>200
	%L	81		65		75		51		51	
Wessex	mm	2678	25-45	700	20-40	1301	80-100	244	70-100	350	20-40
	%L	84		72		75		53		61	
South West	mm	3952	5-10	1039	10-20	1947	20-40	384	20-40	517	30-45
	%L	90		78		82		65		64	
Welsh	mm	4478	5-10	1225	5-10	2221	20-30	419	50-70	656	10-15
	%L	92		83		83		61		74	

		8/88-2/92	R.P. (yrs)	11/88-11/89	R.P. (yrs)	3/90-2/92	R.P. (yrs)	5/90-9/90	R.P. (yrs)	8/91-2/92	R.P. (yrs)
Scotland	mm	5929	50-90	1649	2-5	3149	10	868	5-10	1037	2-5
	%L	113		105		110		117		109	
RPB Areas											
Highland	mm	7545	>200	2212	10-20	4009	40-50	1222	100-150	1358	5-10
	%L	119		117		116		140		118	
North East	mm	3303	20-40	815	100-130	1852	5-10	495	2-5	517	10-15
	%L	89		72		91		89		78	
Tay	mm	4859	2-5	1289	2-5	2495	2-5	590	2-5	785	2-5
	%L	106		94		99		88		96	
Forth	mm	4333	5-10	1135	2-5	2296	2-5	561	2-5	705	2-5
	%L	106		93		103		91		97	
Clyde	mm	7234	>200	1999	2-5	3864	30-40	1036	5-15	1320	5-10
	%L	118		109		116		121		117	
Tweed	mm	3401	5-10	822	40-60	1880	2-5	417	10-15	556	2-5
	%L	93		74		94		75		85	
Solway	mm	5383	2-5	1406		2804	2-5	624	5-10	927	2-5
	%L	103		89		98		83		97	

R.P. = return period (years) %L = percentage of the 1941-70 average
The return periods for wet episodes are underlined.

TABLE 10 RANKED N-MONTH RAINFALL TOTALS FOR A SELECTION OF LONG-TERM RAINGAUGES — NON-OVERLAPPING EVENTS

Duration		6 months				12 months				24 months				48 months			
Gauge	ER	Yr	EM	mm	Ra	Yr	EM	mm	Ra	Yr	EM	mm	Ra	Yr	EM	mm	Ra
East Midlands Pode Hole	1	1976	07	91	1	1976	07	273	1	1741	08	786	1	1743	06	1709	1
	2	1741	07	110	2	1921	12	323	4	1750	08	798	2	1992	06	1854	18
	3	1743	05	112	3	1874	08	336	6	1992	02	843	9	1976	07	1886	32
1726-1992	4	1921	07	114	4	1888	01	343	9	1743	09	847	10	1750	10	1924	48
	5	1740	06	114	5	1741	08	355	15	1934	10	871	22	1965	02	1927	50
	6	1785	06	119	10	1750	03	360	16	1974	06	890	42	1762	07	1972	80
	7	1858	05	129	12	1973	03	370	19	1875	05	890	43	1733	12	2012	115
	8	1731	05	135	14	1760	08	371	20	1922	01	908	57	1896	08	2041	150
	9	1874	05	138	17	1740	06	374	23	1889	08	909	60	1891	02	2072	190
	10	1870	09	140	18	1743	06	383	30	1761	05	926	83	1935	08	2103	232
Norwich Hegham Cemetary	1	1976	07	115	1	1948	04	359	1	1865	01	825	1	1864	12	1961	1
	2	1947	10	118	2	1864	12	372	2	1949	04	885	5	1992	07	2058	13
	3	1921	07	135	3	1921	09	374	3	1992	02	909	12	1976	07	2185	45
1836-1992	4	1858	04	138	5	1976	07	402	9	1934	10	979	35	1935	08	2225	52
	5	1929	06	149	7	1959	10	418	18	1921	12	989	41	1899	08	2233	55
	6	1880	05	151	8	1949	09	424	20	1974	07	990	42	1950	08	2270	66
	7	1874	04	154	11	1991	05	443	30	1960	06	1028	55	1847	11	2311	103
	8	1990	08	155	12	1874	10	444	31	1875	06	1029	57	1981	02	2325	121
	9	1959	09	155	13	1973	03	454	39	1899	09	1051	77	1944	08	2328	125
	10	1870	06	160	17	1938	06	456	41	1977	11	1052	78	1891	04	2332	134
Oxford Radcliffe	1	1921	07	117	1	1976	09	323	1	1803	10	840	1	1803	10	1984	1
	2	1976	07	118	2	1788	12	354	6	1992	02	889	4	1788	12	1987	2
1767-1992	3	1785	07	126	7	1934	07	381	8	1788	12	916	6	1992	03	2097	24
	4	1929	06	133	10	1855	06	383	9	1934	10	923	9	1903	02	2107	32
	5	1964	12	137	11	1922	01	384	10	1785	07	926	10	1893	09	2109	34
	6	1938	07	137	12	1965	04	386	12	1891	07	940	17	1976	08	2174	94
	7	1990	08	142	15	1898	09	386	14	1871	12	975	31	1816	06	2202	129
	8	1944	05	145	17	1991	02	387	15	1976	11	979	37	1945	08	2236	178
	9	1784	02	147	19	1871	03	399	22	1893	12	980	38	1965	02	2263	212
	10	1830	03	148	20	1802	11	402	26	1929	09	984	42	1864	12	2289	260
Kew	1	1938	07	85	1	1921	12	309	1	1934	10	846	1	1743	12	1923	1
	2	1976	06	90	2	1973	03	315	3	1705	09	848	2	1901	09	1973	6
1697-1992	3	1921	07	100	5	1714	12	342	7	1922	10	853	3	1992	03	1988	10
	4	1929	06	114	7	1976	09	349	10	1744	01	860	6	1923	04	2026	31
	5	1972	10	119	10	1898	09	357	14	1974	05	875	9	1935	08	2034	32
	6	1874	05	121	12	1934	06	359	16	1949	07	882	15	1945	08	2046	41
	7	1854	04	121	13	1723	11	382	28	1715	02	882	16	1976	06	2047	43
	8	1895	06	127	14	1847	10	395	36	1992	02	886	19	1870	09	2069	61
	9	1990	08	133	16	1705	07	396	39	1899	08	895	24	1725	11	2069	62
	10	1891	02	137	18	1956	06	397	40	1723	11	912	37	1717	07	2120	117
Exeter	1	1855	04	101	1	1976	07	377	1	1865	12	941	1	1858	01	2229	1
	2	1830	03	109	2	1855	02	384	2	1821	02	1091	16	1838	01	2541	29
1817-1992	3	1887	07	121	3	1921	10	389	4	1922	07	1116	19	1909	11	2549	30
	4	1870	09	125	5	1835	01	453	16	1949	06	1126	22	1992	07	2654	65
	5	1840	08	125	6	1907	03	457	19	1976	08	1132	24	1821	02	2655	67
	6	1976	07	132	7	1821	02	468	27	1859	07	1139	25	1891	02	2671	77
	7	1921	10	132	8	1953	12	493	38	1835	06	1147	30	1956	05	2675	80
	8	1944	06	155	16	1841	02	496	39	1907	03	1155	37	1847	08	2688	88
	9	1820	07	162	18	1858	05	500	41	1954	10	1157	39	1860	04	2702	98
	10	1896	06	171	25	1830	10	507	45	1846	03	1201	59	1921	10	2721	114
Manchester	1	1844	05	100	1	1844	12	467	1	1934	11	1326	1	1806	10	2846	1
	2	1826	06	189	3	1888	05	529	4	1888	10	1326	2	1890	12	2915	2
1800-1992	3	1806	07	191	4	1938	04	546	6	1845	05	1326	3	1903	01	3056	29
	4	1868	09	200	6	1934	07	566	13	1806	10	1341	6	1978	11	3080	36
	5	1921	07	201	7	1921	07	581	18	1992	02	1363	9	1936	05	3083	38
	6	1814	05	211	8	1959	09	588	20	1902	12	1404	23	1907	11	3109	47
	7	1984	08	212	9	1806	08	609	29	1977	01	1410	31	1992	07	3122	62
	8	1887	07	213	10	1905	02	626	34	1905	12	1425	41	1917	05	3130	69
	9	1929	06	222	12	1826	12	630	39	1922	07	1451	57	1858	02	3166	121
	10	1934	04	229	15	1956	06	649	49	1856	03	1466	70	1896	08	3201	178

ER = event rank; Yr = year; EM = end month; Ra = rank (all).

EVAPORATION AND SOIL MOISTURE DEFICITS

Evaporation is perhaps the least tangible of the processes in the water-cycle and considerable difficulties attend the assessment of evaporative demands on an areal basis. Nonetheless, it is clear that throughout much of the 1988-92 period evaporation losses remained inordinately high, and served in large measure to set the recent drought apart from its precursors.

Whilst in terms of public perception the drought assumed a high profile principally in the summer periods, the hydrological character of the drought reflected warm conditions throughout most of 1988-92 (see page 9). For lengthy periods weather conditions were conducive to high rates of evaporative loss which contributed substantially to the development of the drought and its intensification within individual years, especially in 1989 and 1990. In the former (the latter also in a few eastern areas) the combination of a mild dry winter followed by a hot, sunny summer provided a testing examination of the water industry's ability to maintain supplies. Of particular hydrological importance was the persistence of notably dry lowland soils well into the autumn. In eastern and southern England especially, very high soil moisture deficits served to greatly reduce the hydrological effectiveness of rainfall over the latter half of each year, thereby delaying the seasonal recovery in runoff rates and reducing the period available for infiltration to replenish groundwaters.

MORECS

The MORECS (Meteorological Office Rainfall and Evaporation Calculation System) model produces estimates of hydrological variables for a network of 40 km squares over Great Britain and uses a modified version of the Penman-Monteith equation to calculate evaporation losses, and thence soil moisture deficits, for a range of land uses[28,29]. The model has been used retrospectively to produce a data series extending back to 1961. Analyses based on this series enable the singular character of the recent past to be effectively quantified, and MORECS data are widely exploited in the following sections. Figure 19 illustrates the variation in PE (potential evaporation), AE (actual evaporation) and SMDs (soil moisture deficits) for five representative MORECS squares over the 1988-92 period; the general location of the squares is given on page 32. The extreme nature of evaporative losses, in the lowlands especially, during both 1989 and 1990 is especially notable. The two following years appear modest by comparison but generally evaporation rates were well above the normal and soils drier than average.

Potential evaporation 1988-92

Much of Great Britain registered annual mean temperatures for both 1989 and 1990 between 1 and 1.5 degrees Celsius above the 1951-80 average and there is no other warmer pairing of years in the 330-year Central England Temperature series. Sunshine hours were also greatly above average and in some regions relatively windy conditions further boosted evaporation losses. 1991 and 1992 were less outstanding but still notable (see page 32).

A guide to the magnitude of evaporative demands over the recent past is provided by Figure 20 which shows average annual potential evaporation losses over the 1989-91 period. The range is considerable, from less than 450 mm in the Scottish Highlands to over 700 mm in parts of southern England. Equally important, the rates are substantially above the 1961-87 average in most regions. Typically, the 1989-91 annual average was 20% greater than the preceding average with anomalies exceeding 100 mm in parts of eastern Britain - largely those areas where even in a normal year rainfall and evaporation demands are comparable.

Record potential evaporation losses were registered in 1989 over much of Britain only to be eclipsed throughout much of the eastern lowlands in the following year. Table 11 includes the ranked annual PE totals for four representative MORECS squares. Throughout most of Britain, 1990 and 1989 rank first and second highest on record with 1991 and 1992 - commonly 1988 also - clustering in the top quartile. For the lower Thames Valley (MORECS square 161) the recent drought years account for four of the five highest annual PE totals. In southern England some, mostly coastal, locations registered PE totals exceeding 750 mm in both 1989 and 1990, totals which are more typical of southern Europe. Evaporation losses declined appreciably over the two succeeding years but generally remained well above average and, in the four-year timeframe, are without parallel, certainly over the 1960-88 period.

Actual evaporation 1988-92

Actual evaporation is a conservative variable, generally constrained from very high values by the restrictions imposed by deficiencies in soil moisture and from very low ones by virtue of the limited period, at least in the maritime west, over which the soil moisture conditions inhibit transpiration. Using the MORECS model, significant shortfalls of AE relative to PE do not generally occur until soil moisture deficits (SMDs) exceed 60-70 mm. However,

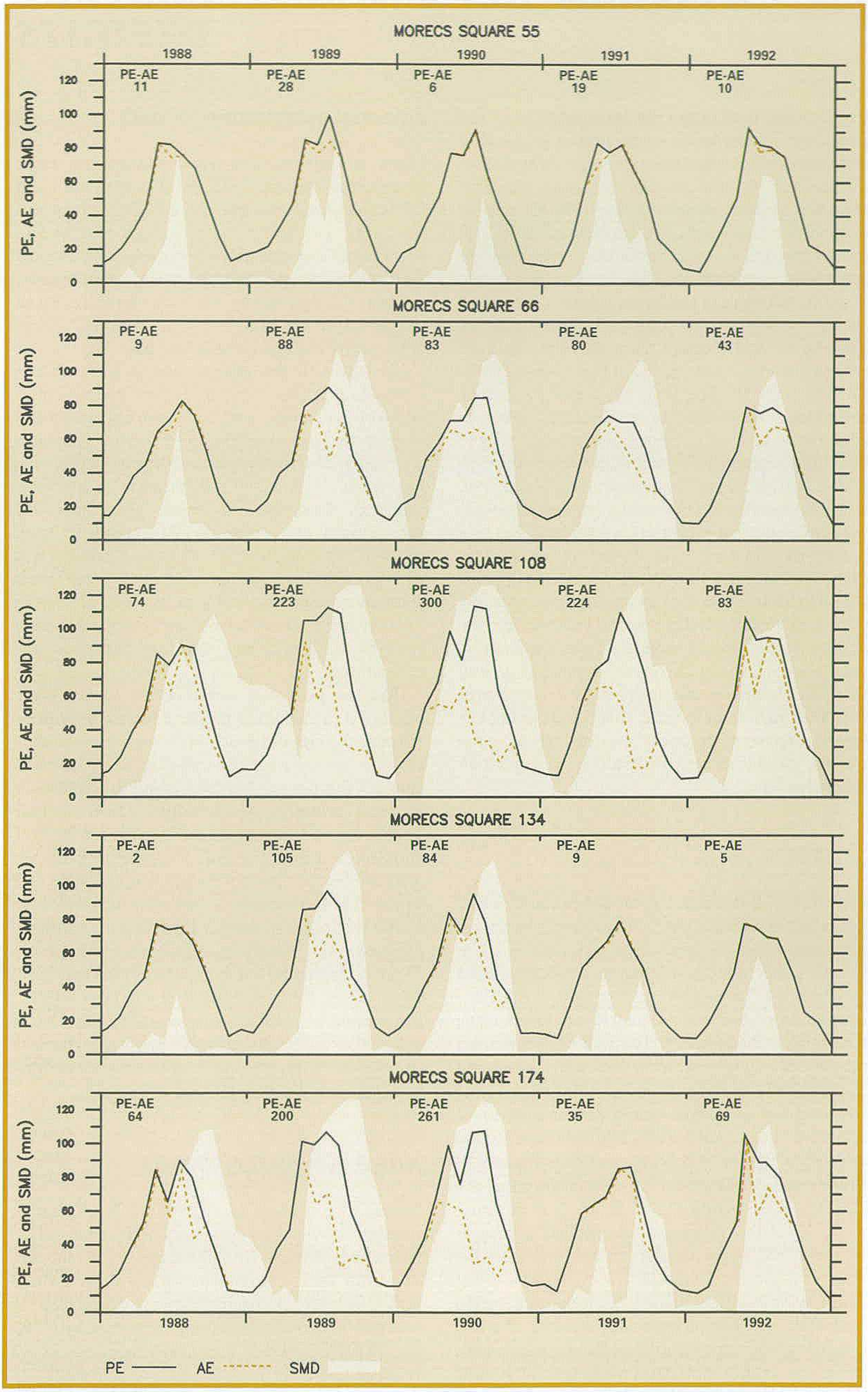


Figure 19 The variation in potential evaporation, actual evaporation and soil moisture deficits for five MORECS squares

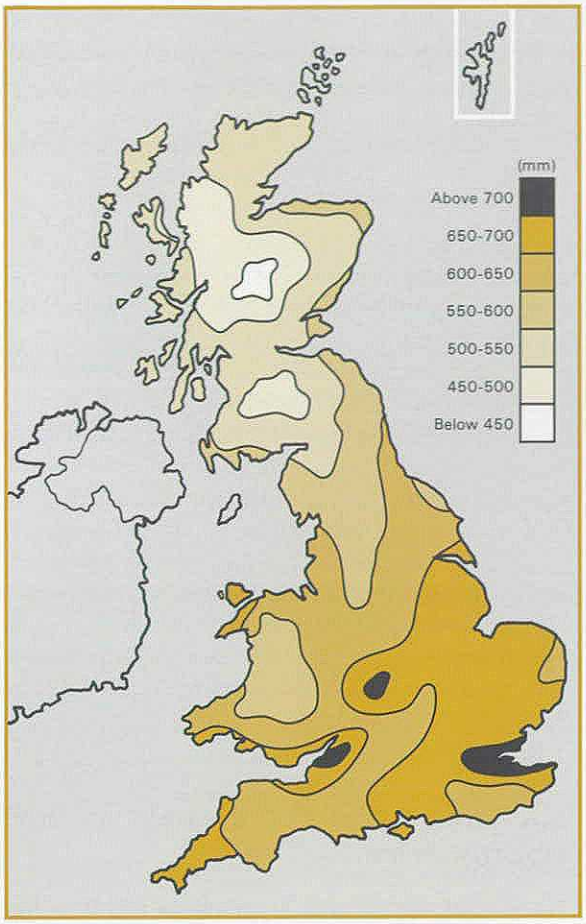


Figure 20 Mean annual potential evaporation 1989-91
Data source: MORECS

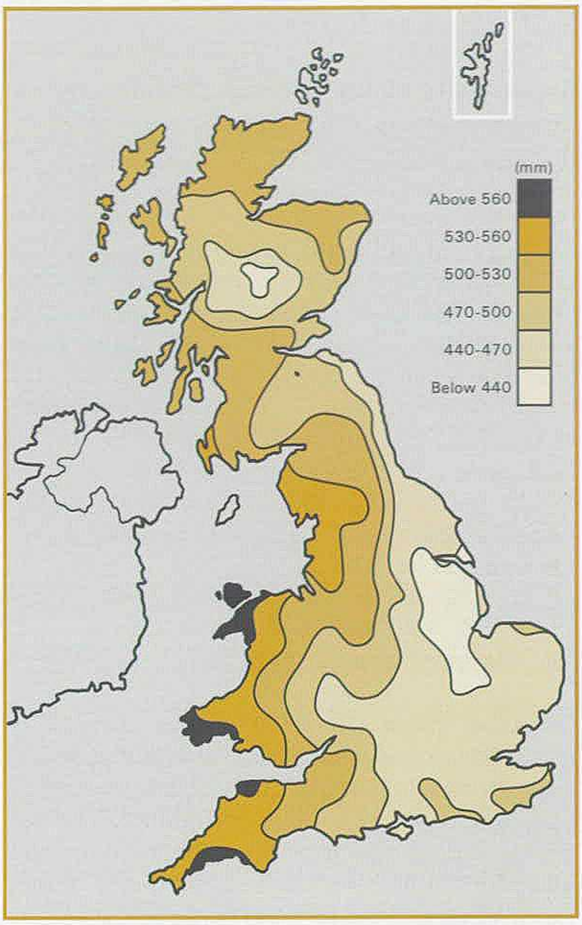


Figure 21 Mean annual actual evaporation 1989-91
Data source: MORECS

marked departures from the average may be expected during periods of exceptional weather especially if warm, dry conditions prevail. 1990 provides an instructive case study of the effect of a very unusual rainfall distribution - both in time and space. The wet winter (December 1989-February 1990) allowed evaporation close to the potential rate over wide areas. The rapid drying of lowland soils through the spring and into the summer of 1990 severely curtailed evaporation in the East and South-East and large shortfalls of AE relative to PE developed. Such shortfalls - their magnitude may be deduced from Table 11 - provide a guide to drought intensity, particularly in the agricultural context. Over wide areas the 1989 and 1990 shortfalls were easily the highest since 1976 and were more than twice the long-term average for the 1989-91 period throughout much of the English lowlands. In a broad zone from Humberside to the Isle of Wight, shortfalls exceeded 150 mm per year and were notable also to the west of the Cotswolds and along the north-eastern seaboard.

In an average year, a large measure of consistency exists between the PE and AE patterns. As a consequence of the parched soils, however, the patterns in the English lowlands were decidedly contrary over the 1989-91 period, maximum PE and minimum AE totals often being coincident. The annual PE and AE totals for Cambridgeshire (Table 11 - MORECS square 128) provides an illustration: the potential evaporation total for 1990 is the highest in the MORECS series by a substantial margin whereas 1976 is the only year with a lower computed actual evaporation total. By contrast, in the South-West figures for square 177 shows that in this more maritime region both PE and AE totals for 1990 were the highest on record.

Figure 21 maps average annual actual evaporation losses for 1989-91. As would be expected the overall range of AE totals is limited and there is a far larger measure of spatial coherence than in the corresponding PE map. Relative to the long-term mean, most areas in eastern, central and southern England registered annual AE totals significantly below average. By contrast, AE losses in much of Wales, the Lake District and most of Scotland were considerably above the 1961-87 mean. Very high evaporation totals, sometimes 20% above normal, were computed for a number of upland areas where strategically important reservoir systems are located.

Soil moisture deficits

Assessments of soil moisture content, unless measured directly, can be significantly affected by the type of water budgeting procedures, or model, used[30]. Normally some representation of land use is required to account for the known differences in the development and decay of soil moisture deficits under different covers. For consistency all data presented here assume a grass cover but in practice substantially higher deficits will have been encountered in the drought affected areas - for example under forests. The most significant feature of the SMD traces shown on Figure 19 are the exceptionally high late-summer and autumn values for the lowlands in 1989, 1990 and 1991 and the associated failure of the deficits to be satisfied over the winter in some areas.

Development and decay of SMDs 1988-92

Saturated soils early in 1988 were succeeded by generally parched conditions from late August and soils remained relatively dry well into the winter. Despite a wet spring in 1989 significant SMDs existed throughout the year in some eastern locations and exceptionally high deficits were registered during the summer and autumn. For instance, close to the mouth of the Thames estuary deficits above 100 mm were maintained from May to November. In the west (MORECS square 134), a new period-of-record maximum SMD value of 120 mm was recorded in August 1989. Over the summer months (June to August), calculated SMDs for most of southern Britain and the eastern seaboard exceeded the 1961-88 mean by some 20-80 mm. The maximum deficit for a grass cover (125 mm for the MORECS model) was reached in southern England as early as July. The areal extent of SMD maxima for grass, aggregated irrespective of the time of year, was almost identical for both 1989 and 1976; this pattern was repeated, broadly, in 1990. In August 1976, however, deficits considerably greater than 125 mm were calculated for ground cover other than grass and, in soil moisture terms, the summer drought was appreciably more severe than in 1989. On the other hand, heavy rain early in the autumn of 1976 led to a brisk decline in SMDs whereas in 1989 (and again in 1990) soils remained very dry and the extent of the area at maximum deficit by the end of September was remarkable.

Despite above, or close to, average rainfall over the 1989/90 winter half-year, SMDs in some eastern areas were not eliminated and, even where field capacity was reached during the very wet February, the warm and dry conditions in March produced a rapid increase in SMDs and the drying-out accelerated through the spring. By late-May 1990, SMDs exceeded 100 mm throughout large parts of eastern Britain, 60-80 mm being typical in a normal year, and very substantial deficits were once more maintained well into the autumn. In many lowland areas the late-September 1990 deficits were the equivalent of two or three months average rainfall. Generally in 1991 soils dried out far less rapidly in the spring and summer than in the previous two years and mid-summer SMDs were close to the normal range in the lowlands. Thereafter, however, the dry autumn resulted in a further, late, drying phase and in the lowlands deficits remained significant into the early winter.

In early 1992 the modest rainfall, combined with the significant SMDs which extended across wide areas at the end of 1991, resulted in soils returning to field capacity for no more than a couple of weeks in the driest areas before evaporation losses accelerated again through the spring. Thereafter, however, deficits developed only sluggishly and the wet spell from March to September heralded an early return to saturation in the autumn - an important factor in the drought's termination.

The severity of the drought in soil moisture terms

The persistence of very dry soils, as much as the magnitude of the maximum SMDs, underlined the very unusual nature of the 1988-92 period. In much of eastern Britain calculated SMDs remained above the 70 mm threshold for over six months in 1989, 1990 and 1991 - two or three times the average duration. The degree to which soil moisture conditions departed from normal in the recent past may be judged by reference to Table 12 which lists the number of months for which month-end SMDs exceeded 70 mm over the 1988-91 period for four widely distributed lowland MORECS squares. The corresponding figures for the preceding four-year periods in the MORECS series are also given. Although persistently dry soils characterised a number of individual years - 1976 and 1964 especially - in aggregate terms, the four years ending with 1991 may be seen as outstanding.

Effective precipitation and infiltration

Effective precipitation (EP) is defined as the difference between rainfall and actual evaporation (allowing for SMD). It represents the net water input from the atmosphere to the land surface and, as such, may be expected to correlate well with measured rates of runoff and estimates of aquifer recharge. A number of simplifying assumptions introduced to allow MORECS EP values to be readily computed limit their precision but Table 13 indicates that the three-year EP totals up until the beginning of 1992 were well below 50% of the long-term average for parts of eastern England. This shortfall was further increased over the first half of 1992.

In water resources terms, the implications of such modest EP totals is further emphasised by Figure 22 which maps average end-of-November SMDs for the 1989-91 period: it provides a telling hydrological illustration of eastern Britain's vulnerability to drought. In western and northern Britain early winter soils in 1988-92 were typically at, or close to, saturation as they are in most years. By contrast, large deficits remained in the lowlands with the three-year averages exceeding 60 mm in a broad zone from Yorkshire to Kent and, remarkably, average values of above 80 mm in a few districts close to the Thames estuary. Over large parts of the eastern lowlands of England the average late-November SMDs were between 30 and 60 mm above the pre-1988 mean.

The significance of such anomalies, and the implied dryness of the early winter soils, emerges more clearly when they are considered alongside the typical winter rainfall expected in the lowlands. In a substantial proportion of the South-East and East Anglia, the average late-November SMDs over the 1989-91 period were the equivalent of around six weeks rainfall, eight weeks in the drier areas. Crucially, this substantially restricted the window of opportunity for aquifer replenishment - to the Chalk especially - and infiltration was typically limited to several weeks rather than two or three months under normal circumstances.

Thus evaporative demands, and the associated parched soils, served to translate a 20-30% rainfall deficiency into a much greater shortfall in runoff and recharge rates.

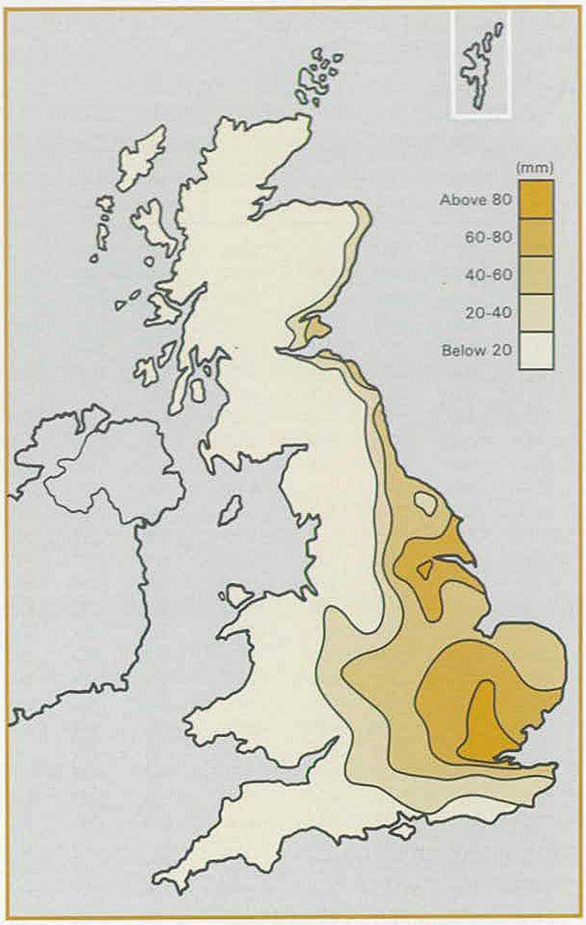


Figure 22 Mean end-of-November soil moisture deficits 1989-1991 Data source: MORECS

TABLE 11 RANKED MORECS ANNUAL POTENTIAL EVAPORATION AND ACTUAL EVAPORATION TOTALS (FOR A GRASS COVER)

MORECS square 108 (Humberside)				MORECS square 161 (Lower Thames Valley)				MORECS square 128 (Cambridgeshire)				MORECS square 177 (Devon)			
Yr	PE (mm)	Yr	AE (mm)	Yr	PE (mm)	Yr	AE (mm)	Yr	PE (mm)	Yr	AE (mm)	Yr	PE (mm)	Yr	AE (mm)
1990	721	1992	557	1990	742	1967	562	1990	725	1992	578	1990	666	1990	604
1989	695	1966	539	1989	731	1966	547	1989	689	1966	543	1989	662	1980	593
1976	650	1986	534	1976	672	1987	540	1976	683	1986	540	1984	627	1985	576
1992	640	1980	524	1992	647	1965	533	1975	646	1967	523	1975	615	1988	575
1991	622	1987	524	1991	637	1968	532	1992	638	1987	518	1976	605	1966	570
1970	617	1988	519	1984	627	1988	530	1970	638	1974	518	1980	604	1973	560
1986	617	1968	517	1970	612	1991	523	1961	636	1968	517	1992	592	1992	558
1975	616	1985	517	1988	612	1985	521	1967	626	1988	516	1961	587	1982	557
1982	608	1973	516	1967	598	1986	519	1974	621	1982	513	1985	583	1975	556
1967	607	1967	514	1986	598	1982	517	1964	621	1973	512	1988	583	1965	553
1964	606	1963	512	1969	594	1971	514	1986	619	1985	512	1983	582	1986	551
1984	606	1982	512	1985	591	1963	506	1991	612	1980	508	1977	577	1970	550
1961	597	1969	504	1983	588	1970	502	1984	606	1989	495	1982	575	1987	547
1988	594	1981	502	1961	586	1992	502	1973	591	1969	489	1966	573	1977	547
1983	591	1974	501	1975	586	1980	500	1983	590	1965	488	1973	566	1969	546
1974	583	1961	500	1964	583	1973	498	1985	587	1975	485	1962	565	1967	545
1977	581	1965	499	1973	578	1964	486	1982	586	1981	483	1970	562	1964	542
1985	579	1983	496	1974	578	1962	486	1962	582	1971	483	1987	560	1979	541
1981	577	1971	491	1982	575	1974	485	1988	581	1963	480	1991	559	1991	539
1965	572	1984	489	1966	571	1984	480	1980	580	1983	473	1967	558	1962	538
1962	567	1979	489	1972	565	1981	479	1979	580	1977	467	1965	557	1968	534
1966	567	1978	487	1987	565	1977	479	1965	579	1984	466	1986	555	1963	533
1980	566	1962	476	1971	561	1961	470	1966	578	1962	464	1969	555	1961	532
1963	566	1977	473	1965	558	1969	465	1977	573	1970	463	1964	554	1981	532
1979	561	1989	472	1968	554	1989	463	1969	569	1978	462	1981	552	1978	527
1971	556	1972	456	1962	551	1979	463	1971	568	1979	462	1979	550	1972	522
1973	552	1970	450	1963	551	1983	463	1963	563	1961	452	1978	550	1983	521
1987	550	1964	434	1980	549	1975	455	1972	555	1964	445	1968	540	1989	518
1968	546	1990	420	1977	536	1978	434	1987	553	1972	421	1963	538	1984	515
1978	541	1975	413	1979	531	1972	402	1981	549	1991	416	1972	536	1974	506
1969	540	1991	398	1978	514	1990	394	1978	543	1990	402	1974	511	1971	498
1972	528	1976	344	1981	506	1976	331	1968	540	1976	317	1971	505	1976	454
61-87 Av.	579		489		573		488		591		482		564		539

TABLE 12 NUMBER OF MONTHS WITH MONTH-END SOIL MOISTURE DEFICITS >70 MILLIMETRES

Period	MORECS Squares 101 (Humberside)	128 (Cambridge-shire)	161 (Lower Thames)	174 (Kent)
1988-91	25	23	27	17
1984-87	16	16	16	13
1980-83	14	17	11	11
1976-79	15	22	13	17
1972-75	18	23	16	14
1968-71	14	14	14	8
1960-63*	12	20	15	11

* Estimated

TABLE 13 RANKED ANNUAL EFFECTIVE PRECIPITATION FOR TWO MORECS SQUARES (1961-91)

MORECS Square 161		MORECS Square 108	
Year	EP (mm)	Year	EP (mm)
1973	0	1989	7
1989	8	1963	10
1991	17	1962	18
1986	53	1973	22
1990	101	1991	48
1972	106	1964	53
1963	110	1985	66
1984	112	1982	70
1965	113	1971	72
1969	121	1990	80
61-88 Av	164	61-88 Av	117

Note: Location of the MORECS squares featured on Figure 19: 55 - Lower Clyde Valley, 66 - Northumberland, 108 - Humberside, 134 - Central Wales, 174 - Kent

Given the ready availability of rainfall data, the density of the raingauge network and, crucially, the length of record for a number of index sites, it is understandable that most initial assessments of drought severity utilise rainfall figures. However, in hydrological and water resources terms runoff is the more significant variable. It assumes a particular importance when, as in 1988-92, drought conditions preferentially affect the drier regions of the country. In such areas the drought's impact depends largely on the balance between rainfall and evaporation losses. Errors in the assessment of the latter can be considerable and since - on an annual basis - they are of a similar magnitude to rainfall, any imprecision will have a substantial influence in determining indirect assessments of river runoff (and aquifer recharge). Fortunately the rapid growth in the network of flow measurement stations over the last 30 years provides a sound basis for monitoring drought development and assessing its severity. However, to successfully exploit the large amount of data potentially available it is essential to select river flow time series which are representative, sensibly continuous and of a reasonably consistent quality.

Problems of low flow measurement

Flow measurement in the United Kingdom does not present the difficulties of access, large velocity ranges and inadequate hydraulic conditions that are common in less hospitable environments. Nonetheless, the character of UK rivers is such that effective utilisation of hydrometric data can present a considerable challenge both to the data archivist and the analyst. Typically, UK rivers are short, shallow and subject to substantial artificial disturbance. The very limited depth places a premium on accurate sensing and recording of water level. The depth of major international rivers may be measured in metres whereas, under low flow conditions, depths of less than 100 millimetres are typical of many lowland streams in England, with even more modest depths characterising the headwaters. Under such circumstances a small systematic error in stage measurement, caused for example by algal growth on a weir crest, can materially affect computed flow rates. For river sections, summer weedgrowth can also greatly disturb the stage-discharge relation. Vigorous station maintenance and data quality assurance procedures are essential to protect the integrity of river flow data in the lowest flow ranges. In addition, the effect of abstractions and discharges (together with other more subtle impacts on the flow regime) require that particular care be exercised in the use of hydrometric data and the interpretation of analyses based on those data.

Changes in flow measurement techniques and the patterns of water utilisation within individual catchments often require a critical review of a station's hydrometric performance and the net impact of artificial influences on the flow regime in order to undertake meaningful historical comparisons.

Runoff in the 1980s

For the greater part of the decade beginning in 1980, runoff rates were generally above the preceding average especially in northern Britain. The result of the dry phase which began, over large parts of England and Wales, in the spring of 1988 was to produce catchment runoff totals for the 1980s which are broadly similar to, but still somewhat greater than, those for the preceding period of record. In runoff terms the positive anomalies were largest in western Scotland but still appreciable throughout much of England and Wales.

In a few southern catchments, including the Kent Stour and the Hampshire Test, the decadal mean flow for the 1980s fell a little short of that for the preceding record. More typically a modest increase in runoff may be identified and, at least in catchments away from the eastern seaboard, this may be partly attributed to the enhanced hydrological effectiveness of the rainfall consequent upon an appreciable change in its seasonal distribution (see page 13). The enhanced runoff in the 1980s relative to the previous two decades principally reflects high flows in the winter and spring periods. Overall, a small increase in the range of flows was associated with this reinforcement of seasonal contrasts. In many lowland catchments, however, the mild accentuation in the seasonality of rainfall was moderated - in terms of its hydrological impact - by the effects of aquifer storage. This served to create a significant lag between the enhanced March to June rainfall and its effect on runoff rates. Commonly the baseflow benefits were felt throughout the summer and autumn periods.

The last 100 years

Prior to 1960, the gauging station network was relatively sparse but sufficient long-term records exist - supplemented by rainfall and groundwater data - to demonstrate that runoff in the lowlands during the 1980s was well within the normal range when viewed in the context of the century as a whole. On the River Thames, for instance, runoff in the 1980s was a little above that for the preceding decade but

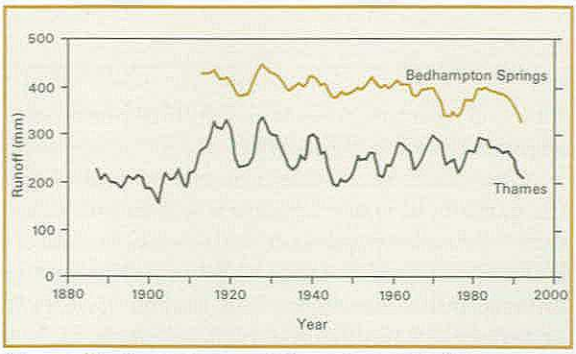


Figure 23 Long term catchment runoff - five-year running means

some 15 per cent below that registered in the decade commencing in 1910. The five-year running mean runoff plots presented in Figure 23 confirm that substantial temporal variations occur but that no compelling overall trend is discernible. The apparent long-term decline in runoff for the Bedhampton Springs (Hampshire) is, in part, a consequence of the series starting during a notably wet period.

The downturn in runoff rates in the recent past is evident from Figure 23 but emerges more clearly if annual runoff totals are examined - for example, the 1989-92 annual runoff totals for the Bedhampton Springs each rank amongst the lowest nine in a 95-year record. But here, as with the Thames, the accuracy band associated with the early data may be expected to be considerably wider than that for contemporary data.

Development of the drought

Early in 1988 rivers were in spate throughout most of the UK and catchment runoff totals in January were commonly amongst the highest on record. The subsequent steep decline in river flows heralded the initial phase of an extraordinarily protracted runoff deficiency. The drought's development, its partitioning in some areas into distinct hydrological phases, and its eventual decline is illustrated in the monthly flow hydrographs shown on Figure 24. The monthly mean flow over the 1988-92 period is shown for each featured gauging station together with the preceding average and an envelope of monthly extreme flows.

Evidence of the deteriorating hydrological situation during 1988 is provided by the failure of the normal autumn recovery in runoff rates to gain any real momentum in most catchments. From the late summer, monthly flows mostly remained within a relatively narrow band through into the spring of 1989. In January and February, monthly period-of-record minimum flows were superseded over wide areas and late winter runoff rates in the eastern lowlands were more typical of an average summer.

A much belated recovery over the March to May period in 1989 was followed by another protracted recession which resulted in especially depressed flows (relative to the monthly average) in July and September. Daily flows throughout much of Britain had declined by early autumn to around the pre-1989 seasonal minimum. In a few catchments, for example in South Wales, new absolute minimum flows were recorded. Runoff rates generally remained depressed into November which saw lowered monthly minima in some catchments in Northumbria and eastern Scotland.

1989-90

Daily minimum flows in 1989 were recorded exceptionally late in the year - a large number in November and even a few in early December[31]. From the second week, however, some remarkable flow recoveries occurred. The River Wye (Bucks) and the Quin (Herts), for example, recorded their maximum daily flow for 1989 within ten days of the minimum. Such transformations are rare in lowland chalk rivers although parallels could be drawn with the terminal phase of the 1929 drought. The increase in runoff rates continued in early 1990 and culminated in February which, for Great Britain as a whole, produced the largest monthly freshwater outflow for at least 30 years, and probably over a much longer timespan. Floodplain inundations showed a very wide distribution and were notably persistent. A few relatively small eastern catchments received less abundant rainfall and the recovery was less dramatic but in the early spring of 1990 evidence of drought conditions was very patchy. However, the volatile hydrological conditions then conspired to create another trough on what was becoming a hydrological rollercoaster ride. River flow recessions were exceptionally steep through the spring (see Figure 24) and continued with little interruption well into the autumn. In the lowlands the recessions were often the most extended since those following the widespread flooding in March 1947. A few rivers achieved the distinction of recording both their highest instantaneous flow and lowest daily mean in the same year.

Autumn 1990 runoff rates fell below the seasonal mean - by a considerable margin for rivers with flow records of less than about 25 years - throughout most regions. It is very unusual for such depressed flows to extend across almost all of Britain. In September both the Kent and Dorset Stours, for example, established new minimum runoff totals for the month and the Thames recorded its lowest naturalised flow since 1949. The September low flows ended a remarkable water-year - it was notable both for the range of flows recorded and the seasonal distribution of runoff. Many lowland rivers registered over three quarters of their water-year runoff total over the December-February period. In extreme cases - for example, the Turkey Brook in North London - around 90% of the runoff total was attributable to a 10-week period ending in late February 1990. Such a marked runoff seasonality is more commonly associated with catchments in southern Europe.

1991-92

In western and northern catchments, river flows increased substantially during October 1990 but, again, recoveries in the English lowlands were very sluggish. Recessions continued in most eastern rivers, particularly those supported principally by groundwater, through into the early winter. Relatively high surface runoff in the first quarter of 1991 suggested that the drought was abating but with baseflows depressed following limited recharge over the preceding three years, a further dry period which began in the late summer produced exceptionally low flows.

Virtually no seasonal recovery could be recognised in the autumn of 1991 in the majority of lowland rivers, and monthly runoff rates remained remarkably stable, as well as exceptionally low, in many chalk catchments. For example, monthly mean flows for the River Itchen showed a variation of less than +/- 20% over the nine months beginning in August 1991. Artificial augmentation from groundwater was a significant factor, but the very unusual consistency in flow rates resulted in monthly runoff totals declining from above average in July 1991 to the lowest on record (for the month) in February 1992. The depressed nature of the late winter river flows in the east is perhaps best exemplified by the Lee in Hertfordshire. Mean flows for each of the winter months (December-February) were the lowest in a 110-year record and the runoff over the winter half-year, around a quarter of the long-term average, is also without recorded precedent.

Rainfall in the spring of 1992 moderated the meteorological drought but, because of the accelerating evaporation demands through the spring, arrived too late in the lowlands to have any great influence on runoff. Recessions were certainly much less steep than in the preceding four years but by the late summer many of the minimum accumulated runoff totals established during the 1976 drought for spring-fed rivers were eclipsed in eastern England.

Termination of the drought

Whilst the meteorological drought declined in severity from March 1992 the limited effective rainfall over the 1992 summer half-year and, in much of eastern and southern England, the extremely low contribution of ground water to river flows, led to a very protracted terminal phase to the runoff drought. Catchment geology exercised a strong influence on the recovery in river flows. In some western impervious catchments flow rates returned to the normal range in the spring of 1992 whereas, for a few baseflow dominated rivers in the east runoff rates were still in decline in the autumn. However, notably wet soil conditions from late September ensured that over the final quarter of the year flow increases were brisk. Lowland flooding was common late in September, impervious catchments in East Anglia being worst affected, and by year-end the focus of hydrological stress had shifted to flood vulnerability throughout much of the UK[21]. Flows in many lowland spring-fed rivers responded more sluggishly but abundant rainfall over the 15 months from July 1992 ensured that flows were restored to most headwater reaches by the autumn of 1993.

Shrinkage in the drainage network

The depressed runoff rates over much of eastern and southern Britain during the 1988-92 period were associated with a shrinkage in the stream network that is without modern parallel; the corresponding loss of amenity and aquatic habitat was considerable. Generally, the environmental problems were most acute in lowland spring-fed rivers where the perennial head migrated downstream as declining water-tables caused successively lower spring sources to fail (see cover).

From late-1990 especially, lengthy stretches of dried-up river bed were reported over wide areas. By 1992, headwater river networks were greatly diminished relative to a decade earlier and in much of eastern England appreciably less extensive than at the height of the 1976 drought. Importantly, shrinking headwaters could be readily identified in areas where the effect of abstractions on river flows is very modest - for example, in parts of the Yorkshire Wolds[32]. The problem of climatically-induced low flows was, however, exacerbated in those catchments where groundwater pumping, often over many years, has steadily reduced river flows. Since its creation in 1989, the National Rivers Authority has examined various strategies for combating the effect of groundwater abstraction on low river flows[33] and rehabilitation programmes are now well advanced on, for example, the Ver (Hertfordshire) where the cessation of pumping from a major supply borehole in the headwaters has allowed groundwater levels to rise and should ensure a more healthy aquatic environment during future drought episodes.

Whilst the deleterious effects of rising abstraction rates were clearly evident during 1989-92, the

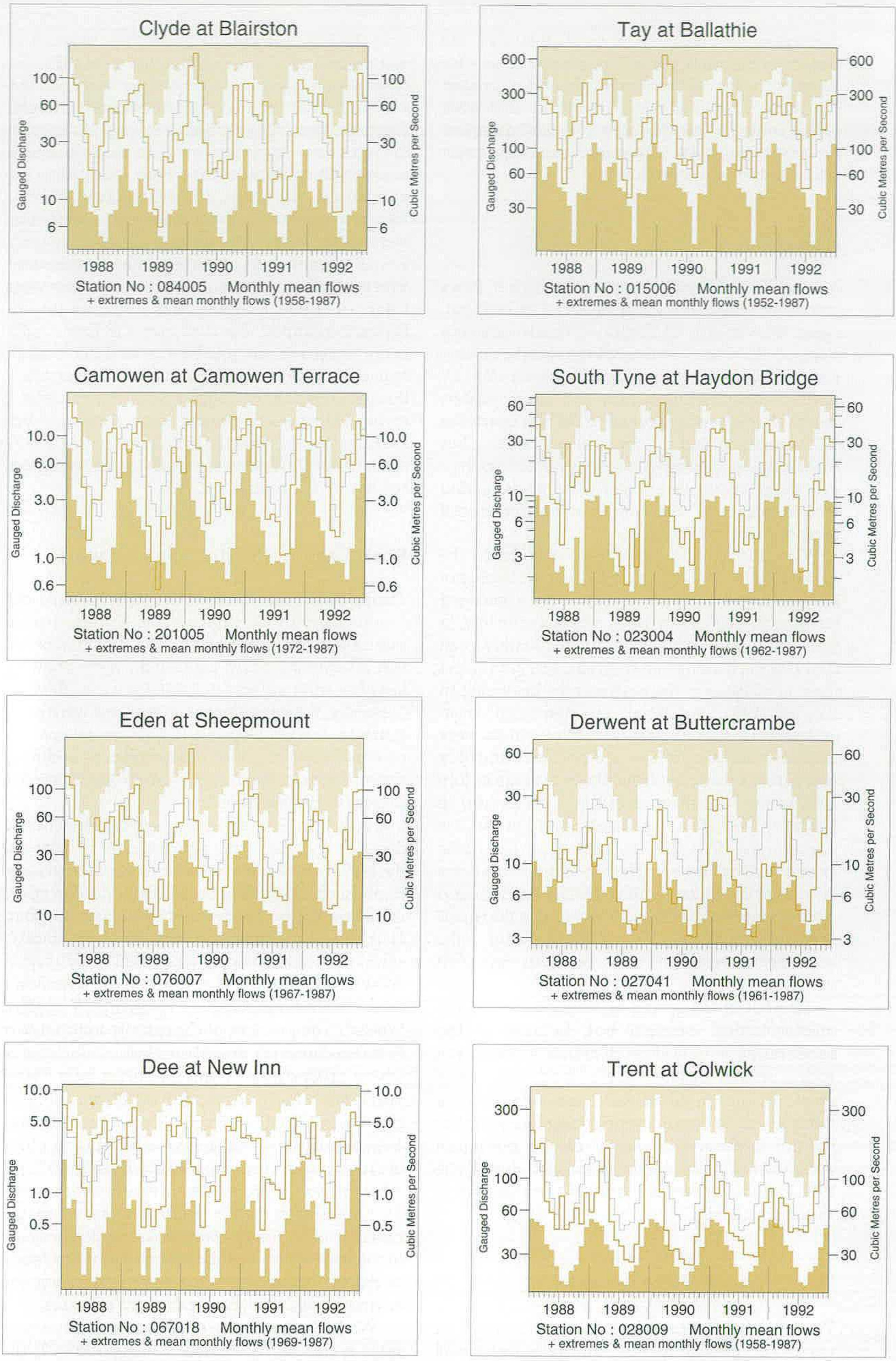


Figure 24 1988-92 monthly river flow hydrographs

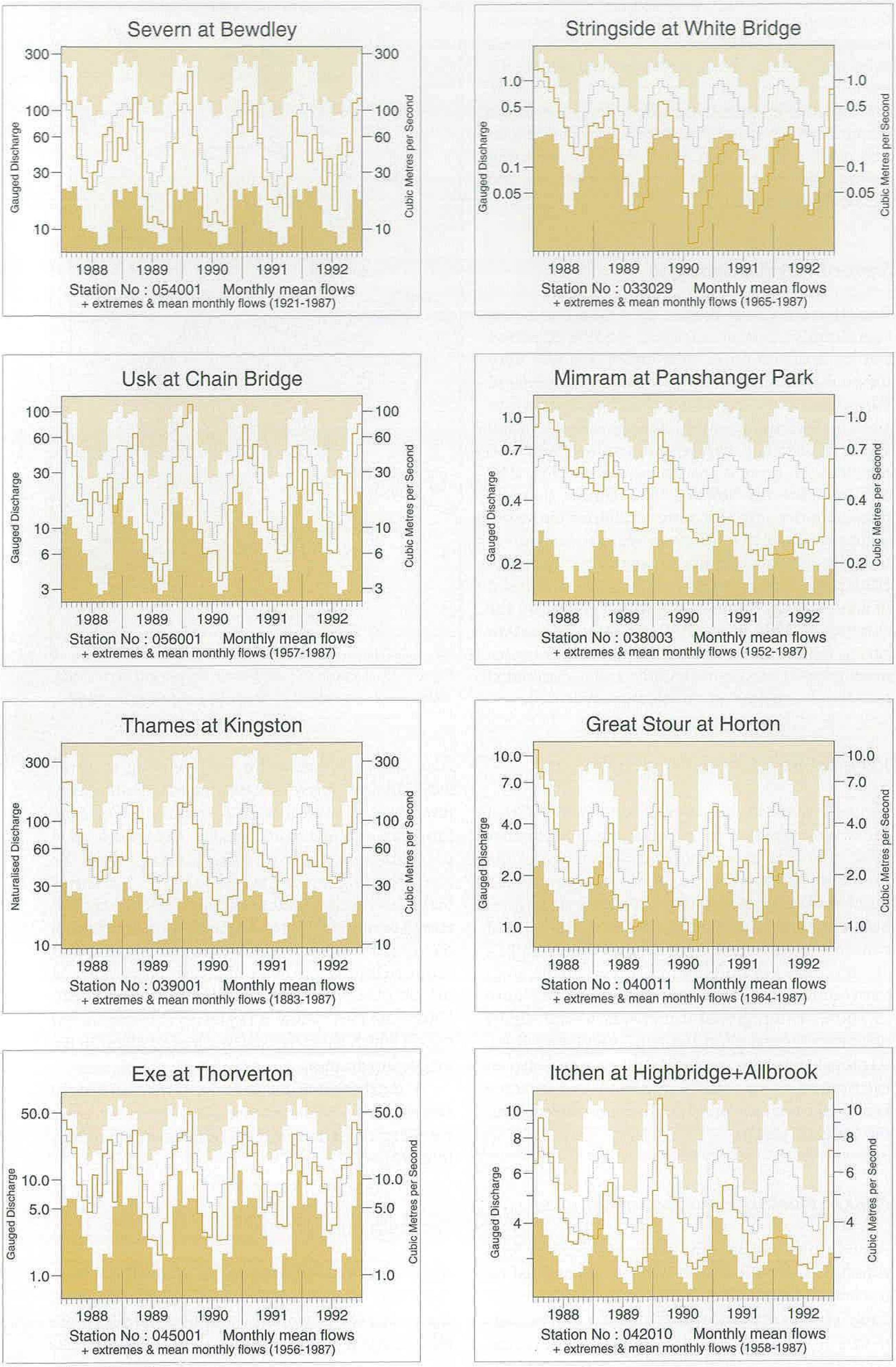


Figure 24 continued

increasingly important contribution made by water management to the maintenance of low flows needs to be emphasised. Procedures involved include the use of regional transfers (e.g. the Ely-Ouse Scheme), groundwater augmentation of low flows (e.g. on the Hampshire Itchen and the Little Ouse in East Anglia) and other methods (e.g. flow enhancement using sewage effluent, controls on abstractions and demand restrictions).

Severity of the drought

Runoff from Great Britain as a whole was not significantly below average over the 1988-92 period but its distribution in time and space was very unusual. Seasonally very low flows characterised the autumn and early winter of each of the first four years of this sequence over large parts of eastern and southern Britain. Very low summer flows were also registered in more maritime regions in 1989, 1990 and, in a few catchments, 1992. During its early phases the drought was more notable for the length of time over which low flows were sustained rather than the absolute minima registered but, from late 1990, period-of-record daily minima were eclipsed in a substantial number of lowland rivers. By the summer of 1992 monthly flows in some eastern spring-fed rivers had remained below average for more than 40 successive months and accumulated runoff deficiencies were often unprecedented.

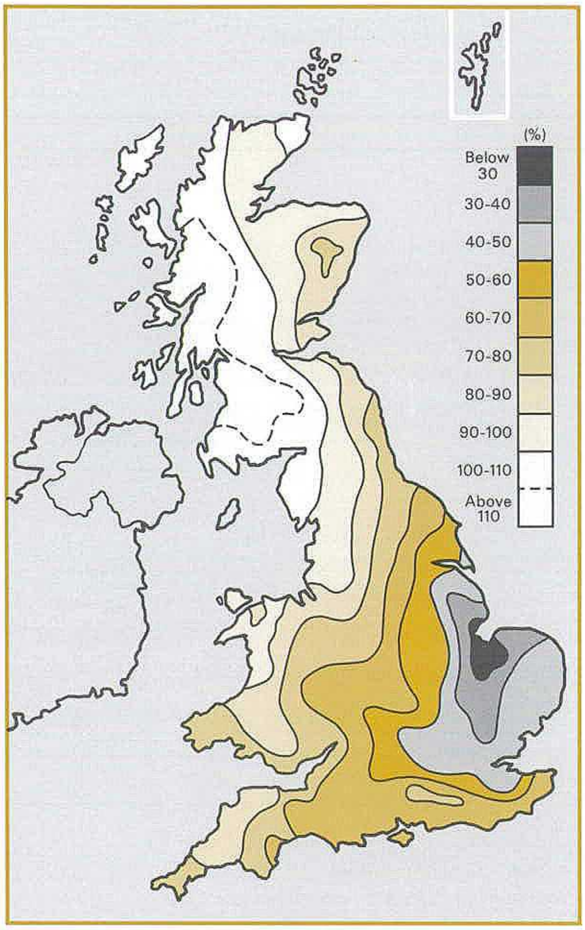


Figure 25 A guide to runoff over the period Sept 1990 - Aug 1992, expressed as % of the long-term average

Regional variation in runoff deficiency

Figure 25 maps the variation of runoff across Great Britain over the two years beginning in September 1990; runoff is expressed as a percentage of the preceding average. The map is based on a restricted number of index catchments but clearly underlines both the remarkable exaggeration in the normal runoff gradient across Britain and the drought's greater impact in runoff terms relative to the long-term rainfall deficiency (see page 31). Whilst Figure 25 shows the regional dimension to the runoff deficiency to good effect, the map is very generalised. At more local scales, geological differences between catchments were readily apparent and in some headwater areas no runoff at all occurred throughout the featured period.

Ranked monthly runoff accumulations

A guide to the outstanding nature of the longer term runoff accumulations over 1988-92 is provided by the entries in the right-hand group of columns in Table 14. This presents runoff totals for four periods over which the drought was generally most severe. Also shown are runoff details relating to three individual months when catchments exhibiting very low flows showed a wide distribution. For each timeframe, the runoff is also expressed as a percentage of the preceding average and the corresponding ranking is given. Table 14 confirms that runoff accumulations for the 27-month and 40-month periods ending in August 1992 are the lowest on record for many catchments in eastern and southern Britain and the April-September runoff total in 1990 is also without precedent in many catchments. Figures for the Clyde and Tay testify to the abundant runoff which characterised much of Scotland in the longer timeframes.

A more searching examination of drought severity can be undertaken if runoff deficiencies are considered for n-month periods starting in any month.

N-month minima

Although noteworthy sequences of low flows were registered within each year of the 1988-92 period, the overall severity of the drought is indexed more effectively when accumulated runoff totals are examined in timeframes ranging from about six to 60 months. Table 15 ranks minimum n-month runoff accumulations (for any start month) for a selection of catchments; only the lowest accumulation is presented for each end-year but the ranking in parentheses relates to the entire population of n-month totals. The recent accumulations are outstanding for many lowland catchments; commonly, the 24-month period beginning in July 1990 produced lower runoff totals than any previously registered. The difference between the 1990-92 accumulations and the deficiency associated with the next highest ranking drought provides a guide to the severity of the recent drought. On the Rivers Leven, Lud and Kennet, for example, the 24-month minima are only three-quarters, or less, of the previous minima. For the Stringside, a small spring-fed chalk stream, the margin is considerably greater. However, the extent to which previous minima have been superseded also often reflects the fact that the average length of UK gauging station records is less than 25 years.

Rankings of 24-month minimum flows for the River Thames (Table 16) suggest that the 1990-92 gauged (or measured) runoff is outstanding. However, this is largely a result of increasing upstream abstractions to meet the growing water supply needs of the London area. Abstraction rates have increased by almost an order of magnitude over the last 100 years and now represent the equivalent of the average August gauged flow. After adjustments to allow for the impact of the major abstractions, the revised rankings - those relating to the naturalised flows - suggest that only during the 1901-03 and 1933-35 droughts have lower 24-month flows occurred this century[32]. The significance of these historical minima is almost certainly exaggerated by the tendency of low flows to be underestimated prior to the major refurbishment of Teddington Weir in 1951. Even more strictures apply to the pre-1883 records for nearby Thames Ditton, where extremely low accumulated runoff totals were reported in the late 1850s, mid 1860s and early 1870s[34] but the uncertainty associated with the flow measurement technique used implies that only broad comparisons can be drawn with recent droughts. For the Bedhampton Springs which have a flow record extending back to 1908, the recent event eclipsed all previous droughts in the 12-, 24- and 48-month timeframes. Over the longer durations the 1988-92 runoff accumulations were, typically, a little below those registered in the 1971-76 period and considerably lower than the minimum recorded in the 1940s.

N-day minima

Examination of the minimum daily and n-day flows recorded for each year provides a means of indexing drought severity and comparing periods of notably deficient runoff. During the recent drought, rivers draining largely impermeable catchments in southern and eastern Britain registered notable low n-day flows in the autumns of 1989 and 1990. Many lowland rivers draining permeable catchments recorded unremarkable minimum flows early in the drought but the very protracted decline in baseflows gave rise to extremely low flows beginning around the summer of 1990. Table 17 confirms that only in parts of eastern England, mostly East Anglia, were the 7-day minima established at the end of the intense 1975/76 drought superseded over the 1989-92 period. However, the margin by which the 240 day-minima for the recent drought in many eastern catchments fell below the corresponding minima in 1976 testifies to the exceptional nature of low flows in the longer timeframes. The River Wissey (Norfolk) drains a catchment where the drought remained severe throughout most of 1989-92. A new minimum daily mean flow was registered in September 1991 but the drought's severity is better indexed by runoff over periods of six months or more: for example the 1989-92 240-day annual minima each fell below the minimum for the preceding record.

Table 18 provides ranked annual n-day minimum flows for six representative catchments. The pre-eminence of the 1989-91 low flows is clearly evident in both the responsive Leven (a tributary of the Tees in Cleveland) and the spring-fed Itchen (where low flows were augmented from groundwater over the 1989-91 period).

Frequency of occurrence of n-day minima

The rankings given in Table 18 provide a rough guide to the likely frequency of low river flows in particular catchments. However, it is possible to examine the low flow sequences within a more rigorous statistical framework which allows return periods to be ascribed to individual runoff episodes. Figure 26 shows a flow frequency diagram for the River Great Stour at Horton; the procedure for producing such diagrams is described fully in the Low Flow Studies Report[35]. The curves indicate the average interval in years (or return period) between flows falling below a given discharge - expressed here as the percentage of the mean flow. The plots may be derived from the lowest daily discharge in each year or from flows averaged over longer durations. Three such plots are shown corresponding to 30-, 120- and 240-day durations. The return period axis allows the frequency of any particular annual minimum to be estimated. For instance a 120-day annual minimum flow of around 30% of the long-term mean would be expected to occur, on average, about once every 30-40 years.

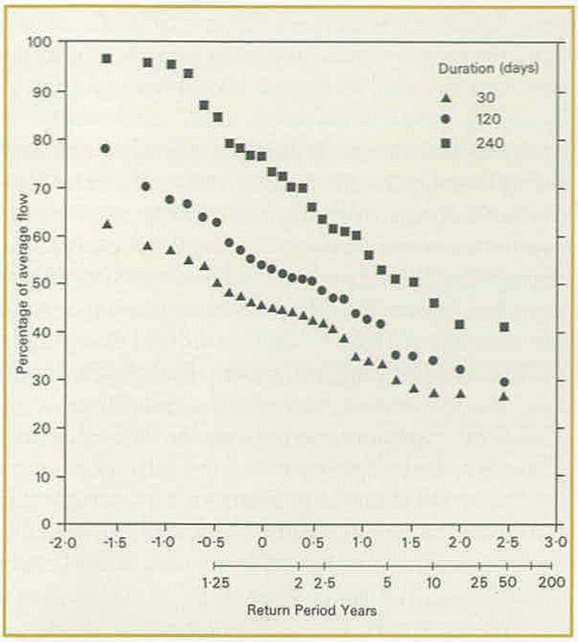


Figure 26 Flow frequency diagram for the Great Stour at Horton

This type of low flow analysis was repeated for a selection of catchments throughout Britain and the resulting return periods are presented in Table 19. The initial set of return periods are based upon the flow record up to and including 1987, the second set incorporate the 1988-92 flows. Using the pre-1988 flows as the reference period, many of the recent drought flows qualify as exceptionally, or extremely, rare. As data for each subsequent year is incorporated in the analysis, the return periods generally decrease markedly. The contrasting results are considered further on page 41.

Problems of low flow measurement together with the difficulties of fully quantifying the impact of artificial influences imply that ascribing a recurrence frequency to recent low flows needs to be done with particular care. The impact of climate change may also complicate the assessment of statistical rarity. Nonetheless, the extremely low flows which typified most of the four years up to the autumn of 1992 clearly underline the need for a continuing careful appraisal of the ability of watercourses to support particular levels of abstraction.

Runoff deficiency indices

The limited length of most runoff series has inhibited the development of runoff deficiency indices in the UK but a similar approach to that used for rainfall (page 22) can help assess the relative severity of droughts over the post-1950 period especially. In the wetter, responsive catchments which characterise most of western and northern Britain, drought indices based on rainfall and river flow tend to produce very similar results. Considerable differences may be expected in the eastern lowlands of England,

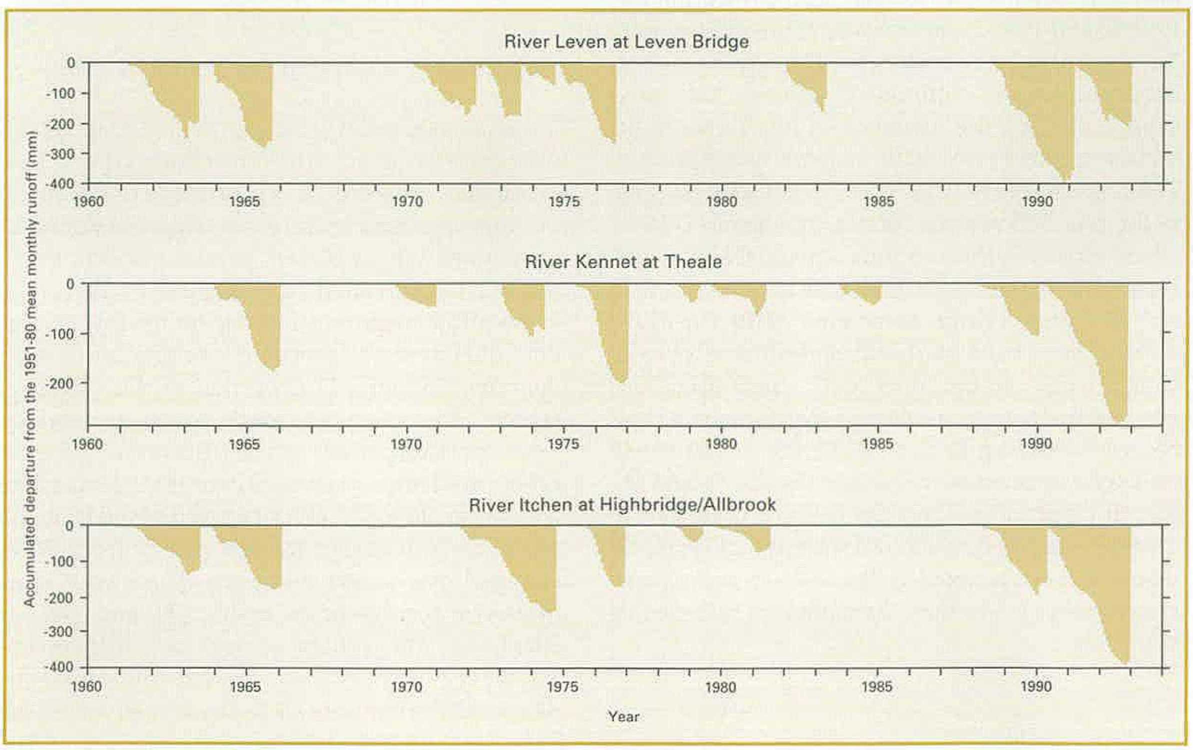


Figure 27 Runoff deficiency indices for the Rivers Leven, Kennet and Itchen (note: a drought is considered to have terminated when runoff exceeds the average over a three-month period).

however, where the moderating influence of baseflow is important in many catchments.

Figure 27 shows that for three index catchments the recent drought is appreciably more severe than any over the last 35 years: it is over this period that the great majority of UK river flow data has been collected. Extending the frame of reference to include earlier drought sequences is complicated by the paucity of long, validated flow records. As indicated on page 33, those that do exist often need to be used with considerable caution.

The re-definition of low flow regimes since 1988

The limited length of flow record for the great majority of the 1300 gauging stations in the national network implies that significant variations in flow statistics are to be expected as additional data are added. Nonetheless, changes in the recent past in the medium and low flow range in England have been exceptional.

In the context of the last 15 years, 1988 may be considered as something of a hydrological watershed throughout much of England. It marked the end of a relatively wet sequence of years which followed the 1976 drought and signalled the beginning of a period over which the recorded range of runoff for many lowland rivers has been extended downwards. Data presented on pages 47 and 48 provide evidence of the degree to which low flow statistics especially have been revised in the recent past.

Figure 28 illustrates the average monthly flow anomalies over the drought period (August 1988 - July 1992) relative to the average for the preceding record for an East Anglian river together with corresponding data for a catchment in western Scotland. The percentage anomalies underline the extraordinary regional contrasts in runoff conditions; many Scottish catchments have recorded very high recent runoff with increased flood frequencies. Figures presented in Table 20 confirm that average flows over the four years from the summer of 1988 were commonly 30-60% below the preceding average in lowland catchments and the effect of this depressed runoff can be detected even in flow records of 25 years or more.

The flow exceeded 95 per cent of the time is an important low flow index widely used in river management, for instance to help determine abstraction arrangements. Table 20 indicates that a 30 % decrease over the 1989-92 period relative to the preceding record may be identified for the River Lud. Very substantial reductions in 95% exceedance flows occurred in smaller rivers draining parts of East

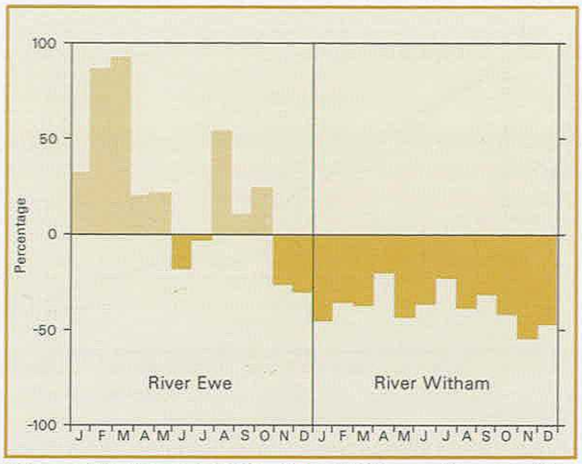


Figure 28 August 1988 - July 1992 runoff anomalies for the Rivers Ewe and Witham

Anglia. On the Waithe Beck (Lincolnshire) and River Heacham (Norfolk), for example, 95 percentiles were only around 20-30% of the pre-1988 values and average flows were similarly depressed. For the Little Ouse, which is a considerably larger river, the decrease in flows is less dramatic but low flows over the 1989-91 period benefited considerably from groundwater augmentation by the Great Ouse Groundwater Scheme. The flow duration curves for the Great Stour and the Thames (Figure 29) testify to a significant recent reduction throughout the great majority of the flow range and this is true of many lowland catchments.

Low flow return periods

With notably low flows registered in many lowland rivers in each of the drought years, the rarity associated with any given low flow sequence would be expected to diminish considerably between the pre- and post-drought eras. Commonly, n-day minima which would have been ascribed 20-30 year return periods in 1988 now qualify as events to be expected, on average, one in only five to ten years. Over the longest durations, order of magnitude reductions in return periods associated with given low flows are not unusual. Very extreme contrasts may be identified at sites where flow measurement commenced after the 1976 drought.

Such changes in return periods emphasise the dangers of undertaking low flow analyses with short records. Nonetheless, our perception of regime variability is, necessarily, influenced greatly by data assembled over the last quarter of a century, and the water management implications of the markedly greater frequency now associated with sustained low runoff rates are considerable.

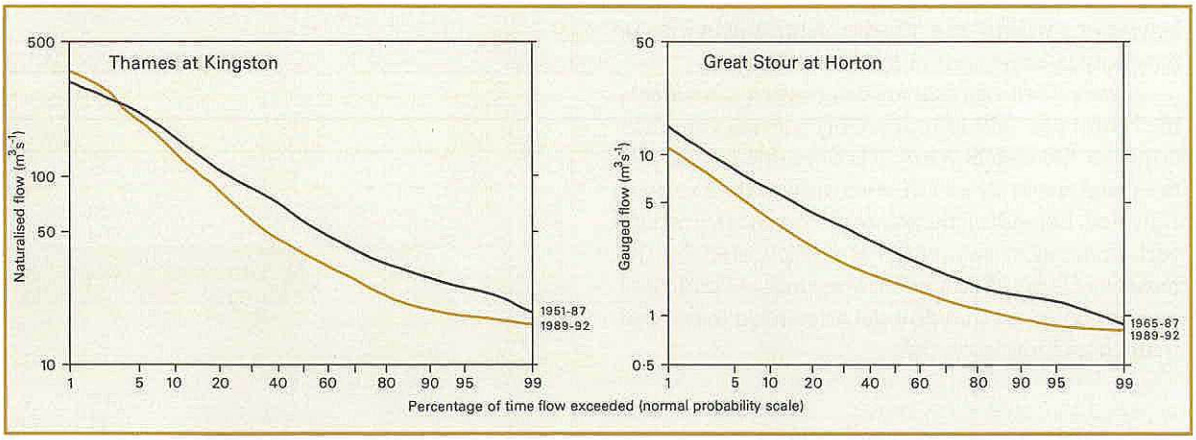


Figure 29 A comparison of pre- and post-1988 flow duration curves for the Great Stour and the Thames

TABLE 14 CATCHMENT RUNOFF ACCUMULATIONS FOR SELECTED PERIODS 1989-92

River/ Station	Sep 1989		Sep 1990		Feb 1992		4/90 to 9/90		9/91 to 8/92		6/90 to 8/92		5/89 to 8/92	
	mm %L	rk y	mm %L	rk y	mm %L	rk y	mm %L	rk y	mm %L	rk y	mm %L	rk y	mm %L	rk y
Dee at	30	6	23	4	38	3	164	1	634	3	1474	4	2124	2
Park	73	17	56	18	53	20	59	20	80	20	88	19	84	18
Tay at	69	20	42	10	111	24	299	8	1225	32	2468	24	3969	29
Ballathie	97	37	59	38	104	40	83	40	108	40	103	39	110	38
Whiteadder Water	7	3	8	6	21	4	52	1	305	6	781	9	966	5
at Hutton Castle	45	21	51	22	44	23	42	23	78	24	95	22	77	21
South Tyne at	8	1	23	5	62	15	105	1	734	10	1547	10	2243	4
Haydon Bridge	15	26	42	27	93	30	46	29	97	28	95	26	92	24
Wharfe at	10	2	14	4	48	13	100	1	606	8	1297	5	1902	3
Flint Mill Weir	23	34	32	35	63	37	44	37	84	37	85	36	83	35
Derwent at	6	1	5	1	15	3	48	1	168	3	467	3	646	1
Buttercrambe	42	28	35	29	37	31	43	31	52	31	67	30	61	29
Trent at	9	2	9	2	16	1	66	2	225	2	525	1	840	1
Colwick	54	31	54	32	38	34	53	34	64	34	69	33	74	32
Lud at	7	3	8	4	7	2	62	6	85	2	208	1	363	1
Louth	60	22	74	23	21	24	54	24	33	24	39	23	45	22
Stringside at	1	1	0	1	5	2	22	4	40	2	79	1	152	1
White Bridge	19	24	8	25	20	27	37	26	26	27	25	24	32	22
Colne at	3	5	2	1	5	2	21	4	58	4	132	2	245	1
Lexden	69	30	46	31	28	33	53	33	43	33	47	32	58	31
Mimram at	6	5	5	4	4	1	48	8	55	1	143	1	267	1
Panshanger Park	79	37	63	38	34	40	78	40	44	40	52	39	65	38
Thames at	6	27	5	11	12	9	50	19	130	9	295	5	549	6
Kingston*	67	107	56	108	36	110	63	110	53	110	57	109	70	108
Coln at	10	2	10	2	32	8	111	4	275	6	582	2	1017	4
Bibury	69	26	69	27	59	29	73	29	70	29	69	28	80	27
Witham at	4	8	3	5	9	7	33	2	98	3	224	2	387	4
Claypole Mill	63	31	54	32	33	33	50	33	54	34	58	33	66	32
Great Stour at	8	1	6	1	15	2	59	2	163	1	399	1	608	1
Horton	56	25	42	26	44	28	58	26	56	26	64	24	65	22
Itchen at High-	20	2	20	3	25	1	177	7	284	1	705	1	1158	1
bridge & Allbrook	75	31	75	32	51	34	86	34	62	34	70	33	77	32
Piddle at	9	2	8	1	24	3	105	3	270	3	610	1	1035	3
Baggs Mill	58	26	51	27	41	29	73	29	68	28	71	26	80	24
Exe at	16	7	10	5	37	4	84	2	589	2	1367	3	2126	5
Thorverton	40	34	25	35	36	36	41	36	72	37	80	36	82	35
Taw at	11	12	5	4	34	4	46	3	449	2	1113	2	1807	5
Umberleigh	44	31	20	32	41	34	31	34	65	34	78	33	85	32
Tone at	8	3	7	2	27	4	60	2	284	2	637	1	1152	2
Bishops Hull	51	29	44	30	37	32	48	32	61	32	65	31	78	30
Severn at	6	5	6	6	22	8	51	1	316	7	732	8	1174	10
Bewdley	27	69	27	70	38	71	40	72	70	72	77	71	83	70
Wye at	100	8	121	11	131	12	496	7	1906	11	4263	8	6294	5
Cefyn Brwyn	60	37	72	38	78	38	68	38	93	35	94	28	94	23
Cynon at	15	2	20	5	55	5	150	2	961	4	2305	6	3769	13
Abercynon	21	31	28	32	43	34	46	34	77	33	88	31	95	29
Dee at	36	4	73	6	102	5	320	4	1526	4	3323	2	5022	2
New Inn	25	21	51	22	64	23	61	23	85	24	87	22	88	21
Eden at	15	3	19	4	57	9	128	2	633	8	1415	9	2145	8
Sheepmount	33	19	41	20	88	22	63	22	92	21	98	19	99	17
Clyde at	33	9	36	10	90	22	204	11	946	27	1916	25	2843	25
Daldowie	56	26	61	27	131	29	88	29	121	29	116	28	116	27

Notes: *Values are based on gauged flows except for the Thames at Kingston where naturalised data have been used.
y = years; rk = rank: values are ranked so that lowest runoff is rank 1.
%L means percentage of long-term average. Runoff totals are rounded to the nearest millimetre.

TABLE 15 RANKED N-MONTH RUNOFF ACCUMULATIONS

Station	Durations (months) 12				24				48			
	Year/month end		Runoff (mm)	Rank (all)	Year/month end		Runoff (mm)	Rank (all)	Year/month end		Runoff (mm)	Rank (all)
25005	1989	12	110	(1)	1990	11	255	(1)	1992	3	708	(1)
	1976	8	116	(2)	1991	1	326	(11)	1965	1	794	(13)
Leven at	1965	3	121	(3)	1965	8	340	(12)	1976	8	804	(19)
Leven Bridge	1964	12	125	(8)	1963	2	349	(13)	1991	12	812	(23)
1959-1992	1992	3	127	(11)	1992	2	385	(26)	1964	12	872	(34)
	1990	1	128	(14)	1976	8	399	(28)	1974	8	908	(37)
	1973	3	138	(24)	1989	12	402	(37)	1973	12	919	(45)
	1963	1	164	(44)	1974	8	405	(42)	1966	1	922	(48)
	1962	10	167	(51)	1973	3	417	(50)	1975	11	940	(58)
	1975	12	179	(61)	1962	12	434	(65)	1990	11	962	(70)
29003	1976	9	79	(1)	1992	9	178	(1)	1992	12	482	(1)
	1992	4	79	(2)	1991	12	221	(13)	1976	12	625	(11)
Lud at	1991	12	83	(9)	1974	9	268	(25)	1977	1	647	(19)
Louth	1973	9	121	(31)	1990	12	275	(28)	1975	2	676	(24)
1968-1992	1977	1	128	(39)	1975	1	306	(40)	1991	12	695	(26)
	1974	1	130	(40)	1973	9	313	(43)	1974	12	701	(29)
	1990	1	133	(42)	1976	12	331	(54)	1978	1	793	(57)
	1989	12	137	(44)	1977	1	342	(63)	1973	12	810	(62)
	1975	1	176	(77)	1978	1	404	(91)	1979	1	939	(90)
	1972	2	187	(81)	1972	12	407	(94)	1990	12	959	(92)
39001N	1976	9	88	(1)	1992	3	264	(1)	1992	7	691	(1)
	1992	3	127	(8)	1965	11	354	(12)	1965	8	807	(13)
Thames at	1965	8	127	(9)	1991	12	358	(13)	1956	12	809	(16)
Kingston	1973	12	134	(18)	1974	8	362	(14)	1957	1	811	(17)
1952*-1992	1954	2	145	(30)	1954	5	364	(17)	1991	12	812	(19)
	1974	1	152	(38)	1973	12	372	(20)	1965	7	808	(16)
	1956	7	155	(43)	1957	7	373	(22)	1966	1	825	(24)
	1953	12	163	(57)	1956	12	387	(57)	1976	9	827	(26)
	1963	2	165	(61)	1990	12	396	(65)	1955	12	887	(70)
	1989	11	168	(65)	1966	1	396	(69)	1977	1	889	(72)
									1973	12	891	(73)
39016	1976	9	106	(1)	1992	6	322	(1)	1992	8	820	(1)
	1992	7	140	(8)	1965	12	414	(12)	1966	1	953	(13)
Kennet at	1977	1	152	(12)	1977	1	420	(14)	1976	12	958	(14)
Theale	1965	10	153	(16)	1966	1	424	(15)	1965	12	962	(15)
1961-1992	1991	12	184	(29)	1976	12	432	(18)	1991	12	972	(16)
	1973	12	190	(38)	1991	12	446	(24)	1977	1	972	(17)
	1966	1	194	(41)	1990	12	476	(46)	1978	12	1099	(60)
	1974	1	197	(44)	1974	8	478	(54)	1973	12	1107	(74)
	1989	11	202	(46)	1973	12	494	(60)	1974	1	1111	(69)
	1963	2	212	(51)	1978	1	510	(79)	1980	1	1126	(80)
33029	1991	5	30	(1)	1992	6	74	(1)	1992	10	207	(1)
	1992	1	38	(11)	1991	12	97	(12)	1991	12	340	(13)
Stringside at	1990	1	57	(24)	1990	12	120	(25)	1974	8	440	(20)
White Bridge	1973	9	57	(25)	1974	9	151	(32)	1976	9	441	(24)
1965-1992	1976	8	58	(31)	1973	12	186	(45)	1975	1	484	(41)
	1989	12	60	(32)	1975	1	231	(59)	1973	12	506	(51)
	1974	1	68	(49)	1989	12	243	(61)	1977	1	517	(54)
	1986	10	111	(78)	1986	12	253	(62)	1990	12	523	(55)
	1987	1	116	(80)	1987	1	254	(65)	1987	7	545	(76)
	1982	9	117	(86)	1972	12	274	(81)	1989	12	577	(87)
40011	1992	8	163	(1)	1973	8	374	(1)	1974	7	909	(1)
	1989	11	164	(2)	1974	1	388	(5)	1973	12	976	(11)
Great Stour at	1973	12	165	(5)	1972	12	475	(23)	1975	1	996	(14)
Horton	1974	1	179	(16)	1982	4	525	(34)	1982	5	1091	(28)
1964-1992	1990	1	181	(18)	1981	8	529	(38)	1976	8	1093	(29)
	1991	4	186	(26)	1975	1	558	(49)	1981	8	1113	(46)
	1976	9	191	(33)	1980	5	566	(54)	1972	12	1150	(62)
	1972	11	198	(45)	1979	12	578	(57)	1979	12	1174	(65)
	1984	9	236	(85)	1971	12	592	(75)	1980	1	1190	(71)
	1981	11	255	(95)	1977	12	596	(78)	1977	1	1225	(87)
42010	1992	8	284	(1)	1992	8	630	(1)	1992	1	1417	(1)
	1976	10	302	(8)	1974	8	731	(12)	1991	12	1560	(13)
Itchen at	1974	1	319	(14)	1990	12	747	(17)	1976	12	1633	(15)
Highbridge	1973	12	325	(15)	1973	12	752	(21)	1965	12	1648	(25)
& Allbrook	1989	12	328	(18)	1991	1	755	(24)	1977	1	1649	(30)
1958-1992	1990	1	341	(24)	1965	12	763	(35)	1966	1	1654	(32)
	1991	5	340	(28)	1966	1	775	(46)	1990	12	1665	(35)
	1965	8	345	(36)	1989	12	788	(58)	1974	1	1689	(48)
	1977	1	354	(38)	1963	6	816	(66)	1973	12	1699	(49)
	1966	1	385	(69)	1977	2	822	(73)	1989	12	1725	(65)

TABLE 15 continued

Station	Durations (months)											
	12				24				48			
	Year/month end		Runoff (mm)	Rank (all)	Year/month end		Runoff (mm)	Rank (all)	Year/month end		Runoff (mm)	Rank (all)
52005	1976	8	168	(1)	1992	3	595	(1)	1992	10	1450	(1)
	1964	12	250	(9)	1976	9	639	(10)	1976	8	1473	(5)
Tone at	1973	12	263	(12)	1965	11	639	(11)	1965	5	1477	(6)
Bishops Hull	1991	2	273	(13)	1973	12	726	(25)	1966	1	1612	(33)
1961-1992	1992	7	282	(14)	1963	2	738	(41)	1974	1	1663	(38)
	1965	6	296	(22)	1974	1	760	(45)	1991	10	1669	(40)
	1963	1	297	(23)	1977	1	772	(48)	1973	12	1685	(46)
	1989	10	311	(29)	1964	12	780	(49)	1975	12	1694	(51)
	1974	1	316	(34)	1990	12	798	(52)	1990	12	1700	(53)
	1975	12	330	(47)	1991	12	802	(57)	1977	1	1723	(68)

* A major refurbishment of Teddington Weir was completed in 1951

TABLE 16 MINIMUM 24-MONTH RUNOFF TOTALS FOR THE THAMES AT KINGSTON/TEDDINGTON

Gauged Runoff			Naturalised Runoff		
End Year	Runoff (mm)	%LTA	End Year	Runoff (mm)	%LTA
1992	120	29.1	1935	246	50.9
1935	179	43.6	1903	255	52.8
1945	200	48.8	1891	260	53.8
1949	210	51.1	1992	265	54.8
1903	211	51.3	1945	270	55.9
1923	218	52.9	1923	272	56.1

LTA = long-term average

TABLE 17 A COMPARISON BETWEEN N-DAY MINIMA IN 1976 AND 1989-92

	1976			1989-92 (year of occurrence in brackets)		
River and station	7-day	30-day	240-day	7-day	30-day	240-day
Don at Haughton	2.906	3.224	7.852	2.954 (90)	3.359 (90)	5.126 (89)
Whiteadder Water at Hutton Castle	0.877	1.087	3.427	0.970 (90)	1.025 (90)	1.618 (89)
Leven at Leven Bridge	0.096	0.121	0.665	0.158 (90)	0.186 (90)	0.419 (90)
Derwent at Buttercrambe	2.762	3.025	8.153	2.854 (90)	2.978 (90)	5.312 (90)
Trent at Colwick	15.489	16.897	31.352	21.629 (90)	22.821 (90)	34.502 (90)
Lud at Louth	0.091	0.096	0.135	0.074 (91)	0.079 (91)	0.115 (91)
Stringside at White Bridge	0.021	0.031	0.095	0.010 (90)	0.011 (90)	0.063 (90)
Mimram at Panshanger Park	0.139	0.143	0.206	0.175 (92)	0.198 (91)	0.234 (92)
Thames at Kingston*	9.646	10.819	21.629	15.186 (90)	17.180 (90)	25.621 (90)
Coln at Bibury	0.194	0.199	0.284	0.310 (90)	0.322 (90)	0.507 (90)
Great Stour at Horton	0.771	0.867	1.459	0.762 (90)	0.839 (90)	1.305 (90)
Itchen at Highbridge	2.210	2.303	3.003	2.414 (92)	2.570 (92)	3.104 (92)
Taw at Umberleigh	0.229	0.356	5.922	0.647 (89)	0.834 (89)	3.991 (90)
Brue at Lovington	0.098	0.115	0.563	0.172 (90)	0.193 (90)	0.400 (90)
Cynon at Abercynon	0.292	0.332	1.423	0.331 (89)	0.419 (89)	1.423 (90)
Kent at Sedgwick	0.610	0.713	4.533	0.517 (89)	0.656 (89)	4.480 (89)

*Based on naturalised flows

TABLE 18 RANKED ANNUAL MINIMUM N-DAY FLOWS

	N-day minima							
	30-day		60-day		120-day		240-day	
River/ Gauging station	Year	Flow (m^3s^{-1})	Year	Flow (m^3s^{-1})	Year	Flow (m^3s^{-1})	Year	Flow (m^3s^{-1})
River Leven at	1976	0.121	1976	0.146	1964	0.239	1964	0.326
Leven Bridge	1990	0.186	1990	0.194	1990	0.272	1990	0.419
	1964	0.188	1964	0.202	1991	0.324	1989	0.459
Period of record	1960	0.228	1989=	0.280	1975	0.331	1991	0.524
	1989	0.240	1991=	0.280	1989	0.343	1962	0.590
1959-1992	1972	0.254	1975	0.284	1992	0.367	1970	0.613
	1965	0.256	1970	0.292	1961	0.370	1976	0.665
	1961	0.257	1961	0.296	1972	0.393	1975	0.693
	1991	0.264	1972	0.298	1962	0.399	1961	0.745
	1975	0.267	1992	0.304	1970	0.418	1982	0.763
Stringside at	1990	0.011	1990	0.013	1990	0.018	1990	0.063
White Bridge	1989=	0.027	1992	0.031	1989	0.035	1991	0.089
	1991=	0.027	1989=	0.032	1991	0.044	1989	0.093
Period of record	1992=	0.027	1991=	0.032	1992	0.048	1992	0.123
	1976	0.031	1976	0.033	1976	0.052	1976	0.148
1965-1992	1986	0.068	1986	0.076	1986	0.086	1973	0.149
	1973	0.075	1970	0.081	1975	0.098	1986	0.210
	1970	0.076	1974	0.083	1974	0.104	1972	0.221
	1974	0.081	1973	0.086	1973	0.106	1977	0.245
	1975	0.087	1975	0.089	1970	0.108	1974	0.250
Itchen at	1976	2.303	1976	2.389	1976	2.520	1976	3.003
Highbridge/	1992	2.570	1989	2.688	1989	2.796	1992	3.104
Allbrook	1989	2.575	1992	2.704	1973	2.804	1973	3.112
	1959	2.637	1973	2.738	1992	2.836	1989	3.313
Period of record	1973	2.651	1959	2.757	1990	2.867	1990	3.338
	1990	2.736	1990	2.777	1959	3.026	1991	3.522
1958-1992	1991	2.834	1991	2.964	1991	3.091	1965	3.826
	1961	2.956	1961	3.102	1978	3.267	1988	3.940
	1987	3.064	1972	3.120	1961	3.301	1959	3.965
	1972	3.070	1978=	3.134	1972	3.303	1962	3.971
			1987=	3.134				
Kennet at	1976	1.264	1976	1.460	1976	1.834	1976	2.781
Theale	1990	3.241	1990	3.438	1990	3.753	1965	4.546
	1991	3.437	1989	3.643	1989	3.905	1990	4.619
Period of	1989	3.473	1991	3.648	1991	4.007	1991	4.802
Record	1965	3.628	1978	3.895	1965	4.038	1992	4.182
	1978	3.756	1965	3.912	1992	4.166	1973	5.118
1961-1992	1984	3.757	1992	3.929	1973	4.238	1989	5.310
	1992	3.788	1984	4.000	1984	4.382	1962	5.902
	1973	3.952	1964	4.101	1978	4.393	1975	6.131
	1964	4.030	1973	4.159	1963	6.500	1984	6.179
Coln at Bibury	1976	0.199	1976	0.201	1976	0.221	1976	0.284
	1990	0.322	1990	0.351	1990	0.375	1973	0.474
Period of	1973	0.341	1973	0.361=	1973	0.386=	1990	0.507
Record	1975	0.347	1975	0.361=	1975	0.386=	1975	0.581
	1989	0.388	1989	0.405	1989	0.459	1984	0.683=
1963-1992	1972	0.393	1972	0.410	1972	0.460	1989	0.683=
	1991	0.420	1991	0.438	1964	0.479	1988	0.687
	1978	0.432	1964	0.441	1984	0.493	1991	0.730
	1964	0.434	1984	0.449	1991	0.510	1972	0.735
	1984	0.439	1978	0.459	1978	0.524	1978	0.738
Brue at	1976	0.115	1976	0.133	1976	0.172	1990	0.400
Lovington	1990	0.193	1990	0.213	1990	0.239	1989	0.492
	1970	0.213=	1989	0.233	1989	0.265	1975	0.525
Period of	1989	0.213=	1972	0.248=	1984	0.282	1984	0.550
Record	1984	0.216	1984	0.248=	1972	0.313	1976	0.563
	1972	0.236	1987	0.271	1970	0.316	1972	0.700
1964-1992	1974	0.242	1975	0.279	1974	0.334=	1970	0.759
	1991	0.258	1974	0.286	1975	0.334=	1973	0.807
	1975	0.264	1978	0.297	1987	0.346	1991	0.816
	1987	0.266	1970	0.312	1969	0.401	1987	0.858

TABLE 19 A COMPARISON OF RETURN PERIODS BASED ON N-DAY MINIMUM FLOWS PRIOR TO 1988 AND UP TO 1992

River/Station	30 days				120 days				240 days			
			Return periods				Return periods				Return periods	
	Year of Min.	Rank	pre-1988	pre-1993	Year of Min.	Rank	pre-1988	pre-1993	Year of Min.	Rank	pre-1988	pre-1993
Don / Haughton	1990	3	10-20	10-20	1989	2	15-25	15-25	1989	1	40-60	25-40
Whiteadder / Hutton Castle	1990	2	5-10	5-15	1989	2	10-20	10-20	1989		20-30	15-25
Leven / Leven Bridge	1990	2	10-20	10-20	1990	2	30-40	20-30	1990	2	40-60	20-30
Derwent / Buttercrambe	1990		25-40	10-20	1991		60-80	15-25	1990		>200	20-30
Trent / Colwick	1990		10-20	10-15	1990	3	10-20	10-20	1990		25-40	15-25
Lud / Louth	1991		150-250	25-35	1991		150-250	60-90	1991		80-120	35-50
Stringside / White Bridge	1990		>200	30-40	1990		>200	40-50	1990		>200	30-40
Little Ouse / Abbey Heath	1991		10-20	5-15	1990	2	10-20	5-15	1991		40-60	20-30
Mimram / Panshanger Park	1991		10-20	10-20	1992	2	15-25	10-20	1992		20-30	15-25
Thames / Kingston (N)*	1990		50-70	20-30	1990	2	150-250	25-35	1990		>200	35-50
Coln / Bibury	1990	2	15-20	10-20	1990	2	15-25	10-20	1990	2	20-30	10-20
Great Stour / Horton	1990		30-40	10-20	1990		80-120	25-35	1990		>200	25-35
Itchen / Highbridge †	1992		10-20	10-20	1989	2	15-25	10-20	1992		40-60	20-30
Taw / Umberleigh	1989	1	5-10	5-10	1989	3	10-20	10-20	1990		30-40	25-35
Brue / Lovington	1990	2	5-15	5-15	1990	2	20-30	15-25	1990		80-120	30-40
Cynon / Abercynon	1989		10-20	5-15	1989		40-60	25-35	1990		5-10	5-15
Kent / Sedgwick	1989	2	20-30	10-20	1989	2	10-20	10-20	1989	3	5	5

*From 1952, after refurbishment of the measuring structure. (N) = naturalised flow. † includes Allbrook

TABLE 20 A COMPARISON BETWEEN PRE-1988, POST-1988 AND FULL-RECORD FLOW STATISTICS

River/ station	C/A (km^2)	First year of record	Mean Flow				95% Exceedance Flow			
			>1988	88-92	Full record	% change 88-92	>1988	89-92	Full record	% change 88-92
Leven at Leven Bridge	196.3	1960	1.95	1.17	1.85	-5	0.28	0.22	0.27	-4
Lud at Louth	55.2	1969	0.48	0.21	0.44		0.14	0.09	0.12	-14
Heacham Bk at Heacham	59.0	1965	0.22	0.07	0.20		0.06	0.02	0.05	[illegible]
Kennet at Theale	1033.4	1962	9.71	7.21	9.5		4.03	3.33	3.83	
Great Stour at Horton	345.0	1965	3.32	2.21	3.18		1.26	0.86	1.08	-14
Stringside at White Bridge	98.8	1966	0.54	0.17	0.49		0.09	0.02	0.05	-44
Waithe Beck at Brigsley	108.3	1961	0.32	0.11	0.30		0.08	0.03	0.06	-25
Little Ouse at Abbey Heath	699.3	1969	3.9	2.24	3.75	-4	1.32	0.988	1.14	-14

C/A = catchment area

Background

Groundwater accounts for about a third of public water supplies in England and Wales. Over large parts of eastern and southern England groundwater is the principal source of supply and is drawn chiefly from the Chalk and Upper Greensand aquifer. Groundwater is also a major component in the flow of many rivers and streams, often providing the bulk of the summer discharge. Overall, groundwater abstractions constitute around one-quarter of the natural replenishment to aquifers in England and Wales each year but geographical variations are large and in some areas sustainable resources are more than fully utilised, leading to declining water-tables and reduced spring flows.

Effective management of groundwater resources requires the marshalling and exploitation of a considerable volume of hydrological information and groundwater level data. Routine monitoring of water levels is carried out at over 2000 wells and boreholes throughout Britain. However, hydrological assessments of drought severity rely heavily on data from the minority of monitoring sites where the impact of groundwater abstractions on natural water level variations is minimal. Notwithstanding the limited precision of some historical groundwater level data, very valuable information concerning the normal range of variation in water-tables, and their behaviour under drought conditions, is furnished by a small number of wells with records extending back 100 years or more. One of these, the Chilgrove borehole in the Chalk of West Sussex where regular measurements began in 1836[36], is thought to have the longest continuous record in the world.

Groundwater levels 1976-88

Water tables rose rapidly following the unprecedentedly low groundwater levels registered in the autumn of 1976 throughout much of eastern and southern England[37]. This recovery heralded a relatively quiescent period during the early and mid-1980s when groundwater levels in most major aquifers remained close to, but normally above, the average. The regular seasonal cycle of groundwater level decline and recovery was well demonstrated over this period but became noticeably irregular from the spring of 1988, and barely identifiable in some eastern aquifer units over the ensuing four years.

Heavy and sustained recharge over the 1987/88 winter raised water-tables in most areas to their highest level for at least a decade. At the Washpit Farm borehole which penetrates the Chalk and Upper Greensand aquifer in Norfolk, the water-table in the late spring stood at its highest in a 40-year record. Similarly, levels at Therfield - a deep well south of Royston (Hertfordshire) - were closely comparable to their highest for 70 years. Subsequent recessions were, however, dramatic and extended.

Development of the drought

The groundwater hydrographs illustrated on pages 50 and 51 provide clear evidence of the very widespread and marked departures from average conditions which characterised water-table variability from 1987. Each hydrograph shows the groundwater level trace for 1988-93 together with the monthly average and extreme levels for the preceding record.

1988-90

The 1988 recession began early in most aquifers and continued in some regions, with only minor interruptions, until beyond year-end. Typically, the fall in groundwater levels following the late winter/early spring peaks was about twice that for an average year. The persistence of dry soil conditions over the last quarter of 1988 reduced substantially the opportunities for appreciable recharge in the lowlands and, generally, aquifer replenishment during the 1988/89 winter half-year was the lowest since 1975/76 (see page 57). Recharge totals of less than half the long-term average typified much of the Chalk and signified the start of the first severe phase of the groundwater drought. In almost all areas the 1988/89 recovery was not only weak but also greatly delayed. This delay was beneficial in the sense that the wet spring in 1989 resulted in an upturn at a time when levels are normally in steep decline. As a consequence, water-tables mostly remained within the normal range through the summer but thereafter the continuing recessions made for a very fragile resources outlook by the late autumn. The singular nature of the storage depletion over the 20 months up to December 1989 becomes clear when the decline in groundwater levels over this period is compared with earlier two-year declines[31] - see Table 21. For borehole records of less than about 30 years duration the 1988/89 fall is generally unprecedented. This is also true of some sites with records extending over 100 years.

Recharge over the 1989/90 winter was again modest in parts of eastern England, particularly over the Chalk outcrop from Humberside to Kent. To the west, recharge was generally above average, and in some districts greatly so, but - as in the east - the water-table recovery needed to be generated from

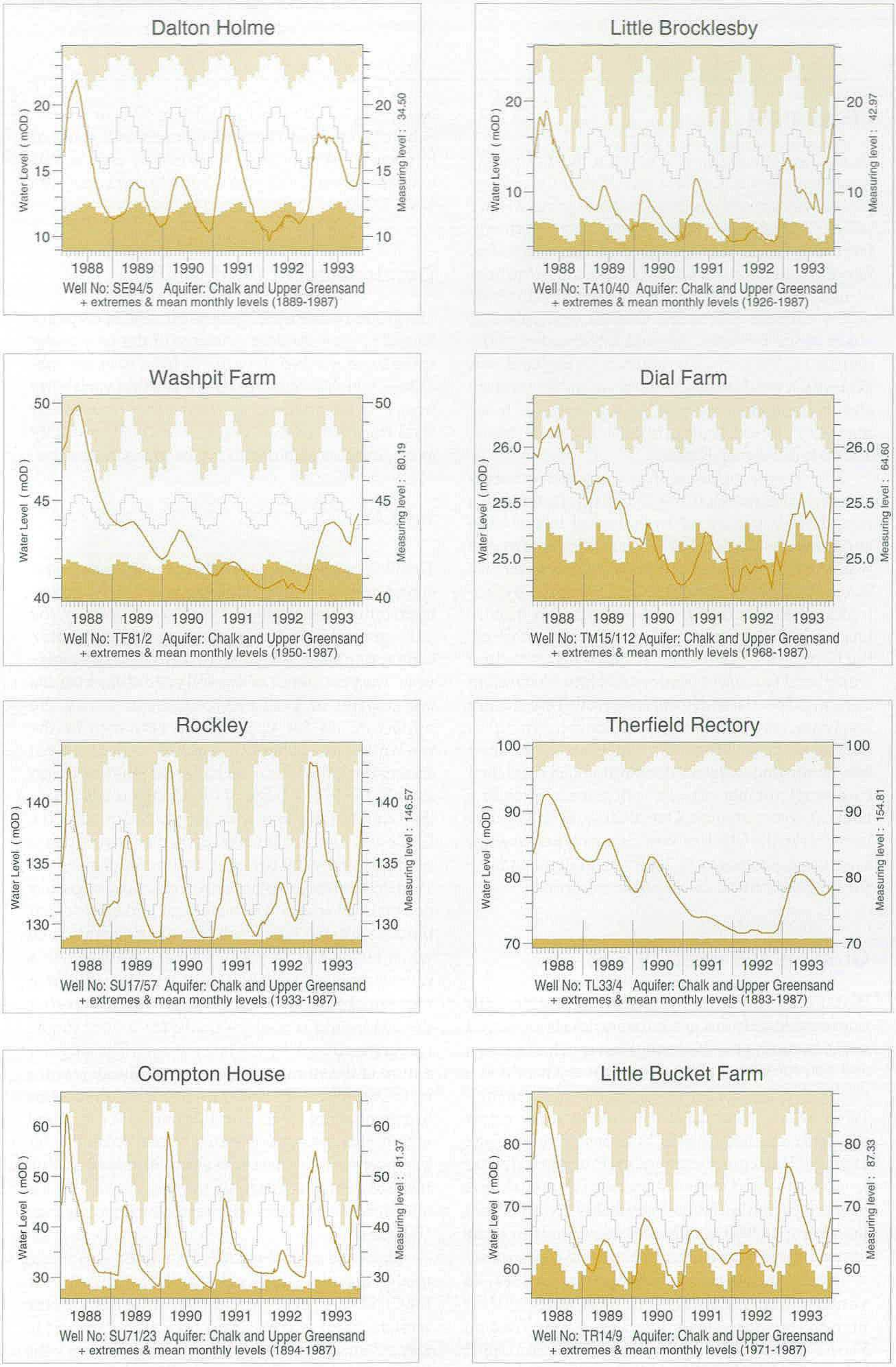


Figure 30 1988-92 groundwater level hydrographs

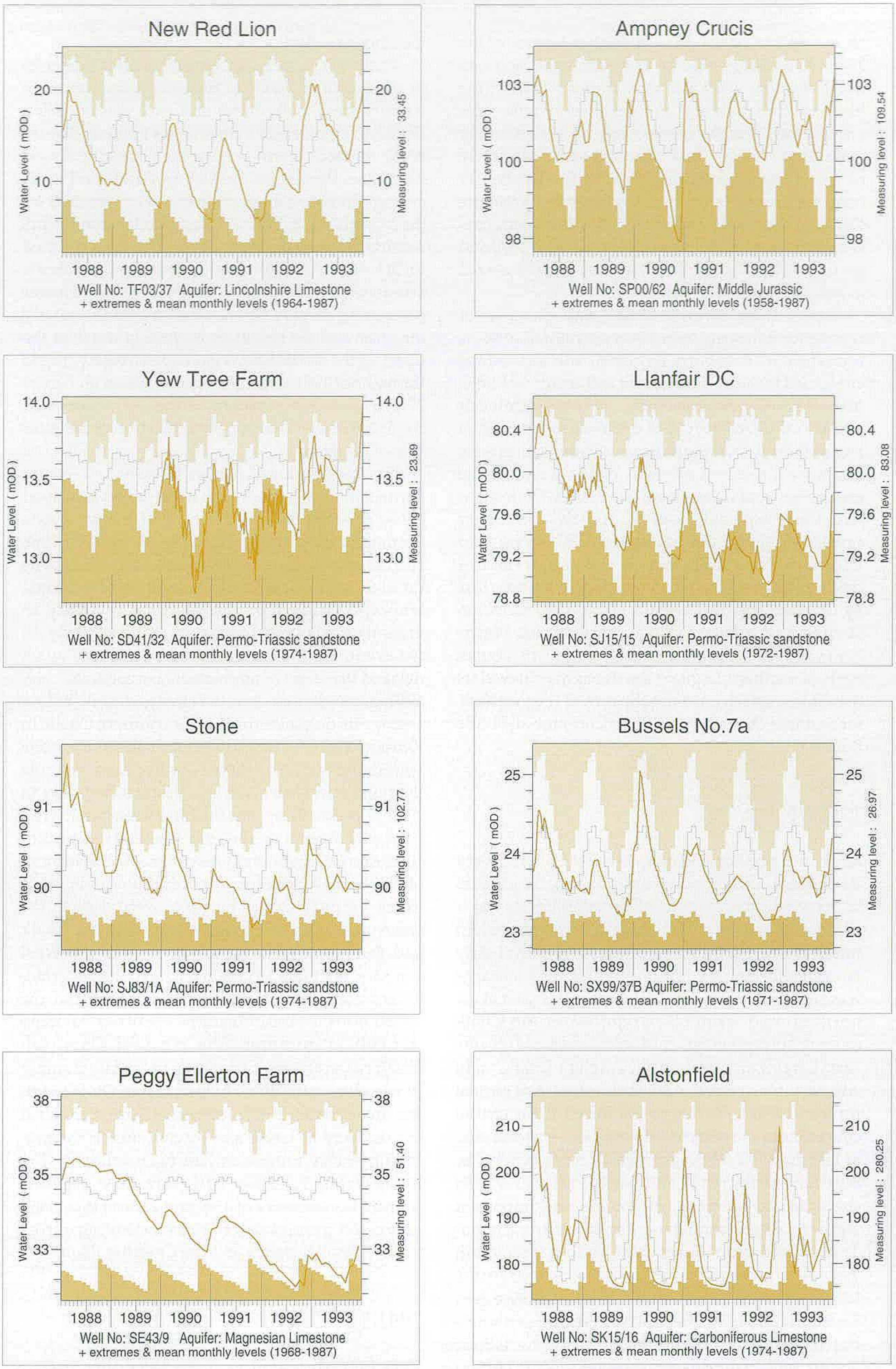


Figure 30 continued

an exceptionally low base. A further feature of the 1989/90 recharge was its very late start, between late-December 1989 and mid-January 1990 in the lowlands (in a normal year, the recovery commences around two months earlier) and its exceptionally early termination. Thus although some extremely rapid recoveries were registered in the late winter (see, for example the hydrograph trace for the Compton borehole on Figure 30), steep recessions were often well established by early March 1990 and groundwater levels again fell well below the seasonal average through the spring.

Apart from a few isolated and short-lived recoveries following heavy August rainfall in some localities in southern England, the recessions continued through the summer and autumn of 1990. In the Permo-Triassic sandstones in Lancashire levels at the Yew Tree Farm Well declined to a period of record minima in the autumn and water-tables were also very depressed in north Wales. Towards the eastern lowlands of England, where the 1976 drought had been especially severe, levels commonly remained above the equivalent 1976 level into December. Near the east coast however, levels in a few wells in the Chalk had reached an all-time low by October, the direct result of the 1990 recession starting from an unusually depressed state. Water-tables in these areas were set to decline further but in parts of southern England the drought achieved its maximum severity around the turn of the year (see, for example, the hydrographs for Compton and Little Bucket).

1990/91

As in the previous winter, the 1990/91 recovery started late. Only modest upturns in groundwater levels were apparent before December 1990 in much of Britain, and over the Chalk outcrop in eastern England water-tables did not start to rise until early or even mid-January 1991. Above average recharge was recorded for the 1990/91 winter half-year at the northern and western extremities of the Chalk outcrop but replenishment diminished rapidly to the east. Large parts of the East Anglian Chalk, as in adjacent areas, recorded well below half their normal replenishment. Recharge exhibited little spatial coherence in the eastern lowlands and was assessed as less than 10% of the average for a few boreholes. Substantial regional and local variability also characterised winter recharge in the other important aquifers. Replenishment to much of the Permo-Triassic sandstone aquifer in the Midlands and north Wales was generally of the order of 60% or less of the long-term mean. Above average recharge was recorded for the North-West NRA region as a whole but this disguises a significant north-south gradient: aquifer replenishment was especially low in parts of the Cheshire Plain.

The 1990/91 recharge produced brisk increases in groundwater levels in the early winter in most outcrop areas to the north and west of a line from Dorset to Humberside. Recoveries in groundwater level started from somewhat less depressed conditions than in the English lowlands and near-average to above-average levels were reached by the late spring of 1991. A substantial recovery was recorded in the Yorkshire Chalk, a marked contrast to the previous two winters, but levels scarcely attained the seasonal norm. The groundwater prospects generally deteriorated in a south-easterly direction and the resources outlook in much of the Chalk of the South-East remained extremely fragile throughout 1991. The hydrograph traces on Figure 30 provide clear evidence of the very depressed condition of water-tables, particularly over the latter half of the year.

For the Chalk and Upper Greensand wells in particular, the length of time water-tables remained below pre-1988 minima during 1991 is notable as is the magnitude of the decline in levels from the 1988 spring peaks. Relatively moist soil conditions throughout much of the 1991 summer encouraged the expectation that the seasonal recovery in groundwater levels would start relatively early. In the event, the dry autumn in the lowlands again delayed the onset of appreciable percolation. Late-1991 groundwater levels remained well below average throughout much of the southern Chalk, in Kent especially. Levels in the Lincolnshire Limestone were depressed also - at the New Red Lion borehole the minimum December level, established only in 1990, was closely approached in December 1991.

Away from the English lowlands, drought conditions were generally less intense in the autumn of 1991. In the Middle Jurassic of the Cotswolds, levels in the Ampney Crucis borehole were close to the seasonal average, a picture repeated in the Chalk and the Permo-Triassic sandstones of the West Country. A similar situation obtained in the Permo-Triassic aquifers of north-west England but the situation in the Midlands and North Wales was more difficult to interpret. The Weeford Flats well (Staffordshire) remained dry from the late summer (it was also dry in 1976). At the Llanfair DC (Clwyd) and Stone (Staffs) boreholes the dry December halted the recovery in levels and by mid-month the pre-1990 monthly minimum had been eclipsed. The hydrographs for these latter sites (see page 51) confirm the existence of a second zone of especially depressed groundwater levels extending across much of the Midlands and the Cheshire Plain.

1991/92

Very limited rainfall over the December 1991 to

February 1992 period ensured that total aquifer replenishment would, once more, be amongst the lowest on record (see Table 22). For some boreholes, including many in the eastern Chilterns, the 1991 recessions continued with barely an inflection in the hydrograph trace. At others, the water-table remained within a narrow range over the twelve months from the autumn of 1991 - commonly the entire period being below pre-1989 minima. Some faltering increases did occur through the spring of 1992 but still left water-tables in the Chalk, prior to the onset of the summer recession, at their most depressed on record.

With natural base levels being approached throughout much of eastern, central and southern England, the decline in water-tables throughout the summer half-year was shallow. Nonetheless, levels by August were below any previously registered in most of the Chalk and close to the minimum on record in the majority of other major aquifers. In the Permo-Triassic sandstones for example, levels at Redbank (Dumfries and Galloway) varied erratically but approached the recorded minimum on several occasions. By October, levels in the Llanfair DC borehole and at Bussels (Devon) were comparable to the monthly minimum.

Very large volumes of water are held in storage below the normal range of seasonal groundwater level fluctuations. However, this water is only exploitable in the Chalk, for example, if wells and boreholes intercept fractures. There are fewer fractures at depth, resulting in decreasing borehole yields as the water-table is lowered. Many dwellings and small holdings located upon the Chalk outcrop of eastern and southern England obtain their water supplies from shallow shafts with only a moderate depth of water in the bottom at the best of times. Falling water-tables caused a number of such sources to fail as they dried out over the two years from late 1990. Although valuable experience was gained in the operation of groundwater sources under circumstances not previously encountered, the prospect of a further dry winter was a matter of real concern.

Termination of the drought

The need to generate groundwater level rises from the exceptionally low base established in the summer of 1992 implied that any post-drought recovery would be protracted and, probably, very uneven. In the event, the relatively wet summer in 1992 produced moist lowland soils, and heavy September rainfall generally arrested the groundwater recessions and triggered an early, and very brisk, start to the seasonal recovery. Thereafter, sustained rainfall over the final quarter of the year produced abundant recharge and some extremely rapid rises

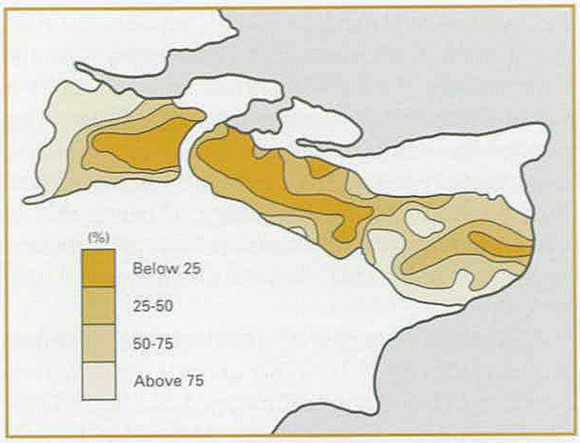


Figure 31 The 1992-93 groundwater recovery in the Chalk and Upper Greensand of Kent expressed as a percentage of the long-term average (Source: NRA)

in groundwater levels - echoing the terminal phases of the 1976 and 1984 droughts. By the turn of the year the water-table in much the greater part of the Chalk had returned to within the normal range although in some eastern areas levels remained substantially below the seasonal mean. This was particularly true of a broad zone from Lincolnshire to Bedfordshire but depressed levels also characterised parts of north Kent where the recovery was especially patchy[38]. Figure 31 shows that the 1992/93 recovery was limited throughout large parts of the northern outcrop zone. In these areas the long dry spell in February and March 1993 heralded a further year during which careful monitoring of groundwater resources would be required. A few other pockets remained, including the Permo-Triassic sandstones of the Cheshire Plain and Nottinghamshire, where the 1992/93 recovery was fragile and the resources outlook uncertain. Mostly these were in areas where groundwater abstraction had exacerbated the meteorological drought.

Recharge during the drought

Depressed groundwater levels throughout most of the 1990-1992 period in eastern England reflected not only the limited winter percolation in these years but the modest recharge over the two preceding winters also. In an attempt to measure the paucity of groundwater replenishment an assessment of recharge was carried out using the fluctuations in groundwater level as observed in monitoring wells. The method employed a *groundwater year*, conventionally defined as the first day of August to the last day of the following July. End-of-month levels were determined, by extrapolation where necessary, for the well in question. The cumulative rise through the groundwater year was summed to determine the *annual fluctuation*. The average of the annual fluctuations over a period of time provides the *mean annual range*. Each fluctuation was then expressed as a percentage of the mean annual range, and this is taken to be the *percentage annual recharge*. The percentage annual recharge was then ranked to illustrate the years in which recharge was at its lowest. This method has the advantage of being able to compare, for example, the percentage recharge for a single year such as 1975-76 with a longer period such as 1988-92.

Estimates of percentage recharge over the four winters 1988/89-1991/92 are given in Table 22 for a selection of boreholes and mapped on Figure 32 for the Chalk and Upper Greensand aquifer. Overall replenishment was substantially below average in most areas and parts of East Anglia - Norfolk and Cambridgeshire especially - registered below 40% of the long-term mean; less than half the four-year average characterised adjacent areas and parts of the North Downs. The extremely modest nature of recharge is confirmed by the ranked annual and n-year recharge percentages presented on Table 23. On an individual year basis, there are several annual recharge totals lower than those for the 1988-92 period - most recently in the 1970s. However, aquifer replenishment over the three or four winters beginning in 1988/89 was exceptionally depressed, most notably at Washpit Farm which is close to the zone of maximum drought severity.

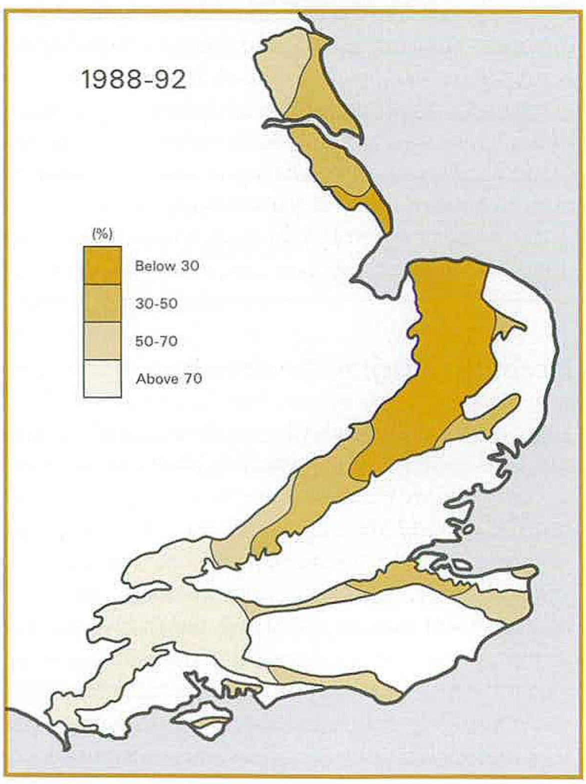


Figure 32 Estimated recharge to the Chalk and Upper Greensand aquifer 1988-92 as a percentage of the pre-1988 average

There have been instances in the past where infiltration over a single winter period has been very modest, and a number where there have been two successive such winters. However, the situation in eastern England in mid-1992 was unique, for this century at least. Table 23 confirms that in West Sussex (as represented by the Compton borehole) a number of broadly similar recharge episodes to 1988-92 have occurred. At Dalton Holme, however, the four-year replenishment was lower than all but that registered in the 1972-76 period. More remarkably, the estimated recharge at the Washpit Farm borehole was less than half that for any pre-1988 three-year sequence in a record from 1950.

How severe was the drought?

Hydrogeological background

Groundwater is not static but is continually in motion. Aquifers discharge water to springs, seepage lines, rivers and the sea. The discharge rate may fall as the head in the aquifer declines, but will not cease until the base discharge level is reached across the whole extent of the aquifer. Any groundwater taken by pumping will be at the expense of natural discharge, and there are many examples of river flows being greatly diminished by the interception of baseflow (see page 35).

The flow of groundwater through aquifers is controlled by the transmissivity and by the head of water present. The resources in storage at any given time may be evaluated in terms of specific yield and effective saturated thickness. While the severity of a groundwater drought may be measured essentially by the remaining saturated thickness, the rate at which that thickness may diminish depends upon the rate of groundwater discharge and abstractions.

In practical terms, the severity of a groundwater drought is normally measured in terms of recharge received by an aquifer and the minimum, or trough level, of the water-table during the drought years.

Problems of long-term comparisons

The difficulties attending the precise measurement of hydrological variables are especially significant in the groundwater context. Quantification of recharge, particularly in areas of low rainfall, can normally only be achieved within a broad uncertainty band. The measurement of groundwater levels - upon which most assessments of severity depend - can introduce errors which though often modest in themselves may well be significant in relation to the limited range of annual minimum levels encountered at most monitoring sites. This is especially true of data collected prior to the use of modern sensing and recording instruments. For the longest records it has often been necessary to adjust recorded levels to account, for instance, for the considerable stretching of the tape used to determine the depth to the water-table. In some cases the extent of the stretch has only been identified after many years of measurement.

Continuous analogue records of hydrograph behaviour are available for a number of wells and boreholes but, except at a few sites where loggers are deployed, levels are typically recorded at monthly intervals. It is likely therefore that the recorded levels within any given year do not represent the full range of variation at any particular monitoring site. In addition, the impact of changing patterns of water abstraction at, or in the vicinity of, the well or borehole can complicate direct comparisons between recessions in different drought years.

1988-92 Groundwater levels

The groundwater hydrographs presented in Figure 30 confirm that, over the period for which a good coverage of monitoring boreholes is available, the recent drought is clearly outstanding. In the Chalk the minima established prior to 1989 were commonly eclipsed in both 1991 and 1992 - in a few areas, 1989 and 1990 also. By the end of 1991, levels at many of the eastern Chalk sites had reached the lowest for the winter in the period of record, and a few had reached their lowest value for any month. In the other major aquifers, the 1976 minima were often closely approached but generally not superseded away from those districts where drawdown due to abstraction was not a factor. Notable exceptions include the Middle Jurassic of the Cotswolds and the Permo-Triassic outcrops in a zone trending north-west from Staffordshire where levels fell to a new period of record minimum in the autumn of 1990. Many seasonal minima were also established during the recent drought, in 1990 particularly, when over wide areas the November/December levels were without precedent.

The very extended recessions in each of the four years prior to 1992 imply that the scope and general severity of the drought, at year-end, may be usefully judged by reference to Table 24 which compares the lowest 1989-92 levels with the pre-1989 minima for a representative set of wells and boreholes.

Particularly compelling evidence of the unprecedented magnitude of the drought in groundwater terms is provided by the levels at a number of long-term index wells and boreholes in the Chalk. At the beginning of 1992, levels at Dalton Holme (in the Yorkshire Wolds) had declined to below any registered before 1990 (in a 103-year record[39]). At Little Brocklesby (Lincolnshire), levels were closely comparable with the minimum in a series from 1926 and the groundwater level had declined at Therfield by over 20 metres since the spring of 1988 to stand at its lowest level since the borehole was last dry in 1923. Similarly, levels at Washpit Farm (see Figure 30) and Redlands Hall (Essex) were unprecedented in records of 42 and 28 years respectively. At both sites these levels were closely matched in the early autumn of 1992. Further south in the North Downs, where the drought was less intense, an incomplete groundwater level record of uncertain accuracy is available for the Rose and Crown borehole from 1879. This suggests only in 1898, 1922, 1934 and 1944 was the water-table more depressed than in the late-spring of 1992. The 1992 minima was, however, closely approached in 1976.

Annual minimum levels

The effective base of an aquifer is rarely known with any accuracy, so the saturated thickness is equally indeterminate, particularly in such aquifers as the Chalk or the Permo-Triassic sandstones. Consequently, trough water-table levels have to be used as a surrogate for the volume of groundwater storage. As with the percentage recharge, trough levels can be ranked for a given number of years to provide a comparison between drought episodes. The singular intensity of the drought is confirmed by the annual minimum levels presented in Table 25. The persistence of groundwater droughts is such that clusters of years with notably low annual minima are to be expected, but the outstanding sequence of minimum trough levels at Dalton Holme is remarkable. In the context of the limited range within which most annual minima fall, the 1992 minimum at Dalton Holme - and at Washpit Farm also - testify to a drought of extreme magnitude.

The great majority of wells and boreholes in the national groundwater level network were selected, so far as is practicable, to avoid the worst effects of groundwater pumping on natural rest water levels. Where, as in large parts of the English lowlands, heavy groundwater abstraction has produced local or regional depressions in the water-table, the depletion in groundwater resources has been even greater than the figures presented in Tables 24 and 25 suggest. Taking into consideration the inordinate nature of the long-term rainfall deficiencies, the elevated evaporation losses and the substantial impact of increasing abstraction rates in some areas, it appears probable that the scale of the groundwater depletion in the Chalk of eastern England is without parallel this century. The limited amount of direct evidence in the public domain concerning the impact on groundwaters of droughts prior to about 1950 implies that full confirmation of this may never be possible.

TABLE 21 1988/89 BOREHOLE LEVEL RECOVERIES AND 1989 MINIMA COMPARED WITH THE PERIOD OF RECORD

Borehole/aquifer	First year of record	1989 minimum (mOD)	Date of 1989 minimum	Years with minimum < the 1989 minimum	Range (m) of the 1988-89 depletion	Rank of the 1988/89 depletion*
Dalton Holme Chalk and UGS	1889	10.73	14/12	None	11	1
Little Brocklesby Chalk and UGS	1926	5.77	15/12	1 (1976)	13	
Washpit Farm Chalk and UGS	1950	42.13	04/12		7.9	
Rockley Chalk and UGS	1933	Dry			14	
Compton House Chalk and UGS	1894	28.30	20/12		34	
Little Bucket Farm Chalk and UGS	1971	57.81	06/12		30	
Lime Kiln Way Chalk and UGS	1969	124.27	09/12	1 (1976)	1.1	
New Red Lion Lincolnshire Limestone	1964	7.20	18/12	1 (1976)	12.7	
Llanfair D.C. Permo-Triassic Sandst.	1972	79.25	23/10	1 (1976)	1.4	
Bussels No 7A Permo-Triassic Sandst.	1971	23.19	14/10	3	1.4	4

UGS = Upper Greensand; Sandst. = Sandstone
mOD = metres above Ordnance Datum
† Rockley is dry during drought years
* 1 = maximum

TABLE 22 ESTIMATES OF PERCENTAGE RECHARGE TO THE CHALK 1988-92

Well site	Measuring Authority	% Recharge 1988/89	% Recharge 1989/90	% Recharge 1990/91	% Recharge 1991/92
Dalton Holme Estate	NRA-NY	40	59	138	22
Hunmanby Hall	NRA-NY	<10	33	171	<10
Little Brocklesby	NRA-A	35	59	101	20
Washpit Farm	NRA-A	<10	76	25	20
The Spinney, Costessey	NRA-A	20	75	69	88
Fairfields	NRA-A	26	17	26	88
Dial Farm	NRA-A	59	30	84	47
Grange Farm	NRA-A	65	17	12	29
The Holt	NRA-T	29	117	16	<10
Stonor Park	NRA-T	32	148	27	20
Little Bucket Farm	NRA-S	39	88	78	18
Alland Grange	NRA-S	31	93	104	24
Little Petts Farm	NRA-S	<10	74	40	<10
Old Rectory, Pyecombe	NRA-S	14	187	87	13

NRA Regions: NY = Northumbria/Yorkshire, A = Anglian, T = Thames

TABLE 23 RANKED SINGLE AND N-YEAR RECHARGE ESTIMATES FOR THREE BOREHOLES IN THE CHALK AND UPPER GREENSAND

	Compton (West Sussex) — POR: 1893-1992						Dalton Holme (Humberside) — POR: 1889-1992						Washpit Farm (Norfolk) — POR: 1950-1992					
	1-year		3-year		4-year		1-year		3-year		4-year		1-year		3-year		4-year	
Rk	Yrs	%	Yrs	%	Yrs	%	Yrs	%	Yrs	%	Yrs	%	Yrs	%	Yrs	%	Yrs	%
1	1975-76	2	1900-03	55	1953-57	62	1913-14	6	1904-07	62	1972-76	60	1972-73	0	1988-91	29	1988-92	26
2	1933-34	3	1955-58	57	1954-58	66	1904-05	7	1947-50	66	1988-92	65	1975-76	3	1989-92	33	1961-65	57
3	1956-57	5	1954-57	61	1955-59	70	1972-73	18	1911-14	70	1901-05	73	1988-89	8	1962-65	51	1970-74	60
4	1897-98	14	1947-50	62	1897-01	71	1991-92	22	1972-75	71	1903-07	74	1981-82	15	1971-74	53	1969-73	64
5	1991-92	21	1906-09	64	1904-08	71	1948-49	25	1912-15	72	1961-65	74	1991-92	20	1970-73	57	1987-91	67
6	1972-73	28	1931-34	65	1899-03	72	1975-76	27	1902-05	72	1904-08	76	1990-91	26	1961-64	63	1972-76	71
7	1943-44	30	1895-98	65	1895-99	72	1964-65	31	1989-92	72	1945-49	78	1963-64	35	1981-84	73	1981-85	75
8	1901-02	30	1956-59	66	1930-34	73	1988-89	43	1962-65	73	1910-14	78	1964-65	39	1983-86	79	1983-87	84
9	1947-48	33	1941-44	68	1988-92	75	1912-13	49	1970-73	73	1970-74	79	1989-90	53	1987-90	82	1962-66	85
10	1964-65	42	1899-02	69	1905-09	75	1947-48	49	1903-06	73	1902-06	79	1983-84	70	1969-72	87	1986-90	87
11	1904-05	43	1904-07	69	1898-02	75	1890-91	55	1966-69	73	1889-93	79	1973-74	74	1963-66	87	1971-75	92
12	1948-49	51	1943-46	72	1931-35	76	1895-96	57	1973-76	74	1964-68	80	1961-62	75	1984-87	90	1982-86	92
13	1941-42	54	1970-73	73	1941-45	76	1920-21	37	1971-74	75	1971-75	81	1962-63	82	1972-75	94	1963-67	92
14	1906-07	54	1896-99	76	1901-05	76	1926-27	57	1987-90	76	1947-51	82	1985-86	83	1973-76	95	1985-89	94
15	1900-01	54	1971-74	76	1940-44	78	1989-90	58	1889-92	78	1969-73	84	1967-68	83	1982-85	97	1980-84	95

Note: a conventional August-July recharge year has been used.

TABLE 24 END-OF-SUMMER RECESSION GROUNDWATER LEVELS IN SELECTED OBSERVATION WELLS

Site	Aquifer	Records Commence	End-of-Summer Recession Levels (metres OD)					
			Lowest pre-1989		1989	1990	1991	1992
			level	year				
Dalton Holme	C & UGS	1889	11.58	1905	10.73	10.34	**9.64**	10.98
Little Brocklesbury	C & UGS	1926	4.58	1976	5.77	4.70	**4.53**	4.59
Washpit Farm	C & UGS	1950	41.24	1978	41.98	41.17	40.51	**40.30**
The Holt	C & UGS	1964	**83.90**	1973	85.95	85.43	84.80	84.26
Fairfields	C & UGS	1974	22.18	1974	22.73	**22.15**	22.16	- -
Redlands Farm	C & UGS	1964	34.53	1965	35.68	33.29.	32.38	**32.29**
Rockley	C & UGS	1933	**128.94 ***	1976	**128.94 ***	**128.94 ***	129.04	130.26
Little Bucket Farm	C & UGS	1971	**56.57**	1976	57.64	57.09	60.09	59.56
Compton House	C & UGS	1894	**27.64**	1976	28.24	27.88	30.79	29.93
West Dean	C & UGS	1940	**1.01**	1949	1.16	1.08	1.38	1.33
Lime Kiln Way	C & UGS	1969	124.09	1976	124.27	124.65	124.00	**123.70**
Ashton FArm	C & UGS	1974	63.32	1976	63.67	**63.10**	64.30	64.66
West Woodyates	C & UGS	1942	**67.62**	1976	69.20	67.90	73.50	72.59
New Red Lion	L Lst	1964	**3.29**	1976	7.04	5.49	5.68	8.72
Ampney Crucis	Mid Jur	1958	97.87	1976	98.99	**97.38**	99.81	100.14
Dunmurray (NI)	PTS	1985	27.80	1985	**27.48**	27.67	27.50	27.81
Llanfair DC	PTS	1972	**78.85**	1976	79.25	79.16	79.05	78.92
Stone	PTS	1974	**89.34**	1976	89.90	89.73	89.50	89.73
Weeford Flats	PTS	1966	**88.61 ***	1976	89.05	88.98	**88.61 ***	**88.61 ***
Bussels 7A	PTS	1972	**22.90**	1976	23.19	23.33	23.39	23.15
Rusheyford NE	Mg Lst	1979	75.27	**1982**	74.81	**74.26**	74.67	74.47
Peggy Ellerton	Mg Lst	1968	**31.10**	1976	33.15	32.40	31.97	31.23
Alstonfield	C Lst	1974	**174.22**	1975	174.96	174.97	175.00	175.95

Minimum levels for each site are shown in bold face. *dry

C & UGS Chalk and Upper Greensand
L Lst Lincolnshire Limestone
PTS Permo-Triassic Sandstones
Mid Jur Middle Jurassic Limestones
Mg Lst Magnesian Limestone
C Lst Carboniferous Limestone

TABLE 25 RANKED ANNUAL MINIMUM GROUNDWATER LEVELS IN THE CHALK AND UPPER GREENSAND AQUIFER

Dalton Holme Period of Record 1889-1993		Chilgrove Period of Record 1836-1993		Washpit Farm Period of Record 1950-1993	
Year*	Min. Level (mOD)	Year	Min Level (mOD)	Year	Min. Level (mOD)
1991/92	**9.64**	1973/74	33.46	**1991/92**	**40.51**
1990/91	**10.34**	1976/77	33.48	**1990/91**	**41.16**
1989/90	**10.73**	**1990/91**	**33.71**	1978/79	41.24
1988/89	**11.35**	**1989/90**	**33.79**	1973/74	41.25
1904/05	11.58	1934/35	34.44	1976/77	41.50
1921/22	11.61	1975/76	35.33	1950/51	41.66
1964/65	11.74	1847/48	35.35	1974/75	41.75
1920/21	11.81	1854/55	35.36	1960/61	41.80
1905/06	11.84	1978/79	35.46	**1989/90**	**41.98**
1975/76	11.87	1958/59	35.66	1957/58	42.06
1983/84	11.88	1951/52	35.66	1965/66	42.18
1941/42	11.89	1921/22	35.66	1972/73	42.25
1948/49	12.09	1969/70	35.90	1956/57	42.37
1986/87	12.14	1837/38	35.97	1951/52	42.37
1953/54	12.17	1944/45	35.97	1964/65	42.39
1949/50	12.32	1933/34	35.97	1952/53	42.40

* Aug-July

Background

Considered on an annual basis, surface water resources far outweigh the demand for water in the United Kingdom. The seasonal variability in runoff, however, requires that reservoir storage be provided to ensure that supplies can be maintained and, where appropriate, river flows augmented during periods of rainfall deficiency. It is the adequacy of this storage - together with available groundwater resources - and the effectiveness of its management which largely determine the magnitude of a drought's impact on the community in water supply terms.

Many of the older reservoirs in the United Kingdom were designed to supply water directly to centres of water demand; normally a minimum flow (or compensation flow) had also to be maintained in the river downstream. The emphasis in England and Wales has now shifted towards reservoirs which supplement runoff by means of river regulation. Releases from the reservoir are used to increase river flows and facilitate the abstraction of water from the lower reaches of the river system. Some reservoirs perform both functions and increasingly groups of reservoirs are being linked to allow a larger gross resource to be operated more flexibly in response to differing patterns of rainfall, reservoir storage and demand across a water supply area. Often including groundwater storage, this growing integration of resources, together with changes in the demand for water, limits the value of comparing individual reservoir levels during the recent drought with the storage available during previous droughts. Where, however, a single reservoir or group of reservoirs are managed as a unit the progress of the drought's development can be effectively charted as the gross storage is depleted.

Reservoirs vary in their susceptibility to drought conditions. The intensity and duration of a rainfall deficiency (or, more precisely, a residual rainfall deficiency) that is critical for an individual supply source depends on the capacity of the reservoir relative to the demand and the proportion of the total resource that the demand represents[21]. Small upland reservoirs tend to have critical periods of less than six months whereas major impoundments (as with important groundwater resources) are sensitive to notable droughts extending over a number of years.

Reservoir contents 1988-92

Minimum start-of-month reservoir contents within each year of the drought period are shown in Table 26 for a selection of major impoundments or reservoir groups; for three representative reservoirs the variation in stocks is shown graphically on Figure 33.

Early 1988 saw most reservoirs at capacity or spilling. Thereafter stocks varied, sometimes in a relatively volatile manner, in response to large temporal variation in inflow and, often complex, operational rules as the drought episodes developed and abated. Generally inflows were moderate over the winter of 1988/89 and stocks were very low late in the following autumn. Over the six months ending in October, the Derwent Valley group of reservoirs registered one of its lowest half-year inflow sequences in a record from 1932. Water levels in Kielder, the largest man-made lake in northern Europe, declined to their lowest since the reservoir's opening in 1982. Nonetheless, the remaining stocks represented a very large resource and allowed local sources in the North-East to be used to a fuller extent and without

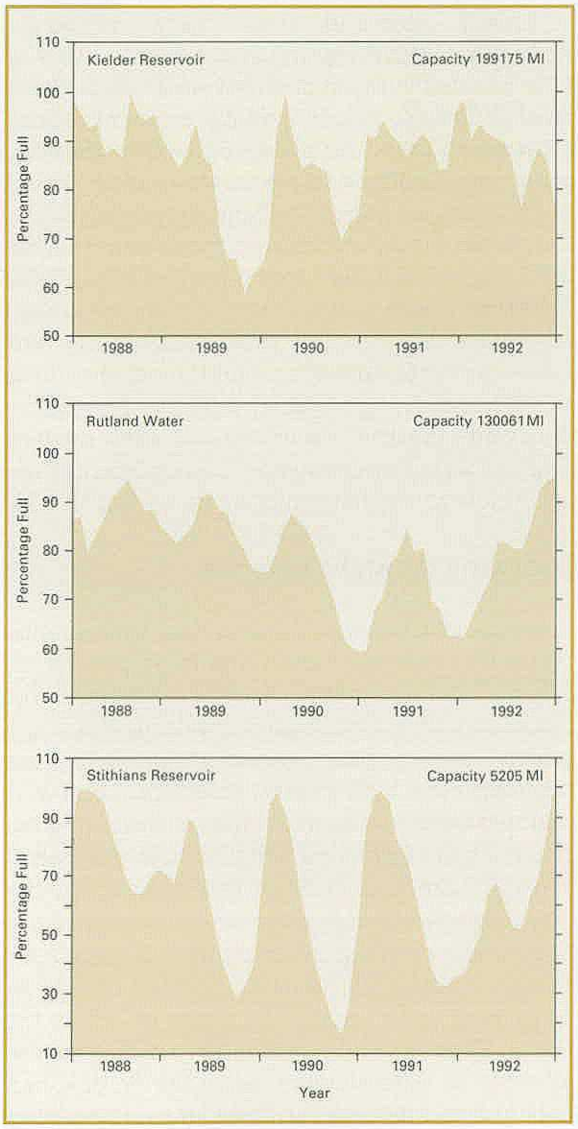


Figure 33 1988-92 reservoir contents

restrictions, in the knowledge that support would be available if required[40]. Thus, storage in the Derwent and Burnhope Reservoirs, which are operated conjunctively, fell to 22% and 13% respectively in late 1989 but water transferred to the Wear catchment, via the Kielder tunnel, obviated the need to introduce restrictions in Sunderland and Durham.

The remarkable hydrological transformation over the winter of 1989/90 was generally echoed in the very brisk recovery of reservoir stocks. Most western reservoirs were at capacity by the end of January. Many of the smaller impoundments, including Stithians in Cornwall, could have been filled again over the ensuing three weeks and, in Wales especially, controlled releases were necessary to provide a measure of flood alleviation storage. The benefit of abundant runoff early in the year was however, counteracted by the very early onset of the seasonal drawdown as demand exceeded replenishment. Thus by mid-April reservoir contents at Stithians, for instance, fell below those registered in 1976 (when capacity was never reached but stocks were recovering slowly throughout the early spring).

Heavy demand and very moderate replenishment in the spring, summer and autumn of 1990 resulted in much depleted stocks throughout most of Britain. A less spatially coherent picture characterised the later phases of the drought with, commonly, healthy stocks in the west but substantial drawdown in some lowland impoundments. Generalisation is particularly difficult because of the differing operating controls governing the abstraction from donor rivers to pumped-storage reservoirs. Nonetheless, total stocks in lowland reservoirs increased substantially through the spring of 1992 and were generally healthy by November. Recoveries in parts of southern and south-western England were slower but most impoundments were at, or close to, capacity entering the spring of 1993.

Indexing drought severity

A comparison between the river flow hydrographs (Figure 24), groundwater level hydrographs (Figure 30) and Table 26 shows that surface water reservoir stocks may often be indicative of a drought severity which can appear inconsistent with the contemporary hydrological intensity. Local and regional water management factors - including the relative cost of drawing supplies from alternative sources - are important in this context but the disparity between drought severities at certain times during the recent past, highlights the need for effective public relations and public education concerning water issues. The spring of 1992 in the lower Thames Valley provides an illustrative example: in meteorological terms the drought had only just past its peak but flows in rivers draining catchments on the impervious London Clay recovered briskly whilst headwater reaches in spring-fed rivers in the nearby Chilterns continued to contract. The associated decline in groundwater levels was still only approaching its climax and many shallow wells continued to fail. By contrast, levels in the confined Chalk below London maintained their steady increase since the early 1960s (largely a consequence of reduced demand[41]) and, as a result of abstractions from the Thames, stocks in the network of major reservoirs to the west of London were healthy.

Water demand

Demand for water is governed by a wide range of factors, including population growth and domestic water use, which vary geographically in terms of their importance. Total abstractions from surface and groundwaters in England and Wales increased only modestly over the decade ending in 1990 although regionally the picture was more volatile. In large part the regional variations reflected changes in the volumes abstracted for non-consumptive usage (e.g. cooling water, gravel washing). Nationally, the figures reflect an overall decline in industrial activity, but also more efficient water usage, including recycling. Since non-consumptive usage generally has little hydrological impact, a more realistic index of potential environmental and water resources stress is provided by the trend in public water supplies.

Overall demand in England and Wales has increased by an average of around two per cent a year over the last 30 years[10] (Figure 34) although an appreciable reduction was achieved during the 1976 drought and, in some regions, during the 1988-92 event. The national figures disguise substantial regional differences; demand in the North West is relatively static whilst the most rapid growth in water supply has been in parts of southern and eastern England. Importantly within the drought context, demand also varies throughout the year reaching a maximum in most regions during the summer months. This is most noticeable in those areas which experience a substantial seasonal influx of population, the South-West for example. In hot summers demand, if not subject to restrictions, may exceed

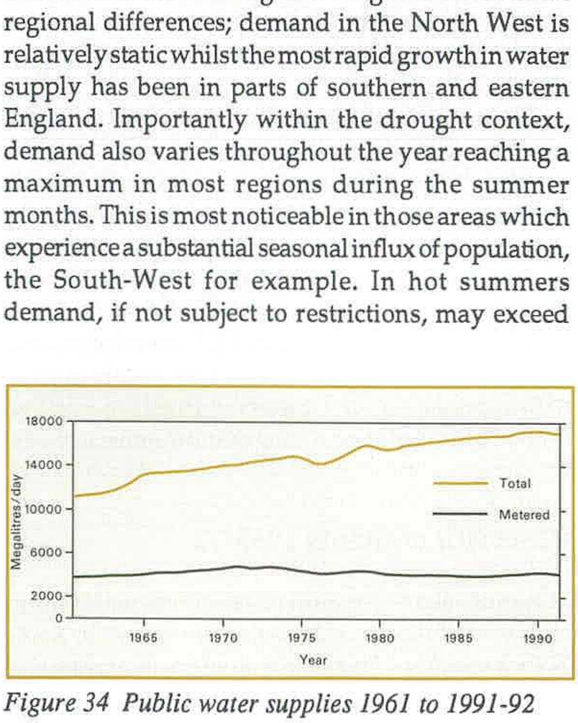


Figure 34 Public water supplies 1961 to 1991-92

the winter average by more than 20%. Heavy summer demand, May and June especially, is also encountered in important agricultural areas where water restrictions at that time would have serious implications. The mild winters during the drought reduced the 'demand' created by bursts of previously frozen pipes but mid-year demand in certain areas was enhanced where the movement of drying soil pulled main joints and increased leakage.

In some areas action to reduce water demand during the 1988-92 drought was introduced in the spring at a time when overall resources were relatively healthy but peak demands (commonly associated with heavy garden watering) overstretched the supply network. Even so a major justification for such action was the need to conserve stocks against the possibility of more general shortages later in the year. Distribution problems - when parts of the water supply system, such as feeder reservoirs and water towers, have insufficient capacity to deal with surges in demand - tend to be localised and short-lived. 'Resource' problems, when the amount of water in reservoirs, rivers or groundwater storage appears insufficient in the face of expected demand, can be much more persistent and widespread. Both categories of problems were experienced over the 1988-92 period.

Water management responses

The UK water industry adopts a hierarchical approach to coping with water shortages, with management options ranging from the implementation of preplanned alterations to usual practice e.g. pressure reductions and re-zoning of supplies, and appeals for restraint by users, through hosepipe bans, emergency changes in operation and restrictions on public use to, as a last resort, rationing. The higher stages in this hierarchy can only be implemented with the permission of the Department of the Environment through the imposition of a 'Drought Order'. A Drought Order might allow a water supply undertaking to extract a greater amount from a river, for example (leaving a lower 'compensation flow'), or might allow the undertaking to impose restrictions on the direct consumption of water by commercial and public organisations. Hosepipe bans do not need the prior approval of the Department of the Environment and can be introduced at short notice by advertising in the press. There is some scope for discretion in the breadth of their application, for example, they may be targeted only on the use of sprinklers.

Table 27 lists the number of Drought Orders made over the 1975-92 period on a regional basis. For the recent drought, the number of Orders restricting the non-essential use of water is given in parentheses. The number of Drought Orders issued in 1976 remains unsurpassed for an individual year but the 1989-91 total is easily the highest in the three-year timeframe. As an index of drought severity the numbers of Drought Orders provide a guide only - largely reflecting the current balance between developed resources and regional demand. The limited number of recent Orders in East Anglia, for instance, is associated with a current surplus of resources whilst the filling of Roadford Reservoir had a mitigating effect on the need for restrictions in parts of the South-West from 1990.

Hosepipe bans and Drought Orders were widely used during the summer of 1989 - hosepipe bans affected around 12.5 million consumers. Many of the Drought Orders approved during 1989 remained in force over the following winter (although not all were implemented) and additional Orders were granted in January and February to allow two water supply undertakings in south-eastern England to increase abstractions from rivers to replenish their depleted reservoirs. The summer of 1990 therefore began with a number of Drought Orders in place and some of these were actually being used.

Water supply companies in southern and eastern England began to appeal for restraint by customers in May 1990 and the first new hosepipe ban of 1990 was introduced in the Medway catchment in Kent. By the end of June, hosepipe bans and restrictions on garden sprinklers were in force across much of southern England, in the groundwater-fed parts of east Yorkshire, and in a small part of Devon. By the end of August 18 million consumers in England and Wales were affected by restrictions[42] (Figure 35); by comparison, a maximum of 21 million consumers

Figure 35 Hosepipe bans in England and Wales, September 1990 Source: Water Services Association

were subject to restrictions in 1976[43]. The Anglian Region of the National Rivers Authority also banned abstractions for spray irrigation in some Fenland catchments in late July. The bans were introduced both to safeguard downstream public supply abstractions and to ensure that low river flows did not lead to water quality problems and increased fish kills.

A number of additional Drought Orders were applied for by water companies and the National Rivers Authority during the summer of 1990, mainly to allow increased abstraction and to relax minimum flow requirements. Drought Orders to restrict non-essential commercial and public uses were applied for by the Eastbourne Water Company in mid-September, and by the Bristol Water Company in early November.

Alongside hosepipe bans and Drought Orders, the water industry implemented a number of preplanned and emergency activities during 1990, as in 1989. Southern Water, for example, began drilling exploratory boreholes to find new sources and rejuvenating old wells in May, and Severn-Trent bought water from North West Water to supply Buxton. Leakage control and the helpful response to public awareness campaigns also served to limit overall demand. In the Southern NRA region average demand over the latter half of the drought was around 15% below the projected rate[44], and for England and Wales the quantity of water put into public supply in 1992-93 was equivalent to the demand levels recorded for 1986-87 (*Demand Management Bulletin*, Issue No.3 - Newsletter of the NRA Demand Management Centre, Worthing).

Hosepipe bans in most areas were lifted by January 1991, although limitations were still in force in spring 1991 in parts of East Anglia and the South. Generally, late spring and summer demand in 1991 and 1992 was not subject to the surges experienced in the two preceding years. However, with the water resources outlook remaining fragile, especially in early 1992, a number of hosepipe bans were maintained. The wet summer and autumn saw a steady relaxation of restrictions - 6.75 million consumers were affected in July and all remaining hosepipe bans removed by early 1993.

TABLE 26 ANNUAL MINIMUM PERCENTAGE CAPACITIES OF RESERVOIRS (BASED ON START MONTH VALUES*)

Area	Reservoir (R)/ Group (G)	Capacity † (Ml)	1988 %	1988 Mth	1989 %	1989 Mth	1990 %	1990 Mth	1991 %	1991 Mth	1992 %	1992 Mth
North	N. Command											
West	Zone[1] (G)	133375	62	Jul	26	Oct	34	Oct	33	Oct	55	Aug
	Vrynwy (R)	55146	78	Nov	32	Oct	39	Oct	71	Oct	80	Aug
Northum-	Teesdale[2] (G)	87936	70	Jul	34	Oct	55	Oct	31	Oct	58	Aug
bria	Kielder (R)	199175	88	May	59	Oct	70	Jan/Oct	85	Oct	77	Aug/Dec
Severn	Clywedog (R)	44922	61	Dec	24	Oct	45	Oct	74	Oct	85	Mar/Aug
Trent	Derwent Valley[3] (G)	39525	67	Jul	24	Oct	27	Oct	22	Nov	62	Oct
Yorkshire	Washburn[4] (G)	22035	64	Jul	30	Dec	37	Oct	28	Nov	64	Sep/Oct
	Bradford[5] (G)	41407	65	Jul	24	Oct	35	Oct	37	Nov	56	Sep
Anglian	Grafham (R)	58707	84	Apr	73	Nov/Dec	59	Dec	60	Jan	88	Jan
	Rutland (R)	130061	82	Dec	76	Dec	62	Dec	63	Dec	69	Feb
Thames	London[6] (G)	206232	77	Dec	61	Nov	52	Nov/Dec	57	Nov	75	Jan
	Farmoor[7] (G)	13843	97	Feb	68	Nov	52	Dec	64	Mar	84	Apr
Southern	Bewl (R)	28170	52	Dec	41	Dec	39	Oct	44	Jan	61	Oct
	Ardingly (R)	4685	76	Dec	50	Nov	56	Nov	71	Jan	71	Oct
Wessex	Clatworthy (R)	4918	64	Dec	19	Nov	37	Nov	36	Oct	38	Sep
	Bristol W.[8] (G)	38666		N/A	29	Dec	24	Nov	40	Nov	53	Jan
South	Colliford (R)	28540	90	Aug	66	Nov	67	Oct	73	Jan	63	Sep
West	Roadford (R)	34500	0		0		20	Jan	68	Jan	70	Sep
	Wimbleball[9] (R)	21320	85	Jul	43	Oct	33	Nov	48	Jan	48	Sep
	Stithians (R)	5205	65	Sep/Oct	29	Oct	18	Nov	34	Nov/Dec	37	Jan
Welsh	Celyn & Brenig (G)	131155	95	Jul	39	Oct	53	Oct	68	Oct	87	Aug
	Brianne (R)	62140	95	Jul	49	Oct	67	Oct	84	Oct	77	Aug
	Big Five[10] (G)	69762	83	Jul	21	Oct	28	Oct	69	Oct	66	Aug
	Elan Valley[11] (G)	99106	67	Oct	43	Oct	52	Oct	77	Oct	87	Aug
Lothian	Edinburgh/											
	Mid Lothian (G)	97639	83	Jul	62	Aug	72	Jan	71	Oct	79	Aug
	West Lothian (G)	5613	72	Jul	55	Oct	74	Jan	53	Nov	49	Aug
	East Lothian (G)	10206	84	Oct	43	Dec	48	Jan	67	Oct/Nov	68	Sep

* gross storage/percentage gross storage   Note: Roadford Reservoir did not begin to fill until November 1989.   N/A = Not available

† capacity is live or usable capacity, except for Kielder and the Bristol Group where gross storage is used

1. Includes Haweswater, Thirlmere, Stocks and Barnacre.
2. Cow Green, Selset, Grassholme, Balderhead, Blackton and Hury.
3. Howden, Derwent and Ladybower.
4. Swinsty, Fewston, Thruscross and Eccup.
5. The Nidd/Barden group (Scar House, Angram, Upper Barden, Lower Barden and Chelker) plus Grimwith.
6. Lower Thames (includes Queen Mother, Wraysbury, Queen Mary, King George and William Girling) groups - pumped storages.
7. Farmoor 1 and 2 - pumped storages.
8. Blagdon, Chew Valley and others.
9. Shared between South West (river regulation for abstraction) and Wessex (direct supply).
10. Usk, Talybont, Llandegfedd (pumped storage), Taf Fechan, Taf Fawr.
11. Claerwen, Caban Coch, Pen y Garreg and Craig Goch.

TABLE 27 NUMBER OF DROUGHT ORDERS BY REGION, 1974 TO 1992 ENGLAND AND WALES

NRA region	'74	'75	'76	'77	'78	'79	'80	'81	'82	'83	'84	'85	'86	'87	'88	'89	'90	'91	'92	Total
Anglia		1	15													1	3		1	21
Northumbria			2																	2
North West											31					21				63
Severn Trent			13								6					5(2)				25
Southern	1	1	4													19(6)	25(10)	18(7)	11(3)	79
South West		1	39						7	5	45					21(2)	10		1(1)	141
Thames			8														2(1)		3(3)	13
Welsh			20							1	22					13(1)	1			63
Wessex		3	19														3(1)			28
Yorkshire	3	2	16		-	-	-	-	-	-	-			-	-	9	17	9	1	57
Total	4	9	136		19		4	-	15	6	104	-				89	61	28	17	492

Note: The numbers in parentheses relate to Orders restricting the non-essential use of water *Source:* DOE

Introduction

The following sections provide a brief overview of hydrological conditions in continental Europe over the period 1988 to 1992, concentrating on rainfall and river flows in Europe north of the Alps. The scope of the review was significantly constrained by the availability of historical and contemporary hydrological data. As a consequence, the analyses presented below should for the most part, be regarded as indicative only. One objective of this initial appraisal is to encourage a wider exchange of hydrological data throughout Europe and stimulate greater cooperative effort between the relevant national agencies concerned with hydrometeorology and water resources. Certainly, many of the policy issues raised and the problems encountered during the drought had a Europe-wide dimension and the pooling of data, knowledge and expertise offers the best prospect of developing new approaches to water management designed to meet the challenges of the next century.

The climatic conditions that led to drought in the United Kingdom between 1988 and 1992 also affected large areas of continental Europe, and in some respects parts of the continent were much more severely affected by drought than was the UK. This was especially true in relation to agriculture, but hydrological stress was also evident in environmental and water resources terms: for example, by late 1990 over 3000 km of rivers had dried up in southern France and Athens was frequently close to running out of water during the early 1990s. Low river flows and depleted reservoir stocks caused problems for irrigation over a large part of Europe ranging from Hungary to Spain where, in the south, some hydropower stations were forced to shut down in 1992 and the unequal distribution of water triggered inter-regional political conflict.

To a large extent, the impacts of the low rainfall and high rates of evaporation were, as in the UK, exacerbated by the rapid increases in water use in mainland Europe over the last few years. Irrigation in particular has expanded rapidly since the early 1970s, and this expansion occurred largely in areas prone to drought.

Rainfall

Historical background

As in the United Kingdom, much of western Europe experienced above average rainfall in the 1980s. Commonly the winter half-year was especially wet and this had particular water resources benefits since groundwater is the principal source of supply in many regions. Over the longer term a number of European rainfall series exhibit more compelling trends than are found in the UK but, generally, little or no tendency for average rainfall to increase or decrease has yet been firmly established. However, sustained periods of wet or dry conditions are characteristic of many long time series (see Figure 36). As in the UK, the partitioning of rainfall between the winter and summer half-years has also been subject to considerable variation - with some evidence for increased winter precipitation in the recent past[45].

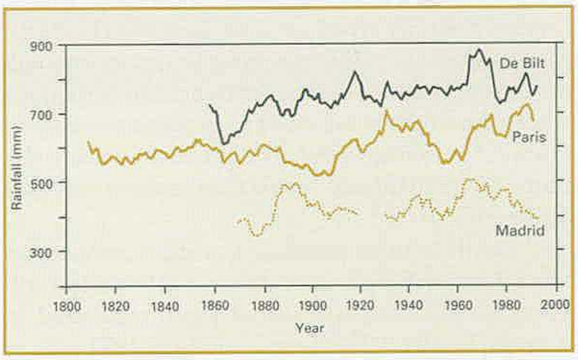


Figure 36 Ten-year running mean annual rainfall totals

Unsurprisingly, good correlations exist between historical rainfall patterns in large parts of western Europe and the English lowlands and a number of important drought episodes embraced both regions. Very moderate winter rainfall totals were widely recorded during the 1933-35 drought but protracted deficiencies in March-October precipitation were appreciably more common in the nineteenth century, the 1850-1910 period featuring a number of lengthy sequences of dry, or relatively dry, winters[46]. When, as around the turn of the century in western France, summer rainfall was also below average some obvious parallels may be drawn with the recent drought. Importantly however, temperatures were generally not as high as those recorded in 1988-92. With less instrumental confirmation, the 30-year period beginning around 1775 also was notably dry, in the Low Countries particularly, although in the early part of this period the agricultural impact of the persistent drought conditions would have been moderated by the relatively wet summers.

1988-92

Over large areas, the drought in mainland Europe developed more unevenly and was less sustained than that experienced in the eastern lowlands of England. On the other hand, rainfall deficiencies (in the three- to four-year timeframe) were greater in some regions and the terminal phase was even more gradual than in the United Kingdom. Notably dry sequences of months were common on the continent - in the winters these were often associated with limited aquifer recharge and a fragile water resources outlook; rainfall deficiencies over the summer half-year tended to manifest themselves in agricultural stress which was sometimes aggravated by high temperatures.

A simplistic guide to the drought's development is provided by Table 28 which lists percentage annual rainfall totals for six index locations over the 1988-92 period. The wide separation of these index sites, and the provisional nature of some of the 1992 figures, implies that only broad generalisations can be made. More importantly, the figures for the index sites will not be representative of the deficiencies in the regions where the drought achieved its greatest severity. In France, for example, the drought was substantially more severe in the south-east than in the north[47] (see Table 29).

Except for short interludes, rainfall deficiencies were rare at Bergen and the exceptionally high precipitation totals paralleled those registered in western Scotland. For Bergen 1990 and 1992 rank as the second and third wettest years in a series from 1921, 1989 ranks fifth. Further south 1988 began very wet in most regions but, by the early summer, modest drought conditions could be recognised over large parts of western Europe. As in the UK, the early winter of 1988/89 constituted the first severe phase of the drought and rainfall deficiencies in some regions were of a greater magnitude than those in eastern and southern Britain. Dijon (France), for example, registered only 50% of average winter rainfall and, remarkably, Madrid recorded a mere 20% with no rainfall at all in December.

As important as the deficiencies themselves was the fact that 1988/89 was commonly the first of a cluster of dry winters. For Copenhagen, the November 1988 to February 1989 rainfall total was the second lowest in 40 years and the three subsequent November-February periods produced below average rainfall also. In some of these years, winter rainfall deficiencies were partially counterbalanced by a wet March. In broad terms, similar patterns are indicated for De Bilt (Holland) and Paris where none of the individual November-February periods were exceptionally dry but 1988/89, 1990/91 and 1991/92 each rank amongst the driest ten such sequences since 1950. More notable was the sequence of winters in south-eastern France - substantial rainfall deficiencies were registered in each of the four winters beginning with 1988/9.

The spring of 1990 marked the beginning of notably dry 5-7 month periods in Paris and De Bilt - longer in Madrid - and large rainfall deficiencies extended well into eastern Europe by the autumn. Generally, the spring and summer period of 1991 was also dry in many regions and rainfall deficiencies were substantial where, as at Nuremberg, the preceding winter had been dry. From Denmark to Spain the drought intensified again at the beginning of 1992 but generally declined in severity thereafter although not as briskly as in the UK. The August-November period in 1992 was wet in some regions and produced substantial reductions in rainfall deficiencies. In others, for example the Paris Basin, the drought abated at a slower pace but, by the spring of 1993, overall deficiencies had moderated by comparison with those obtaining 12 months previously. In southern Spain, however, water resources problems continued well into 1993 with demand restrictions operating in, for example, Seville and Cadiz. Conditions improved rapidly throughout the country in the autumn. Provisional data suggest that October was the wettest month this century in Madrid and replenishment to local reservoirs increased stocks to their highest for five years[48].

Table 30 lists n-month minimum rainfall totals for a selection of long European rainfall series; the corresponding 1988-92 minima are also featured together with their ranking. To provide an index of the exaggeration in the rainfall gradient away from Europe's north-western seaboard, maximum n-month rainfall totals for Bergen are also shown. As in southern and eastern Britain, the 1988-92 drought was most notable over the longer timeframes, but - for Paris and Copenhagen - the severity was appreciably more modest over, for example, 36 months than other major rainfall deficiencies over the last 150-200 years (see Table 31). However for Madrid the drought was exceptionally severe across a broad range of durations. To the north, the drought - at the index sites - was less severe in the context of the full historical rainfall record but very notable in relation to twentieth-century deficiencies.

River flows in continental Europe: 1988-92

As with rainfall, runoff deficiencies displayed large regional variations throughout the drought period but the water-year mean flows presented for the River Ebro in Spain (Figure 37) provide a useful guide to the depressed runoff which characterised much of Europe in the recent past. Although changing patterns of water usage in the Ebro catchment imply that temporal comparisons of annual minimum flows are of limited value, average flows in 1989 and 1990 were the lowest in a 63-year record and medium-term runoff accumulations easily eclipsed the minima established during the extended droughts of the 1940s. The year-on-year variability in the Ebro flows is such that any attempt to identify trends

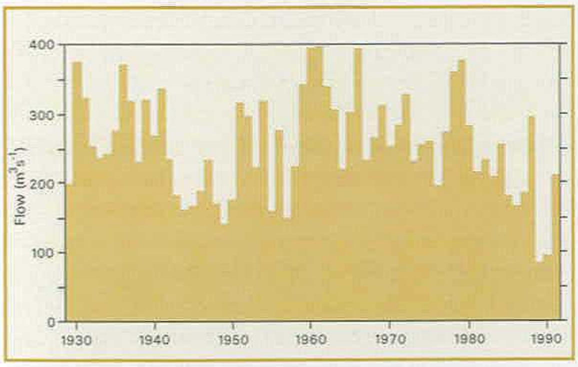


Figure 37 Water-year mean flows for the River Ebro at Zaragoza

would be speculative. Nevertheless, the tendency for runoff to decline over the 15 years up to 1992 is a feature also of the lengthy flow series for the Rhine and the Weser (Figure 38). By contrast the River Eidselv (Norway) has seen a steep increase in runoff in the recent past consistent with the pattern evident in the Scottish Highlands.

A wider geographical coverage is provided by Figure 39 which shows monthly flows for eight European catchments, together with the long-term mean and extreme flows. Reference information concerning the featured catchments is listed in Table 32.

Development of the drought

River flows in much of Europe were above average in the winter of 1987/88, and occasionally the largest on record. Thereafter, flow recessions were commonly steep, if uneven, and monthly runoff totals in many catchments remained well below average for lengthy periods. Whilst in Spain the initial phase of the drought was most severe, in Germany (see the hydrographs for the Rhine and the Weser) and high baseflow rivers in parts of France, runoff deficiencies were greatest in 1991 and 1992.

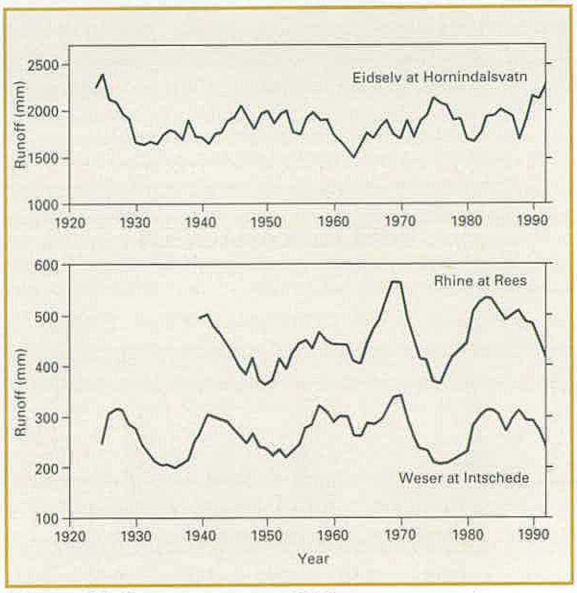


Figure 38 Long term runoff (five-year running mean) for three European rivers

1988-89

Flows during the summer of 1988 were close to average throughout most of Europe, but in many catchments across northern France and the North Germany Plain they fell below average during the winter of 1988/89. The shortfall in runoff is particularly clear in the Evel catchment in Brittany where, as in southern Britain, the winter recovery in runoff rates did not gather any momentum until March 1989. Flows in much of central France remained close to average during the winter of 1988/89, as did flows in the major rivers flowing through Germany. Spain was particularly badly affected by the lack of winter rainfall, and flows in the Ebro remained very low for most of the winter. For much of the time discharge rates were lower than any recorded in the winter since at least 1960. By contrast, western Scandinavia - like north-western UK - experienced *above* average flows during the winter of 1988/89. Peak flows in much of Scandinavia also occurred earlier than average because the mild conditions resulted in much of the extra precipitation falling as rain rather than snow.

The summer of 1989 saw flows below average across a large part of Europe. In catchments as widely distributed as the Loire, the Weser, the Elbe, the Rhine and the Danube, monthly mean flows fell close to the period of record minima: only in the Nordic countries and further east in Russia were summer flows generally close to average. Flows also remained healthy in some of the chalk catchments in the Paris basin (e.g. the Nonette), due to the continuing beneficial effects of the high winter recharge during 1987/88.

1990-91

Low flows continued in many mainland catchments through the winter of 1989/90: again only in the Nordic countries were flows above average. The sequence of vigorous depressions that passed across Europe in January and February 1990 produced short-lived maxima in many catchments and flows in the Evel catchment in Brittany peaked dramatically in February. Further east, in Denmark and the Elbe and Weser catchments, the February peak was not as marked and the peak winter flows occurred slightly later in the year. Flows in the Ebro again remained well below period of record minima for

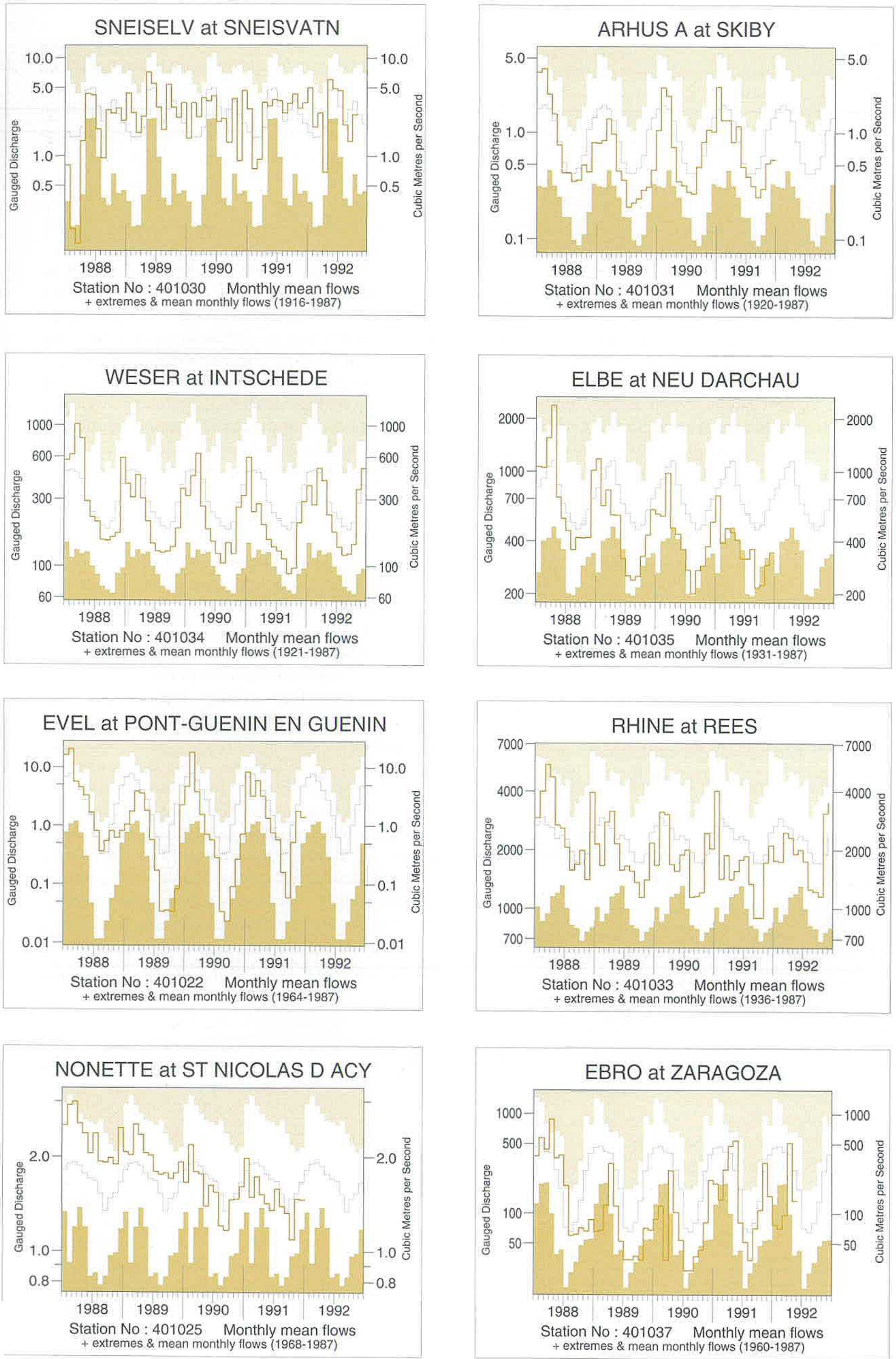


Figure 39 1988-92 monthly river flow hydrographs (Europe) most of the winter.

The spatial extent of low flows during the summer of 1990 was exceptional - away from parts of north-western Europe, flows were depressed in most regions and in many catchments fell below the minimum values reached in 1989. The below-average flows in the Danube during the summer of 1990 reflect not just the warm, dry conditions but also the below-average snowfall during the preceding winter. Typically, the seasonal recovery in runoff rates was extremely late in 1990 and notably low flows were recorded until year-end in many regions. In Finland, the countrywide runoff total for November and December combined was the lowest for over 40 years, but still substantially greater than during the 1941/42 drought[49].

The runoff pattern during the winter of 1990/91 was more complicated. In catchments such as the Loire and the Dordogne flows were lower than average, but higher than in the previous year. In other catchments in relatively close proximity - for instance in Brittany and the Paris Basin - flows during the 1990/91 winter were *lower* than in the preceding winter. Flows in the major German catchments were similar to those in 1989/90. The Ebro saw the largest winter runoff for three years, although for much of the early winter flows were below average.

Flows during the summer of 1991 were again well below average across much of France and northern Germany. The Loire, in common with many French rivers, was close to its period of record minimum, and some clay catchments in the Paris Basin virtually dried up (although many chalk catchments had still not reached the minima recorded in 1976). Flows in the Rhine, Weser and Elbe were close to, or below, recorded minima during the summer of 1991. Total runoff on the Elbe between November 1990 and October 1991 was only 51% of the long-term average; high winter snowfall meant that summer flows in the Danube were close to average, although spring and autumn flows were below average.

1992

The limited amount of data available for 1992 restricts the analytical coverage of the later stages of the drought. Flows in the Rhine and Weser were closer to the long-term average from the winter of 1991/92, but were still consistently below: only in winter 1992/93 did flows exceed the long-term average. Flows in some rivers in central France were reported to be at exceptionally low levels towards the end of the 1991-92 hydrological year (November-October): effective precipitation over the twelve months was assessed as the lowest for 45 years[47]. Thereafter widespread rainfall meant that the situation at the beginning of winter was better than at the same time in the preceding three years. Flows in the Ebro were still well below average during 1992, but the focus of the water shortage in Spain had by then shifted further south: the greatest runoff deficits were in the Guadalquivir and other southern catchments.

The relative severity of the recent sustained runoff deficiency compared to other twentieth century droughts may be judged by reference to Table 33. For the post-1960 period, the 24-, 36- and 48-month minimum runoff accumulations all occurred in the 1989-91 period on the Ebro. The longer flow record for the Weser demonstrates that runoff deficiencies were greater, for instance, in the mid-1930s and at the end of the 1950s. The recent deficiencies are moderately severe on the Rhine over the shorter and medium durations but very notable in the 48-month timeframe.

Some information is available from eastern Europe, suggesting that low flows were experienced in many countries over the period 1988 to 1992. The annual runoff totals for the Ialomita catchment in Romania for 1989, 1990 and 1992, for example, were amongst the lowest in a 60-year record.

Conclusion

Most of western Europe experienced runoff deficits between 1988 and 1992. The timing and intensity of maximum deficit varied considerably. In some catchments the deficits were worse during 1991; in others the drought was most extreme during 1990. The rapid change from low to high and back to low flow conditions observed in parts of Britain can also be seen in some continental catchments. New record minimum flows were set in many catchments with up to 100 years of data. As in the English lowlands, the groundwater contribution to summer and autumn flows diminished greatly over the 1990-92 period and, although difficult to quantify, the shrinkage in the river network was very substantial.

The Nordic countries, and especially western Norway, had generally higher than average runoff between 1988 and 1992. Runoff in western Norway was particularly high in the winters of 1988/89 and 1989/90, in marked contrast to the rest of Europe and in parallel with north-western Britain.

The impact of a 'drought' depends on the combination of hydrological conditions and water resource pressures. The biggest impacts of the 1988-1992 drought in Europe have been in areas with the greatest pressures on resources, and especially in those areas with high irrigation demands: these are not necessarily the same as the areas with the greatest hydrological drought.

TABLE 28 1988-92 RAINFALLS FOR SELECTED EUROPEAN SITES

	Rainfall	1988	1989	1990	1991	1992
Bergen	mm	2325	2844	2980	2399	2935
	%LTA	117	144	151	121	148
Copenhagen	mm	669	532	612	594	576
	%LTA	105	83	96	93	90
De Bilt	mm	887	661	716	649	918
	%LTA	110	82	88	80	113
Madrid	mm	418	561	328	289	376
	%LTA	92	124	72	64	83
Nuremburg	mm	808	519	581	518	541
	%LTA	126	81	91	81	85
Paris	mm	757	601	493	512	503
	%LTA	120	96	78	81	80

%LTA = percentage of 1941-70 average

TABLE 29 REGIONAL RAINFALL IN FRANCE, NOVEMBER 1988 - OCTOBER 1992

Region	Rainfall (mm)	48-month average	Nov. 1988 - Oct. 1992 as % of average	Deficiency/Surplus relative to the average (mm)
West	2638	3088	85	- 450
North	2278	2536	90	- 258
North-East	2825	3084	92	- 259
Central/East	2815	3148	89	- 333
South-West	3145	3432	92	- 287
South-East	2213	2864	77	- 652
Corsica	2133	2232	96	+ 99

TABLE 30 RANKED N-MONTH EUROPEAN RAINFALL EXTREMES

Site	Duration (months)	Min (mm)	End month	Year	1988-92 min (mm)	end mth	end yr	Rank 1988-92 wrt POR	Rank 20th century
Paris	12	274	10	1921	439	04	1992	28	10
1770-1992	24	800	12	1954	918	02	1992	08	04
	36	1278	01	1902	1475	04	1992	09	04
	48	1827	08	1901	2139	10	1992	13	05
Madrid	12	173	04	1992	173	04	1992	01	01
1860-1992	24	532	03	1869	555	04	1992	02	01
(incomplete data	36	842	07	1876	988	12	1992	07	05
for 1920)	48	1155	04	1871	1473	05	1992	10	06
Copenhagen	12	286	04	1858	431	06	1992	>10	06
1821-1992	24	751	01	1859	1098	09	1992	>10	11
	36	1269	04	1871	1689	08	1992	>10	09
	48	1766	04	1872	2246	09	1992	>10	09
		Max (mm)			1988-92 max				
Bergen	12	3174	01	1968	3163	08	1989	02	02
1921-1992	24	5962	06	1990	5962	06	1990	01	01
	36	8314	12	1992	8314	12	1992	01	01
	48	11208	07	1992	11208	07	1992	01	01

TABLE 31 RANKED NON-OVERLAPPING MINIMUM 36-MONTH RAINFALL ACCUMULATIONS FOR SELECTED EUROPEAN SITES

Site	Rank	Minimum (mm)	End/month	Year
Copenhagen 1821-1992	01	1269	04	1871
	02	1287	07	1859
	03	1389	06	1940
	04	1400	10	1888
	05	1432	04	1840
	06	1464	05	1978
	07	1469	09	1833
	08	1489	08	1880
	09	1492	05	1849
	10	1504	07	1925
Paris 1770-1992	01	1278	01	1902
	02	1390	09	1791
	03	1397	07	1956
	04	1405	02	1922
	05	1417	04	1796
	06	1445	02	1896
	07	1450	07	1864
	08	1460	09	1870
	09	1475	09	1992
	10	1489	05	1815
Madrid 1880-1992 (incomplete data for 1920)	01	842	07	1876
	02	865	07	1870
	03	926	11	1950
	04	982	10	1983
	05	983	10	1934
	06	984	12	1900
	07	988	12	1992
	08	1017	12	1954
	09	1036	10	1946
	10	1038	10	1925

TABLE 32 EUROPEAN SITES - INDEX CATCHMENTS

Catchment	Location	Period of Record
Evel at Pont Guenin	France: Brittany	1965-1991
Nonette at St Nicholas	France: Paris basin	1969-1991
Arthus at Skiby	Denmark	1920-1991
Rhine at Rees	Germany	1935-1992
Elbe at Neu-Darchau	Germany	1965-1991
Weser at Intschede	Germany	1921-1992
Sneisalv at Sneisvatn	Norway: north west	1918-1992
Ebro at Zaragoza	Spain	1961-1992

TABLE 33 RANKED MINIMUM ACCUMULATED RUNOFF TOTALS FOR SELECTED EUROPEAN RIVERS

Duration (months)		24			36			48		
River/Station	Rank	Year	End Month	mm	Year	End Month	mm	Year	End Month	mm
Weser at	1	1935	1	308	1935	1	510	1936	1	729
Intschede	2	1960	9	323	1974	7	543	1974	11	762
	3	1977	7	327	1979	2	551	1979	2	790
1921-1992	4	1964	12	333	1965	4	586	1992	10	829
	5	1973	2	342	1992	2	596	1952	2	842
	6	1930	9	353	1954	6	609	1931	12	907
	7	1950	2	361	1951	2	612	1965	11	978
	8	1954	6	372	1930	10	614	1946	1	995
	[9	1992	3	381]						
Rhine at Rees	1	1950	9	559	1973	11	962	1950	9	1350
	2	1973	2	598	1950	4	992	1974	9	1354
1936-1992	3	1964	9	640	1965	4	1069	1992	10	1498
	4	1944	8	650	1944	9	1074	1965	2	1558
	5	1977	1	684	1992	5	1087	1945	12	1574
	6	1960	7	701	1978	2	1146	1979	1	1631
	7	1992	3	706	1960	7	1216			
	8	1947	11	726	1947	11	1218			
Ebro at	.1	1990	10	129	1991	8	277	1992	5	420
Zaragoza	2	1987	9	249	1988	1	422	1987	9	615
	3	1974	9	323	1984	1	502	1977	4	683
1960-1992	4	1983	1	330	1976	9	510			
	5	1977	5	330	1965	9	539			
	6	1965	9	332						
	7	1969	1	354						
	8	1964	12	357						

Note: Only non-overlapping droughts are featured. For the longest durations the rankings are incomplete because there were insufficient separate drought events of notable magnitude.

Figure 40 UK location map

REFERENCES

1. Central Water Planning Unit 1976. The 1975-76 drought: a hydrological review. Technical Note No. 17.
2. Hamlin, M.J. and Wright, C.E. 1978. The effects of droughts on river systems. Proc. Roy. Soc., London, 363, 69-96.
3. Marsh, T.J. and Lees, M.L. 1985. *The 1984 Drought*. Hydrological data UK series.
4. Manley, G. 1974. Central England Temperatures: monthly means 1659 to 1973. *Quart. J. Roy. Met. Soc.*, 100, 389-405.
5. Gustard, A., Roald, L.A., Demuth, S., Lumadjeng, H.S. and Gross, R. 1989. *Flow Regimes from Experimental and Network Data*. Institute of Hydrology.
6. Institute of Hydrology 1992. *1991 Yearbook*, Hydrological data UK series. Institute of Hydrology, Wallingford.
7. Marsh, T.J., Monkhouse, R.A. 1991. 1990 - a year of hydrological extremes. *Weather*, Vol 46, No. 12, 365-376.
8. Institute of Hydrology 1993. *1992 Yearbook*, Hydrological data UK series, Institute of Hydrology, Wallingford.
9. Van der Leeden, F. 1975. *Water Resources of the World*. Water Information Center, Port Washington, New York.
10. Water Services Association 1992. *Water Facts 1991*.
11. Houghton, J.T., Callander, B.A. and Varney S.K. (Eds) 1992. Climate change 1992 - The supplementary report to the IPCC Scientific Assessment. WMO/UNEP. Cambridge University Press.
12. Wigley, T.M., Lough, T.M., Jones, P.D. 1984. Spatial patterns of precipitation in England and Wales and a revised homogeneous England and Wales precipitation series. *J. Climatol.*, 4, 1-27.
13. Arnell, N.W., Reynard, N.S., Marsh, T.J., and Bryant, S.J. 1993. Hydrology. In: *Impacts of the Mild Winters and Hot Summers 1988-90*, Cannell, M.G.R. and Pitcairn, S.E.R. (Eds). Department of the Environment. HMSO.
14. Jones, P.D. and Hulme, M. 1933. The Climate - temperatures and windiness. In: *Impacts of the Mild Winters and Hot Summers 1988-90* Cannell, M.G.R. and Pitcairn, S.E.R. (Eds), Department of the Environment. HMSO, 3-11.
15. Webb, J.C.D. and Meadon, G.T. 1993. Britain's highest temperatures by county and by month, *Weather*, Sept. 1993, 282-291.
16. Cannell, M.G.R. and Pitcairn, S.E.R. (Eds) 1993. *Impacts of the Mild Winters and Hot Summers 1988-1990*. Dept. of the Environment. HMSO.
17. Gregory, J.M., Jones, P.D. and Wigley, T.M.L. 1991. Precipitation in Britain: an analysis of area-average data updated to 1989. *Int. J. Climatol.* Vol 11, 331-345.
18. Wilby, R.L. 1993. The influence of variable weather patterns on river water quantity and quality regimes. *Int. J. Climatol.* 13, 447-459.
19. Lamb, H.H. 1972. British Isles weather types and a register of the daily sequences of circulation patterns, 1861-71. *Geophys. Mem.* 116. HMSO, London.
20. Marsh, T.J., Monkhouse, R.A., 1990. Hydrological aspects of the development and rapid decay of the 1989 Drought, *Weather*, Vol. 45, No. 8, 290-299.
21. Institute of Hydrology 1993. Hydrological Summaries for Great Britain. Monthly series.
22. Tabony, R.G. 1977. The variability of long duration rainfall over Great Britain. Met. Office Scientific Paper No. 37.
23. Wright, C.E. 1978. Synthesis of river flows from weather data. Central Water Planning Unit, Technical Note No. 26.
24. Wheeler, D.A. 1991. Water supply problems in north-east England as a result of the 1989 drought. *Geography* 76, 2, 167-172.
25. Mawdsley, J., Petts, G. and Walker, S. 1994. Assessing the severity of droughts. British Hydrological Society Occasional Paper No. 3 (in press).
26. Bryant, S.J., Arnell, N.W., and Law, F.M. 1994. The long term context for the current hydrological drought. *J. IWEM* (in press).
27. Marsh, T.J. and Bryant, S.J, 1992. The Yorkshire Drought - 1991 update. Report to the National Rivers Authority. Institute of Hydrology.
28. Thompson, N., Barrie, I.A., Ayles, M. 1981. The Meterological Office Rainfall and Evaporation System: MORECS (July 1981). Met. Office Hydrological Memorandum No. 45.
29. Penman, H.L. 1948. Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc.*, London A., 193, 120-145.
30. Calder, I.R., Harding, R.J., Rosier, P.T.W. 1983. An objective assessment of soil-moisture deficit models. *J. Hydrol.*, 60, 329-355.
31. Institute of Hydrology 1990. *1989 Yearbook*, Hydrological data UK series.
32. Marsh, T.J. and Macruairi, R.E. 1993. A demonstration of the United Kingdom's vulnerability to drought. *Proc. 4th BHS Nat. Hydrol. Symp.*, Cardiff. Institute of Hydrology. 1.1 - 1.8.
33. National Rivers Authority 1993. Low flows and water resources.
34. Taylor, J. 1876. The flow of the River Thames. *Min. Proc. Instn Civ. Engrs*, vol. xlv pt iii, 102,

and lxiv, pt ii (1881), 328.

35. Gustard, A., Bullock, A. and Dixon, J.M. 1992. Low flow estimation in the United Kingdom. *Institute of Hydrology Report No. 108.*
36. Monkhouse., R.A., Doorgakant, P. and Neale, R. 1990. Long term hydrograph of groundwater levels in the Chilgrove House well in the Chalk of southern England.
37. Day, J.B.W., Rodda, J.C. 1978. The effects of the 1975-76 drought on groundwater and aquifers. *Proc. Roy. Soc.* London A., 363, 55-68.
38. Anon. 1993. Groundwater recovery in the Kent Chalk, winter 1992-93. National Rivers Authority.
39. Monkhouse, R.A., Doorgakant, P., Marsh, T.J. and Neale, R. 1992. Long term hydrograph of groundwater levels in the Dalton Holme well in the Chalk of the Yorkshire Wolds. British Geological Survey, Wallchart Series No. 2.
40. Marriot, R. and Archer, D. 1993. Kielder Water - White Elephant or White Knight? *Proc. 4th BHS Nat. Hydrol. Symp.*, Cardiff. Institute of Hydrology. 1.37 - 1.45.
41. Simpson, B., Blower, T., Wilkinson, W.B. and Craig, R.N. 1989. The engineering implications of rising groundwater levels in the deep aquifer beneath London. CIRIA special report No. 9.
42. Anon. 1990. Water Bulletin. No. 422. Water Services Association. Water Services. September 1990.
43. Rodda J.C. 1978. A review of the 1975/76 drought. Unpublished memorandum. Water Data Unit.
44. Anon. 1992. Sustaining our resources - Southern Region water resources development strategy. National Rivers Authority.
45. Bonacci, O. 1993. Hydrological identification of droughts. *Hydrol. Processes*, Vol. 7, 249-262.
46. Thomsen, R. 1993. Future droughts, water shortages in parts of western Europe. *Trans. AGU*, Vol. 74, No. 14, 164-165.
47. Merillon, Y. and Scherer, J.C. 1993. La secheresse de 1992. *La Houille Blanche*, 8, 559-569.
48. Anon. 1993. Rain in Spain cracks record drought. *Financial Times Newsletters*, Water Briefing, Issue 1 Nov. 1993.
49. Kuusisto, E. 1992. Runoff from Finland in the period 1931-1990. *Aqua Fennica* 22, 1, 9-22.

APPENDIX 1

Selected bibliography of major English droughts

(Various) 1869. Evidence to Royal Commission on Water Supply (after 1868 drought shortages). HMSO.

Symons, G. J. 1888. The droughts of 1887. *British Rainfall 1887*, pp 148-154.

Currie, I et al. 1992. The scorching summer of 1911, in *The Essex Weather Book*. Froglets Publications, Westerham, p 34.

Brooks, C. E. P. and Glasspoole, J. 1922. The drought of 1921. *Quart. J. Roy. Met. Soc.*, Vol. 48, pp 139-166.

Glasspoole, J. 1930. Some remarkable features of the rainfall of 1929. *British Rainfall 1929*, pp 272-281.

Glasspoole, J. and Andrew, W.L. 1934. The exceptional summer of 1933. *Quart. J. Roy. Met. Soc.*, Vol. 60, pp 29-56.

Glasspoole, J. 1937. Drought in Scotland, November 1935 to June 1936. *British Rainfall 1936*, pp 266-271.

McClean, W. N. 1948. 1947 and its place in meteorological history. *Weather*, Vol. 3. pp 117-8.

Atkinson, A. 1955. 1947: Drought and Water - shortage crisis, in Manchester Waterworks 1945-55. *JIWE*, Vol. 9, pp 380-383.

Rowntree, N. A. F. 1961. Rainfall and runoff at reservoired catchments in 1959, in Conf. on Surface Water Resources and the Drought of 1959. *JIWE*, Vol. 15, pp 151-178.

Guild, W. G. 1960. The drought of 1959 in Scotland, in Scottish Section Presidential Address. *JIWE*, Vol. 14, pp 371-374.

Hamlin, M. J. and Wright, C. E. 1978. The effects of drought on the river systems, in Scientific Aspects of the 1975-76 drought in England and Wales. *Proc. Roy. Met. Soc.* London, Series A, Vol. 363, pp 69-96.

Speight, H. 1977. Paper 1: Setting the Scene. Proc. of Seminar on the operational Aspects of the Drought of 1975-76. IWES/ICE, pp 1.1-1.8.

Day, J. B. W. and Rodda, J. C. 1978. The effects of the 1975-76 drought on groundwater and aquifers. *Proc. Roy. Soc. London*, Series A, Vol. 363, pp 55-68.

National Water Council 1977. *The 1975-76 Drought.* 48 pp.

Doornkamp, J. C., Gregory, K. J. and Burn, A. S. 1980. *Atlas of Drought in Britain 1975-76*. Institute of British Geographers, 86 pp.

Marsh, T.J. and Lees, M.L. 1985. *The 1984 Drought*, Hydrological data UK series. Institute of Hydrology, 82pp.

Water Authorities Association. 1985. *Drought '84*. 28pp.

Anon. 1986. *1984 Yearbook*, Hydrological data UK series. Institute of Hydrology, 180pp.

APPENDIX II

Publications in the *Hydrological data UK* series

Title	Loose-leaf*	Bound
Yearbook 1981	£10	£12
Yearbook 1982	£10	£12
Yearbook 1983	Out of print	
Yearbook 1984	Out of print	
Yearbook 1985	£12	£15
Yearbook 1986	£12	£15
Yearbook 1987	£12	£15
Yearbook 1988	£12	£15
Yearbook 1989	£15	£18
Yearbook 1990	£15	£18
Yearbook 1991	*	£20
Yearbook 1992	*	£20
Hydrometric Register and Statistics 1981-85	£12	£15
Hydrometric Register and Statistics 1986-90		£20
The 1984 Drought		£12
The 1988-92 Drought		£20

* Loose-leaf versions of the *Hydrological data UK* publications have been discontinued.

Concessionary rates apply to the purchase of two or more of the pre-1988 Yearbooks.

All the *Hydrological data UK* publications may be obtained from: Institute of Hydrology, Wallingford Oxfordshire OX10 8BB.
Telephone: (0491) 838800 Facsimile: (0491) 832256

Enquiries or comments regarding the series or individual publications are welcomed and should be directed to the National Water Archive Office at the above address.

Hydrometric Register and Statistics 1986-90

This reference volume includes maps, tables and statistics for over 1000 river basins and 150 representative observation boreholes throughout the United Kingdom. The principal objective of the publication is to assist data users in the selection of monitoring sites for particular investigations and to allow more effective interpretation of analyses based upon the raw data. To this end, concise gauging station and catchment descriptions are given for the featured flow measurement stations - particular emphasis is placed on hydrometric performance, especially in the high and low flow ranges, and on the net effect of artificial influences on the natural flow regime. Summary hydrometric statistics, for each of the years 1986-90, are provided alongside the corresponding long-term averages, or extremes, to allow the recent variability in surface and groundwater resources to be considered in a suitable historical context.

The 1984 Drought

This, the first occasional report in the *Hydrological data UK* series, concerns the 1984 drought. The report documents the drought in a water resources framework and its development, duration and severity are examined with particular reference to regional variations in intensity. Assessments are made of the likely frequency of occurrence of the drought and its magnitude is considered both in the perspective provided by historical records of rainfall and runoff, and in the context of the recent somewhat erratic climatic behaviour.

Associated Publications

Representative Basin Catalogue

Data collection for the national Flood Event Archive, maintained by the Institute of Hydrology, concentrates on a selection of basins that form a representative sample of UK catchments. A catalogue providing comprehensive hydrological and reference information for 200 representative basins has been prepared and is available as national (five volumes) or regional sets; user-selected groups of catchments can be provided for particular investigations.Enquiries concerning the cost and availability of the catalogue should be directed to the above address.

Long-term groundwater level hydrographs

In 1990 the British Geological Survey launched a series of wallcharts depicting long-term variations in groundwater levels. The following are currently available:
i. Long-term hydrograph of groundwater levels in the Chilgrove House well in the Chalk of southern England
ii. Long-term hydrograph of groundwater levels in the Dalton Holme estate well in the Chalk of Yorkshire

Copies may be obtained from: British Geological Survey, Wallingford, Oxfordshire OX10 8BB.
Telephone: (0491) 838800. Facsimile: (0491) 825338

Natural
Environment
Research
Council