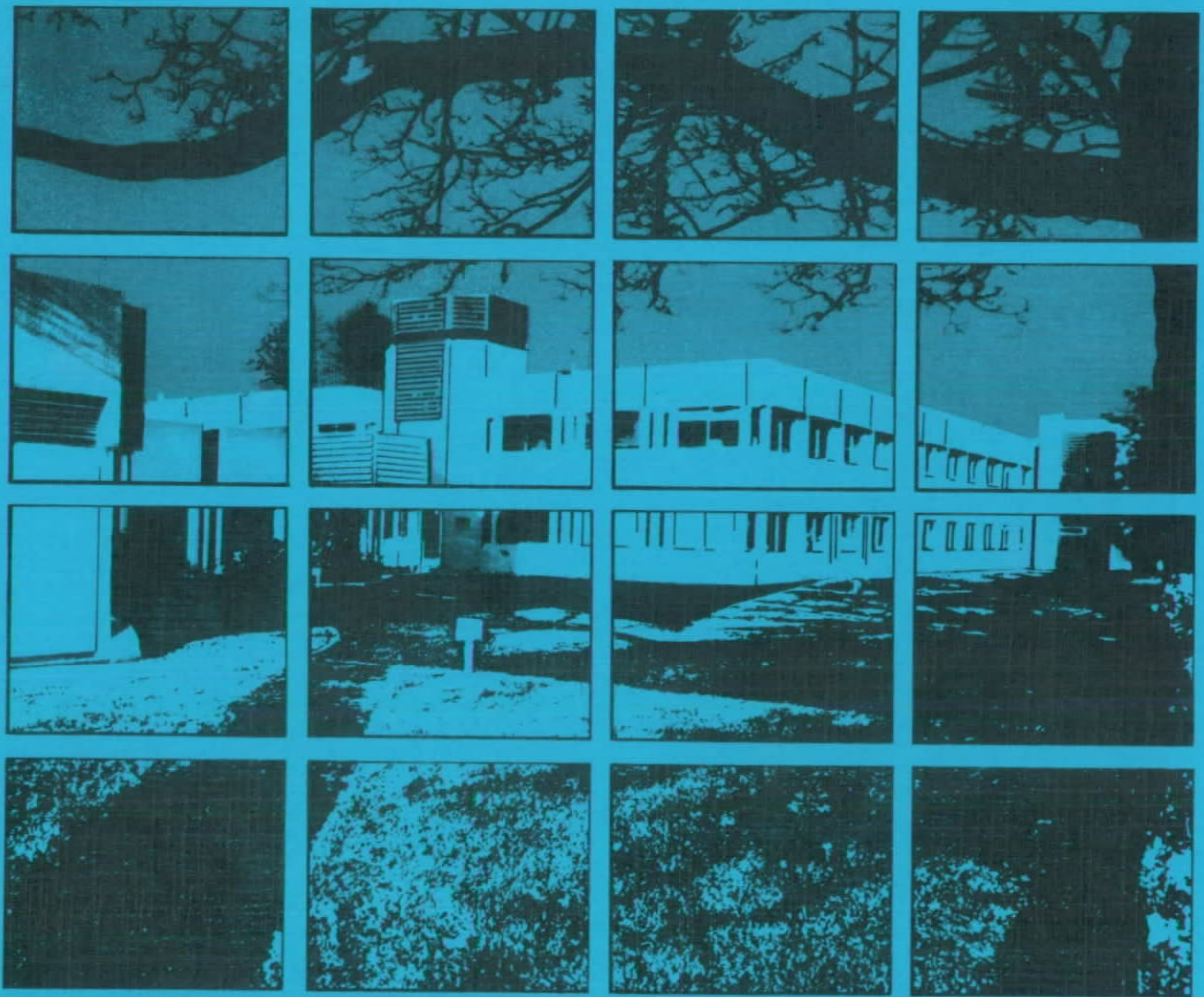
INSTITUTE of HYDROLOGY

Impact of Climatic Variability and Change on River Flow Regimes in the UK



Report No 107

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Impact of climatic variability and change on river flow regimes in the UK

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Abstract

The objectives of this report are to examine past variability in river flow regimes, concentrating in particular on recent years, and to consider the possible consequences of future climate change for river flow regimes in the United Kingdom.

The geological and climatic characteristics of a catchment determine how variations in rainfall from year to year impact upon river flow variability. In general terms, the drier the catchment (as indexed by the proportion of rainfall which runs off from a basin) and the lower the base flow component, the greater the variation in flow regime between years. There is some evidence that years containing similar hydrological characteristics tend to cluster: wet winters tend to follow wet winters, for example. There is no conclusive evidence, however, that 'recent' years (*excluding* 1989 and 1990) have seen an unusually large number of extreme events, although the test used is rather conservative and the period defined as 'recent' influences the results. Annual and seasonal runoff totals during the 1980s were generally higher than in previous decades, and there are some indications that year-to-year variability was also higher. Data from 1989 and 1990 were not included in the analysis.

Future changes in UK flow regimes depend very significantly on assumed changes in evapotranspiration and, particularly, precipitation, which are currently very difficult to predict. The study therefore examined the sensitivity of river flow regimes to a range of feasible climate change scenarios, biased towards generally wetter conditions but assuming both wetter and drier summers. Simple regression-type relationships were considered, but most of the analyses used monthly water balance models applied at a range of representative sites. Changes in average annual runoff under a given climate change scenario were found to depend strongly on catchment dryness. If potential evapotranspiration is assumed to remain constant, for example, a 10% increase in annual rainfall could produce up to 30% extra runoff in south east England, whilst in more humid western regions it would result in only an additional 12 to 15%. Increases in average annual rainfall of between 8 and 10% would be required to offset the effects of 15% higher potential evapotranspiration. The effect of drier summers on summer river flows depends upon the current summer water balance and catchment geology: the greatest relative reductions are expected in responsive catchments which currently have a close balance between rainfall and potential evapotranspiration. In catchments with a large groundwater storage, delayed drainage of additional winter rainfall may mitigate the effects of drier, warmer summers.

Acknowledgements

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The project has benefited directly from the involvement of the following current and past staff of the Institute of Hydrology: Max Beran, Dr Andrew Bullock, Janet Whiteley, Terry Marsh, Dr Graham Thomas, Stephen Heaney, David Kelly and Chris Nunwich. Dr P. D. Jones of the Climatic Research Unit, University of East Anglia, provided climate data and the reconstructed flow series used in some of the analyses.

Contents

1. Objectives of the report

1.1 THE IMPACT OF CLIMATIC VARIABILITY AND CHANGE ON FLOW REGIMES

The late 1980s and early 1990s have again demonstrated the notorious variability in the climate of the United Kingdom. The winter of 1988/89, for example, was exceptionally mild and the period from November to January was the driest over England and Wales for over 100 years. Only heavy rainfall in late spring prevented the summer of 1989 beginning with large-scale water deficits. However, this was followed by prolonged dry weather and drought, peaking in severity first in one part of the UK and then another. Water supply difficulties arose in the south east, south west, Yorkshire and some other parts of the UK. The winter of 1989/90 has, like 1988/89 been very mild, but has also been very wet (except in parts of Kent and the east coast): 1990 has seen some of the most widespread flooding for forty years in some areas, and river flows have broken many records.

Against this background of apparently extreme variability, seemingly replicated worldwide, there has been increasing scientific, public and political interest in the theory that an increasing concentration of greenhouse gases, principally carbon dioxide, methane, nitrous oxide and chlorofluorocarbons (CFCs), will lead to global warming and significant changes in climate. It has frequently been claimed - though not always supported by scientists - that the recent apparent increase in extreme climatological events is the first sign that global warming is taking place, and is a foretaste of things to come.

If global warming is occurring or is about to occur and regional climates were to change, one of the most significant impacts would be on hydrological processes and regimes, and hence water resource availability. The long-term planning of water resources should if possible take account of the potential impacts of future change, which requires an understanding of both sensitivities to change and current variability over time.

This report is concerned with the impacts of climate variability and change on river flow regimes in the United Kingdom, and in particular with the following questions:

(1) How have river flow regimes varied between years in the UK in the recent past, and what catchment and climate characteristics control this variability? Are extreme events distributed randomly through time, or do they tend to cluster? What is the long-term 'significance' of the various extreme hydrological events experienced during the 1970s and 1980s?

(2) How might river flow characteristics change in the United Kingdom with global warming? What properties of a catchment will influence the sensitivity of flows to climate change?

The report is primarily concerned with river flow regimes, and makes little reference to groundwater. Direct assessments of variability and change in water resources - such as reservoir contents and reliability - are not made, although many of the hydrological indices considered are of direct relevance to water resource studies, and implications for water resources are drawn in concluding chapters.

It is important to state at the outset what the report does not attempt to achieve. Firstly, no attempt is made to test specifically the hypothesis that global warming is already having observable effects on river flow regimes in the U.K. Secondly, the analysis of recent variability has not incorporated much information from 1989 and 1990, years which have both seen some notable hydrological events. Any conclusions about the nature of recent variability must inevitably be subject to revision in future studies. Finally, the study does not attempt to make definitive predictions about river flows and water resources in the U.K. under a changed climate, because estimates of that future climate are currently uncertain.

The study does, however, provide useful information about the nature of variations over time in aspects of flow regimes, and indicates those aspects of catchment and climate change which will determine how sensitive flow regimes and water resources are to possible future changes.

1.2 PROJECT HISTORY

The project is closely associated with an investigation into techniques for estimating the low flow characteristics of British rivers (Gustard *et al.,* 1991), and much of the data collection and quality control was common to both studies. The project began in October 1986, and ran until March 1990.

During the course of the project, two associated desk studies on the effects of climate change on water quantity (Beran and Arnell, 1989) and water quality (Jenkins and Whitehead, 1989) were prepared. A subcontract had also been let with the Climatic Research Unit at the University of East Anglia to develop climate change scenarios for Britain (Hulme and Jones, 1989).

1.3 STRUCTURE OF THE REPORT

The report breaks into two halves, the first concentrating on the assessment of past and recent variability in flow regimes (Chapters 2 to 5), and the second on possible future changes (Chapters 6 to 11). Conclusions are drawn at the end of each half, and Chapter 12 identifies future research needs.

2. Recent variability in river runoff: introduction

2.1 RECENT VARIABILITY IN FLOW REGIMES

The first half of this report is concerned with the analysis of past and recent variability in flow regimes in the United Kingdom and, in particular, with two key questions:

(i) how much variation is there in flow regimes in the UK from year to year, and what causes both this variation and differences in variation between catchments?

(ii) how 'unusual' have some of the extreme events experienced in the 1970s and 1980s been when looked at over the longer term?

An appreciation of current patterns of variability in flow regimes between years helps with the interpretation of the 'significance' of the occasional extreme event, and allows predictions of possible future conditions to be placed in the context of recent history.

A comprehensive range of hydrological and climatological data was used in the assessment of recent variability in flow behaviour. This chapter summarises the data used and introduces the indices considered.

2.2 RIVER FLOW AND CLIMATE DATA

2.2.1 River flow data

The UK Surface Water Archive contains daily flow records for around 1200 river gauging stations across the country. The data are collected by the regions of the National Rivers Authority in England and Wales, the River Purification Boards in Scotland, the Department of the Environment in Northern Ireland, and by a number of other, mainly private, bodies.

The assessment of the quality of flow data from these gauging stations was a major element in the current study and the associated investigation into low flow estimation (Gustard *et al.,* 1991). A two letter grade was assigned to each station. The first letter represents the hydrometric quality of the station at low flows; the second represents the extent to which artificial influences within the catchment modify the flow regime at low flows. A detailed description of the way in which grades were assigned to a gauging station can be found in Gustard *et al.* (1991). A brief summary of the methodology used is presented here.

The hydrometric performance of a gauging station was assessed in two ways. The sensitivity of the control and accuracy of the rating were determined at the ninety-five percentile flow (Q95), and the two measures were combined to derive one of three single letter grades representing the hydrometric quality of the flow data: 'A' being assigned to the most sensitive and accurate stations; 'B' assigned to stations showing moderate performance; 'C' being assigned to stations with unacceptable hydrometry.

The artificial influences in the flow regime caused by surface and groundwater abstractions, industrial and sewage treatment works discharges, and impounding reservoirs, were derived for each catchment from licences and consents held by regional offices of the National River Authority, the Regional Purification Boards, the Department of the Environment (Northern Ireland) and the compensation flow archive at the Institute of Hydrology (Gustard *et al.,* 1987). The impact of these influences on the ratio of naturalised Q95 to mean flow was calculated as a bias. An A, B, or C grade was assigned to each station depending on the size of the bias - an 'A' grade representing insignificant influence down to a 'C' grade for an unacceptable influence on the low flow regime.

Dates of changes in hydrometric controls, or the commencement of major schemes influencing the flow regime, that resulted in a change to the grade of the station were also recorded.

Once grades had been assigned to gauging station records in this manner, regional offices of the National Rivers Authority and the River Purification Boards were approached for their comments on the grades, based on their more local knowledge of each site and catchment. Any modifications they suggested were discussed and incorporated into the station grade.

A subset of the gauging stations was selected for the current study into climatic variability on the basis of both their grade and their length of record. Stations with a 'C' in either their hydrometric or artificial influence grade were excluded on the grounds that their data are insufficiently accurate or unrepresentative of the flow regime at the station. All other combinations of grade were included.

In order to establish past variability in hydrological response flow records need to extend back a sufficient length of time. Due to rationalisation of hydrometric networks in various regions over the past ten years or so a number of stations with records extending back beyond the 1960s were closed. In order to make full use of these records, stations which covered a common period from 1961 to 1980, and with less than five years in this period missing data, were selected from the main set.

One hundred and twelve of the approximately 1650 stations graded (the grading exercise included catchments not currently on the Surface Water Archive) met these criteria. They are listed in Table 2.1 and located in Figure 2.1. Less than 7% of gauging stations in England, Scotland and Wales were thus deemed useable for studying past hydrological behaviour.

River flow records in Northern Ireland are short, and no series on the Surface Water Archive begin before 1970. The longest records (more than 15 years of data) were, however, used in parts of the current study in order to ensure as wide a geographical coverage as possible. The catchments used are listed in Table 2.2.

Table 2.1 Gauging stations used in this analysis

Number	Name	Area (km^2)	Record used	
7001	Findhorn at Shenachie	416.	1960	1987
7002	Findhorn at Forres	782.	1958	1988
8002	Spey at Kinrara	1012.	1951	1988
8004	Avon at Delnashaugh	543.	1952	1988
8005	Spey at Boat of Garten	1268.	1951	1987
8006	Spey at Boat o Brig	2861.	1952	1988
8009	Dulnain at Balnaan Bridge	272.1	1952	1988
8010	Spey at Grantown	1749.	1953	1988
9001	Deveron at Avochie	442.	1959	1988
9002	Deveron at Muiresk	955.	1960	1988
9005	Allt Deveron at Cabrach	67.	1948	1988
12001	Dee at Woodend	1370.	1929	1988
15008	Dean Water at Cookston	177.	1958	1988
15013	Almond at Almondbank	175.	1955	1988
18001	Allan Water at Kinbuck	161.	1957	1988
18002	Devon at Glenochil	181.	1959	1979
19002	Almond at Almond Weir	44.	1962	1988
19004	North Esk at Dalmore Weir	82.	1960	1988
19007	Esk at Musselburgh	330.	1962	1988
20001	Tyne at East Linton	307.	1961	1988
21003	Tweed at Peebles	694.	1959	1988
21005	Tweed at Lyne Ford	373.	1961	1988
21006	Tweed at Boleside	1500.	1961	1988
21007	Ettrick Water at Lindean	499.	1961	1988
21008	Teviot at Ormiston Mill	1110.	1960	1988
21014	Tweed at Kingledores	139.	1961	1988
21031	Till at Etal	648.	1956	1980
22002	Coquet at Bygate	60.	1957	1980
22003	Usway Burn at Shillmoor	21.	1957	1980
23003	North Tyne at Reaverhill	1008.	1959	1980
24001	Wear at Sunderland Bridge	658.	1957	1988
24002	Gaunless at Bishop Auckland	93.	1958	1983
24003	Wear at Stanhope	172.	1958	1988
24004	Bedburn Beck at Bedburn	75.	1959	1988
24006	Rookhope Burn at Eastgate	37.	1957	1980
25003	Trout Bech at Moor House	11.	1957	1980
25006	Greta at Rutherford Bridge	86.	1960	1989
25007	Clow Beck at Croft	78.	1961	1980
27007	Ure at Westwick Lock	915.	1958	1988
27008	Swale at Leckby Grange	1346.	1955	1984
27010	Hodge Beck at Bransdale Weir	19.	1936	1979
27023	Dearne at Barnsley Weir	119.	1960	1988
27024	Swale at Richmond	381.	1961	1980
28008	Dove at Rocester Weir	399.	1953	1989
28009	Trent at Colwick	7486.	1958	1989
28085	Derwent at St. Marys Bridge	1054.	1935	1989

Table 2.1 Continued

Number	Name	Area (km^2)	Record used	
32003	Harpers Brook at Old Mill Bridge	1054.	1935	1989
32004	Ise Brook at Harrowden	194.	1943	1988
33003	Cam at Bottisham	803.	1936	1987
33009	Bedford Ouse at Harrold M.	1320.	1955	1986
33011	Little Ouse at County Br.	129.	1948	1988
33013	Sapiston at Rectory Bridge	206.	1949	1988
33014	Lark at Temple	272.	1960	1988
33015	Ouzel at Willen	277.	1962	1987
33022	Ivel at Blunham	541.	1959	1988
33024	Cam at Dernford	198.	1949	1988
34001	Yare at Colney	232.	1959	1988
34002	Tas at Shotesham	147.	1957	1988
34003	Bure at Ingworth	165.	1959	1988
34004	Wensum at Costessey Mill	536.	1960	1988
35003	Alde at Farnham	64.	1961	1988
36002	Glem at Glemsford	87.	1960	1988
36003	Box at Polstead	54.	1960	1988
36007	Belchamp Br. at Bardfield Br.	59.	1960	1988
37005	Colne at Lexden	238.	1959	1988
38003	Mimram at Panshanger Park	134.	1952	1989
38014	Salmon Brook at Edmonton	21.	1956	1989
39016	Kennet at Theale	1033.	1961	1989
39054	Mole at Gatwick Airport	32.	1961	1989
40007	Medway at Chafford Weir	255.	1960	1988
41001	Nunningham St. at Tilley Br.	17.	1950	1988
41002	Ash Bourne at Hammer Wood Br.	18.	1951	1988
41004	Ouse at Barcombe Mills	396.	1956	1988
41005	Ouse at Gold Bridge	181.	1960	1978
41013	Huggletts St. at Henley Br.	14.	1950	1988
42001	Wallington at North Fareham	111.	1951	1988
42003	Lymington at Brockenhurst Pk.	99.	1960	1988
42006	Meon at Mislingford	73.	1958	1988
42010	Itchen at Highbridge	360.	1958	1989
45001	Exe at Thorverton	601.	1956	1979
45002	Exe at Stoodleigh	422.	1961	1979
46002	Teign at Preston	380.	1956	1987
46003	Dart at Austins Bridge	248.	1958	1989
47001	Tamar at Gunnislake	917.	1956	1988
52003	Halse Water at Bishops Hull	88.	1961	1989
53005	Midford Brook at Midford	147.	1961	1989
53006	Frome(Bristol) at Frenchay	149.	1961	1989
53007	Frome(Somerset) at Tellisfd	262.	1961	1989
54008	Teme at Tenbury	1134.	1956	1989
54010	Stour at Alscot Park	319.	1959	1979
54016	Roden at Rodington	259.	1961	1989
55002	Wye at Belmont	1896.	1935	1984
55003	Lugg at Lugwardine	886.	1939	1980

Table 2.1 Continued

Number	Name	Area (km^2)	Record used	
55004	Irfon at Abernant	73.	1937	1982
55007	Wye at Erwood	1282.	1937	1984
55008	Wye at Cefn Brwyn	11.	1951	1988
55010	Wye at Pant Mawr	27.	1955	1982
55011	Ithon at Llandewi	111.	1959	1982
55023	Wye at Redbrook	4010.	1936	1984
55026	Wye at Ddol Farm	174.	1937	1988
55029	Monnow at Grosmont	354.	1948	1988
57004	Cynon at Abercynon	106.	1957	1988
60002	Cothi at Felin Mynachdy	298.	1961	1988
62001	Teifi at Glan Teifi	894.	1959	1988
68001	Weaver at Ashbrook	622.	1937	1988
68005	Weaver at Audlem	207.	1953	1987
72004	Lune at Caton	983.	1959	1988
75002	Derwent at Camerton	663.	1960	1988
79002	Nith at Friars Carse	799.	1957	1988
79003	Nith at Hall Bridge	155.	1959	1988
84003	Clyde at Hazelbank	1093.	1956	1988
84004	Clyde at Sills	742.	1957	1988
84005	Clyde at Blairston	1704.	1958	1988

Table 2.2 Northern Ireland catchments

Number	Name	Area (km^2)	Record used	
201002	Fairy Water at Dudgeon Bridge	161.2	1972	1989
201005	Camowen at Camowen Terrace	274.6	1972	1989
201006	Drumragh at Campsie Bridge	324.6	1972	1989
203010	Blackwater at Maydown Bridge	951.4	1970	1989
203012	Ballinderry at Ballinderry Br.	419.5	1970	1989
203013	Main at Andraid	646.8	1970	1989
203017	Upper Bann at Dynes Bridge	335.6	1970	1989
203018	Six Mile Water at Antrim	277.3	1970	1989
203020	Moyola at Moyola New Bridge	306.5	1971	1989
203021	Kells Water at Currys Bridge	127.0	1971	1989
203025	Callan at Callan New Bridge	164.1	1971	1989
203026	Glenavy at Glenavy	44.6	1971	1989
203028	Agivey at White Hill	98.9	1972	1989
205004	Lagan at Newforge	490.4	1972	1989
205008	Lagan at Drummiller	85.2	1974	1989

Figure 2.1 Location of the gauging stations used in the study

'Naturalised' flow data for a number of the catchments with significant artificial influences are held on the Surface Water Archive, although few of the records beginning before the 1960s continue into the 1980s. Eleven of the longer naturalised records on the Surface Water Archive were used in the current study (Table 2.3). Four of the records end in the late 1970s, and three are from the River Thames. No attempts were made to assess the quality of the naturalisation, and these data are to be regarded with considerably greater caution than the gauged flows used in the analysis (low flows before 1951 for the Thames at Kingston are known to be inconsistent with those in later years, for example). They do, however, provide some information about flow regimes before the 1950s.

Table 2.3 Naturalised flow records

Number	Name	Area (km^2)	Record used
36001	Stour at Stratford St Mary	844.3	1932 1976
37001	Roding at Redbridge	303.3	1950 1974
37002	Chelmer at Rushes Lock	533.9	1932 1976
38001	Lee at Feildes Weir	1036.0	1883 1988
39001	Thames at Kingston	9948.0	1883 1988
39002	Thames at Days Weir	3444.7	1938 1988
39008	Thames at Eynsham	1616.2	1951 1988
47015	Tavy at Denham/Ludbrook	197.3	1957 1986
50001	Taw at Umberleigh	826.2	1958 1989
54001	Severn at Bewdley	4325.0	1921 1984

More information on the variation in flow regimes over the long term was provided by the flow series reconstructed by Jones (1984) from long rainfall records, using Wright's (1978) regression-based monthly flow estimation model (the data are published in Jones *et al.* (1984), and were provided by Dr P.D. Jones of the Climatic Research Unit). Jones's reconstructions, however, only extended to the late 1970s (between 1974 and 1979), and the reconstructed flows were combined with observed flows to extend the series to 1988. Rather than add the observed data onto the end of the synthetic series, the synthetic data were added to the beginning of the observed series. Table 2.4 shows the gauging stations used, together with the periods of the synthetic and observed data, and the correlation coefficient between observed and synthetic data during the overlap period. The correlations are all high, and visual inspections suggested that there were no obvious systematic biases in the synthetic flows. Similar synthetic data sets prepared at the Central Water Planning Unit (Wright, 1978) were not used because the data were not available on a computer data base.

Gauging stations are frequently referred to in this report by Surface Water Archive number rather than name. Figure 2.2 shows the locations of the hydrometric areas that provide the basis for station numbering: for example, catchment 32003 is in hydrometric area 32.

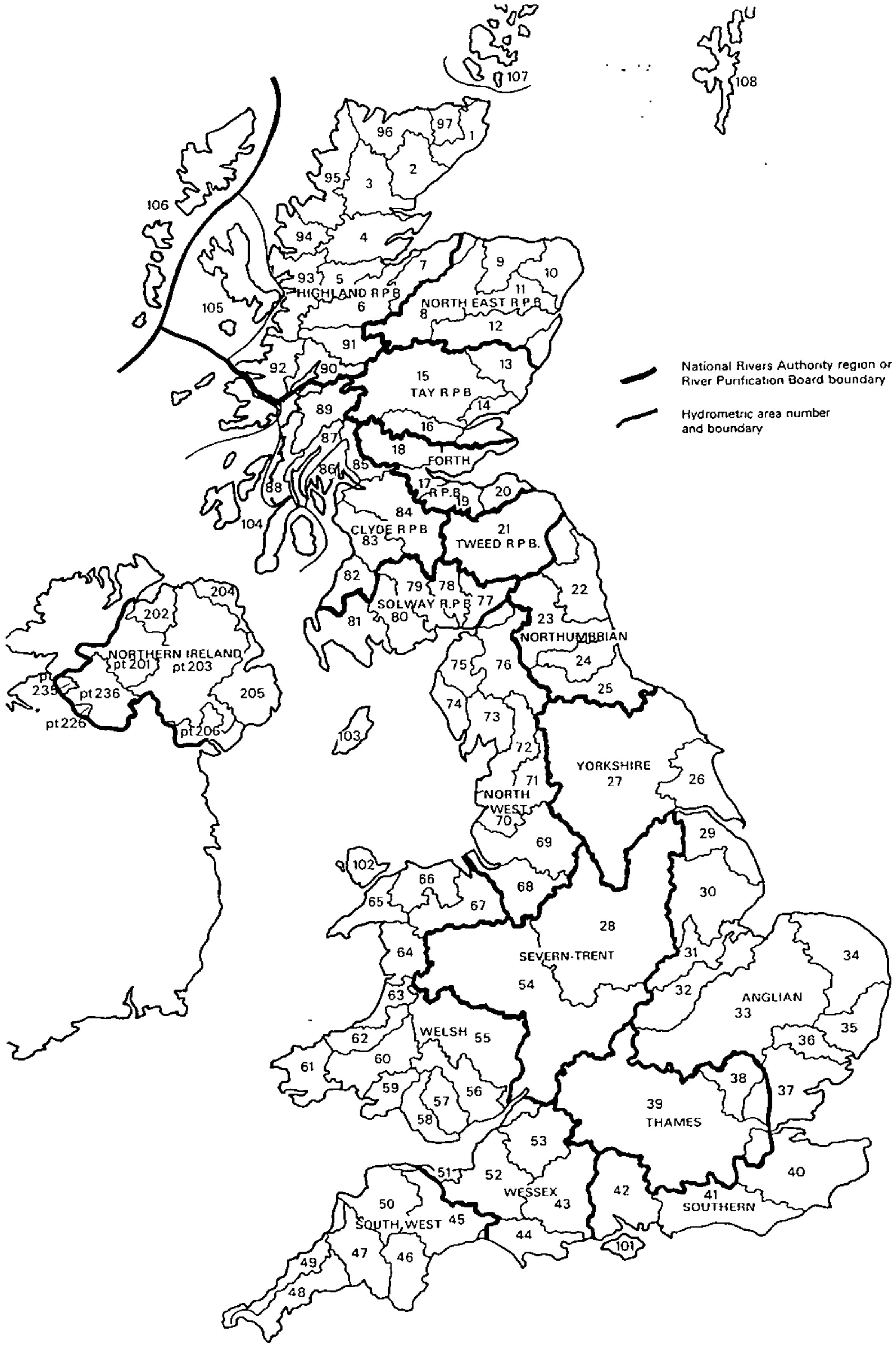


Figure 2.2 Hydrometric areas in the U.K.

Table 2.4 ***Reconstructed flow series used in the study***

	Catchment	Reconstructed	Observed	overlap correlation
76005	Eden at Temple Sowerby	1858-1979	1965-1988	0.947
76002	Eden at Warwick Br.	1855-1979	1967-1988	0.946
45001	Exe at Thorverton	1856-1979	1957-1988	0.959
25001	Tees at Broken Scar	1844-1977	1956-1988	0.925
23001	Tyne at Bywell	1863-1977	1957-1988	0.934
34004	Wensum at Costessy Mill	1838-1977	1961-1988	0.956
27043	Wharfe at Addingham	1854-1977	1974-1988	0.975
55023	Wye at Redbrook	1860-1979	1937-1988	0.948

2.2.2 Climatological data

Time series of catchment average monthly rainfall are held on the Surface Water Archive for the majority of river flow gauging stations, and data were extracted for the long-record catchments used in the analysis. Long-term average annual rainfall and potential evapotranspiration were also extracted for each catchment. The variability in seasonal potential evapotranspiration from year to year was defined for each catchment using the MORECS data base (Thompson *et al.*, 1981). Each catchment was allocated to one or more of the 188 40 km x 40 km MORECS grid boxes, and the coefficient of variation over the period 1961-1980 was calculated.

Two long monthly temperature series, both supplied by the Climatic Research Unit at the University of East Anglia, were used in the comparisons with flow behaviour. The Central England Temperature series (Jones, 1987) extends from 1659, and represents a notional site in 'central England'. The Northern Hemisphere land temperature series reaches back to 1851 (Jones *et al.*, 1986), and gives monthly temperatures as departures from the 1951-1970 average. The data represent average temperatures across the land surface of the Northern Hemisphere.

The final set of climatic data assembled was the series of daily weather types, as classified by Lamb (1972 - see also Jones and Kelly, 1981). A total of twenty-seven weather types are defined, including hybrids, representing seven basic types, namely anticyclonic, cyclonic, northerly, easterly, southerly, westerly and northwesterly. Data extend back to 1851, and seasonal and annual totals in various groups of types were calculated.

2.3 FLOW INDICES

A variety of aspects of flow and climate behaviour were considered in the study, with the emphasis on low flows over several durations, seasonal runoff totals and runoff seasonality through the year.

2.3.1 Daily data

Several indices summarising daily flow behaviour in a year were investigated. Those used were:

(i) annual maximum n-day flow: the highest flow averaged over n days to occur in each year.

(ii) annual minimum n-day flow: the lowest flow averaged over n days to occur in each year.

(ii) standardised annual range in n-day flow: the difference between the n-day highest and n-day lowest flows in each year, divided by the mean flow.

These measures were calculated for one day, seven day, and thirty day (n = 1, 7, 30) moving averages in each year.

2.3.2 Monthly data

The following indices of flow regime were defined from monthly data:

(i) four seasonal runoff totals: December to February (DJF), March to May (MAM), June to August (JJA) and September to November (SON): DJF runoff was referenced by the year containing the January;

(ii) calendar year annual runoff;

(iii) the minimum monthly runoff in a calendar year (note that this is not the same as the lowest 30-day runoff);

(iv) 'flow seasonality', defined as DJF/JJA runoff. A higher value denotes a greater variation in runoff through the year.

Indices (i) to (iii) were expressed as millimetres of runoff.

Similar indices were calculated from the monthly catchment average rainfall series.

2.4 FINAL COMMENTS

The assessment of the quality of over 1600 river flow gauging stations and the degree of artifical influence proved a time-consuming task, and took three years to complete. Very few gauging stations with long records (greater than 40 years) were found to be suitable for the analysis of variations over time, primarily because the longest running gauging stations tend to have a high degree of artifical influence which may vary considerably over time. Only twelve stations have good or reasonable quality flow records extending back to 1940, four of which were discontinued in the late seventies or early eighties. Only one station, the Dee at Woodend, has a useable record prior to 1930. The net result is that known periods of hydrological extremes in the first half of this century are poorly represented by reliable gauged river flow data. There is a clear need to maintain a representative hydrological network across the country for the purpose of monitoring and understanding the long-term interaction of climate and catchment. Additional long records exist at a number of reservoirs and springs (in particular), and these data need to be assembled and critically evaluated: they may help to plug important gaps in the understanding of past variability in UK flow regimes.

3. Variations over time in river runoff

3.1 INTRODUCTION: OBJECTIVES OF CHAPTER

River flows vary considerably from year to year. Some years, or even sequences of years, contain 'extreme' events, and these events may occur in many catchments at once. Although the basic variability of river flows in the UK is well known, there have been no systematic studies into the association between climatic and hydrological variability, the variations in variability over time between catchments, and the spatial consistency of temporal patterns. This chapter considers these issues, and concludes by discussing the implications of the general patterns found. First, however, it is necessary to summarise the variability in flow regimes experienced in UK rivers.

3.2 VARIABILITY BETWEEN YEARS

This section presents a summary of the variation in flow regime characteristics from year to year across Britain, considering annual and seasonal runoff totals first, then extreme flow statistics and finally the variability in flow through the year. The reasons for the differences between catchments are examined in Section 3.3. All the descriptive statistics use runoff data from the common period 1961-1980, using up to 86 catchments (different rules for dealing with missing values meant that fewer stations were used in some of the analyses involving daily data). No catchments from Northern Ireland were included in this part of the analysis.

Table 3.1 shows the range in coefficient of variation (CV: standard deviation divided by mean) in annual and seasonal runoff (calculated over the period 1961-1980) by region and for Britain as a whole. There is some variability between catchments - which will be considered further in Section 3.3 - but from the median values it is clear that the greatest relative variability is in autumn, with least relative variability in winter. The CV of annual runoff ranges from 0.14 to 0.38 - over 1961 to 1980 - and is considerably lower than is found in other drier and more seasonally-variable environments. Several catchments in eastern France and Germany, for example, have CVs of annual runoff greater than 0.4 (Gustard *et al.,* 1989: the different record lengths used hinder direct comparisons).

In the 'average' UK catchment, annual runoff is greater than 126% of the mean in 10% of years, and less than 65% of the mean in a further 10%, although there are of course differences between catchments. Figure 3.1 shows the annual and seasonal runoff totals exceeded in a given proportion of years (over the period 1961-1980), averaged across all the sites in each of several regions (as shown in Figure 3.2). In southern England, for example, summer runoff is, on average, less than 55% of the mean summer value in 10% of years, whilst winter runoff falls below 43% of the mean winter value one year in ten.

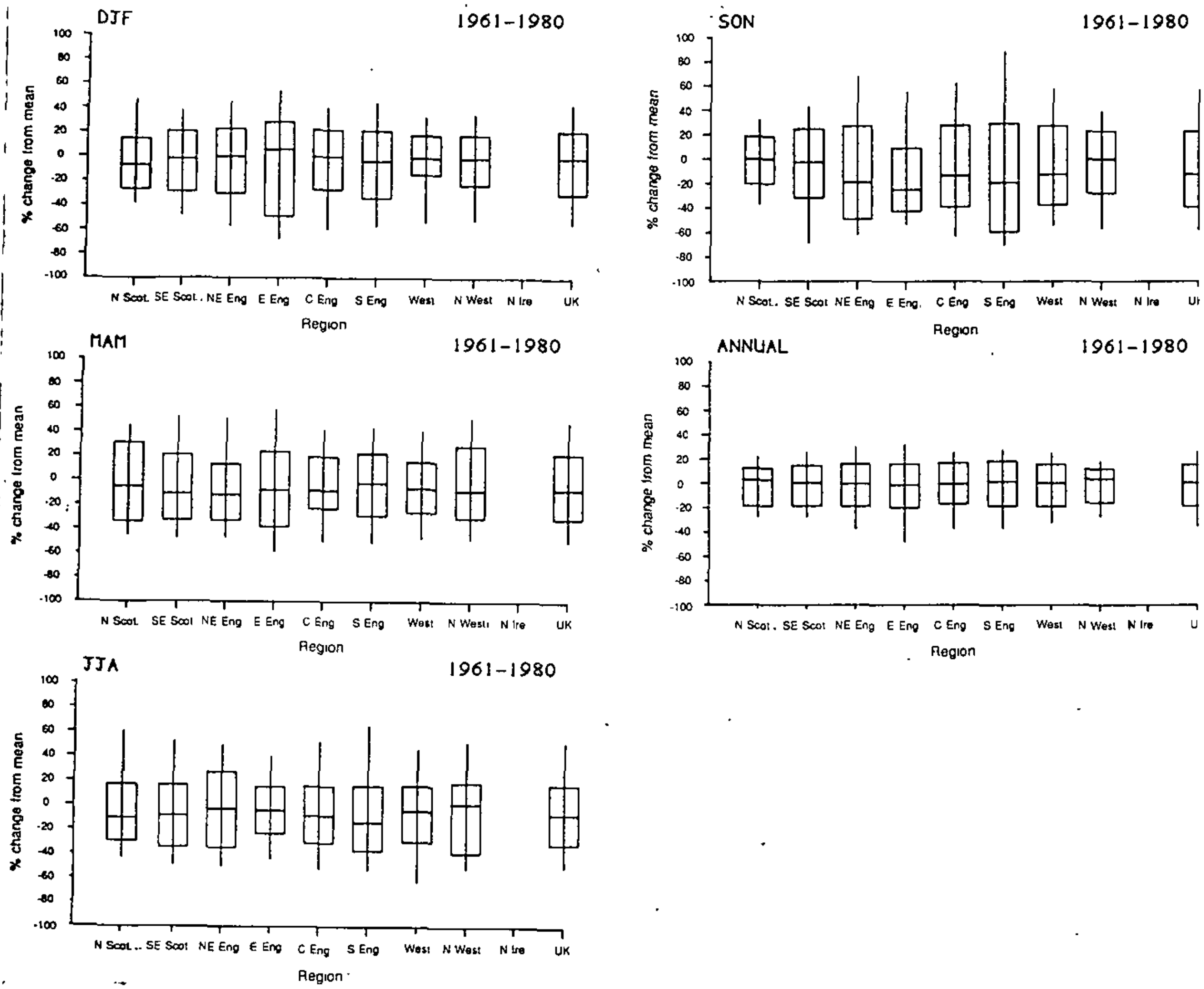


Figure 3.1 *Average variation between years in seasonal and annual runoff, by region. The figure shows the median runoff, the flows exceeded in 75% and 25% of year (the box), and the flows exceeded in 90% and 10% of years (the line).*

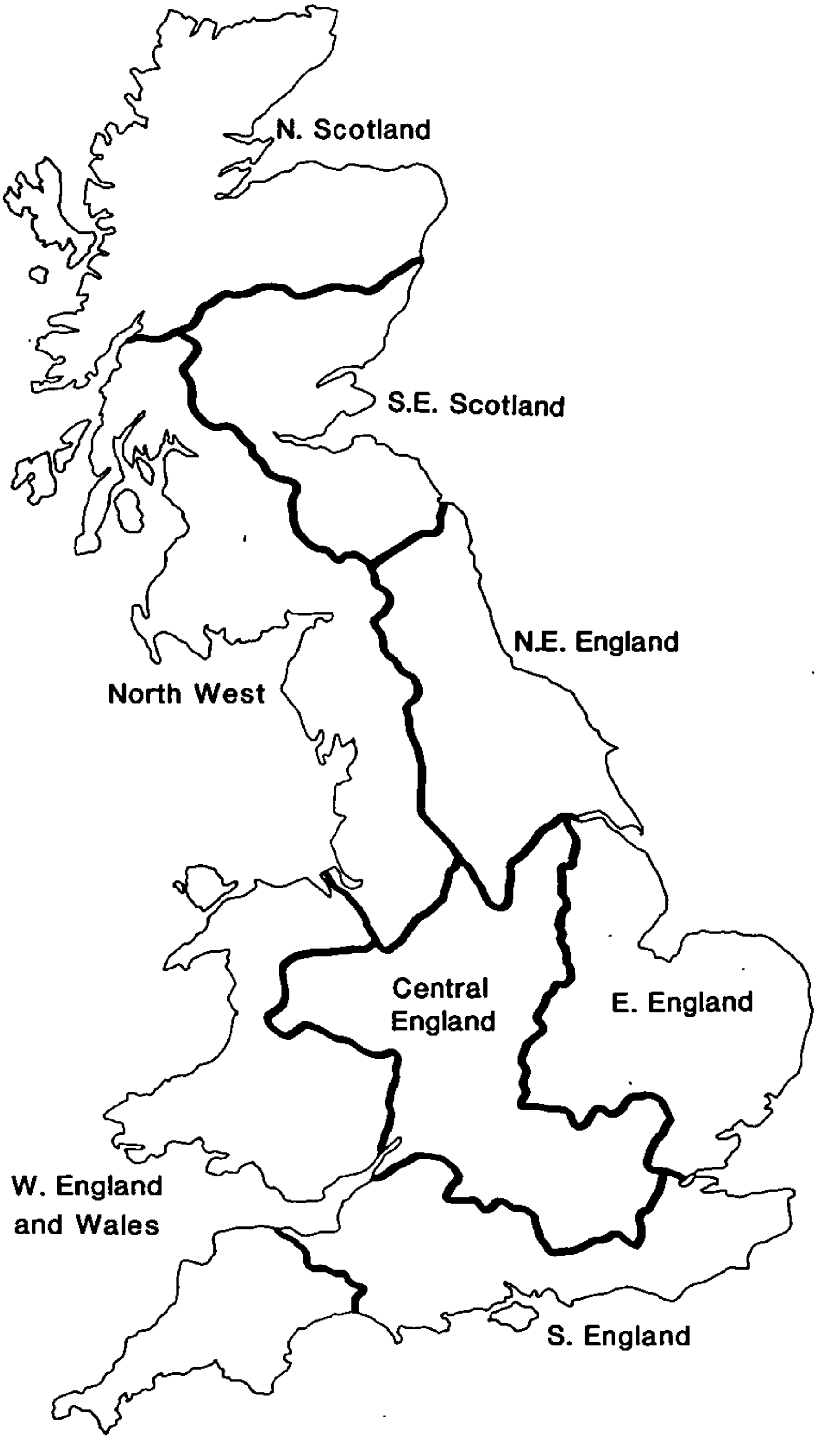


Figure 3.2 Division of UK into regions

Table 3.1 The coefficient of variation in seasonal and annual rainfall and runoff across Britain: minimum, maximum, median and interquartile range. Data from 1961 to 1980 only

	min.	25%	median	75%	max.
Rainfall (85 catchments)					
winter (DJF)	0.233	0.278	0.303	0.323	0.376
spring (MAM)	0.228	0.256	0.293	0.315	0.388
summer (JJA)	0.198	0.238	0.279	0.328	0.396
autumn (SON)	0.179	0.251	0.310	0.382	0.442
annual	0.101	0.120	0.132	0.140	0.162
Runoff (86 catchments)					
winter (DJF)	0.252	0.308	0.342	0.405	0.556
spring (MAM)	0.201	0.346	0.385	0.431	0.683
summer (JJA)	0.154	0.323	0.394	0.473	0.914
autumn (SON)	0.206	0.363	0.440	0.646	1.108
annual	0.138	0.193	0.229	0.276	0.382

Table 3.2 shows the range across the UK in the CV of minimum and maximum flows over several durations. The relative variability of minimum flows decreases as the duration over which flows are averaged decreases, indicating that there is greater relative variability from year to year in the minimum mean 30-day flow than, for example, in the minimum daily flow. This is due to the frequent occurrence of rain in the UK. The lowest flows during a year occur at the end of a dry spell and reflect both geological controls and the integration of rainfall inputs over a long preceeding period. As the duration over which flows are averaged increases, however, there is a greater chance of including a rainfall event and its streamflow response. These interruptions vary considerably in magnitude from year to year, and hence the flows averaged over long durations show greater relative variability than averages over short durations. The relative variability of annual maximum flows, in contrast, increases as the duration over which the flows are averaged reduces, and this is due to the variation over time in short-duration rainfall characteristics. The CV of annual maximum flows varies less between catchments than the CV of annual minimum flows, because maximum flows are influenced more by climate characteristics than by catchment and geological characteristics.

The variation in flow through the year was indexed in a variety of ways. In the average UK catchment, winter season runoff (December, January and February) is 3.4 times summer season runoff (June, July and August), with the ratio ranging widely from 1.04 to 6.9. There is considerable variability in this index of runoff seasonality from year to year, and the median CV of the winter/summer ratio across Britain is 0.51: it ranges from 0.22 to 1.81.

On a shorter time-scale, the average range between the maximum and minimum daily flows across the country varies greatly from 1.1 to 21.5 times the mean flow, with a median of 9.2. The range over a seven-day period is from 0.9 to 8.9 times the mean flow with a median of 4.5, and over a thirty-day period ranges from 0.7 to 4.0 with a median of 2.4 times the mean flow. The variability from year to year in this index of seasonality decreases as longer averaging periods are considered within a catchment. The range in CV at the one-day scale is from 0.16 to 1.03 but narrows to between 0.22 and 0.44 when flows are averaged over thirty days, indicating a relative consistency in seasonal regimes across the country for longer durations.

3.3 VARIATIONS IN VARIABILITY BETWEEN CATCHMENTS

The previous section has summarised the variability in flow regimes over time, and it is clear that there is a great variation in temporal variability between catchments. A cursory examination of Figure 3.1 and Table 3.1 suggests some regional differences in behaviour, which may have a climatic origin, but there is considerable variability within a region which may reflect the importance of more local, for example geological, controls on variability. This section presents results from a series of investigations into the climatic and catchment characteristic controls on the variability in flow regime from year to year in a catchment.

Table 3.2 The coefficient of variation of minimum and maximum flows over different durations: minimum, maximum, median and interquartile range. Data from 1961 to 1980 only

	min.	25%	median	75%	max.
Minimum flows					
calendar month	0.137	0.275	0.342	0.412	1.021
30 day	0.140	0.267	0.318	0.411	1.129
7 day	0.121	0.239	0.290	0.361	0.776
1 day	0.113	0.236	0.286	0.360	0.734
Maximum flows					
30 day	0.204	0.233	0.273	0.316	0.421
7 day	0.195	0.264	0.313	0.358	0.544
1 day	0.156	0.301	0.384	0.461	1.014

The CV of annual runoff is consistently higher than the CV of annual rainfall. A median value of 0.23 compares with a median rainfall CV of 0.13 over the common 20-year period 1961-1980. If evaporation were constant from year to year, then a given millimetre change in annual rainfall would result in the same millimetre change in annual runoff: the standard deviation of runoff would be the same as that of rainfall, but because mean runoff is less than mean rainfall, its CV would be larger. In practice, of course, evaporation varies from year to year, but this variation is less in absolute terms (though not necessarily in relative terms) than that of rainfall.

The CV of annual runoff can be derived directly from the CVs of annual rainfall and annual losses, the runoff coefficient and the correlation between annual rainfall and annual losses. If annual rainfall is denoted by X and annual actual evaporation by Y, then the variance of annual runoff, X-Y, is simply:

$$\mathrm{var}(X-Y) = \mathrm{var}(X) + \mathrm{var}(Y) - 2\,\mathrm{cov}(X,Y)$$

and the CV of (X-Y) is

$$\mathrm{CV}(X-Y) = \frac{\left[\mathrm{var}(X) + \mathrm{var}(Y) - 2\,\mathrm{cov}(X,Y)\right]^{1/2}}{\bar{X} - \bar{Y}}$$

where $\bar{X}$ and $\bar{Y}$ denote the mean annual rainfall and actual evaporation.

This expression can be rearranged by substituting the runoff coefficient

$$k = \frac{\text{average annual runoff}}{\text{average annual rainfall}} = \frac{\bar{X} - \bar{Y}}{\bar{Y}}$$

and the correlation coefficient

$$r = \frac{\mathrm{cov}\,(X,Y)}{\mathrm{sd}(X)\mathrm{sd}(Y)}$$

to give

$$\mathrm{CV}(X-Y) = \frac{\left[\mathrm{CV}(X)^2 + \left[(1-k)\mathrm{CV}(Y)\right]^2 - 2\,r(1-k)\mathrm{CV}(X)\mathrm{CV}(Y)\right]^{1/2}}{k} \quad \ldots (4.1)$$

From this equation it is possible in principle to estimate the CV of annual runoff (and a similar derivation allows the estimation of the CV of annual evaporation from the CV of annual runoff). Figure 3.3 shows the variation of the CV of annual runoff with the CV of rainfall, the CV of evaporation and runoff coefficient, for a correlation between rainfall and evaporation of 0.7. For high runoff coefficients, the CV of runoff is most influenced by the CV of rainfall (and insensitive also to correlation): for lower runoff coefficients, as found in East Anglia, for example, the CV of runoff shows much greater sensitivity to all the controlling influences.

However, both the CV of annual actual evapotranspiration and the correlation between annual evapotranspiration and annual rainfall are difficult to estimate

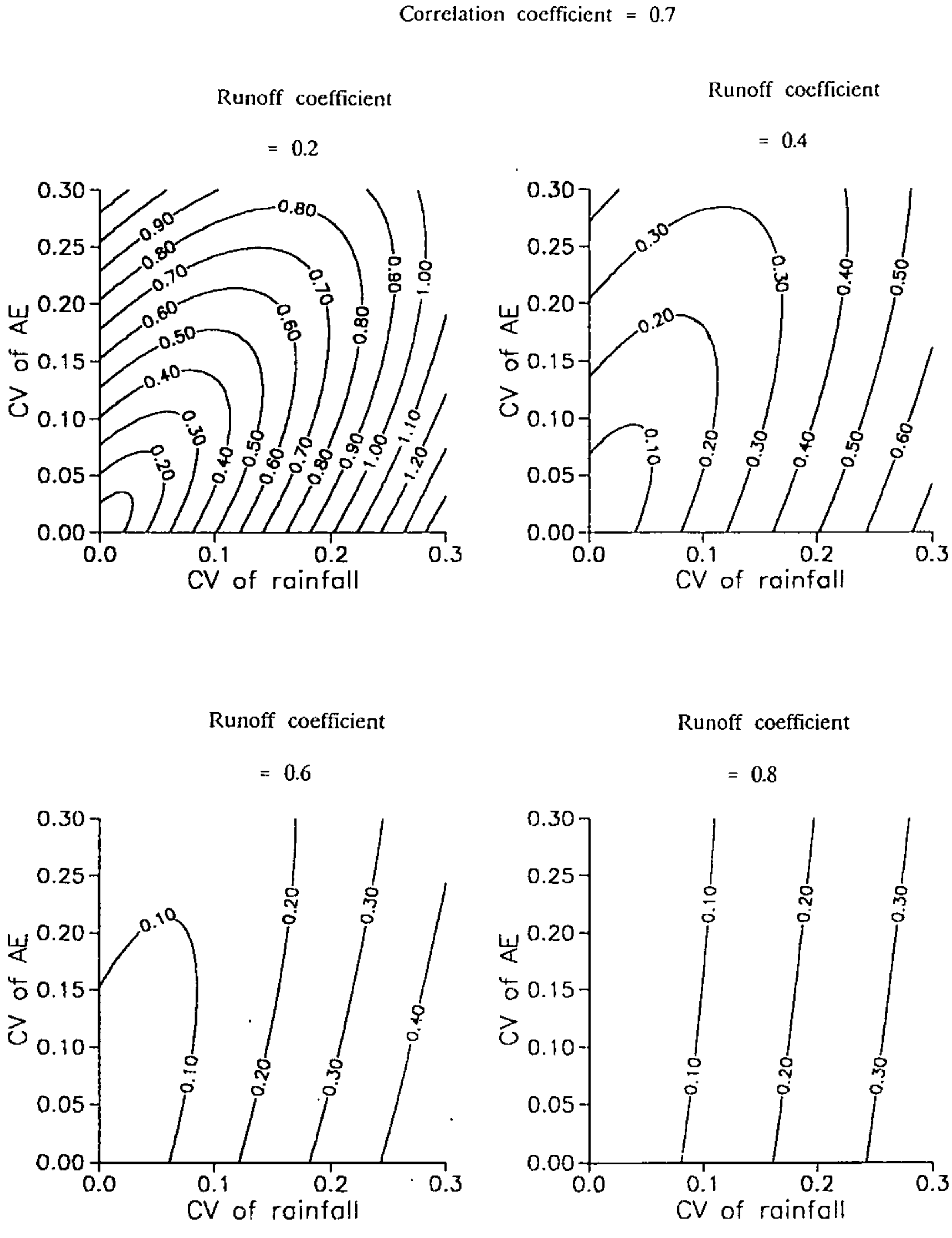


Figure 3.3 *The variation of the CV of annual runoff with the CVs of annual rainfall and annual evaporation, the runoff coefficient and the correlation between annual rainfall and annual evaporation*

in practice. Actual catchment evapotranspiration is rarely directly estimated (although MORECS data allow estimation of 'point' actual evaporation), and is difficult to estimate from annual water balances partly due to carry-over from year to year and partly due to high sensitivities to measurement errors in both rainfall and runoff. Annual actual evapotranspiration was, however, estimated for the current study from annual water balances over the period 1961 to 1980 in 112 catchments (using an October to September year). The median CV was 0.146 and the interquartile range between 0.132 to 0.176 (extreme values were found to occur in catchments where annual runoff was occasionally higher than rainfall, reflecting measurement errors). This is somewhat higher than the CV of annual potential evapotranspiration, due to the addition of variability in rainfall to variability in potential evapotranspiration (the CV of annual potential evapotranspiration over the period 1961 to 1980 at Heathrow is 0.07). The correlation between rainfall and actual evapotranspiration is expected to be lowest in humid areas, where actual evapotranspiration is consistently close to potential evapotranspiration (except insofar as there is a correlation between annual rainfall and the climatic factors, such as temperature, influencing the potential evapotranspiration). In drier areas, actual evapotranspiration falls below potential evapotranspiration, and the amount evaporated therefore depends much more on rainfall availability. Figure 3.4 shows the correlation between annual rainfall and annual evapotranspiration (estimated by the rather crude water balance) plotted against runoff coefficient: correlation is higher in catchments with lower runoff coefficients, and averages around 0.8 in catchments with runoff coefficients less than 0.4.

In principle, a similar theoretical approach can be applied to the variability of seasonal runoff (where X and Y denote, for example, winter rainfall and evapotranspiration), but in practice seasonal runoff totals are very much influenced by the rainfall in preceding seasons. Investigations into the controls on the CV in seasonal runoff were therefore based on multiple regression analysis. Several hypotheses to explain differences between catchments were proposed and tested:

(i) the CV of seasonal runoff increases as the CV of seasonal rainfall increases;

(ii) the CV of seasonal runoff increases (for a given CV of seasonal rainfall), as the catchment runoff coefficient increases;

(iii) the CV of seasonal runoff increases as the CV of seasonal evaporation increases;

(iv) the CV of seasonal runoff increases as the responsiveness of a catchment to rainfall increases. Catchments with subdued response are expected to show less variation between years, as their hydrological characteristics reflect the integration of climatic inputs over several seasons, and perhaps years. Catchment responsiveness was indexed by the Base Flow Index (BFI: Institute of Hydrology, 1980);

(v) the CV of seasonal runoff increases as catchments become smaller: larger catchments show a response integrated over a longer timescale.

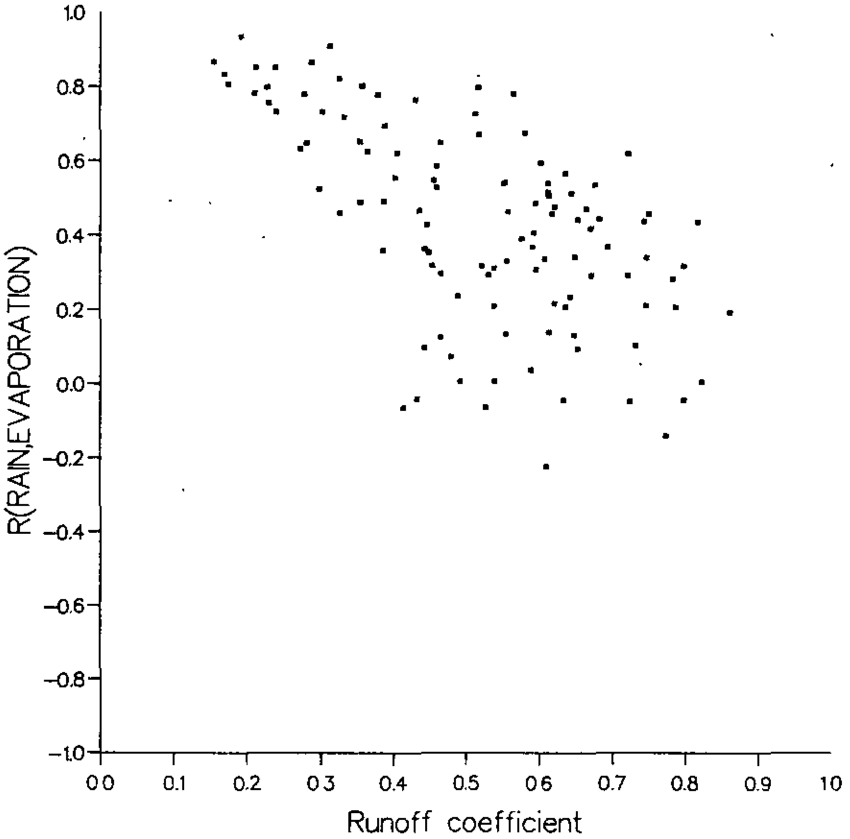


Figure 3.4 ***The correlation between annual rainfall and annual actual evapotranspiration, plotted against runoff coefficient. Actual evapotranspiration was estimated from an annual water balance over an October to September water year. Data from 1961-1980***

The equations resulting from a stepwise analysis are shown in Table 3.3, which also indicates the order in which variables entered each equation. A few general conclusions can be drawn. Firstly, catchment characteristics, as defined by BFI and catchment area, have a greater influence on the differences between catchments in the variability of spring, summer and autumn runoff than on winter runoff. Catchment BFI is shown to be the most important control on the relative variability in the CV of summer runoff, for example. The difference between catchments in winter runoff variability is more closely related to differences in climatic variability, and in particular to 'aridity' (as reflected by the annual runoff coefficient) and the variability in winter rainfall. Secondly, catchment lags mean that the variability over time in spring, and summer runoff is influenced by rainfall and evapotranspiration variability in preceding seasons. Thirdly, the differences between catchments in spring and, to a lesser extent, summer and autumn runoff variability are more influenced by the differences in the variability in potential evapotranspiration than rainfall: in winter, however, variability in rainfall is considerably more important than the differences between catchments in the CV of potential evapotranspiration. Although the CV of spring, summer and autumn potential evapotranspiration is

Table 3.3 Stepwise regression equations to predict the variability in CV of seasonal runoff between catchments

---

Winter

$$
\begin{aligned}
(\mathrm{DJF.CV})^{1/2} = 0.581 &+ 0.599\ \mathrm{CV}\ (\mathrm{DJF\ rainfall}) \\
&- 0.294\ \mathrm{Runoff\ coeff.} \\
&- 0.089\ \mathrm{BFI}
\end{aligned}
$$

N=86 $R^2 = 0.70$

Order of introduction: Runoff coeff., CV(DJF rainfall), BFI

Spring

$$
\begin{aligned}
(\mathrm{MAM.CV})^{1/2} = 0.888 &- 0.266\ \mathrm{Runoff\ coeff.} \\
&- 0.000011\ \mathrm{AREA} \\
&- 0.256\ \mathrm{BFI} + 0.354\ \mathrm{CV(DJF\ PE)}
\end{aligned}
$$

N=86 $R^2 = 0.67$

Order of introduction: Runoff coeff., BFI, CV(DJF PE), AREA

Summer

$$
\begin{aligned}
(\mathrm{JJA.CV})^{1/2} = 0.730 &- 0.406\ \mathrm{BFI} \\
&+ 0.665\ \mathrm{CV(JJA\ rainfall)} \\
&- 2.418\ \mathrm{CV(MAM\ PE)} \\
&+ 0.963\ \mathrm{CV(JJA\ PE)}
\end{aligned}
$$

N=86 $R^2 = 0.50$

Order of introduction: BFI, CV(JJA rainfall), CV(MAM PE), CV(JJA PE): note that the coefficient of CV(MAM PE) implies a reduction in the CV of runoff as the CV of PE increase.

Autumn

$$
\begin{aligned}
(\mathrm{SON.CV})^{1/2} = 0.867 &+ 1.069\ \mathrm{CV(SON\ rainfall)} \\
&- 0.443\ \mathrm{BFI} \\
&- 0.332\ \mathrm{Runoff\ coefficient} \\
&- 1.250\ \mathrm{CV(SON\ PE)}
\end{aligned}
$$

N=86 $R^2 = 0.75$

Order of introduction: CV(SON rainfall), BFI, Runoff coefficient, CV (SON PE)

All the regression coefficients are significantly different from zero at at least the 95% level.

---

rather less than that of rainfall, it does vary more between sites (the CV of spring potential evapotranspiration is highest along the west coast and in parts of East Anglia, summer CV is highest in the south and east of England, and autumn CV is, in contrast, greatest in Scotland and lowest in the south east).

The variation between catchments in the variability in shorter-duration flows was harder to interpret in terms of the catchment and climate characteristics available.

Few studies have had much success in developing regression relationships between the CV of annual maximum flows and catchment characteristics. In the Flood Studies Report (NERC, 1975), for example, regression models to estimate the CV of the annual maximum instantaneous flood peak could explain no more than 11.7% of its variation. In the current study, the best regression equation explained 22% of the variation across 86 catchments in the CV of the annual maximum daily flow. Rather higher percentage explanations were found, however, with maximum flows averaged over longer durations. Nearly 45% of the variation in the CV of the maximum 7-day flow can be explained by catchment runoff coefficient and the CVs of spring and summer rainfall and autumn potential evapotranspiration: nearly 50% of the variability of the maximum 30-day flow is explained by runoff coefficient and the CV of summer potential evapotranspiration. The model fits are poor, but it can be inferred that the differences between catchments in the variability of maximum flows is due more to climatic than catchment (such as geological) variations. Information on the year-to-year variability in flood-producing rainfalls (such as the annual maximum 5-day rainfall) might lead to improved prediction equations.

The differences between catchments in the variability from year to year in minimum flows, however, are more closely related to catchment geological characteristics. In the Low Flow Studies report (Institute of Hydrology, 1980), different frequency curves were produced for catchments with different values of the ratio of the mean annual minimum 10-day flow to the average flow (MAM(10)). This ratio was controlled by catchment geology, and regression relationships were developed to predict it from the Base Flow Index. More recent developments are reported in Gustard *et al.* (1991). In the current study, it was found the the CV of winter rainfall and potential evapotranspiration helped BFI discriminate between catchments, but the final models were poor with R^2 values less than those for maximum flows (ranging from 30% for the 30-day minimum to 34% for the 1-day minimum). This perhaps reflects the difficulties in indexing catchment geological conditions in a way which captures all the subtle variations between catchments.

The variation in flow during a year (its 'seasonality') was indexed by the difference between the annual maximum n-day flow and annual minimum n-day flow, divided by the mean flow (as indicated in Chapter 2). The variation in mean seasonality across the UK should reflect both climatic seasonality (the relative amounts of winter and summer rainfall, for example) and catchment geological conditions, with high baseflow catchments showing the least variability during the year. Regression analyses using 1, 7 and 30-day seasonality indices indicated that differences in catchment geology (as indexed by the base flow index) were far more important than climatological differences in explaining variations in mean seasonality between catchments, with R^2 values ranging from 46% for the 30-day index to 54% for the 1-day index. Adding the runoff coefficient to the models increased the percentage of variability explained to just over 70% for the 1 and 7-day indices, and rainfall seasonality only helped to explain the variability in flow seasonality using the 30-day index.

Differences between catchments in the variability in flow seasonality from year to year were, however, rather harder to model. Variability in the 1-day seasonality index is of course dependent on year to year variability in flood-producing rainfall, and less than 10% of the variation between catchments could be explained with the catchment and climate characteristics available. For longer durations, the different degrees of variability in flow seasonality were found to be related more to climatic than to catchment characteristics. Higher variability in seasonality is found in catchments with a low runoff coefficient (accounting for 28% of the difference between catchments at the 7-day scale and 44% at the 30-day scale): in such catchments a given millimetre change in rainfall has a larger effect on runoff than in more humid catchments.

This section has shown that the relative variability between catchments in flow regimes from year to year depends on both catchment climatic and geological characteristics, with different aspects of flow regime sensitive to different controls. The differences between catchments in the relative variability from year to year in high flows, as indexed by winter runoff and short-duration maxima, are due more to climatic differences between catchments than to their landscape and geological characteristics: in contrast, differences in low flow variability (as indexed by short-duration minima and summer flows) reflect difference in catchment geology.

3.4 DISTRIBUTIONS OF EVENTS OVER TIME AND SPACE

The coefficient of variation of an index of flow regime gives only limited information about the nature of temporal variations in flow regimes. It is also important to define how extreme values of the index are distributed over time (are they periodic, clustered or random, for example?), and to characterise spatial patterns in the rate of occurrence of extreme flow indices. Both temporal and spatial dependence have important implications for the assessment of risk. This section describes patterns in the variability in runoff and flow regimes, and the following section interprets variability in climatic terms.

The analyses in this section are based on the construction of simple discretised 'space-time' variation plots. First, the annual values of a defined flow index are ranked and divided into four percentile classes (classes may define, for example, the 0-10, 10-30, 30-50 and 50-100 percentile values). Each class is allocated a symbol, and a time series of the four symbols plotted. The process is repeated for all the catchments, and a table is built up, showing both temporal patterns - in the horizontal direction - and consistencies in temporal patterns over space - in the vertical direction. By grouping annual values into just four classes some information is lost, but the generalisation does allow the ready identification of spatial and temporal patterns. A similar

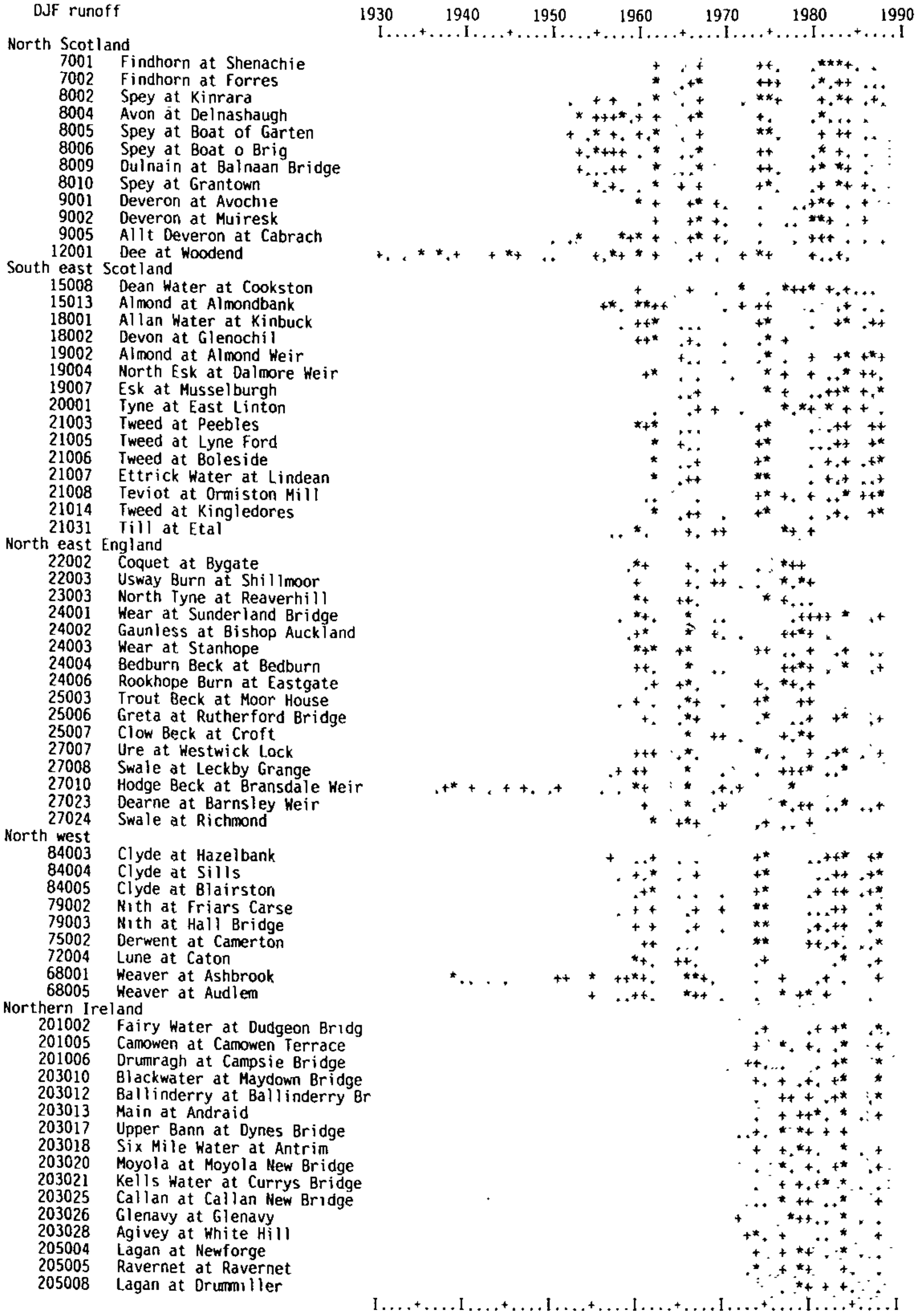


Figure 3.5a Variation over time in winter (DJF) runoff: each winter is dated by the January. The flow values are divided into percentile classes, ranked from smallest to largest. The first class contains the smallest 50% of the annual observations. The shading defines the period of record.

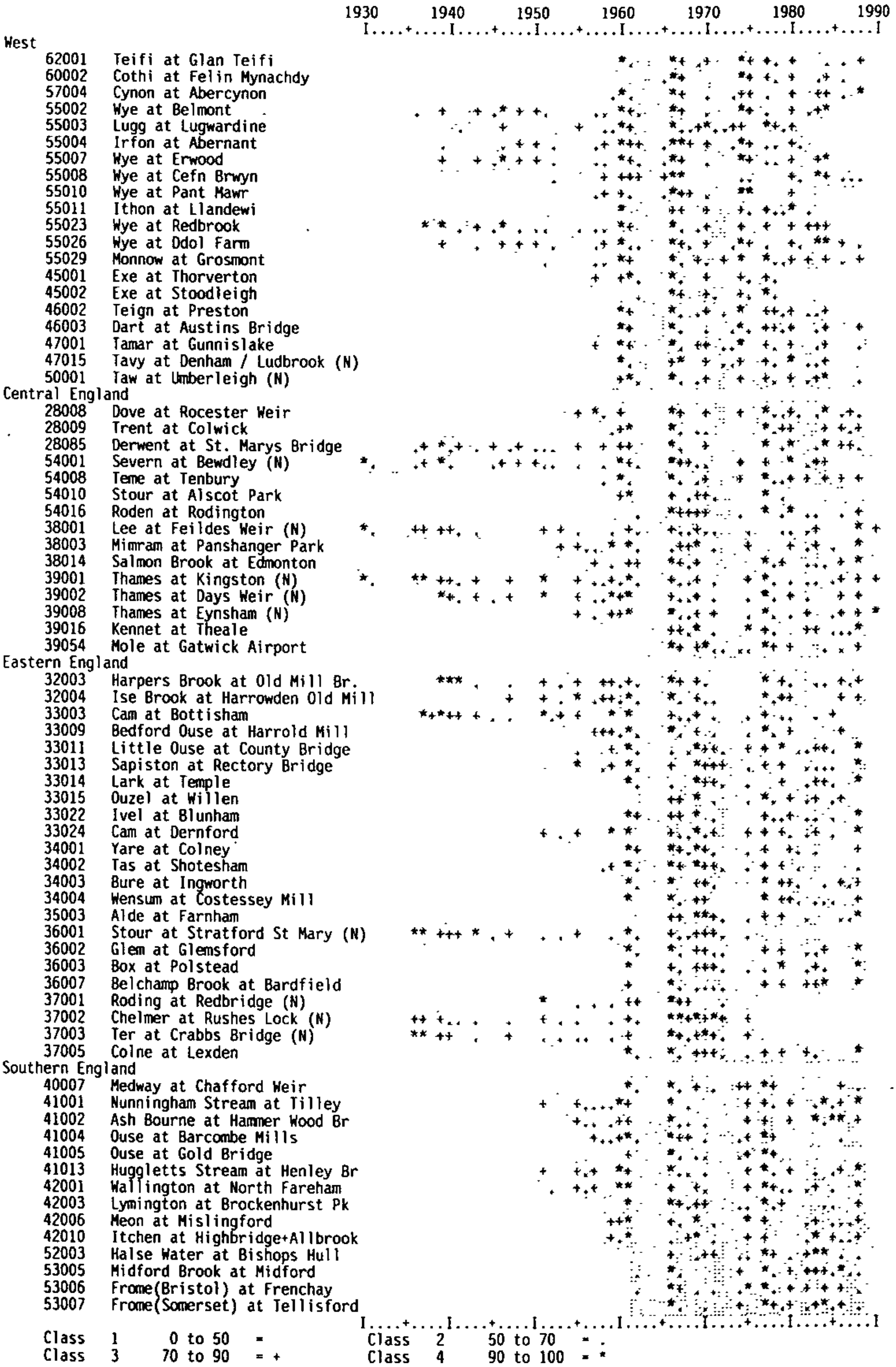


Figure 3.5a continued

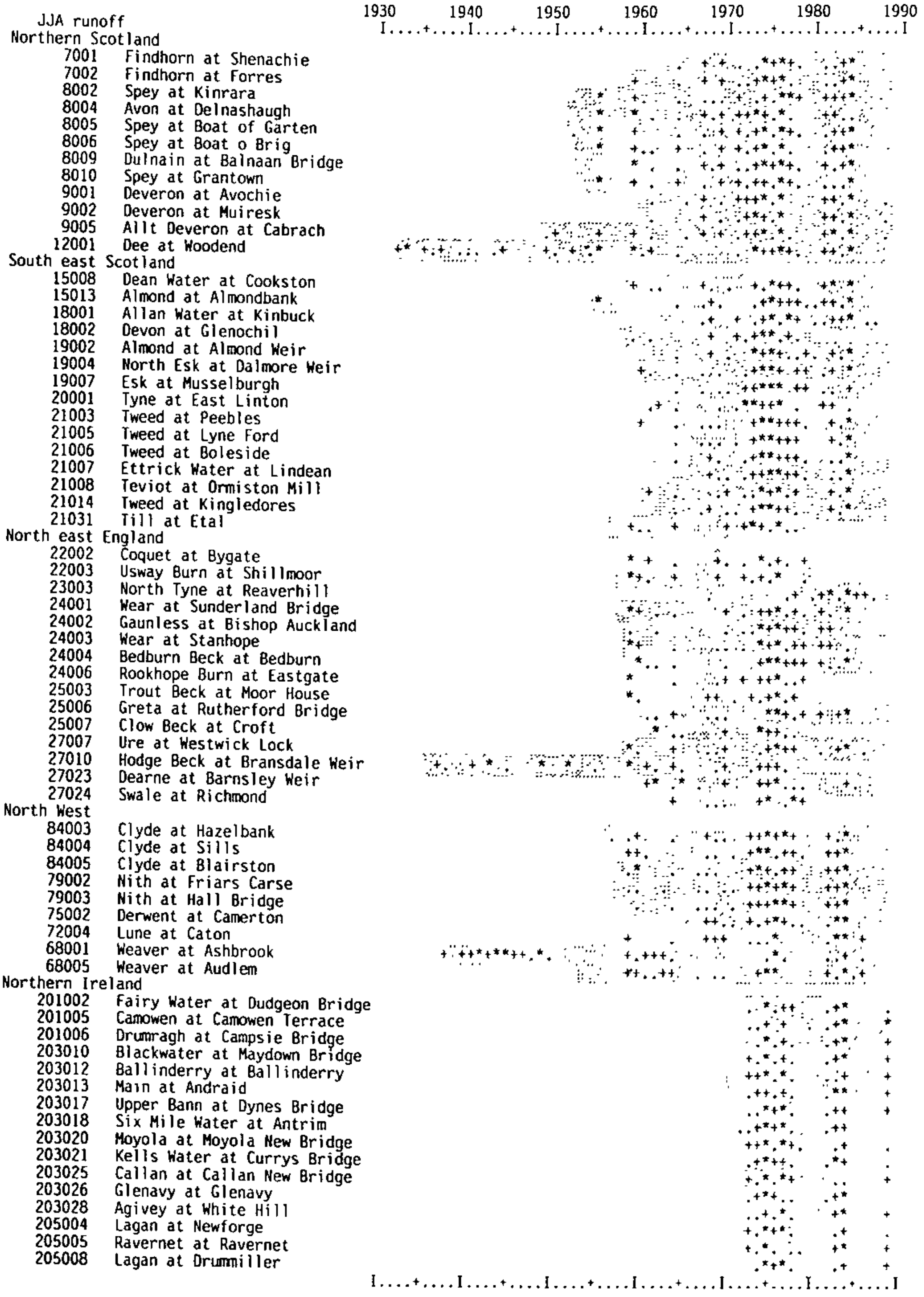


Figure 3.5b *Variation over time in summer (JJA) runoff. The flow values are divided into percentile classes, ranked from smallest to largest. The first class shows the smallest 10% of the annual values.*

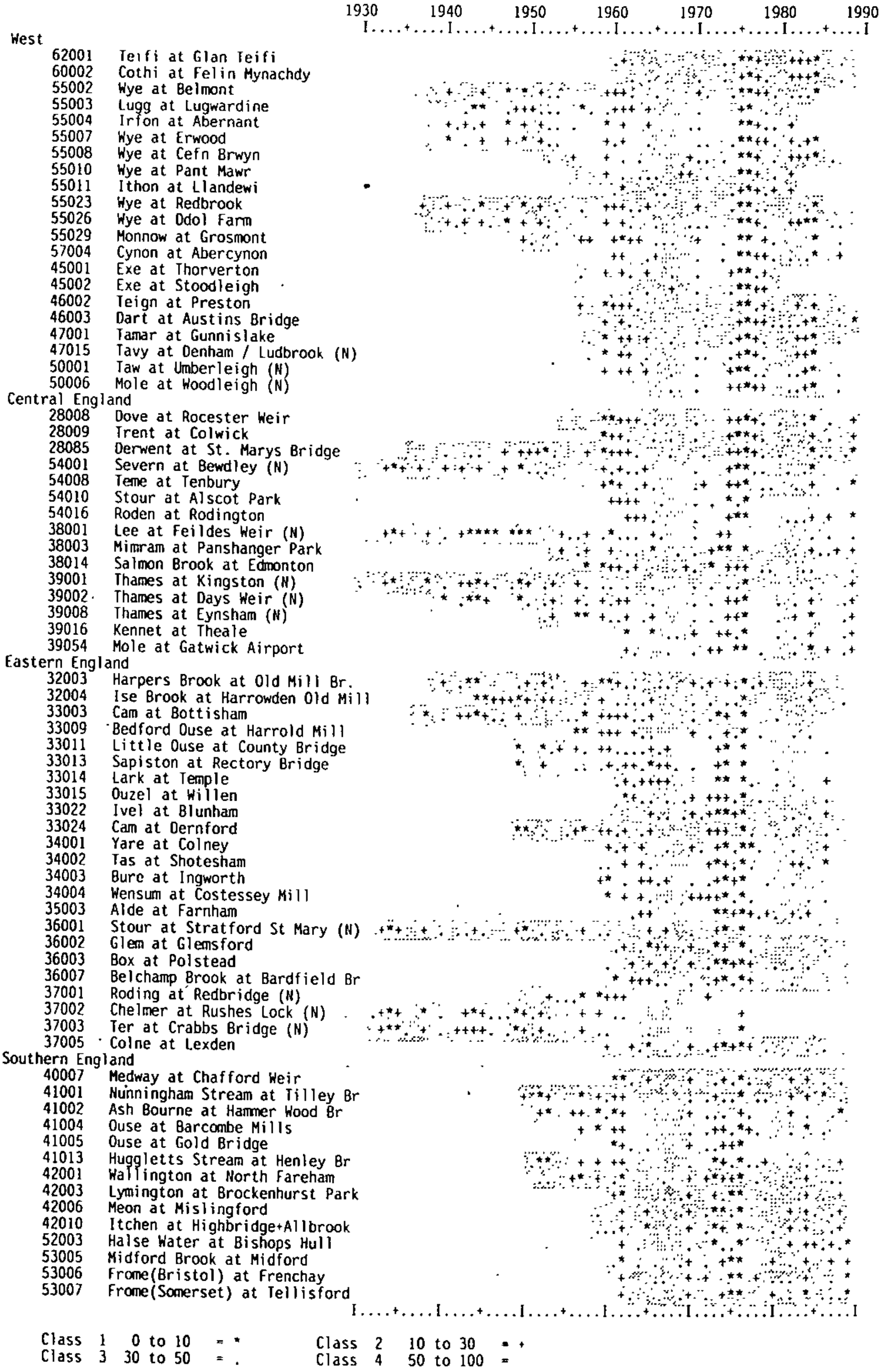


Figure 3.5b continued

approach, but with absolute rather than percentile class intervals, was used during the FREND project with European flow data (Gustard *et al.,* 1989; Arnell, 1989a).

Figures 3.5a and 3.5b show variations over time in winter and summer runoff totals across 139 catchments in the UK (11 of them have naturalised records, and 16 are short record sites from Northern Ireland). The figures highlight high values of winter runoff, but low values of summer runoff. Strong patterns in both the vertical dimension - implying spatially-consistent patterns of variation over time - and the horizontal dimension - suggesting some form of clustering - are apparent, and similar features were found with spring, autumn and annual runoff totals. Note that because the plots show year-to-year variability in relative terms, they do not pick up the greater *magnitude* of variability in particular catchments: the lesser absolute variability between years in summer runoff in high baseflow catchments, for example, is not highlighted.

Although it is possible to draw inferences about spatial variability from the 139 individual stations, a clearer picture of regional patterns is obtained from regional average plots, as shown in Figure 3.6. These plots are constructed by first expressing each year's runoff value at a site as a ratio of that site's median runoff, and deriving a regional 'super-population' by taking for each year the median of all the site ratios: these median ratios are then allocated to four frequency classes as before. Some sub-regional variation is of course hidden, but the strong degree of consistency in behaviour over time is clear.

Winter runoff was high in the late 1950s and early 1960s across much of the UK, and was high too everywhere in 1965/66 and 1966/67. Runoff in winter was below the median in Scotland from the late 1960s to the mid 1970s, and again in the late 1970s, but different patterns can be observed in England and Wales: here, winter runoff was relatively high in the late 1960s and late 1970s. In the early 1980s, Scotland had several years with high winter runoff, whilst runoff was less high in England and Wales. There is less information about earlier periods, but the late 1930s and early 1940s seem to have been characterised by high winter runofff, at least in England.

Spring runoff shows a more consistent variation over time across the UK as a whole. The most notable feature is the relatively low spring runoff totals in the early 1970s which have been followed, since 1977, by a period with high spring runoff which has continued into the late 1980s. In Eastern England, however, there have been rather more years with relatively low spring runoff.

Summer runoff was low over the UK as a whole in the mid 1970s, following a period in the late 1960s when summer runoff was higher than average. Runoff was low too in 1982, 1983 and particularly 1984 in western and northern UK, but was less extreme in the south and east. The late 1980s have seen high runoff totals (except in the south), and the low runoff during the summer of 1989 is shown by the few stations with data available. Summer runoff totals were also low in many parts of Britain, particularly the centre and south, in the early 1960s.

Autumn runoff was high in much of the UK during the 1960s, early 1980s and late 1980s: 1981 and 1982 had particularly high totals in northern and western regions.

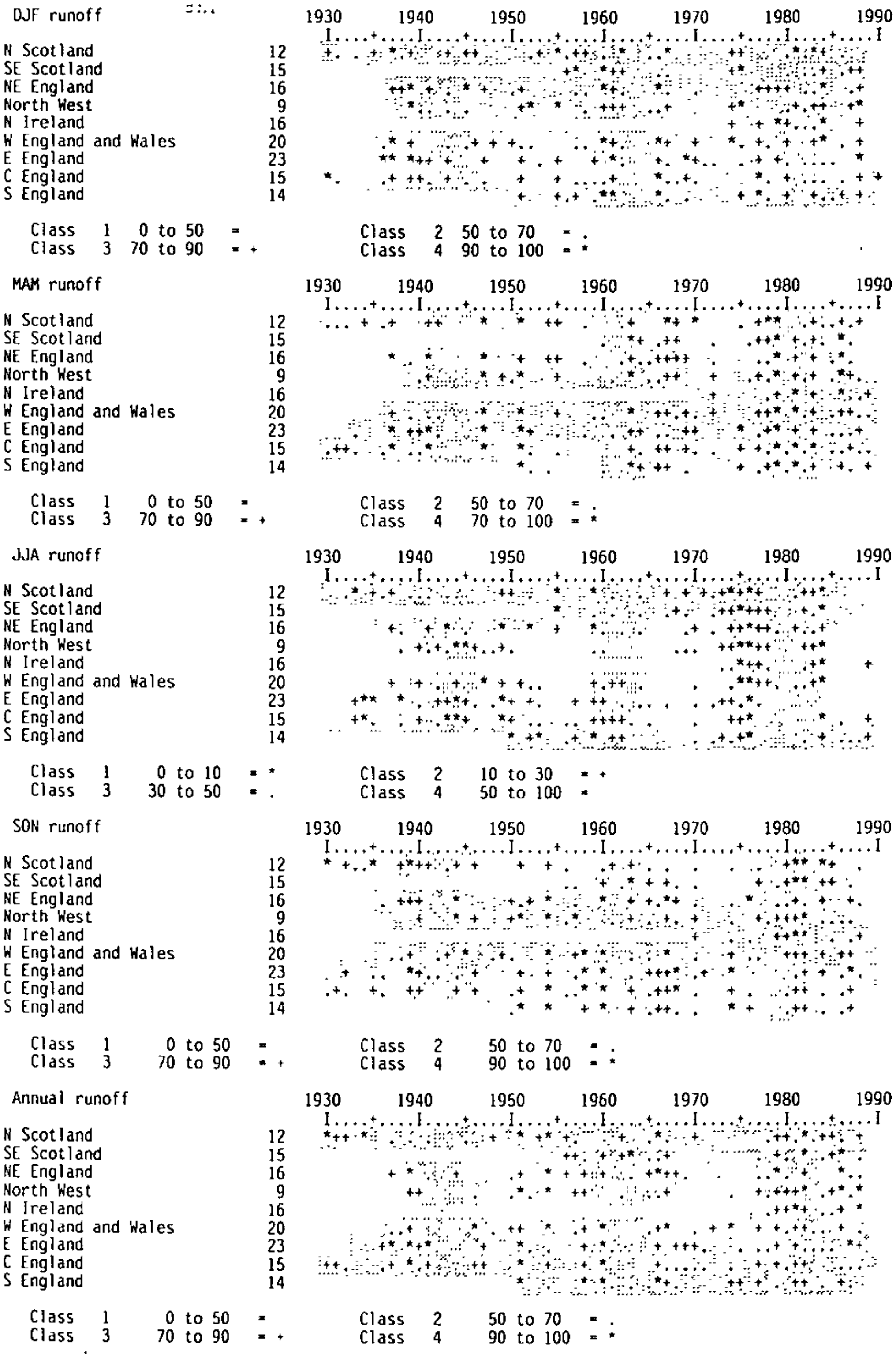


Figure 3.6 Regional average variation over time in seasonal and annual runoff. The flow values are divided into percentile classes, ranked from smallest to largest. The number refers to the maximum number of stations contributing to a given year.

Annual runoff patterns basically follow the winter, spring and, particularly, autumn patterns. Runoff totals were low in the early and mid-1970s, especially in Scotland, with high runoff in preceding and following periods.

The temporal patterns in seasonal runoff follow closely the patterns in the variability of seasonal rainfall. This is indicated in Table 3.4, which gives the percentage of the year-to-year variability in seasonal runoff explained by that season's rainfall for a few example catchments. The table is based on multiple regression analyses predicting year-to-year variability in runoff from seasonal rainfall, temperature, Lamb weather types and the preceding season's runoff.

Table 3.4 Percentage of year-to-year variation in seasonal runoff explained by variations in seasonal rainfall

		n	DJF	MAM	JJA	SON
8005	Spey	36	80	75	71	77
12001	Dee	58	59	60	68	87
33003	Cam	51	27	59	18*	46
41001	Nunningham St.	38	50	64	56	75
55026	Wye	50	86	86	83	91
68001	Weaver	47	57	77	30	62

* The variation in seasonal rainfall did not explain the greatest amount of variation in seasonal runoff.

Once the effect of rainfall was removed, seasonal temperatures did not correlate well with seasonal runoff: temperature had some minor influence on year-to-year variability in only four of the 24 season models. Lamb weather types were found to explain some of the remaining variation between years, but different weather type indices appeared in the different seasons and catchments. The most important influence other than seasonal rainfall, however, was the preceding season's runoff.

The temporal and spatial variability of both minimum and maximum flows shows consistency across the one, seven, and thirty-day timescales. Reflecting the seasonal pattern, minimum flows tended to be lower than average in the early 1960s and higher in the late 1960s. The early 1970s had lower minimum flows quite consistently across the country as a whole, while the latter half of the 1970s again tended to have higher minimum flows but the pattern was more regionally variable. Minimum flows in the first part of the 1980s tended to be less than the average, particularly so in Scotland, Wales, and the west of England.

Maximum one, seven, and thirty-day flows have tended to follow a complementary pattern to the low flows, with high flows above average occurring in years when low flows were also above average. The pattern can be generally traced through the 1960s and 1970s. One notable exception to this occurred in 1974 when both maximum and minimum flows were significantly above and below their means respectively right across the country. In the early 1980s, however, this latter pattern appeared more persistently, particularly over Scotland and south west England.

Identification of regional and temporal patterns in the annual range of flows proved to be more elusive. Most of Scotland had a wider range than average through the late 1970s and early 1980s. From the Scottish Borders down the East Coast of England there was a concentration of years with above average ranges in the early to mid 1960s and below average ranges in the 1970s - the 1980s having a mixture of above and below average ranges. In East Anglia there has perhaps been a tendency for wider ranges in flow to occur in the 1980s, but over the rest of England and Wales such trends are more difficult to infer. However, this index of flow regime may not be the most sensitive to detecting extremes in both high and low flows since variability in high flows covers a wider range than variability in low flows.

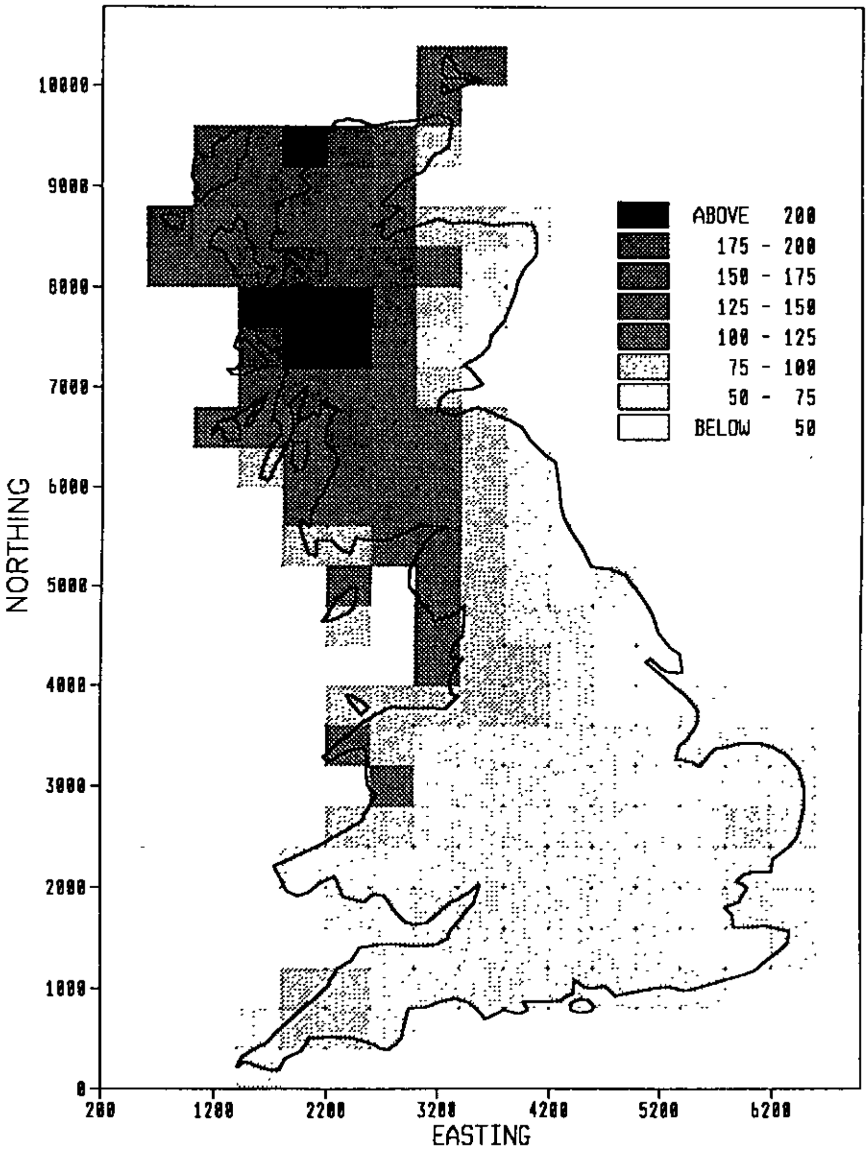


Figure 3.7 Rainfall in winter 1988/89 as a percentage of the 1961/62 to 1980/81 average (based on MORECS data: Arnell et al., 1989)

The spatial consistency across the UK in variability between years has been clearly demonstrated, and is not unexpected: it reflects the strong consistency in climatic behaviour across large parts of the British Isles. All parts of the UK do not, however, vary over time in the same way, as is shown in Figures 3.5 and 3.6, and in some years the contrast in behaviour between different regions can be striking. Figure 3.7 shows the rainfall in winter 1988/89 as a percentage of the 1961/62 to 1980/81 average, and the difference between the very wet north west and the dry east and south is clear. This difference between east and west can be seen to an extent in the site flow data, but there are unfortunately few long records in the north and west of Scotland (and data for the winter 1988/89 were available for very few catchments at the time of analysis).

More surprisingly, the simplified time series plots imply that years with similar hydrological characteristics tend to cluster: years with seasonal runoff above the median, for example, tend to follow each other, and to be succeeded by periods of several years with runoff below the median. The visual impression is that years are not independent, and there is a propensity for irregular clustering. Similar patterns have been observed across the whole of northern and western Europe (Gustard *et al.,* 1989; Arnell, 1989a). It is, however, very difficult to test the assumption that events are not distributed randomly across time when samples are as small as currently available.

Serial correlation coefficients are frequently calculated in order to detect some pattern in a time series, but they are most effective in detecting pattern when that pattern is regular. Lag one serial correlation coefficients were calculated for each of the four seasonal runoff totals and annual runoff. Table 3.5 gives the numbers of catchments (from a total of 112) showing a positive or negative serial correlation coefficient significantly different from zero at the 5% significance level. Relatively few catchments show serial correlation at the seasonal scale, but slightly more - approximately 1 in 6 - show significant positive serial correlation in annual runoff totals. The catchments with the greatest correlation, however, are not necessarily those with the greatest visual impression of clustering. The magnitude of the correlation coefficient was found to be strongly dependent on the period of record spanned, and in particular on whether the record began or ended during an 'extreme' cluster.

Table 3.5 The number of catchments with a lag one serial correlation coefficient significantly greater than zero at the 5% level

		Positive	Negative
Winter	DJF	2	0
Spring	MAM	2	1
Summer	JJA	14	0
Autumn	SON	14	7
Annual		21	1

Correlation coefficients were calculated from 112 catchments.

Mandelbrot and Wallis (1968) termed the propensity for extreme events to cluster the 'Joseph Effect', after the Biblical seven years of feast and seven of famine, and suggested that the Hurst coefficient could be used to define the propensity to cluster. Hurst (1951) developed the relationship:

$$\frac{R(n)}{S(n)} = c\, n^{H}$$

where R(n) is the 'rescaled range' over a sample of length n (the maximum cumulative departure above the mean minus the maximum cumulative departure below the mean), S(n) is the standard deviation over the n observations, and c and H are coefficients. If the process was independent from year to year, H would equal 0.5. Hurst (1951) found, however, that H was greater than 0.5 for many geophysical time series, with values typically around 0.7. Although there are problems in its estimation from a single sample (Mandelbrot and Wallis, 1968), the Hurst coefficient H can in principle define the degree of clustering. The Hurst coefficient was calculated from monthly data for 30 catchments with at least 30 years of record, using the estimation procedure in the WMO Time Series Analysis Program (WMO, 1988). Calculated coefficients ranged from 0.54 to 0.75 with a mean of 0.65, and although all are greater than 0.5, it is not possible to state how significant the departure from 0.5 is. Nevertheless, the Hurst coefficients do imply that time series of UK runoff exhibit clustering, and may not be samples from an independent process.

Further evidence of clustering comes from the application of a runs test (WMO, 1988) to monthly flows from 30 catchments with more than 30 years of data. The test basically counts the numbers of runs - sequences above or below the median - and compares the number observed with that expected from a sample of the same size drawn from a series with complete independence between years. Table 3.6 shows the number of catchments with a statistically significant (at the 90% level) number of clusters. In a third of the catchments, for example, annual runoff totals show 'statistically significant' clustering.

Table 3.6 The number of catchments with 'significant' clustering in monthly flows

	J	F	M	A	M	J	J	A	S	O	N	D	Ann.
clustering	3	4	6	3	4	2	4	15	6	8	-	9	11
systematic	-	-	-	2	-	1	-	-	-	-	2	1	1

30 catchments were analysed.

'clustering' denotes significantly more runs (at the 90% level) than expected;
'systematic' denotes significantly fewer runs: implying systematic alternation.

However, whilst it is possible to show that there may be a 'significant' degree of clustering in a time series, it is rather more difficult to assess the practical importance of clustering. One approach would be to generate synthetic time series which exhibit clustering and compare, for example, the number of exceedances of 'extreme' events in a particular time period with the number expected under an assumption of no clustering. Synthetic time series with a specified Hurst coefficient could be generated using, for example, a fractional Gaussian model (Mandelbrot and Wallis, 1969). In the current study, however, the effect of clustering on the probability of experiencing M events in N years was explored by assuming that the probability of an event occurring increased if the preceding year contained an event.

The probability of no events in the next N years is

$$P(M=0) = p(\text{no event in first year}) \times (p\ \text{no event}|\text{none before})^{N-1}$$

The probability of experiencing an event in the first year depends of course on whether the preceding year ('year zero') contained an event. The probability of experiencing one event in the next N years is

$$\begin{aligned} P(M=1) = {} & p(\text{event in first year}) \times p(\text{no event}|\text{one before}) \\ & \times p(\text{no event}|\text{none before})^{n-2} \\ & + p(\text{no event in first year}) \times p(\text{event}|\text{none before}) \\ & \times p(\text{no event}|\text{one before}) \times p(\text{no event}|\text{none before})^{n-3} \times (n-1) \end{aligned}$$

and similar - but longer - expressions can be derived for M=2, 3 or more. Table 3.7 shows the probability of 0, 1, 2, 3 or 4 or more events occurring in the next 20 years, under different degrees of clustering and under different assumptions about whether an event occurred in year zero. The clustering is represented by the ratio of the conditional probability of an event occurring to the long-term unconditional probability: a ratio of 3 indicates very high clustering. In each case, the probability of having no events in the next 20 years increases, but so does the probability of experiencing large numbers of events. If 'year zero' contained a 10-year event, the probability of 4 or more extra events occurring in the next 20 years increases from 13.4% to 23%, as the conditional probability of experiencing a 10-year event increases to 0.3. The probability of experiencing fewer events is relatively less affected.

The assessment of the consequences for water resource reliability requires, of course, a rather more sophisticated analysis using representations of, for example, reservoir performance in a succession of events. The ability of the system to recover between the succession of events in a cluster will control the sensitivity of that system to the effects of clustering.

3.5 WHY DOES SEASONAL CLIMATE VARY FROM YEAR TO YEAR?

The previous section has indicated that there are apparent clusters in the occurrence of notable runoff 'events' over time, and that these clusters mirror clusters in seasonal rainfall. But why do seasonal rainfall totals vary between years?

Jones and Wigley (1988) have shown that seasonal rainfall totals across different regions of England and Wales are closely correlated with circulation types. Years with a high number of anticyclonic days tend to have relatively

Table 3.7 The probability of experiencing m events in 20 years, with different degrees of clustering

Conditional prob. as ratio of unconditional probability.	Number of events				
	0	1	2	3	4 or more
Unconditional probability = 0.1 (1 in 10 years)					
Year zero did not contain an event					
3	0.198	0.254	0.216	0.147	0.185
2	0.155	0.266	0.249	0.168	0.161
1	0.122	0.270	0.284	0.190	0.134
Year zero did contain an event					
3	0.150	0.232	0.222	0.166	0.230
2	0.136	0.252	0.251	0.178	0.182
1	0.122	0.270	0.284	0.190	0.134
Unconditional probability = 0.05 (1 in 20 years)					
Year zero did not contain an event					
3	0.400	0.334	0.168	0.064	0.034
2	0.379	0.356	0.178	0.062	0.025
1	0.358	0.377	0.188	0.060	0.017
Year zero did contain an event					
3	0.356	0.338	0.187	0.077	0.042
2	0.358	0.357	0.188	0.069	0.029
1	0.358	0.377	0.188	0.060	0.017

less rainfall than years with more frequent cyclonic-type days. However, whilst several studies across Europe have described the relationships between climate circulation and rainfall occurrence, there have been no convincing explanations of why groups of years with particular dominant circulation patterns appear to cluster. Fraedrich (1990), however, has recently shown a link between climate in western Europe and the El Nino phenomenon, and there is the possibility that clusters in European climate may be associated with multi-year patterns observed in west Africa or the Pacific coast of south America. There is clearly a need for continuing studies into the reasons for apparent temporal patterns in climatic variability.

3.6 SUMMARY

This chapter has summarised the variability in flow characteristics in British catchments, and attempted to define those aspects of catchment and climate that cause differences in variability between catchments. In general, variability between years increases as catchment 'aridity' - as indexed by the ratio of average annual runoff to average annual rainfall - increases, and reduces as the importance of base flows increases. The differences between catchments in year-to-year variability in high flows are related most closely to variations in climatic characteristics, whilst differences in low flow variability reflect differences in catchment geology.

The analysis of time series of various hydrological characteristics has shown a strong degree of spatial consistency in behaviour across much of the UK - with Scotland showing different distributions over time to much of England and Wales - but has also indicated a propensity for 'notable' events to cluster. Years with high winter runoff tend to follow each other, for example. This clustering was observed in all the hydrological indices considered, and has important implications for the assessment of the risk of events which last for several seasons. Variations in hydrological characteristics between years are most strongly related to variations in seasonal rainfall, and these have been shown to reflect variations in seasonal weather circulation patterns (Jones and Wigley, 1988). Both the propensity for years with similar climate characteristics to cluster and the physical reasons for such a pattern need to be investigated: if the underlying structure of any climatic clustering can be defined, the assessment of the future risk of, for example, failure or stress of a particular water resources system can be refined.

The next chapter considers the hydrological characteristics of the 20-year period 1969-1988 in the longer term context. Note that the 1989 drought could not be formally included in the analysis in the time available.

4. River flow regimes in recent years

4.1 INTRODUCTION

The previous chapter has summarised the characteristics of time series of hydrological indices in the UK, and has indicated the factors influencing variability over time and controlling differences between catchments. This chapter concentrates on the characteristics of flow regimes in recent years - defined in several ways - in an attempt to identify whether recent years have been unusual.

The analysis of 'recent' behaviour unfortunately could not include the dry summer of 1989 and wet winter of 1989/90, because data were not available from enough sites in the timescale available. However, in the discussions that follow, information from 1989 and 1990 is included informally.

It is important to make some general points before discussing whether recent years have been 'unusual'. Firstly, it is difficult to define objectively what is meant by 'recent'. It would be possible - if dishonest - to contrive to select a 'recent' period which either maximised or minimised the implied unusual behaviour. In this study, the decision was made before the analysis to concentrate on the 20-year period 1969 to 1988. Subsequent investigations illustrated the consequences of using a different window of interest. Secondly, the records available for study are short. Long records exist only in a very few catchments, and many long records are considered unreliable, particularly at the extremes (see Chapter 2). The analysis of recorded data presented in this chapter concentrated on the thirty-year period 1959 to 1988. Information on longer timescale patterns was derived from the reconstructed flow records.

The interpretation of the 'significance' of the characteristics of recent years is fraught with difficulties. Hydrological behaviour varies considerably from year to year, and this 'noise' may overwhelm the signal from some long-term trend. There may also be several reasons for any 'unusual' activity which may be identified in a recent period. Climate change caused by increasing greenhouse gas concentrations is one potential cause which has received a high profile in recent years, but other causes must be considered. Catchment change, for example, might lead to an increase in high seasonal runoff, but this should be a catchment-specific impact. More generally, aperiodic variations in climatic inputs can lead to periods with unusual hydrological activity, and it was shown in the previous chapter how years exhibiting certain characteristics tend to cluster. 'Unusual' activity in one period may be followed by a period of quiescence. Such a wandering climate does not necessarily imply a progressive change, but has important implications, of course, for the meaningfulness of a long-term average.

Finally, it is appropriate to warn that although the chapter is concerned with assessing the 'significance' of hydrological behaviour in recent years, there is no explicit intention to test the hypothesis that global warming is leading to changes in the hydrological characteristics of British rivers. Records are too short for any meaningful conclusions to be drawn, and the ways in which evolving climate change may manifest itself in Britain are very uncertain (see Chapter 6 for further discussion). A test for the potential effects of global warming would need to incorporate an understanding of the nature of variability over time under stable conditions (reflecting, for example, the apparent tendency to cluster), would need to be multivariate (considering changes in many catchments across a large region), and would need to consider multidimensional aspects of flow regimes, such as the tendency for increased winter runoff plus reduced summer runoff and a propensity for increased variability. Construction of such a test is beyond the scope of the current report.

4.2 SOME NOTABLE RECENT EVENTS

The 1970s and 1980s have seen a variety of notable hydrological events, with the droughts of 1975/76, 1984 and 1989 particularly noteworthy. However, these and other events have affected different parts of Britain to varying degrees. Figure 4.1 shows the timing and spatial extent of high runoff totals in winter, spring, summer and autumn from 1970 to 1988, and Figure 4.2 shows the same for low runoff totals. Note that the winters of 1988/89 and 1989/90 and the summer of 1989 are not included (the winter of 1988/89 would have appeared amongst the most extreme low runoff totals, whilst the winter of 1989/90 would appear across much of the UK in the high runoff table: the summer of 1989 would rank among the most extreme low summer flows). The figures were constructed by selecting only those catchments with data spanning the period 1959 to 1988, and extracting the five largest and five smallest of each season's flows over this 30-year period: the figures show those events which occurred between 1970 and 1988. Although event severity is indicated only by rank, the figures do give an indication of the occurrence of notable seasonal runoff events in recent years. The coarse seasonal time scale means that some notable short-term events are omitted: the flooding in the winter 1981/82 is not highlighted, for example.

Particularly notable events, in water resources terms, were the 'Great Drought' of 1975-1976, the drought of summer 1984, the low flows in winter 1988/89 and subsequent summer low flows, and the low winter flows in 1972/73 and 1973/74. Figures 4.1 and 4.2 show that many other seasons exhibited some form of extreme - over a short record - behaviour. There have been many studies into the origins and characteristics of the most notable events, particularly the 1975/76 drought. Important reports include the comprehensive *Atlas of Drought in Britain: 1975/76* (Doornkamp *et al.* 1980) and the review of the 1984 drought (Marsh and Lees, 1985). The hydrological aspects of the winter of 1988/89 are summarised in Arnell *et al.* (1989), and Marsh and Monkhouse (1990) review the dry summer of 1989. Many of these reports assign return periods to each event, but several problems need to be noted. Return periods can be assigned to many characteristics of an event - its duration, maximum intensity, or deficit volume, for example - and may be rather different. Joint probabilities of particular durations and magnitudes, for example, are also difficult to define. Estimated return periods may vary considerably across space, making it difficult to assign a single return period to an event with a widespread spatial impact. More practically, the record lengths that are available for frequency analysis tend to be short, and considerable

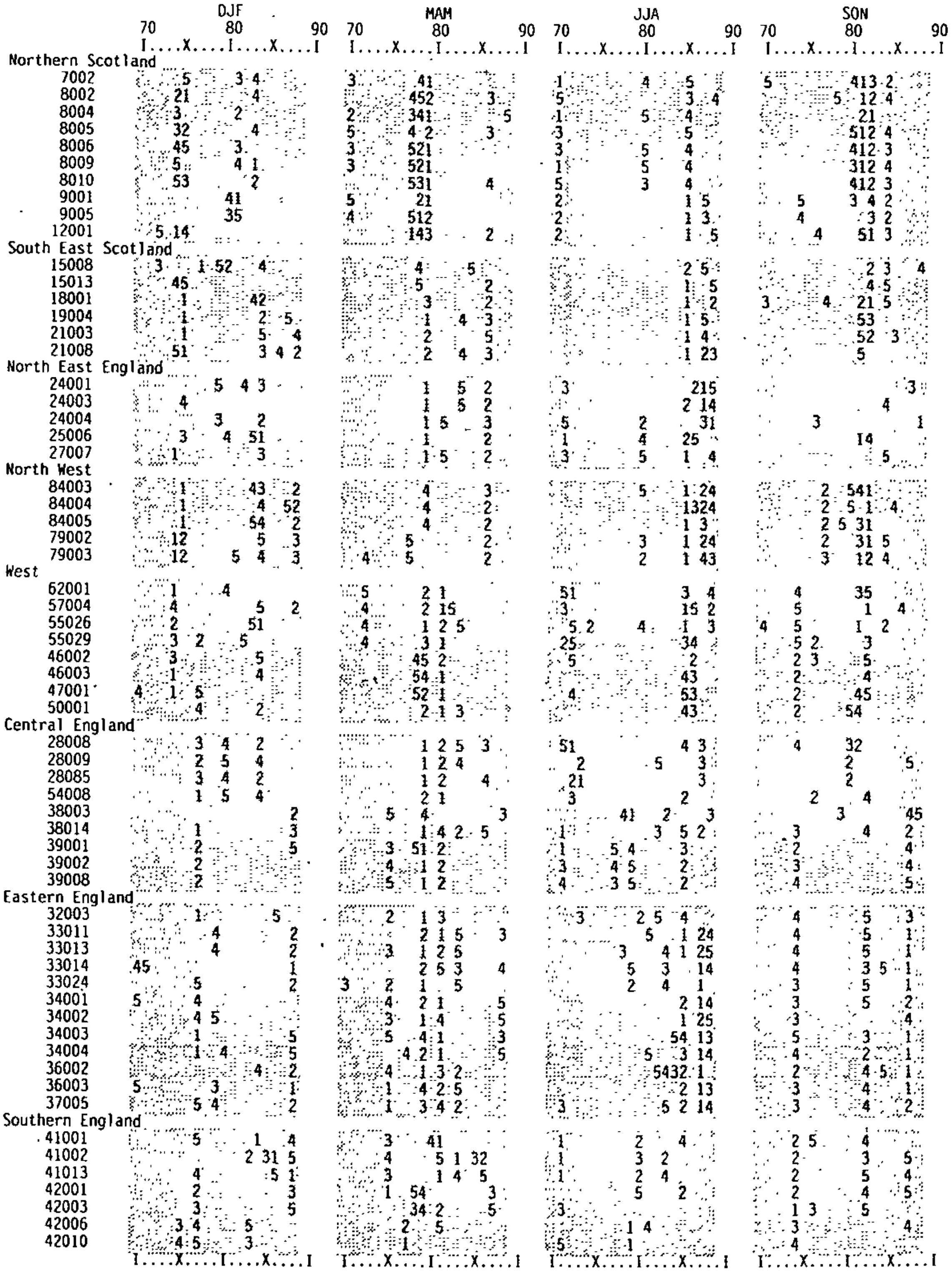


Figure 4.1 *The five largest seasonal runoff totals over the period 1959 to 1988 occurring during 1969-1988: 1 is the largest.*

```
                        DJF                     MAM                     JJA                     SON
               70        80        90  70        80        90  70        80        90  70        80        90
               I....X....I....X....I   I....X....I....X....I   I....X....I....X....I   I....X....I....X....I
Northern Scotland
      7002     4      1 2               4  1     23                342       1           1  4   3      5
      8002     3      1                 2  1     43                  234     1           1  4
      8004     4  1   2                    1 3                    24 1                  31      4      5
      8005     3      1                 4  1     23                 3 2     4 1         31
      8006     5  2   4 3               4  1                      43 2       1          31      5
      8009     1  5   3 2                  1 5   24                 3 2       1          41
      8010     3      1                 4  1     52               54 2       1          31             5
      9001      3 1  4          5        534 2                    43 1     5 2          41         5  3
      9005      3 1  5                  5  4 2    3                 2 1     4 3          1     5    4  3
     12001        5   4                 3 24                      45 2       1          314
South east Scotland
     15008        2  1                 3  1 4                     4 2      3 1           21 3          4
     15013      3    4                 1  253                       2 35    4 1         412
     18001           5                  2  41    5                 52 3      1          51243
     19004        1  4        5           324                      314  5    2          412 3       5
     21003        3  4                    312    4       5         23  5     1          412 3
     21008        5  2                 4  12         5             253       1          321 5       4
North east England
     24001        3           5           532      4               452       3          423 5
     24003           5        4            32    4   5             3 2 5                432
     24004        3  5                 4    2      1 3   5         534       1          32  4       5
     25006           5        3            352   4   1              21      53          352 4
     27007           3        4            413       2              41 5     3           25 3
North West
     84003                              4 521                     542 3      1           12 43
     84004                              4 521                      32 4      1          312  5
     84005                    5         3  12    5                52  4      1          512  4
     79002                    5         2  31        4            5 3 2     41          321         5
     79003      5             4         2  31        5              532     41          312 45
West
     62001      4    3    5               42 3       1              314      2           1  5  2
     57004           3    5                345       2              3145     2            3 4  2
     55026       4            3         4  2 3       1              31    5 42           1  3  5      2
     55029           1      5             24 1       3              31       2           5  3  24
     46002           1    4             5 2 41       3              31       4          3   2  1      5
     46003           1    4             2 5 43       1              31      52          245 3  1
     47001           2    4             4 25 3       1               1       2           5    41    2
     50001           2    5             5 42 3       1              31       2           4  2  1      3
Central England
     28008           3        4            5 2       4              51       4               3  5
     28009           1        5           32 1                     431       5               2  45
     28085        5  3        4            4 1       25            542       1               1  4
     54008           1    5             5 42 1       3             531       4               1  34
     38003        31 5                    14 2          5         23 1                   41  2        5
     38014        4  3                     3 1                  2 4                            2      5
     39001           1    5               2  1                     5 1       4           54    3
     39002           1    5               2  1       4              51       2            5 4  3
     39008           1    5               2  1       5             451       2           3  4
Eastern England
     32003         4 1                    32 1                     5 1                   52 4  3
     33011        35                      12 3                    42 1                    4  35
     33013        3                       12 4                    53 1                       4
     33014        25                      12 3                    23 1                   43  25
     33024        25 4                    24 1                    23 1                   43  5
     34001        2  5                    32 1     5               2 13                  5    23      4
     34002        15                      23 1       45           34 1      5  2         32   45
     34003        14                      42 1                     2 1                    5    34
     34004        15                      32 1     5              43 1                   2    35      4
     36002        3  5                    14 2                 5  3  1                         5      3
     36003        25 4                    24 1                    32 1                    2  543
     37005        2  3                    23 1                 5  43 1                   34   52
Southern England
     41001       3   2    5               23 1     5              5  1      4 2         523    1
     41002        5  1    4               25 1                            4     3         1   53    4    2
     41013       34  1                    23 1                    14 2          3       513    2
     42001        3  1    4               32 1                    3 51                  542    1
     42003        4  1    5             5 42 1                      31          4         2    15     4
     42006       35  2                    2  1                    23 1                  521    4
     42010       5   2    4               2  1                    24 1                   31    4
               I....X....I....X....I   I....X....I....X....I   I....X....I....X....I   I....X....I....X....I
```

Figure 4.2 The five smallest seasonal runoff totals over the period 1959 to 1988 occurring during 1969 to 1988: 1 is the smallest.

extrapolation is therefore necessary. The drought of 1976, for example, was in many catchments significantly more extreme than the previously recorded minimum flows. Finally, the assignment of return periods assumes that the data upon which the assessment is based are representative of conditions in the long term. Despite these problems, return periods give an extremely valuable indication of the severity of an event, expressed in terms useful to water resource planners.

This chapter does not attempt to reassign return periods to some of the recent notable events, and adopts a more generalised approach. Attention is focussed on the rate of occurrence of extreme events in recent years, and on the average characteristics of river flow during the 1980s in relation to earlier characteristics.

4.3 THE RECENT RATE OF OCCURRENCE OF EXTREME EVENTS

4.3.1 Introduction

The probability of experiencing during an M year time window n of the K largest events in N years can be calculated using the hypergeometric distribution:

$$\mathbf{p(n\ events)} = \binom{K}{n}\binom{N-K}{M-n} / \binom{N}{M}$$

For example, the probability of experiencing 4 of the 5 largest events in 30 years in a particular 10-year period is 0.0295. The hypergeometric distribution was used in the current study to determine the probability of experiencing the observed numbers of extreme (largest or smallest) hydrological indices in several defined recent periods. There are, however, several limitations with the hypergeometric distribution which need to be noted. First, it is a relatively coarse tool for defining a 'significant' number of extreme events in a time period, particularly if the period of interest is long relative to the total sample period. For example, the probability of all of the five largest events in 30 years occurring in a 20-year period is 0.109: such a cluster could be extremely important, but the high probability - one in ten - of experiencing such a sample even when there is no pattern means it is difficult to reject the null hypothesis of no increase in frequency in recent years. The test can therefore be somewhat conservative. Secondly, the probabilities calculated assume that each year is independent. If events tend to cluster - as is possibly the case with hydrological extremes - the probabilities of experiencing large numbers of extreme events will be underestimated, and the apparent significance overestimated. A small simulation experiment was conducted to examine the effect of clustering on the probabilities of experiencing n events in M years, and the results are shown in Table 4.1. The experiment used an extreme case where the probability of an event occurring doubled if the previous year also contained an event. It is clear that clustering increases considerably the probability of experiencing large numbers of events. The chance of experiencing

8 of the top 10 events in a particular 20-year time period in a 50-year record, for example, increases from 0.006 to 0.018 - a factor of three - under the assumed degree of clustering. However, although the probabilities of experiencing n or more events change when clustering is considered, the changes are not large enough to alter the number of occurrences which may be regarded as significant, if a probability of 0.05 is chosen as the significance level (Table 4.1 shows an extreme degree of clustering).

Table 4.1 *The effect of clustering on the probability of experiencing n of the K most extreme events in an N year period during an M year test window*

	N=50, M=20 k=10			N=30, M=10 k=5		
	no cluster		cluster	no cluster		cluster
n	theoretical	simulated	simulated	theoretical	simulated	simulated
0	0.0029	0.0028	0.017	0.1088	0.1065	0.169
1	0.0279	0.0281	0.062	0.3400	0.3484	0.313
2	0.1083	0.1074	0.137	0.3600	0.3600	0.293
3	0.2259	0.2272	0.197	0.1600	0.1550	0.165
4	0.2801	0.2737	0.213	0.0295	0.0289	0.053
5	0.2151	0.2246	0.179	0.0018	0.0012	0.008
6	0.1034	0.1019	0.116			
7	0.0306	0.0279	0.055			
8	0.0053	0.0061	0.018			
9	0.0005	0.0003	0.005			
10	0.0	0.0	0.001			

In the 'clustered' experiments, the probability of experiencing an event doubled if the previous year contained an event.

The probabilities are based on 10000 repetitions: the theoretical probabilities are shown for the 'no-cluster' case for comparative purposes.

Jones and Wigley (1988) used the hypergeometric distribution for assessing the rate of occurrence of extreme rainfalls in different regions of England and Wales. They counted the number of the five largest events over the period 1873 to 1987 which occurred in the 20 years from 1968 to 1987, and found a tendency for an 'excess' of wet springs and dry summers. Spring and summer rainfall are statistically independent, and Jones and Wigley (1988) showed that the joint occurrence of wet springs and dry summers was higher than would be expected by chance (assuming independence between years).

4.3.2 Reconstructed flow series

The good quality observed records available for analysis are rather short, with few records longer than 40 years. An attempt to consider the occurrence of extremes in the period 1969-1988 in the rather longer term was therefore made using the reconstructed flow series provided by the Climatic Research Unit and described in Chapter 2. There are two assumptions which need to be noted. Firstly, it is assumed that there is no systematic bias in the model used to reconstruct the long flow series, and in particular that the relative magnitudes of the extreme flows are accurate. This may be optimistic: models tend to perform best under average conditions. The other assumption is that the combination of the observed and reconstructed records (largely in the late 1950s or early 1960s: Chapter 2) did not introduce a marked discontinuity in the occurrence of extreme low flows.

Table 4.2 shows the number of the 10 largest and 10 smallest events over the 100 years from 1889 to 1988 which were recorded in the 20 years from 1969 to 1988. The Wharfe and the Wensum experienced too many high spring flows, but more catchments experienced few high seasonal flows during 1969-1988 (although the probability of experiencing no extremes is 0.095). There is no evidence from the eight catchments considered that recent years have experienced unusual numbers of events. A slightly higher number of unusual occurrences was found with a 50-year base period running from 1939 to 1988, but no strong pattern was evident.

Although there is no evidence that the recent past has had a particularly 'unusual' rate of occurrence of extremes, similar analyses in earlier periods could have been capable of concluding that the number of extremes recently experienced had been unusual. In the 20-year period to 1930, for example, five of the eight catchments had more high spring flows than would be expected, and four of the catchments had a high rate of occurrence of high annual runoff totals (Table 4.3): five catchments also had too few low annual runoff totals. A hydrologist in 1930 would be able to conclude with some confidence that runoff was increasing: subsequent years, however, would show a reduction in runoff.

4.3.3 Recorded river flow data

The previous section has implied that the hydrological characteristics of recent years are not particularly unusual in the longer term, and indeed in some earlier periods - particularly the 1930s - it would have been possible to claim that recent behaviour had been quite unusual. But have the hydrological characteristics of the 1970s and 1980s been unusual when a shorter timescale is considered?

Extreme high and low seasonal runoff totals were determined from recorded river flow data, using two base periods. The first evaluations were based on the 40 years from 1949 to 1988, and counted the number of the 10 largest and 10 smallest minimum monthly, seasonal and annual runoff totals in the 20 years from 1969 to 1988. Only nine catchments had sufficient data, with a rather restrictive spatial distribution (and two were naturalised flow records

Table 4.2 ***The number of the 10 largest and 10 smallest seasonal and annual runoff totals over the 100 years from 1889 to 1988 recorded between 1969 and 1988***

	Largest events					
	Min.	DJF	MAM	JJA	SON	Annual
76005 Eden at Temple Sowerby	0	0	2	0	0	1
76002 Eden at Warwick Bridge	1	1	2	2	0	0
45001 Exe at Thorverton	0	1	2	1	1	3
25001 Tees at Broken Scar	1	1	4	0	0	1
23001 Tyne at Bywell	1	0	3	1	0	1
34004 Wensum at Costessey Mill	2	1	5*	3	3	4
27043 Wharfe at Addingham	0	2	5*	1	2	3
55023 Wye at Redbrook	2	0	2	1	0	1

	Smallest events					
	Min.	DJF	MAM	JJA	SON	Annual
76005 Eden at Temple Sowerby	3	1	3	3	1	4
76002 Eden at Warwick Bridge	4	1	3	3	2	3
45001 Exe at Thorverton	3	1	2	3	3	2
25001 Tees at Broken scar	3	2	4	3	4	3
23001 Tyne at Bywell	3	0	2	2	2	3
34004 Wensum at Costessey Mill	3	1	3	2	1	1
27043 Wharfe at Addingham	4	2	2	3	1	2
55023 Wye at Redbrook	2	1	2	3	2	3

Prob.(4 or more) = 0.109
Prob.(5 or more) = 0.025
Prob.(0) = 0.095

Min. denotes minimum monthly runoff

* denotes number expected with a probability of less than 5%

from the River Thames: Table 4.4). There are few instances of 'too many' events occurring in 1969 to 1988. There were significantly too many high runoff totals in spring and summer in 33024 (in the Bedford Ouse catchment), and too many high spring runoffs in the Wye (55026). There were rather too few low winter runoff totals in the Monnow (55020) catchment, too many low autumn runoffs in south east Scotland (12001) and in Harpers Brook (32003), and too many low spring and summer flows in the Thames at Kingston (39001). The results are, however, inconclusive.

Sixty-two catchments covering a larger area of Britain were considered when the base period was reduced to the 30 years between 1959 and 1988 (catchments were allowed up to two missing years: the number of occurrences expected with a probability less than 0.05 are not affected). Table 4.5 shows

Table 4.3. The number of the 10 largest seasonal and annual runoff totals over the 50 years from 1881 to 1930 recorded between 1911 and 1930

	Largest events					
	Min.	DJF	MAM	JJA	SON	Annual
76005 Eden at Temple Sowerby	3	6	3	4	7*	5
76002 Eden at Warwick Bridge	5	5	4	4	6	7*
45001 Exe at Thorverton	4	8*	7*	4	5	7*
25001 Tees at Broken Scar	4	6	4	4	6	4
23001 Tyne at Bywell	4	7*	4	4	5	6
34004 Wensum at Costessey Mill	5	8*	6	4	4	7*
27043 Wharfe at Addingham	5	7*	3	4	7*	7*
55023 Wye at Redbrook	5	7*	5	5	5	5

Prob. (7 or more) = 0.036
Prob. (8 or more) = 0.007

Min denotes minimum monthly runoff

* denotes number expected with a probability of less than 5%

the numbers of the 10 most extreme events occurring in the period 1969 to 1988. Again, there are very few instances of too many events occurring, the most notable feature being 'too many' high runoff totals in eastern England. However, several catchments recorded 9 of the 10 lowest summer and autumn runoff totals in 1969 to 1988, particularly in the north and west.

The results of this analysis do not support the suggestion that recent years have seen unusually large numbers of extreme events, whether they be high or low runoff totals. This may in part reflect the conservative nature of the test used, and the addition of the low runoff totals in all seasons in 1989 would increase the number of catchments showing unusually low summer and autumn runoff totals in particular. The conclusions are also influenced by the definition of 'recent', and the exercise was therefore repeated with windows covering shorter periods of the recent past.

Table 4.6 shows the number of catchments showing a number of extreme events expected with a probability of less than 0.05, with a range of definitions of 'recent'. The table implies that the shorter the 'recent' period, the greater the number of catchments with unexpectedly large or few numbers of exceedances. Once the period defined to be 'recent' excludes 1976, the conclusion is that recent years have experienced too many large events. The differences should be treated with some caution, due to the relatively major changes in probability with n and the possibility that a reduction in the size of window M means that a given number of events suddenly becomes 'significant', but do serve to emphasise that the definition of 'recent' does influence perception of recent behaviour.

Table 4.4 The number of the 10 largest and 10 smallest seasonal and annual runoff totals over the 40 years from 1949 to 1988 recorded between 1969 and 1988

			Largest events			
	Min.	DJF	MAM	JJA	SON	Annual
12001 Dee at Woodend	5	5	7	4	5	5
28085 Derwent at St. Mary's Br	5	5	7	5	2	4
32003 Harpers Bk at Old Mill Br	6	5	6	6	4	5
33024 Cam at Bottisham	7	6	8*	8*	6	6
39001 Thames at Kingston (N)	4	5	6	6	3	4
39002 Thames at Days weir (N)	5	4	7	5	2	4
41001 Nunningham St at Tilley Bar	3	6	6	4	4	6
55026 Wye at Ddol Farm	4	5	8*	4	5	7
55029 Monnow at Grosmont	7	7	6	5	3	5
			Smallest events			
12001 Dee at Woodend	6	5	5	7	8*	4
28085 Derwent at St. Mary's Br	6	4	3	5	5	5
32003 Harpers Bk at Old Mill Br	6	4	3	5	8*	4
33024 Cam at Bottisham	4	5	3	3	3	4
39001 Thames at Kingston (N)	3	3	2*	3	6	2*
39002 Thames at Days weir (N)	4	4	4	4	6	3
41001 Nunningham St at Tilley Bar	7	6	4	5	7	6
55026 Wye at Ddol Farm	6	4	4	6	6	3
55029 Monnow at Grosmont	5	2*	4	4	7	3

Prob.(7 or more) = 0.137
Prob.(8 or more) = 0.028
Prob.(2 or less) = 0.032

Min. denotes minimum monthly runoff
(N) denotes naturalised runoff record
* denotes number expected with a probability of less than 5%

It is even harder to draw conclusions about the recent rate of occurrence of extreme events when fewer events are selected. For example, the probability that all five of the largest five events in a 30-year period occur in the last 20 years is greater than 0.05, and it is difficult to justify rejecting the null hypothesis of no unusual grouping. However, in many catchments in southern and eastern England, the period 1969 to 1988 saw all five of the five largest spring and summer flows, and nearly all catchments experienced at least four of the largest spring flows. A few catchments experienced all five smallest summer flows, but the vast majority only experienced three or four (no attempt was made to determine the joint likelihood of experiencing the five lowest and the five highest summer flows in a 20-year period).

4.3.4 Conclusions

This section has failed to demonstrate clearly that the 'recent' past has experienced an unusual number of extreme hydrological events. This may in part reflect the rather conservative nature of the test considered: with few extremes it is very difficult to reject the null hypothesis of no unusual clustering, particularly when the total record available is short. However, there is evidence that, in some catchments at least, the period since the late 1970s has been characterised by rather too many extreme high seasonal runoff totals, and too few extreme low flows. Across Britain as a whole, the 1980s was the wettest decade on record (Marsh and Monkhouse, 1990), although it did contain some notable dry periods. The addition of 1989 runoff data would increase the likelihood of an excess of low runoff extremes being identified.

4.4 THE CHARACTERISTICS OF FLOW REGIMES IN RECENT YEARS

4.4.1 Introduction

The previous section has indicated that 'recent' years have not been characterised by the occurrence of too many extremes. How, then, have the 'average' flow regimes in recent years compared with earlier periods? Are average seasonal runoff totals notably higher than previous averages, and has variability between years changed?

The 1980s were the wettest decade on record in Britain, particularly in Scotland and the north and west of England, and the increase in rainfall tended to be concentrated in winter and spring (Marsh and Monkhouse, 1990). Analysis of catchment average monthly rainfalls shows that average summer rainfall was higher in the 1980s than the 1970s across all of Britain, but was lower than in the 1960s in the north and west. Autumn rainfall was again, on average, higher than in the 1970s, but was lower than during the 1960s across the whole of Britain. The average annual rainfall in the 1980s was therefore not only higher than in the 1960s (and was even higher relative to the 1970s), but the extra rainfall mainly occurred during the runoff generation season in winter and spring. Annual rainfall was between 15 and 20% higher in the 1980s than the 1970s in Scotland and parts of the north and west of England, and typically between 5 and 15% higher in the south and east. The 1980s had an annual average rainfall less than 10% higher than the 1960s, and in parts of southern and eastern England the 1960s average was higher. Table 4.7 shows the 1980s seasonal rainfall averages as percentage differences from 1960s and 1970s averages, averaged across a number of sites in several large regions. With respect to the 1970s, the greatest relative increase in summer, autumn and winter rainfall in the 1980s was found in Scotland and northern England, whilst the greatest relative increase in spring rainfalls was further south, and in southern and eastern England in particular. Average minimum monthly rainfalls were lower in Scotland and parts of northern England in the 1980s than the 1970s. Average summer and autumn rainfalls were higher in the 1960s than the 1980s across much of the UK, and in south and east England annual rainfall was much higher.

Table 4.5 The number of the 10 largest and 10 smallest runoff totals over the period 1959-1988 experienced between 1969-1988

	LARGEST						SMALLEST					
	MIN.	DJF	MAM	JJA	SON	ANN.	MIN.	DJF	MAM	JJA	SON	ANN.
North Scotland												
7002	7	6	8	6	7	7	7	6	6	8	8	7
8002	6	8	8	5	9	7	9	6	6	9	6	6
8004	7	6	8	7	5	6	7	6	6	8	9	7
8005	6	5	7	5	7	6	6	6	7	9	8	7
8006	8	7	8	7	6	8	6	5	6	8	8	7
8009	6	7	8	6	7	8	7	7	6	8	7	8
8010	7	7	8	7	8	7	7	6	6	8	7	7
9001	6	6	9	6	7	6	8	7	8	9	8	8
9005	7	5	8	7	7	6	8	6	7	8	9	7
12001	6	7	8	7	5	6	8	5	6	8	9	5
South East Scotland												
15008	5	8	7	7	6	7	8	4	5	8	8	5
15013	4	6	5	4	6	5	9	6	8	9	8	8
18001	4	7	6	4	7	6	10	6	8	9	7	7
19004	5	8	6	5	5	5	10	6	6	9	8	7
21003	5	6	6	6	6	6	8	7	8	9	9	9
21008	6	10	7	6	6	5	9	7	8	8	8	8
North East England												
24001	5	7	5	6	4	6	7	5	8	8	6	7
24003	7	5	7	5	5	5	8	6	8	8	7	8
24004	6	7	6	7	5	5	8	7	8	9	7	7
25006	5	6	6	7	6	6	10	7	9	8	7	8
27007	5	6	6	7	6	5	8	6	9	8	6	7
North West												
79002	5	7	7	6	8	8	7	6	8	9	7	7
79003	6	7	7	6	9	9	8	6	8	10	7	6
84003	4	8	7	6	8	8	8	6	6	8	8	6
84004	5	7	7	6	8	8	7	6	6	8	8	7
84005	6	7	7	7	8	8	8	6	6	9	7	6

Table 4.5 continued

	LARGEST						SMALLEST					
	MIN.	DJF	MAM	JJA	SON	ANN.	MIN.	DJF	MAM	JJA	SON	ANN.
West												
55026	6	7	8	6	8	9	7	8	6	8	7	5
55029	8	7	7	9	6	6	6	5	8	5	7	6
57004	6	6	8	8	8	8	8	6	8	7	6	6
62001	6	7	7	6	7	7	8	6	8	8	8	7
46002	6	7	6	7	7	5	8	6	7	6	8	7
46003	5	7	6	6	6	5	8	5	8	8	9	8
47001	6	7	7	7	6	6	6	5	6	6	6	8
50001	6	6	8	7	7	7	7	6	5	6	8	7
Central												
28008	6	7	8	8	5	8	4	5	5	5	6	5
28009	5	6	7	7	4	7	7	6	6	6	7	5
28085	6	6	8	8	4	6	8	6	7	6	6	5
54008	6	8	7	7	5	6	6	5	7	6	7	5
38003	6	6	6	7	5	6	7	6	6	7	6	6
38014	8	6	7	7	7	7	5	6	4	6	8	5
39001	6	7	7	7	5	6	7	7	6	6	7	6
39002	6	6	8	7	5	6	6	7	6	6	7	7
39008	7	6	7	8	5	6	6	7	5	5	7	6
East												
32003	7	6	7	9	6	7	7	7	5	7	8	7
33011	9	8	10	10	8	8	5	6	3	3	4	4
33013	10	7	10	10	8	10	4	6	4	3	5	3
33014	9	8	9	10	8	9	5	7	5	4	6	5
33024	9	7	9	9	7	8	5	6	6	5	6	6
34001	5	6	7	6	5	5	7	7	7	6	8	7
34002	4	5	7	7	5	6	8	7	8	7	7	7
34003	9	7	10	9	6	9	5	5	6	5	6	6
34004	5	8	8	8	6	8	9	6	6	7	8	6
36002	9	7	8	9	7	9	6	7	5	5	8	5
36003	7	8	8	7	6	8	7	7	7	7	8	4
37005	7	7	8	8	6	8	8	6	7	6	9	6
South												
41001	6	7	7	6	5	6	8	6	6	7	7	6
41002	5	7	7	6	5	7	7	7	6	7	8	6
41013	4	6	7	5	5	5	8	7	6	7	7	7
42001	5	7	7	5	7	6	6	5	5	7	7	5
42003	5	7	6	6	6	4	8	6	7	8	9	8
42006	4	5	6	4	5	5	8	7	6	8	8	6
42010	5	7	7	6	5	5	6	6	5	8	7	6

Table 4.6 The numbers of catchments showing numbers of extreme events expected with a probability of less than 0.05, over different recent periods

	DJF	MAM	JJA	SON	Ann	DJF	MAM	JJA	SON	Ann
69-88										
(i)	1	3	5	-	1	-	-	2	1	-
(ii)	-	-	1	8	-	-	3	3	4	3
71-88										
(i)	1	-	4	-	1	-	1	8	-	-
(ii)	1	-	2	-	-	-	1	3	-	1
73-88										
(i)	4	3	7	3	6	-	2	18	-	-
(ii)	1	-	-	-	-	-	1	–	-	-
75-88										
(i)	2	3	5	3	4	-	-	3	-	-
(ii)	1	-	1	1	-	15	15	8	7	19
77-88										
(i)	5	14	9	6	16	-	-	-	-	-
(ii)	-	-	-	-	-	13	17	16	15	39
79-88										
(i)	4	11	16	9	24	-	-	-	-	-
(ii)	-	-	-	-	-	1	3	6	3	11

Notes:

(i) = 'too many' extreme events (ii) = 'too few' extreme events

Table 4.7 Rainfall in 1979-1988 as a percentage difference from 1969-1978 and 1959-1968

1979-1988 as a percentage difference from 1969-1978

	DJF	MAM	JJA	SON	Ann.	N
N. Scotland	15.8	6.2	17.7	24.9	15.8	10
SE Scotland	3.1	19.9	16.5	27.2	14.4	6
NE England	11.0	20.9	13.8	23.7	12.1	5
E. England	5.4	29.4	17.9	6.1	11.5	11
C. England	1.8	29.5	6.9	14.2	8.9	9
S. England	5.6	24.4	8.4	5.7	6.0	6
W. Eng.+Wales	0.6	26.9	6.7	20.8	10.2	8
North West	2.9	12.9	26.5	22.9	15.1	5

1979-1988 as a percentage difference from 1959-1968

	DJF	MAM	JJA	SON	Ann.	N
N. Scotland	14.7	6.8	-8.8	-15.9	7.1	10
SE Scotland	10.4	4.2	-11.9	4.6	0.8	6
NE England	10.3	6.1	-3.6	-0.4	1.7	5
E. England	6.3	27.2	-2.4	-6.8	-3.8	11
C. England	5.2	17.7	-5.0	-2.7	1.9	9
S. England	4.7	5.9	-8.9	-11.3	-4.7	6
W. Eng.+Wales	7.2	4.3	-5.2	1.9	1.5	8
North West	9.8	-4.5	-2.7	7.1	3.8	5

N denotes number of catchments

It is expected, therefore, that runoff in the 1980s has been higher than in earlier periods, and that the concentration of the increase in rainfall in winter and spring increased its effectiveness in generating more runoff. Differences in rainfall will not be mirrored exactly in runoff, partly because other climatic variables, such as evapotranspiration, may differ, and partly because of the effects of catchment lag.

4.4.2 Changes in average seasonal and annual runoff volumes

Average seasonal and annual runoff totals were calculated for all the catchments with data covering the three decades 1959-1968, 1969-1978 and 1979-1988. Up to two missing values were allowed in each season, producing a data base of 63 catchments spread across Britain. The analysis includes very few catchments in central and southern England.

In all but two of the catchments average annual runoff in the 1980s was greater than in the 1970s, and was greater than in the 1960s in all but seven catchments. Table 4.8 gives the average change in runoff in the 1980s with respect to the 1960s and 1970s by region: average annual runoff in the 1980s was over 20% higher than in the 1970s in many regions, with lesser increases - except in eastern England - over the 1960s. A Student's t test showed that average annual runoff in 35 of the 63 catchments was significantly higher in the 1980s than the 1970s, and these catchments are concentrated in the north of Britain, although it is not necessarily these catchments which show the greatest relative increase (the statistical significance of the difference between the two samples depends also on inter-annual variability). The average runoff in the 1980s was statistically significantly higher than that in the 1960s in six of the 63 catchments.

Winter and spring runoff averages in the 1980s were consistently higher than in either the 1960s or 1970s (Table 4.8), and summer and autumn averages were higher than during the 1970s across all regions. Summer and autumn averages were, however, higher during the 1960s in more western and northern regions. The greatest proportional differences in runoff are in spring, summer and autumn, although the absolute changes are greater in winter. A comparison of Tables 4.7 and 4.8 shows that runoff differences are generally larger than rainfall differences - as outlined in Chapter 3 - and that reductions in summer runoff are much less frequent than the reductions in summer rainfall. This reflects the importance of the higher winter and spring rainfalls in maintaining relatively high flows during the summer.

Catchment type can be expected to control the translation of rainfall differences to runoff differences, with high base flow catchments less prone to lower summer and autumn flows in periods with drier summers but wetter winters and springs. Variations between catchments in the differences between summer and autumn rainfall in any two periods, however, make it difficult to test this hypothesis.

Table 4.8 Runoff in 1979-1988 as a percentage difference from 1969-1978 and 1959-1968

1979-1988 as a percentage difference from 1969-1978

	DJF	MAM	JJA	SON	Ann.	N
N. Scotland	18.3	10.4	24.4	36.3	20.0	10
SE Scotland	14.7	36.3	47.8	60.2	30.8	7
NE England	17.2	37.8	29.4	42.0	26.2	5
E. England	9.8	25.6	50.7	34.9	23.2	12
C. England	10.3	32.7	19.3	32.6	20.5	9
S. England	20.3	37.7	24.4	15.9	23.7	7
W. Eng.+Wales	0.4	31.2	15.0	36.8	14.5	8
North West	13.8	25.7	85.7	50.7	32.1	5

1979-1988 as a percentage difference from 1959-1968

	DJF	MAM	JJA	SON	Ann.	N
N. Scotland	7.4	14.2	-3.0	11.2	8.2	10
SE Scotland	17.9	5.3	-6.9	-2.3	4.6	7
NE England	14.4	9.2	6.4	-5.1	6.2	5
E. England	13.2	40.9	55.4	5.5	23.9	12
C. England	5.9	27.3	17.0	-8.9	9.1	9
S. England	10.6	21.6	-2.9	-22.5	4.4	7
W. Eng.+Wales	6.5	11.8	2.7	2.9	5.0	8
North West	23.0	2.3	20.1	21.1	18.1	5

N denotes number of catchments

The available evidence suggests that runoff in the 1980s was considerably higher than in the 1970s and - particularly in winter and spring - higher than during the 1960s, which were themselves characterised by rather higher runoff than the 1970s. The reconstructed river flows were used to place average runoff in the 1980s in the longer context. Table 4.9 shows the rank of the average seasonal and annual flows in 1979-1988 over the 10 decades in the 100-year period from 1889 to 1988 (1 is the largest). Average runoff totals during the 1980s were large in all catchments, relative to longer term averages, in winter, spring and autumn. High - and in some catchments higher - runoff totals were also experienced in the 1910s and 1920s, as indicated in the previous section which noted the larger number of extremes in the 20 years before 1930.

Table 4.9 The rank of 1979-1988 average runoff over the 10 decades in the 100 years from 1889 to 1988

	DJF	MAM	JJA	SON	Ann.
76005 Eden at Temple Sowerby	5	3	8	2	3
76002 Eden at Warwick Bridge	5	3	6	1	3
45001 Exe at Thorverton	2	1	5	2	1
25001 Tees at Broken Scar	3	1	7	8	2
23001 Tyne at Bywell	2	1	3	2	1
34004 Wensum at Costessey Mill	1	1	1	1	1
27043 Wharfe at Addingham	2	1	8	1	1
55023 Wye at Redbrook	1	1	5	3	1

1 denotes the largest, 10 the smallest.

4.4.3 Changes in the variability in runoff between years

Runoff in several seasons has been higher, on average, in the 1980s than in many previous decades. How has variability between years in the 1980s compared with earlier variability? Differences in variability between periods are, however, harder to define than differences in averages, because measures of variability show much greater sampling variability between samples than measures of average behaviour. The sampling distribution of the standard deviation of 10 observations, for example, is larger (in relative terms) than the sampling distribution of the mean of those 10 items. It is also important to distinguish between absolute variability - as expressed for example by the standard deviation - and relative variability - as expressed by the coefficient of variation. If absolute variability remains constant but mean values increase, relative variability reduces.

Table 4.10 shows the proportion of the sample catchments where the standard deviation in seasonal rainfall - in other words the absolute variability - was greater in the 1980s than in the 1970s or 1960s: note that no attempt was made to assess the significance of the difference, and some differences were much larger than others. Nevertheless, the table implies that spring, summer and autumn rainfall totals have been rather more variable in the 1980s than in earlier periods, with fewer instances of higher variability with winter and annual rainfall. The sites with higher variability in summer and autumn rainfall in the 1980s are concentrated in Scotland and northern England: variability between years appears to have been less in the east and south of England. Very few catchments had higher variability in annual rainfall in the 1980s than in the 1960s and, particularly, the 1970s.

Table 4.10 The percentage of catchments with higher variability in rainfall and runoff in 1979-1988 compared with 1969-1978 and 1959-1968

Rainfall (61 catchments)

1979-1988 compared with	% showing higher standard deviation in 1979-1988					
	Min.	DJF	MAM	JJA	SON	Ann.
1959-1968	25	11	87	92	48	16
1969-1978	51	40	86	93	18	3

Runoff (63 catchments)

1979-1988 compared with	% showing higher standard deviation in 1979-1988					
	Min.	DJF	MAM	JJA	SON	Ann.
1959-1968	41	15	71	63	33	17
1969-1978	78	17	51	62	49	2

Table 4.10 also shows the proportion of catchments where variability in runoff in the 1980s was higher than in previous decades. Again, the catchments with increased summer and autumn variability are concentrated in the north, although some catchments in the south and east show increased variability in summer runoff.

The impression of increased variability in the 1980s in summer and autumn flows is supported by the results from an application of the Kruskal-Wallis test for the equality of sub-period variances (WMO, 1988). This test basically divides a long record into five or six subperiods, and examines whether the variabilities within each sample are significantly different. Visual inspection of plots is necessary to determine the variation over time in variability in a particular sample that contains significantly different sub-period variabilities. The test was applied to 30 long-record samples with different record lengths, and although the length and timing of the subperiods considered varied between catchments (they were most 5 or 6 years long), the results do give a general indication of patterns in variability. Table 4.11 shows the numbers of the 30 catchments showing 'significant' (at the 10% level) differences in variability over time, classified according to the apparent direction of change. The test was applied to monthly, rather than seasonal, data. More catchments show a significant change in variability over time in spring, summer and autumn, and there is a bias towards trends to increasing variability. Fewer sites show significant differences in the variability of annual runoff, and those that do imply lower variability in recent years. In sum, these results are consistent with the more informal comparisons of the magnitudes of variability in recent years.

Table 4.11 The numbers of catchments showing a significant difference in variability between subperiods, using the Kruskall-Wallis test for equality of sub-period variances

	Increase over time	Decrease then increase	No pattern	Increase then decrease	Decrease over time	Total
January	3	1	-	-	-	4
February	-	2	1	-	1	4
March	2	3	1	-	-	7
April	6	1	1	-	-	8
May	13	-	-	-	-	13
June	5	1	4	3	-	13
July	3	6	8	1	1	19
August	4	11	3	1	-	19
September	5	1	2	2	3	13
October	8	1	3	2	1	15
November	4	3	3	-	-	10
December	5	-	-	-	-	1
Annual	-	-	4	1	1	6

30 catchments were analysed.

How has the variability in the last decade compared with variability over the longer term? Table 4.12 shows the rank of the standard deviation of the reconstructed flows in 1979-1988 over the standard deviations in the 10 decades in the 100 years from 1889 to 1989, where the largest standard deviation is rank 1. Over the long term, the variability in the 1980s does not appear high, and autumn, winter and annual variability in the 1980s has been amongst the lowest over the 10 - defined decades (note that other 10-year periods may have experienced less variability, but the emphasis has been placed here on fixed decades).

Table 4.12 The rank of standard deviation of runoff during 1979-1988 over the 10 decades in the 100 years from 1889 to 1988

	DJF	MAM	JJA	SON	Ann.
76005 Eden at Temple Sowerby	9	1	5	9	10
76002 Eden at Warwick Bridge	9	3	3	10	10
45001 Exe at Thorverton	7	2	6	8	10
25001 Tees at Broken Scar	9	1	7	9	9
23001 Tyne at Bywell	10	2	3	9	10
34004 Wensum at Costessey Mill	10	4	5	1	9
27043 Wharfe at Addingham	3	1	4	8	4
55023 Wye at Redbrook	9	5	5	9	10

1 denotes the largest, 10 the smallest

4.5 CONCLUSIONS AND IMPLICATIONS

This chapter has examined river flow characteristics in recent years, concentrating in particular on the rate of occurrence of notable extreme events and average characteristics over a number of years. No reference has been made to groundwater characteristics, or to other hydrological variables such as evapotranspiration. The lack of widespread, reliable long river records has limited the analysis, and little attempt has been made to define spatial patterns. Also, the winter of 1988/89, the summer of 1989 and the winter of 1989/90 could not be analysed in detail in the course of the study: preliminary indications are that these data may lead to substantial revisions both of the conclusions of the study and of the understanding of the response of British rivers to variable climatic inputs. Nevertheless, some conclusions can be drawn from the analyses.

Firstly, there is no real evidence that there have been an unusually high number of 'extreme' high or low seasonal runoff totals in recent years, although this may reflect the conservative nature of the test used. There is a tendency for catchments to show more high seasonal runoff extremes than would be expected if events were independent from year to year, with the greatest implied effect when a period beginning *after* the 1976 drought is taken to be 'recent'. Analysis of the reconstructed flow series showed that it was possible to find periods in the past which contained large numbers of extreme runoff events, but which subsequently were followed by a period of relative inactivity: the 20 years to 1930, for example, contained many large seasonal runoff totals. The implied probability of experiencing n of the largest K events in an M-year window is dependent on the degree of clustering assumed, and increases with an increased propensity to cluster.

The average runoff characteristics of the 1980s have, however, been consistently different to those of previous decades. In general terms, the 1980s have had higher runoff totals than the 1970s - which were relatively dry - and the 1960s. Absolute increases in winter runoff have been highest, although greater relative increases in spring, summer and autumn were recorded in many catchments. This concentration of extra rainfall in winter increased its hydrological effectiveness. In over half of the catchments considered, the average annual runoff between 1979 and 1988 was significantly (statistically) higher than the average between 1969 and 1978. The contrasts in rainfall between decades are amplified in average seasonal flows, as also shown in Chapter 3. Rainfall in a number of catchments was lower in summer in the 1980s than in the 1960s, but the higher winter and spring rainfalls meant that summer flows in the 1980s were only in a very few cases lower than in the wetter summers of the 1960s.

Average annual, winter and spring flows were notably high during the 1980s with respect to flows over the last 100 years, although autumn flows were less notable.

There is also some limited evidence that the variability in runoff from year to year was higher in the 1980s than in previous decades, particularly in summer and in the north. The large sampling variability of measures of inter-annual variation, however, makes it difficult to draw strong conclusions.

What are the implications of the higher runoff and (possible) increased variability that has characterised flow regimes in the 1980s? It is important to emphasise at the outset that recent experience of 'unusual' behaviour does not imply that that behaviour will continue into the future. Indeed, many examples have been given of earlier periods which seemed to show an increase in the rate of occurrence of notable events, but which were followed by a return to more average conditions. The hydrological characteristics of the 1980s cannot therefore be used to infer that global warming has begun to have an effect: they equally cannot be used to dismiss the possibility of future warming.

The results do serve to indicate, however, that any assessment of hydrological characteristics or water resources potential based on a short record may turn out to be very inaccurate over the longer term. Even in mild, temperate Britain, it is possible to experience statistically significant differences in mean flows over successive 10-year periods. An assessment of British water resources based on data from just the 1960s would have appeared in the 1970s to have been over-optimistic, whilst an analysis using just data from the 1970s would appear to underestimate resources. Of course, an estimate based on 1980s data need not be any more indicative of longer term resource availability than data from earlier periods, and substantially lower flows could be experienced in the 1990s. The intrinsic variability of British climate means that average behaviour over even 10 years may not give a reliable indication of long-term resource potential.

5. Variability in river flows over time: a summary

5.1 PATTERNS OF VARIABILITY

The previous chapters have shown that indices of flow regime vary considerably in Britain from year to year - although not as much as in more arid environments - and have attempted to define the factors influencing this variability. Analyses are limited by the paucity of high-quality long-term flow records. The conclusions from the investigations are:

* The variability in river flow characteristics between years is, unsurprisingly, related to variations in rainfall characteristics, and is generally larger. However, there are complications. The clearest relationships between climatic and hydrological variability occur in winter, with the poorest relationships in summer. This reflects the role of the catchment: summer flows represent an integration of climatic characteristics over several months, with the memory depending on catchment geology. High winter and spring rainfalls frequently maintain - or limit the reduction in - river flows through dry summers.

* Different catchments show different degrees of variability between years, and this is only partially related to differences in the degree of variability in climatic inputs. The catchment runoff coefficient - reflecting 'aridity' - and base flow index are both very important in determining relative variability between years. The greatest variability is found in highly-responsive catchments with low runoff relative to rainfall. The variation in short-duration aspects of flow, such as the annual minimum 7-day flow, are much harder to relate to generalised indices of catchment and climate variability than seasonal flow characteristics, reflecting the multitude of influences on short-duration events.

* 'Notable' events tend to cluster in time. There is evidence that time series of annual values of a range of indices do not represent samples from independent distributions, and that if there is an 'event' (such as high winter runoff) in one year, there is a greater chance of experiencing an event the next year. Several tests indicated the presence of some form of clustering, but it has not been possible in the context of the study to derive a time series model reproducing observed temporal characteristics. The climatic origins of the apparent clustering of 'interesting' years therefore remain unclear.

* The hypothesis that there have been an unusually large number of 'extreme' events in recent years has not been supported, although this may reflect the conservative nature of the test used. There is a tendency for recent years to have experienced more high runoff seasons than previous periods, but the apparent tendency is very dependent on the period defined as 'recent'.

* The 1980s, however, have exhibited rather different average hydrological characteristics than earlier decades. They had higher average seasonal flows than the 1970s, which were themselves rather drier than the 1960s, and analysis of long records showed the 1980s to have the highest annual runoff in many catchments over a 100-year period. Average annual runoff in a large

number of catchments was statistically significantly higher in the 1980s than the 1970s (over most of the UK average annual runoff in the period 1979-1988 was over 20% higher than in the period 1969-1978). There is evidence that increased winter season rainfalls have compensated during summer for lower summer rainfalls. There is also some inconclusive evidence that the 1980s have shown increased year-to-year variability, particularly in summer, but the idea that this is part of a longer-term trend is not supported by the very long record sites.

5.2 IMPLICATIONS OF PATTERNS IN VARIABILITY

Three sets of implications can be drawn from these conclusions:

(i) Implications for hydrological analyses: the variability in time and the apparent clustering of high and low runoff years both imply that data from different time periods could give rather different indications of hydrological regimes and water resources. An assessment of water resources in the 1960s, for example, would have appeared over-optimistic during the 1970s. Short hydrological records can give very misleading impressions of long-term average behaviour (if it is appropriate to think of long-term averages under a climate which seems to show some 'wandering' characteristics), and differences in behaviour between catchments may simply be due to the different periods of record spanned. The adoption of a standard reference period for hydrological analysis would appear to be essential (see Gustard *et al.*, 1991).

(ii) Implications for the assessment of the occurrence of notable events in the future: the estimation of the probability of experiencing an extreme event in the future traditionally assumes that each year is independent. If there is a tendency for years with similar characteristics to cluster, the probability of experiencing several events over the next, say, 30 years will be underestimated. This is important for the estimation of risk and the evaluation of benefits, and will be particularly important for water resources schemes which are influenced by hydrological characteristics in several successive years.

(iii) Implications for future changes: it is not possible to conclude from the available data whether global warming is influencing flows in British rivers. Records are too short, and although river flows have been higher in the 1980s than in the 1970s, the 1960s too had higher flows than the 1970s: there is currently no reason to believe that the 1990s will continue to experience high flows. Nor indeed is there any reason to predict that the 1990s will be characterised by a return to lower flows. Records available are too short to identify conclusively periodic variations.

Although it is not possible to test whether global warming is yet affecting British rivers, attention in the next few chapters is turned towards the assessment of the sensitivities of British catchments to possible climate change.

6. Future changes in river flow regimes: introduction

6.1 THE CONTEXT

The threat of global warming due to an increase in greenhouse gases has received considerable scientific, public and political attention in recent years. The physics behind the process are relatively simple, and have been widely publicised (see Rowntree, 1990a, for a recent review). A series of 'greenhouse gases' - primarily water vapour and carbon dioxide CO_2 - allow incoming short-wave radiation from the sun to penetrate to the earth's surface, but a proportion of the outgoing long-wave radiation is blocked and heats up the lower atmosphere. These greenhouse gases mean that the earth's surface temperature is approximately 33°C higher than it would be without an atmosphere. However, since the mid-19th century increased industrial and agricultural activity has led to increases in the concentrations of such greenhouse gases as CO_2 and methane, and the addition to the atmosphere of new greenhouse gases, including chlorofluorocarbons (CFCs) and nitrous oxide.

Although the physics of the greenhouse effect are indisputable - notwithstanding the complex chemistry of the interactions between the various greenhouse gases - the consequences of increases in greenhouse gas concentrations are more controversial. There are great uncertainties in estimates of the rates at which such gases will continue to be emitted into the atmosphere (they depend on economic activity, energy efficiency and emission control policies), the rate at which plants and the oceans can absorb extra carbon dioxide, and finally the consequences of the increase in greenhouse gases on global and, particularly, regional climate. However, a consensus is evolving that increased greenhouse gas concentrations could lead to global average temperatures between 2 and 4°C higher than at present (Bolin *et al.*, 1986). The United Nations Intergovernmental Panel on Climatic Change (IPCC) forecast an increase in global mean temperature of 0.3°C per decade, leading to global temperatures 3°C higher by the year 2090.

One of the most significant impacts of a change in global climates will be on hydrological processes and, consequently, water resources. The second section of this report is therefore concerned with an investigation into the potential effects of a range of scenarios of possible climate change on river flow regimes in Britain. How sensitive are flow regimes in Britain to the types of changes in climate that are being projected? How does the nature of the catchment influence the impact of a given climatic change? How do potential changes compare with experience of variability in recent years?

Three basic approaches are adopted in this report, namely a regionalised approach based on empirical relationships developed across many sites in a region and the transfer of information from one region to another (Chapter 8), a catchment modelling approach applied at a range of representative catchments (Chapter 9), and a comparison of flow regimes in recent warm and cool periods (Chapter 10). Chapter 7 discusses in some detail methods for constructing climate change scenarios, and their drawbacks. First, however, it as necessary to consider some general points and qualifications which underpin all the studies.

6.2 SOME QUALIFICATIONS

The first important qualification to the chapters that follow is that they do not attempt to produce definitive predictions for changes in flow regimes in particular catchments. A 'generic' approach is followed, with the objective of defining the general directions of potential changes and the aspects of a catchment which influence the magnitude of such changes.

The major reason why it is not possible to make definitive predictions of changes in flow regimes in a particular catchment is that definitive forecasts of future climate are not yet available. The problems in estimating the climatic consequences of an uncertain increase in greenhouse gas concentrations were noted in the previous section. These uncertainties mean that it is unrealistic to rely on the forecasts from a single General Circulation Model (GCM) simulation of climate change, as some impact studies appear to have done. In this study, a range of climate change scenarios has been developed and applied. As the estimation of future greenhouse gas concentrations and the modelling of the climatic effects of these increases improves, the range of scenarios considered in a study can be reduced.

In common with the vast majority of impact studies, this study considers the effects of a changed climate once climate has reached a new, stable, equilibrium condition (and, indeed, assumes that there will be an equilibrium condition). This is important in order to provide an indication of the potential 'ultimate' situation, and the degree of impact expected: it is possible that the impacts would be shown to be very small and considerably less important than those resulting from, for example, land use or economic change. However, climate may undergo some very significant changes in the evolution to this new equilibrium, and the rate of change of climate is forecast to be far greater than at any other time in the past. The dynamic impact of a changing climate will be very different to the stable consequences of a changed climate, and this has important implications for policy responses. It is conceivable, for example, that a policy designed to cope with new equilibrium conditions could exacerbate problems in the period leading to the new equilibrium, or at least not represent an optimal strategy. In water management terms, the planning of a water resources system which is appropriate for the changed hydrological conditions of the mid-21st century must take into account the likely behaviour of the system during the period when climate is evolving. The change in hydrological response within 30 years will not necessarily be half the change expected in 60 years, and may not even qualitatively be the same. Unfortunately, the regional transient response to a continuing increase in greenhouse gases is currently very difficult to estimate, primarily because it depends on the thermal inertia of oceans and possible shifts in ocean circulation (Hansen *et al.* 1989). Such shifts could mean that some regions could experience a period of cooling before temperatures increase, or a period of increased storminess.

Changes in physical climate are not the only changes that may be experienced in a catchment over the next few decades. Land use has an influence on river flow regimes, and changes in vegetation cover, for example, can have significant effects on both annual yields and the distribution of flow over time (Gross *et al.*, 1989, give an example of the effects of changing forest cover on flow regimes). Catchment vegetation cover can be expected to change as climate evolves, but changes in land use and agricultural policy may possibly be as important in an intensively-exploited landscape such as Britain. These policy changes may be independent of climate, but could themselves be policy responses to changing climatic conditions, perhaps at the European scale. What, for example, would be the land use implication in Britain of EEC agricultural policies in response to increasing desertification in southern Europe, and what effects would they have on flow regimes? Demand for water from all sectors can also be expected to change over the next few decades, and again this change in demand may be climatically-influenced. It is important to remember that climatic inputs to catchments are not the only controls on flow regimes and water resources that may change in the future. Figure 6.1 summarises the interactions between the various influences on water resource availability. The relative importance of each influence will vary between different catchments.

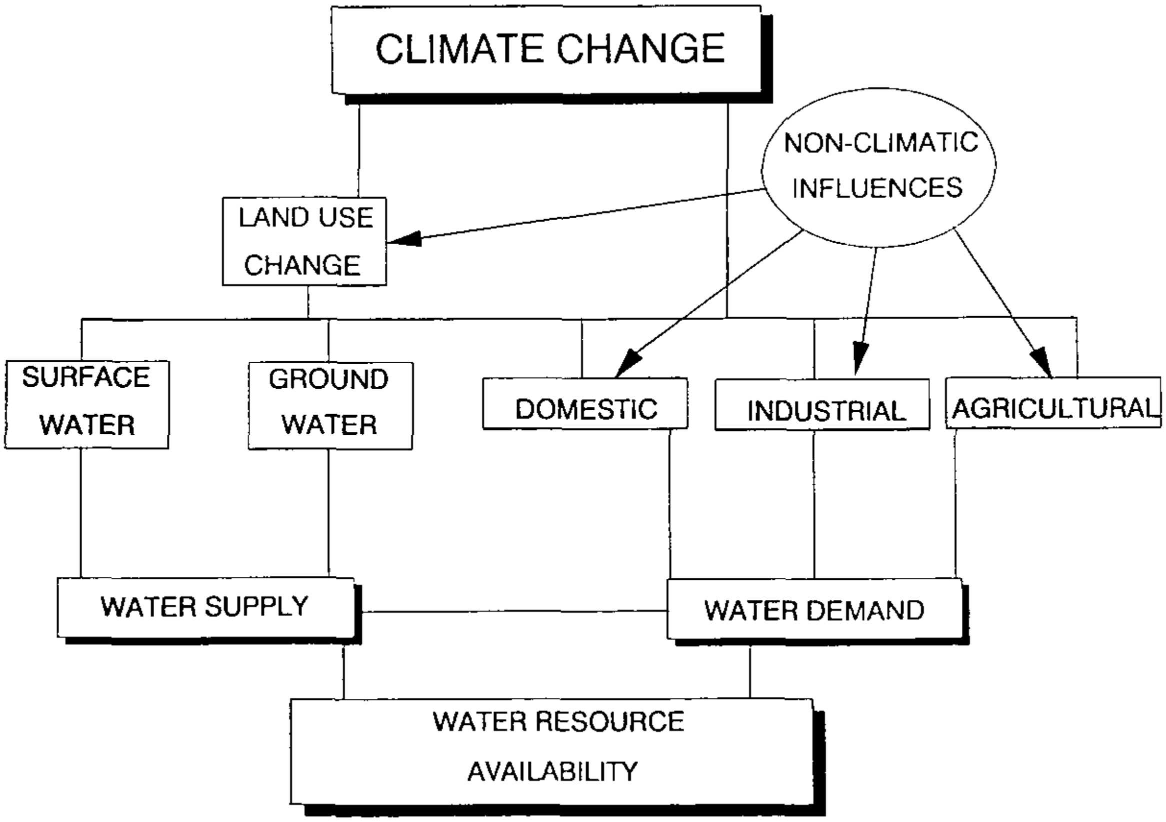


Figure 6.1 The interrelationships between factors influencing water resource availability, and the effect of climate change

6.3 IMPLICATIONS FOR HYDROLOGICAL PROCESSES AND WATER RESOURCES

Global warming resulting from increased concentrations of greenhouse gases would have both direct and indirect effects on hydrological processes, which in turn feed back into influences on climate at local and regional scales.

Changes in the magnitude, intensity, duration and frequency of rainfall events will have the most obvious effects on hydrological response, and indeed the estimated effects of climate change depend largely on the assumed changes in rainfall characteristics. Changes in rainfall characteristics will depend not only on changes in the vigour of weather patterns which currently impinge upon a region, but also on changes in prevailing weather patterns.

Snowfall frequencies would also be affected by changes in the frequency of different circulation patterns as well as by generally higher temperatures. In many regions - though not the UK - winter snowfall provides the bulk of water resources, and a reduction in the amount of snow stored would have very significant effects on summer supplies (Gleick, 1987, for example). At the much larger scale, the earlier removal of snow cover in a warmer world has been shown to lead to increased spring evaporation and higher summer soil moisture deficits (Manabe *et al.,* 1981).

Changing temperature, humidity, windspeed and cloudiness will all affect evaporative demand, to varying degrees (Martin *et al.,* 1989). In general, sensitivity to changes in the parameters controlling evaporation is dependent on the initial values of those parameters. Although evaporation changes are hard to define, due to the large number of possible combinations of changes in controls on evaporation, transpiration changes at the catchment scale are still harder to estimate. Experimental evidence shows that some important groups of plants undergo significant physiological changes in a CO_2-enriched atmosphere, and higher stomatal conductance reduces evapotranspiration rates by up to one third (Idso and Brazel, 1984). However, studies also show that plant growth becomes more luxuriant, and an increase in leaf area may compensate for a reduction in the conductance of individual stomata. Gifford (1988) concluded from experimental studies that plants maintained some form of balance between stomatal resistance and leaf area in order to maintain a particular water usage, and from this inferred that changes in regional evapotranspiration due to plant physiological changes were insignificant. More important at the catchment scale, however, are possible climate or policy-induced changes in catchment vegetation cover. What effects, for example, would drier summers have on ground vegetation cover and hence interception in summer storms? Changes in evaporation can also feed back to produce changes in rainfall patterns.

The infiltration of rainfall and snowmelt into soil is dependent not just on rainfall and vegetation characteristics, but also on soil structure properties. These too may change - perhaps slowly - with a changing climate and vegetation cover. Increased temperatures might encourage summer cracking, for example, whilst longer periods of water-logging in winter could lead to increased gleying.

Finally, the processes by which stream runoff is generated may be altered by climate change. Soil structure, for example, has an important influence on the rate at which storm rainfall reaches channels, and changes in soil structure would therefore alter hydrograph shape. If, for example, storm rainfall were to be directed to river channels more rapidly, less water would be available for maintaining flows during dry periods.

Climate changes, and the effects of climate change, might therefore influence all aspects of the hydrological cycle, although some potential impacts are more likely and more significant than others. Studies into the hydrological effects of climate change have tended to fall into two groups, with one group representing studies of detailed process changes at the micro or plot scale (studies into leaf and stand transpiration changes, for example), and the other making more generalised assessments of changes in flow regimes and water resources using simpler, usually conceptual or empirical, models. The complexity of hydrological processes at the catchment scale and the multi-dimensional impacts of climate change mean that it is very difficult to pass from detailed process studies to catchment scale impact studies.

All aspects of water resource management will in principle be affected by climate change, but the sensitivity of a particular management system to change will depend on many factors, including the degree of change expected, the pressure under which the resource system is operated, and the potential for adaptation. Although there have been many studies of the hydrological impacts of climate change, there have been few studies of the impacts of these changes on the reliability and operation of water resources. Callaway and Currie (1985) and Gleick (1989) both described the general sensitivities of various water management activities to change, and Gleick (1990) has produced maps showing the vulnerability of different parts of the United States to potential changes in, for example, the volume of water available for supply and for hydropower generation. Riebsame (1988) describes the potential impact of climate change on the management of the Sacremento River basin in California. In Britain, Beran and Arnell (1989) undertook a desk study for the Department of the Environment, itemising the areas of water management which may be affected and estimating sensitivities to change. Table 6.1 (Arnell, 1989b) lists several water management activities in Britain, and gives an initial assessment of their sensitivity to several dimensions of climate change. These sensitivities will need to be revised as further studies are completed. An indication of the sensitivity of different regions in Britain to changes in water resource is given in Table 6.2, which shows the volume of water supplied in 1987 as a proportion of average annual river runoff in each (old) Water Authority area (note that much water is used several times). Local and short-term resource pressures, such as high seasonal demand, are obscured by the averages in the table. Water resources in the Thames region are currently very heavily utilised, and changes in flow regimes could, when coupled with changes in demand, have very significant impacts on resource availability.

This report concentrates on estimating the sensitivities of flow regimes in different types of catchments to changes in climate. Water resource sensitivities as such are not explicitly considered, although some of the hydrological indices used are commonly employed in water resources evaluations. Estimation of explicit water resource impacts - such as the frequency of demand restrictions - requires a site-specific approach, which was not considered to be appropriate within the objectives of the current study. Changes in groundwater are not considered. Chapter 11 does, however, attempt to draw some implications for water resources from the hydrological sensitivities.

Table 6.1 An initial assessment of the sensitivities of water management issues in the UK to climatic change (Arnell, 1989b)

Water management activity	DIMENSION OF CLIMATE CHANGE				
	'HYDROLOGICAL'				
	Total runoff	Seasonal distribution	Extreme behaviour	Increased temperatures	Higher sea level
Surface water supplies ('small storage')	*	**	**	**	-
Surface water supplies ('large storage')	**	*	**	*	-
Groundwater supplies	**	**	**	*	*
Agricultural water use	**	**	**	**	-
Flood management	-	*	**	-	**
Urban stormwater drainage	-	-	**	-	*
Reservoir safety	-		**	-	-
Drainage of low-lying lands	**	**	**	-	**
Power generation	**	**	*	-	-
Water quality	*	**	**	**	-
Effluent dilution	*	**	**	*	-
Inland navigation	*	**	-	-	-
Fisheries	-	**	*	**	-
Recreation	-	*	-	*	-
Saline intrusion into estuaries	*	*	-	-	**
Aquatic ecosystem management	-	**	**	**	-

- little sensitivity
* some sensitivity
** very sensitive

Table 6.2 Volume of supply, 1987, as a percentage of long-term average annual runoff

Water Authority Region	Supply as % of runoff
North West	12
Northumbrian	9
Severn-Trent	14
Yorkshire	13
Anglian	18
Thames	55
Southern	14
Wessex	9
South West	3
Wales	5

Sources: Supply data from Water Facts'88 (Water Authorities Association, 1989)
Average annual runoff from the Surface Water Archive.
Note that a proportion of water is used several times.

7. Climate change scenarios

7.1 SCENARIOS FOR CLIMATE CHANGE STUDIES

Despite the best efforts of climate modellers and economic forecasters, it is not yet possible to determine with any accuracy the climate of the mid-21st century. There are large uncertainties not only in the modelling of the effects of a given change in greenhouse gas concentrations, but also in estimates of the rate at which these gases will be both emitted by human activities and absorbed by oceans and plants.

Studies of the impact of future changes in climate cannot therefore use definitive climate forecasts, and must be based on climate change scenarios. A climate change scenario is an internally-consistent description of a climate which may feasibly exist in the future following, for example, an effective doubling of atmospheric CO_2 (an 'effective doubling of CO_2' refers to the combined effect of all the greenhouse gases). The current inability to forecast accurately the climate fifty or hundred years in the future means that several alternative scenarios may be considered to be equally feasible, and these scenarios may be rather different. The range of scenarios derived gives an indication of the 'reliability' of any one estimate of changes in, for example, water resource availability, but the differing response of a system to different scenarios also gives insights into the general sensitivity of a system to change: it is as important to know that different scenarios give very different results as it is to estimate the potential consequences of one particular scenario, however 'realistic' that scenario is deemed to be.

This chapter outlines how scenarios can be developed, paying particular attention to the derivation of scenarios appropriate for hydrological studies. A range of scenarios for changes in monthly precipitation and potential evapotranspiration by a notional date in the middle of the next century is defined. No attempts are made to define scenarios to describe the evolution of climate over the next few decades, and the scenarios are intended to represent 'equilibrium conditions'. A large part of the chapter is based on work undertaken at the Climatic Research Unit (CRU) of the University of East Anglia under contract to the Institute of Hydrology (Hulme and Jones, 1989).

7.2 THE DEVELOPMENT OF CLIMATE CHANGE SCENARIOS

Several techniques have been employed to define regional climate change scenarios in many parts of the world. Different techniques work at different spatial and temporal scales, and some methods can provide only qualitative information about the directions of possible change. An ideal scenario for hydrological purposes would give information on changes in both the mean and variability of precipitation and potential evapotranspiration at short time scales - for example daily - at the catchment scale, and would give some indication of how such changes might themselves vary across a region. Unfortunately, such scenarios are currently very difficult to construct with any degree of realism. Hulme and Jones (1989) identify six basic groups of methods for deriving scenarios, supplemented by a seventh 'combination' group. These are described below.

7.2.1 Scenarios from climate models

Numerical models of climate have become the most popular basis for the construction of quantitative climate change scenarios. Simple zero-dimensional or one-dimensional models have been used to estimate global average changes (Lamb, 1987), but only General Circulation Models (GCMs) have the spatial and temporal resolution to construct regional scenarios. The effects of a change in atmospheric CO_2 concentration are calculated by comparing a simulation of the current climate with a simulation run with changed atmospheric composition (a 'perturbed' climate). There are, however, some significant limitations to the use of GCMs for scenario construction.

GCMs have proved to be very good at simulating global climates and different GCMs tend to produce similar estimates of global average changes. However, GCMs are much less good (and less consistent) at modelling regional climates and hence estimating the regional consequences of change, even when the region is as large as Europe. The modelling of regional temperature is most accurate and consistent (although consistency does not necessarily guarantee accuracy: each model treats oceans in a similar, but over-simplified, way, for example: Rowntree, 1990a), but precipitation is very poorly simulated (Schlesinger and Mitchell, 1987). There are several reasons why GCMs are relatively poor at simulating current regional climates, let alone possible future changes, although it must be remembered that current GCMs are not designed to estimate regional climate. Most important are the spatial resolution, the representation of topography, the representation of cloud processes, the simulation of land-atmosphere interactions and the treatment of the interactions between the atmosphere and the oceans (see Rowntree, 1990a for a review of GCMs). These factors influence both the simulation of large-scale processes - the generation and location of significant circulation features such as the Azores High, for example - and the translation of these large-scale features into local or regional climate.

The spatial resolution of current GCMs is currently very coarse, and the grid points at which model calculations are made are typically over 400 km apart. There can be very considerable variability within a 400 x 400 km region, and sub-grid scale topographic features may affect significantly climatic patterns over a much larger area. The representation of the coastline and topography of western Europe, for example, is very over-simplified in GCMs used for climate modelling, and both these features determine European climates. GCMs can be expected to perform least satisfactorily in maritime areas with significant sub-grid variation in topography, such as western Europe. The other major controls on GCM performance - the representation of clouds and the treatment of atmosphere-ocean and land-atmosphere interactions - have greater significance for the modelling of large-scale features, although modelled climates of coastal areas are of course influenced by the modelled interchanges of energy and moisture between ocean and atmosphere.

The results of GCM simulations have been compared with observed data at a variety of spatial and temporal scales. Schlesinger and Mitchell (1987) present global comparisons of seasonal temperature and precipitation, for example, and Santer (1988) describes attempts to compare GCM-simulated and observed pressure patterns in the northern hemisphere. At a much smaller timescale, Reed (1986) showed how poorly a GCM simulated daily temperatures and rainfalls at several sites in western Europe, and Rind *et al.* (1989) also compared observed and modelled interannual variabilities in temperature and precipitation. Table 7.1 is taken from Hulme and Jones (1989), and shows the differences in modelled seasonal precipitation totals between three GCMs for 'Britain'.

Table 7.1 A comparison of observed England rainfall with estimates from three GCMs (Hulme and Jones, 1989)

	Dec-Feb		June-Aug	
Observed	2.7	mm/day	2.4	mm/day
General Circulation Model estimates				
UKMO	1.2	mm/day	3.0	mm/day
NCAR	3.5-4.5	mm/day	<2.0	mm/day
GISS	3.5-4.0	mm/day	2.0-2..5	mm/day

UKMO, NCAR and GISS are three General Circulation Models: more details are provided in Hulme and Jones (1989)

GCM-based change scenarios are most frequently expressed as changes in monthly or, most frequently, seasonal mean temperature, precipitation and soil moisture content. Rind *et al.* (1989) have published some initial estimates of changes in interannual variability, but did not construct scenarios for use in impact assessment.

In summary, GCMs provide an initially appealing source for the derivation of regional climate change scenarios: they appear to be able to provide quantitative information on a range of climatic variables at different spatial and temporal scales. However, at present GCMs do not simulate current short time-scale regional climates sufficiently accurately for their indications of short time-scale regional changes to be taken too literally, and it is difficult to define scenarios for changes in year-to-year variability. GCMs do nevertheless provide a basis for the construction of scenarios showing changes in the mean at longer time-scales, such as the month or season, and in practice underpin most attempts at scenario construction. As GCMs improve, it will be easier to derive climate change scenarios directly from them.

7.2.2 Scenarios from past instrumental data

Another way of estimating the effects of climate change is to compare the climate of warm and cool periods in the instrumental record. The method assumes that the causes of warming would not influence how that warming manifested itself both across space and through time, and that the local climate system had had time to respond to the changed climatic circumstances (Hulme and Jones, 1989). Further uncertainties arise over the selection of the temperature data to use - global, hemispherical or regional - and the absolute difference in temperature between the warm and cool periods may be a lot smaller than that which might occur as a result of the doubling of CO_2 concentration. Nevertheless, the use of past instrumental records shows how climate has differed in the past between cool and warm periods, and can provide good spatial detail. Lough *et al.* (1983), for example, compared precipitation and temperature in northern Europe during the warmest and coolest periods this century as defined by the Northern Hemisphere annual mean surface air temperatures. Maps were produced showing differences between the cool period 1901-1920 and the warm period 1934-1953. Hulme and Jones (1989), however, found some differences in estimated change in British precipitation using the warm period 1968-1987.

Instrumental analogues can be used to define changes in climatic variables, and these changes can be combined with a hydrological model to estimate the associated hydrological changes. It is also possible in principle to compare observed hydrological data from the warm and cool periods, and hence estimate changes directly. However, hydrological records tend to be shorter than climatological records, and the opportunity for finding sufficiently different warm and cool periods is more limited.

7.2.3 Palaeoclimatic analogues

One of the main problems with the construction of change scenarios from instrumental records is the short period of data available: records only rarely extend as far back as the early 19th century. Much earlier climates have been deduced from palynological and sedimentary evidence, and such 'palaeoclimatic reconstructions' have been proposed as analogues for future warmer climates (Kellogg and Schware, 1981). The post-glacial climatic optimum (or Hypsithermal) at around 6000 to 9000 BP (Before Present) was possibly up to 2°C warmer than present, for example (Lamb, 1987). Budyko (1989) presents maps showing changes in Northern Hemisphere precipitation between current conditions, the Holocene climatic optimum and the Pliocene. This last period occurred between 3 and 4 million years ago, and is assumed to represent a world 4°C warmer than present.

There are, again, major problems with the use of palaeoclimatic analogues. It must be assumed that the causes for the change in temperature do not influence how the change takes place, and that differences in boundary conditions (such as the amount of incoming radiation, day length and the presence of ice sheets) are unimportant (Lamb, 1987). Palaeoclimatic reconstructions tend to be very generalised and cover very large areas - although site-specific reconstructions could be developed in some cases - and are strongly reliant on data quality and availability. Information tends to be qualitative rather than quantitative, although Budyko (1989) does present results in terms of quantitative changes in precipitation. No climate change scenarios based on palaeoclimatic reconstructions have yet been prepared specifically for Britain.

7.2.4 Scenarios based on physical or statistical reasoning

General Circulation Models are physically-based models of the global climate system, and as such produce estimates of climate and climate changes that have some theoretical foundation and internal consistency. However, more realistic indications of regional changes may be obtained through 'thought experiments' by climatologists using understanding of the physical controls on local climate and their relation to larger-scale phenomena. Pittock and Salinger (1982) suggest that in Australia, for example, a warmer world would show a more intense summer monsoon and higher sea surface temperatures would lead to an increased penetration of tropical cyclones. Physically-based arguments could be developed to indicate the possible changes in the frequency of occurrence of summer anticyclones in Britain, for example, or the frequency of blocking anticyclones. At present such scenarios would probably be more qualitative than quantitative, and none have been developed for Britain. Hulme and Jones (1989) suggest, however, that they will become more widely used in the future.

Statistical methods have been proposed to improve the spatial and temporal resolution of GCM simulations. These methods rely on the development of relationships between large-scale phenomena and local behaviour. Kim *et al.* (1984), for example, estimated site monthly temperature and precipitation in Oregon by constructing regression relationships between historical site values and regional averages, and the procedure was developed further by Wigley *et al.* (1990): the method can be used to estimate the sub-grid impact of a given regional change. It is, of course, assumed that the GCM estimate of regional climate is accurate, and if this is not the case the estimated sub-grid patterns will not be very meaningful. However, the approach is one way of combining explicitly GCM predictions with understanding of local and regional climate.

7.2.5 Spatial analogues

An alternative method of deriving a scenario is to assume that the future climate of place X will be like the current climate of place Y. This assumption could be based on results from a GCM or from physical reasoning, and spatial analogues are frequently used to indicate the types of changes that may be expected in Britain. Many newspaper articles, for example, have reported that the climate of Britain will become more 'Mediterranean' and hence similar to that of southern or southwestern France.

Such statements give a useful indication of the possible future climate in an easily understandable form, but spatial analogues may be difficult to apply in a more quantitative way. Climate is a result of the combination of large-scale features with local orography and land-ocean interactions, and these local features are obviously not transportable (Hulme and Jones, 1989). Spatial scenarios can be expected to work best where large-scale controls on climate are dominant, which is unfortunately not the case in western Europe. Differences in length of day, and hence patterns of vegetation growth, may also limit the transfer of information between regions. However, spatial analogues may give some indications about the consequences of change, and as is the case with instrumental scenarios, non-climatic information may be transferred from the analogue region. Parry *et al.* (1989), for example, describe instances where agricultural information is transferred from one analogue region to another. The use of spatial analogues for the transfer of hydrological information is discussed briefly in Chapter 8.

7.2.6 Arbitrary change

One response to the problem of constructing physically-based climate change scenarios is to employ arbitrary change scenarios. Such scenarios comprise arbitrary changes of, for example, plus or minus 20 per cent in rainfall or plus 2 and 4°C in temperature. They are widely used (see Nemec and Schaake, 1972, for example) because they are of course easy to define, but some particular combinations of arbitrary changes in precipitation and temperature may be most unlikely.

7.2.7 Combination or 'committee' scenarios

It is of course possible to construct climate change scenarios using a combination of the methods outlined above. The scenario used in the CSIRO-funded Australian study, for example (Pearman, 1988) was a combination of the results from GCM experiments, instrumental analogues, palaeoclimatic analogues and physical reasoning.

7.3 CLIMATE CHANGE SCENARIOS FOR BRITAIN

7.3.1 Methods employed

The ideal characteristics of a climate change scenario for hydrological studies were mentioned at the beginning of Section 7.2. It is clear from the rest of the section, however, that these requirements are currently very difficult to meet. This section describes the construction of a series of scenarios, based on background work undertaken by the Climatic Research Unit (Hulme and Jones, 1989). This background work concentrated on predictions from several GCMs and on the use of instrumental analogues.

The scenarios are assumed to reflect average conditions from the middle of the next century. Rowntree (1990b) has suggested that global temperatures will be around 2.5 to 3.8°C higher than late nineteenth-century values by the year 2050 (and 2 to 2.9°C warmer than 1990), with a commitment for a similar extra increase as the oceans slowly respond to the changing conditions. Local or regional temperature changes may, of course, be rather different from the global average. The scenarios show changes in mean monthly potential evapotranspiration and precipitation. Changes in daily precipitation were not considered because short time-scale scenarios are currently difficult to define (as shown above), and it is believed that the estimated effects of changes in daily precipitation would depend strongly on how those changes take place. Would extra precipitation, for example, fall as heavier daily rainfalls or in additional rain days? It has been assumed that the relative variability around the mean from year to year is unchanged.

7.3.2 Potential evapotranspiration

Potential evapotranspiration is driven by net radiation and controlled by humidity, windspeed and plant characteristics. The humidity deficit of air is a function of air temperature. All these factors may change as greenhouse gas concentrations increase. Net radiation is on average reduced by cloudiness, for example, and a reduction in snow cover would allow earlier and increased absorption into the soil (Rowntree, 1990b: this is unlikely to be particularly important in Britain). Humidity may change as temperatures rise and the amount of water held in the atmosphere increases, but local values will also be influenced by changes in the frequency of occurrence of different air masses. Windspeeds too could change, but to an unknown extent (Rowntree, 1990b). Plant characteristics, such as stomatal conductance and leaf area also influence evapotranspiration rates, and have been shown in experimental studies to change in a CO_2-rich atmosphere. Stomatal conductances tend to reduce, thus reducing evapotranspiration, but leaf area may increase to compensate. The effects of physiological alterations are still uncertain, and even greater uncertainties apply at the catchment scale: not only may plant physiological properties change, but the composition of vegetation types in a catchment will evolve in response both to an altered climate and to agricultural and land-use policy developments (which may themselves be related to a change in climate, perhaps at the European scale).

Several studies (Martin *et al.,* 1989, Kuchment *et al.,* 1989 and Bultot and Gellens, 1989, for example) have examined the sensitivity of potential evapotranspiration to changes in temperature, net radiation, humidity, windspeed and plant characteristics. Sensitivity has repeatedly been shown to be high and dependent on initial values of these parameters, and hence varies considerably between sites and through the year. The changes in these controlling parameters associated with climate change are currently very difficult to assess (with the exception of temperature). These uncertainties and high sensitivities make it inappropriate at present to attempt to derive scenarios for changes in potential evapotranspiration from first principles.

Most water resources impact studies have developed potential evapotranspiration scenarios by defining a temperature change and using a simple relationship estimating potential evapotranspiration from temperature alone. Gleick (1986) and Cohen (1986) both used the Thornthwaite formula, for example, and Berndtsson *et al.* (1989) used the Blaney-Criddle formula. Nemec and

Schaake (1982) used Budyko's conclusion that potential evapotranspiration increases by 4% for every degree rise in temperature. None of these reports provide the actual numbers used. Bultot *et al.* (1988), however, give monthly changes for their three study catchments in Belgium. They based their scenario on assumed changes in some of the controls on evapotranspiration.

Three scenarios for changes in monthly potential evapotranspiration in Britain are given in Table 7.2, and are denoted by EVP1, EVP2 and EVP3. The scenarios are not calculated from 'first principles' because of the difficulties of assuming changes in input variables and the high sensitivities to some of these inputs, and are not based on simple relationships between temperature and evapotranspiration because it was found that the type of relationship controlled the results. For comparative purposes, Table 7.2 also shows the estimated changes in potential evapotranspiration for a site typical of south east England using the Penman, Thornthwaite and Blaney-Criddle formulas with a temperature increase of 4°C.

Table 7.2 Percentage change in potential evapotranspiration

month	EVP1	EVP2	EVP3	Penman	Thornthwaite	Blaney-Criddle
J	40	20	50	23	50	61
F	40	20	40	17	45	60
M	30	15	30	15	26	52
A	25	12	20	13	18	44
M	15	7	15	11	15	37
J	8	4	7	9	15	32
J	8	4	6	9	16	30
A	10	5	10	9	16	31
S	12	6	20	10	15	33
O	20	10	25	13	15	38
N	35	17	40	18	22	49
D	40	20	50	21	37	57

The table shows the percentage increase on current monthly potential evapotranspiration.

Scenario EVP0 assumes no change in potential evapotranspiration.

The Penman, Thornthwaite and Blaney-Criddle values are based on data from a site typical of south east England subject to a rise in temperature of 4°C. Net radiation, windspeed and relative humidity are assumed constant when the Penman formula is applied.

Although the numbers used in the scenarios are not derived directly from evapotranspiration equations, the assumed variation through the year - with the highest relative changes in winter - is based on them. The annual increase in potential evapotranspiration with each scenario varies with its distribution through the year, but is between around 15% for EVP1 (60 to 80mm over the year), 7% for EVP2 (30 to 40mm annually) and 15% for EVP3. No scenario showing a reduction in potential evapotranspiration was developed because of the considerable uncertainties over the effect at the catchment scale of changes in plant physiology, although scenario EVP0 assumes no change.

It is also clear from Table 7.2 that the inferred sensitivity of potential evapotranspiration to changes in temperature is strongly dependent on the equation employed: the Blaney-Criddle formula, for example, indicates much higher sensitivities to temperature.

The scenarios used in the current study imply a smaller change in potential evapotranspiration than suggested by Rowntree (1990b), who made a rough estimate of 50mm extra over the six-month summer season per degree celsius increase in temperature.

Annual rainfall currently exceeds potential evapotranspiration across the whole of Britain. The difference is small in south east England, however, and if potential evapotranspiration were to increase, it is possible that the annual water balance would tip into deficit. Figure 7.1 shows future rainfall, as a percentage of current rainfall, necessary to maintain an excess of annual rainfall over annual potential evapotranspiration, if evapotranspiration increased according to scenario EVP1. In the more humid western regions, annual rainfall would still exceed annual potential evapotranspiration even if rainfall fell to 50% of the current average, but in much of eastern England a 10% reduction in rainfall would lead to a net annual surplus of potential evapotranspiration. In parts of Essex and the Fens, rainfall would need to increase by over 10% in order to maintain a positive water balance.

7.3.3 Precipitation

Estimates of the possible changes in monthly precipitation in a warmer world made with the aid of either GCMs or instrumental scenarios are extremely uncertain. The five GCMs compared by Hulme and Jones (1989) for Britain, for example, produce very different estimates of changes in precipitation, with some suggesting drier summers and the rest wetter summers. A comparison of warm and cool periods in the instrumental record (as described in Section 7.2.2) implies that winter and annual total precipitation is less in Britain during warm periods, the opposite conclusion to that drawn from the GCMs. Hulme and Jones (1989) considered the implications of the GCM and instrumental record results, and concluded that annual precipitation could increase by between 20 and 200mm, but that the seasonal distribution of this change was unclear. The strongest signal was for drier summers and wetter autumns, and there were indications from the GCMs that the north and west would show a relatively greater increase in precipitation than the south and east. Rowntree (1990b) has suggested - tentatively - an increase in annual precipitation of 5 to 15%, with the bulk of the increase concentrated in winter.

Given this high degree of uncertainty, a wide range of scenarios for precipitation change was constructed for the current study. The scenarios are shown in Table 7.3, and fall into two groups:

(i) Scenarios PA1 to PA5 represent relatively straightforward percentage changes in monthly precipitation. Scenario PA1 assumes a 20% increase in

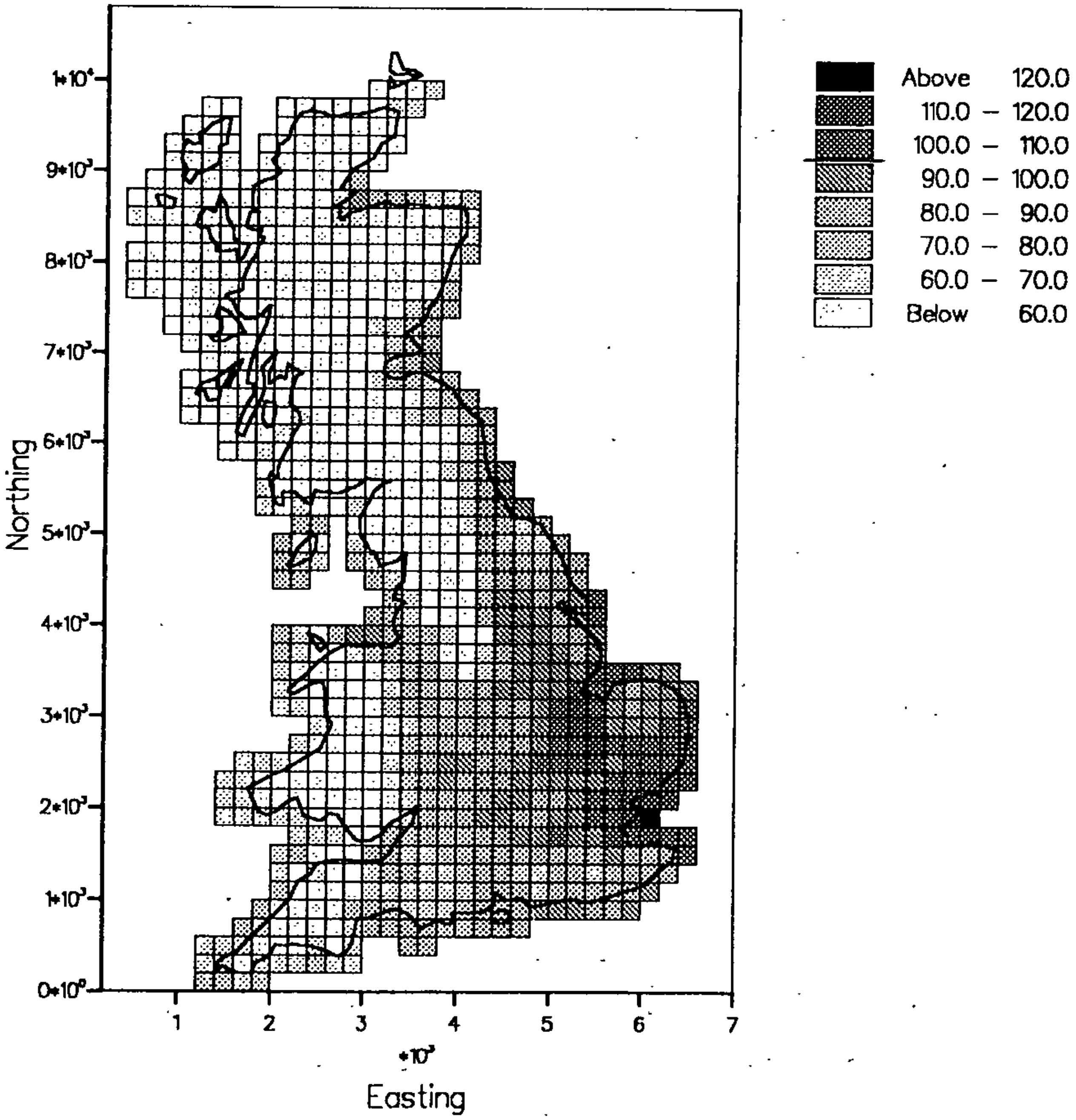


Figure 7.1 *Future rainfall, as a percentage of current rainfall, which would be required to maintain an excess of annual rainfall over annual evapotranspiration, if evapotranspiration were to increase according to scenario EVP1 (i.e. by around 15%)*

each month, whilst PA2 assumes that summers become drier. The annual increase with scenario PA2 varies with the seasonal distribution of precipitation, but lies between 10 and 12%. Scenarios PA3 and PA4 are basically scaled-down versions of PA1 and PA2: scenario PA4 gives an annual increase of between 5 and 6%. PA5 assumes a 10% reduction in rainfall in each month. Most precipitation change scenarios used in climate change impact studies are of this form.

Table 7.3 Scenarios for change in precipitation

	Percentage change					Percentage of increase in average annual rainfall that applies in each month		
	PA1	PA2	PA3	PA4	PA5	PB1/4	PB2/5	PB3/6
J	20	20	10	10	-10	8.33	16	22
F	20	20	10	10	-10	8.33	12	19
M	20	20	10	10	-10	8.33	10	15
A	20	20	10	10	-10	8.33	8	10
M	20	10	10	5	-10	8.33	7	5
J	20	-10	10	-5	-10	8.33	4	-6
J	20	-15	10	-7	-10	8.33	3	-8
A	20	-10	10	-5	-10	8.33	3	-6
S	20	10	10	5	-10	8.33	7	5
O	20	20	10	10	-10	8.33	8	10
N	20	20	10	10	-10	8.33	10	15
D	20	20	10	10	-10	8.33	12	19

The figures for scenarios PA1 to PA5 show the percentage change to be applied in each month. The figures for scenarios PB1 to PB3 and PB4 to PB6 show the percentage of the increase in the average annual rainfall (10% for PB1 to PB3 and 20% for PB4 to PB6) which applies in each month. This value - in millimetres - is subsequently expressed as a percentage of the average rainfall for each month, and these percentages are applied to the individual monthly rainfalls. These final percentages depend of course on the seasonal distribution of rainfall, so are site-specific.

(ii) Scenarios PB1 to PB3 are all based on the assumption that total annual rainfall increases by 10%, but the distribution of that increase through the year varies. Scenarios PB4 to PB6 assume total annual rainfall increases by 20%. These scenarios were primarily designed to assess the sensitivity of estimates of change in annual runoff to the seasonal distribution of change.

Changes in snowfall are omitted because, as outlined in Chapter 9, the models used did not account for precipitation falling as snow. It is appropriate to note, however, that snowfall in Britain, particularly in the south, could show a marked decline in frequency (Rowntree, 1990b).

All the assumed changes in mean seasonal rainfall are within the current range of variation of 5-year means (5-year average winter rainfall in southern England may vary by plus or minus 30% of the long-term mean, for example), but the larger changes are at the extremes of current variation in 10-year means. The scenarios represent considerable - indeed unprecedented - changes in *long-term* average conditions.

It is important to note that under the scenarios assuming a 10% increase in annual rainfall (or less), some parts of eastern England would move into a net annual water deficit if potential evapotranspiration were to increase according to Scenario EVP1 (see Figure 7.1).

7.4 SUMMARY AND CONCLUSIONS

It is currently too early to estimate the climate of the mid-21st century with any accuracy, and climate change impact studies must use a scenario-based approach. This chapter has summarised how climate change scenarios can be derived, emphasising the difficulties in defining scenarios at the temporal and spatial scale most ideal for hydrological studies.

A series of scenarios for changes in monthly potential evapotranspiration and precipitation have been constructed, based largely on the Hulme and Jones' (1989) interpretation of the predictions of several GCMs and comparison of warm and cool periods. No one scenario is to be regarded as more 'realistic' than any other, although each are feasible, and the object of the exercise is to evaluate the sensitivity of water resource characteristics in Britain to different scenarios rather than to produce one 'prediction'.

It has been shown that although feasible temperature changes are relatively simple to define, potential evapotranspiration changes are very sensitive to both the form of equation used to estimate potential evapotranspiration and the assumed changes in other controlling parameters. Implied sensitivities of water resources systems to temperature change are therefore strongly dependent on the model used to link temperature and evapotranspiration.

8. Estimating the effects of climate change using simple empirical methods

8.1 INTRODUCTION AND OBJECTIVES

Most studies of the effects of climate change on water resources adopt a case study approach, and apply locally-calibrated hydrological models to estimate flow characteristics at the site of interest under current and changed conditions. This chapter, however, considers a range of generalised approaches to estimating impacts, based on the analysis of regional hydrological data. Generalised ('empirical') approaches do not require the local calibration of a model, and can provide very quick estimates of sensitivities to change in many catchments. Unlike site-specific methods, procedures based on the analysis of regional data can be readily applied to evaluate the spatial implications of change.

This chapter considers both the sensitivity of average annual runoff across Britain to climatic change and the potential effects of change on flow regimes, concentrating in particular on the flow duration curve. Most attention is paid to the use of simple empirical models based on regional data, but the transfer of information from one region to another - the 'spatial analogue' approach - is also considered. The importance of model form is highlighted.

Chapter 9 presents results from the application of rainfall-runoff models to estimate changes and sensitivities in selected catchments, and contains a comparison of the 'generalised' and 'modelling' approaches.

8.2 A REVIEW OF OTHER STUDIES

A few studies have used simple relationships between average annual runoff, rainfall and evapotranspiration or temperature to determine the possible effects of changes in input on runoff.

Beard and Maristany (1979), for example, constructed regression models to estimate average annual runoff from average annual precipitation. They divided the United States into 100 districts, and calculated runoff and precipitation for each district. Their 'national' regression model, converted to metric units, is:

$$R = 0.000071\ P^{2.2} \qquad R^2 = 0.792 \qquad \ldots . (8.1)$$

where P and R are average annual rainfall and runoff respectively, both in millimetres. The model implies the following sensitivity of average annual runoff to changes in average rainfall:

$$\frac{R_1}{R_0} = \left[\frac{P_1}{P_0}\right]^{2.2} \qquad \ldots . (8.2)$$

where the subscripts 0 and 1 refer to current and future conditions respectively. A 10% increase in average annual rainfall would increase average annual runoff by 23%.

Revelle and Waggoner (1983) went a stage further and attempted to incorporate the effect of evaporative losses. They used the empirical relationships between average annual runoff, precipitation and temperature developed by Langbein (1949) - from only 22 basins spread across the United States - to show that the sensitivity to change varied considerably over space. An increase in average annual temperature of 2°C coupled with a reduction in annual precipitation of 10% would have a much less significant effect in the humid north-east US than in the arid south west. Revelle and Waggoner's (1983) use of Langbein's relationships, however, has attracted two criticisms.

First, Idso and Brazel (1984) noted that the relationship between temperature and evapotranspiration implied in the model did not allow for changes in evapotranspiration with increasing CO_2 concentrations. They showed that reductions in annual evapotranspiration due to changed stomatal conductance could outweigh the effects of increased temperature or even reduced precipitation, and concluded that increases in average annual runoff were just as feasible, given the current state of knowledge, as the decreases Revelle and Waggoner (1983) had described. Secondly, and more recently, Karl and Riebsame (1989) have noted that the use of temperature as a surrogate for evapotranspiration assumes that there is an association between temperature and the other factors controlling evapotranspiration, namely humidity, net radiation and windspeed. The slopes of the relationships between temperature, precipitation and runoff in Langbein's graph reflect these associations across space, but the associations may be very different at one place over time. Karl and Riebsame (1989) concluded that the use of Langbein's relationships overestimates the sensitivity of average annual runoff to changes in temperature.

A rather different generalised approach to estimating the sensitivity of average annual runoff to change was developed by Wigley and Jones (1985). They showed that if average annual runoff was calculated from rainfall less evaporation

$$R = P - E \qquad \ldots . (8.3)$$

where E is average annual actual evaporation, and that the runoff coefficient g_o was calculated as

$$g_o = R_o / P_o \qquad \ldots . (8.4)$$

then the sensitivity of average annual runoff could be calculated from:

$$\frac{R_1}{R_0} = \frac{\alpha - (1 - g_0)\,\beta}{g_0} \qquad \ldots . (8.5)$$

α and β are the factor changes in precipitation and evaporation:

$$P_1 = \alpha P_0 \text{ and } E_1 = \beta E_0 \qquad \ldots . (8.6)$$

Equation (8.5) shows that the sensitivity of runoff to precipitation and evaporation changes is dependent on the current runoff coefficient, and increases as the runoff coefficient reduces (i.e. as aridity increases). Wigley and Jones (1985) also showed that a given percentage change in precipitation has a greater effect on runoff than the same change in evaporation. In a later paper (Glantz and Wigley, 1987) the approach was extended to allow for non-evaporative losses. However, actual evapotranspiration E is not necessarily independent of precipitation P - at the extreme E is limited by P - and changes in precipitation will affect the amount of actual evapotranspiration. Several studies dating back to the beginning of the century have attempted to express E in terms of precipitation P and potential evapotranspiration PE, and the Turc-Pike formula (Dooge, 1989) has been found to approximate reasonably well the relationship across sites between average annual precipitation, potential evapotranspiration and actual evapotranspiration. It has the form:

$$E = \frac{P}{\left[1 + (P/PE)^2\right]^{1/2}} \qquad \ldots . (8.7)$$

When the Turc-Pike formula is used to estimate actual evaporation, the sensitivity of average annual runoff to change in precipitation is reduced. The difference between the sensitivities implied by the Turc-Pike formulation and Equation 8.5 reduces as the runoff coefficient increases.

All these studies represent simple empirical approximations to complicated processes. The regression-based studies make the important assumption that variations across space can be substituted for variations over time, and that the parameters of the regression models would not vary as climate changed (but changing vegetation could influence the proportion of precipitation that goes to evaporation, for example). Finally, all the approaches ignore the effect of the distribution of changes in precipitation and evapotranspiration through the year. Nevertheless, generalised approaches have been shown to provide potentially useful first estimates of sensitivities of average annual runoff to change.

Very few studies have attempted to use generalised techniques to estimate possible changes in more sophisticated indices of hydrological behaviour. Beard and Maristany (1979) constructed regression relationships to relate seasonal flows to seasonal precipitation, but there appears to be considerable scope for the application of regional relationships between climate, catchment type and indices of flow regime such as flow duration curve shape. This potential is explored in Section 8.4.1.

8.3 ESTIMATING AVERAGE ANNUAL RUNOFF

8.3.1 Introduction and methods

This section attempts to use regional relationships between average annual runoff, rainfall and potential evapotranspiration to determine the sensitivity of average annual runoff in different UK catchments to change. The influence of model characteristics on such assessments will be examined.

Most of the investigations are based on regional regression relationships developed between average annual runoff and climatic indices. Several important assumptions are made:

(i) it is possible to substitute variations over space for variations over time: in other words, a model that is developed using average data from different catchments can be assumed to apply to annual data from an individual catchment. Too few long time series of potential evapotranspiration data exist to allow the construction of regression relationships between annual data at individual sites;

(ii) the coefficients of the model do not change over time (changes in land use, for example, which may influence evaporative losses are ignored);

(iii) changes in precipitation and evapotranspiration apply equally throughout the year.

The data base used consists of all the catchments in Britain with hydrometric and artificial influence grades A and B (see Chapter 2: at least one grade must be A) and at least 10 years of data. Average annual runoff was calculated from Surface Water Archive flow data for a total of 470 catchments in England, Wales, Scotland and Northern Ireland, and catchment average 1941-1970 rainfall (SAAR) and potential evapotranspiration (PE) were extracted for each site from the SWA gridded data base. Potential evapotranspiration data were used in preference to average annual temperature data (*cf* Revelle and Waggoner, 1983) both because it was anticipated that the relationships derived would have a greater degree of physical realism, and because it was not necessary to assume a simple relationship between temperature and evapotranspiration (see discussion in Section 8.2 on Karl and Riebsame's (1989) conclusions).

8.3.2 The models used

Seven models to estimate average annual runoff were considered:

(i) a simple linear regression relationship between average annual runoff, SAAR and PE, where average annual runoff is calculated over the entire period of flow record available:

$$R = 0.998\ \text{SAAR} - 0.215\ \text{PE} - 347 \qquad \ldots\ (8.8)$$

$R^2 = 0.950$
se = 109.5 mm
n = 470

(ii) a logarithmic regression model using the same data:

$$R = 0.015\ \text{SAAR}^{1.780}\ \text{PE}^{-0.314} \qquad \ldots\ (8.9)$$

$R^2 = 0.907$
fse = 1.250
n = 470

(iii) a simple linear regression, as (i), but using average annual runoff calculated over the period 1971 to 1984:

$$R = 0.996\ \text{SAAR} + 0.118\ \text{PE} - 528 \qquad \ldots\ (8.10)$$

$R^2 = 0.964$
se = 77.0 mm
n = 224

The coefficient for PE was not statistically significant from zero.

(iv) a simple linear regression derived in the FREND project (Gustard *et al*, 1989) from 214 catchments with basin area less than 500 km^2:

$$R = 0.97\ \text{SAAR} - 0.55\ \text{PE} - 147 \qquad \ldots\ (8.11)$$

$R^2 = 0.98$
se = 57 mm
n = 214

(v) the procedure recommended in the Low Flow Studies Report (Institute of Hydrology, 1980):

$$R = \text{SAAR} - E \qquad \ldots\ (8.12)$$

E is estimated from potential evapotranspiration using a ratio which is dependent on SAAR:

$$E = r\ \text{PE}$$
$$r = 0.0002\ \text{SAAR} + 0.78 \qquad \ldots\ (8.13)$$
$$r < 1.0$$

In contrast to the previous models, this model states that actual evapotranspiration is dependent on SAAR as well as PE.

(vi) Wigley and Jones's (1985) 'model', as defined in equation (8.5) was used to examine sensitivity to changes in actual evapotranspiration.

(vii) The Turc-Pike equation (equation 8.7) was also used. It is important to note that although Dooge (1989) claimed the Turc-Pike equation fitted average annual precipitation, potential evapotranspiration and runoff data well, it fitted UK data very poorly.

8.3.3 Sensitivity to changes in rainfall and potential evapotranspiration

The sensitivity of average annual runoff to changes in average annual rainfall and potential evapotranspiration was assessed using data from the eight gauging stations listed in Table 8.1. Most of these sites are also used in the modelling studies in Chapter 9. Actual evapotranspiration E is required for the Wigley and Jones model, and was estimated by subtracting observed runoff from SAAR. In four cases the implied actual evapotranspiration was greater than the potential evapotranspiration, which reflects in part the use of different periods of record in the flow and rainfall averages.

Table 8.1 Catchments used in comparison of estimated sensitivities to changes in precipitation and potential evapotranspiration

SWA number	Name	SAAR	PE (all in mm)	Runoff
12001	Dee at Woodend	1194	308	838.6
25006	Greta at Rutherford Bridge	1259	416	825.8
32003	Harpers Brook at Old Mill Bridge	620	519	176.1
34004	Wensum at Costessy Mill	670	524	249.0
39019	Lambourn at Shaw	737	527	234.3
43005	Avon at Amesbury	768	523	340.4
76005	Eden at Temple Sowerby	1216	407	734.3
84004	Clyde at Sills	1250	406	770.6

Figure 8.1 shows the effect of an increase in SAAR of 10% on average annual runoff (i.e. scenario PA3 in Chapter 7). There is a close agreement between five of the seven models, and it is clear that sensitivity is highest in those catchments with the lowest runoff coefficients. The Turc-Pike model shows relatively little sensitivity to changes in SAAR, and this is because as SAAR increases, actual evapotranspiration increases too. A similar, though much smaller, effect is seen with the Low Flow Studies procedure. The logarithmic model implies that sensitivities are independent of the runoff coefficient.

There is, however, a much greater variation between the models in implied sensitivity to changes in potential evapotranspiration (Figure 8.2: note that the sensitivities calculated from the Wigley and Jones model refer to changes in actual evapotranspiration). The three linear regression equations give quite different sensitivities, and this is due to differences in the implied treatment of actual evapotranspiration. The form of the regression models implies that actual evapotranspiration E can be calculated from

$$E = b\,PE + c \qquad \ldots.\ (8.14)$$

and the coefficients b and c vary considerably between the models. A high constant term c indicates that E is largely consistent between sites, and the higher this term the less sensitive runoff is to changes in potential evapotranspiration. The difference between the three linear regression models lies primarily in the numbers of stations used, because the SAAR and PE data were the same in each analysis, suggesting that the coefficients of a simple linear regression model to estimate average annual runoff are very sensitive to the data set used. This in turn indicates that the implied sensitivity of average annual runoff will also be very dependent on the data used to construct the model.

The Low Flow Studies procedure implies a much greater sensitivity to changes in potential evapotranspiration, because c in equation (8.14) is zero and b is close to 1. A given percentage change in potential evapotranspiration using the Low Flow Studies procedure has a very similar effect on runoff to the same percentage change in actual evapotranspiration as calculated using Wigley and Jones' (1985) model. Less sensitivity is implied by the Turc-Pike model.

Figure 8.3 shows the joint effect on average annual runoff of an increase of 10% in both SAAR and an increase of 15% in PE. The differences between the six models reflect the differences in the sensitivity to PE.

In summary, this section has shown how the implied sensitivities of average annual runoff to changes in rainfall and potential evapotranspiration may be strongly dependent on model formulation. Implied sensitivities to changes in rainfall alone appear to be quite consistent between models - with the important exception of the Turc-Pike model - but sensitivities to evapotranspiration changes may be very different. The effects of differences in the data set used are indicated by the differences between the three simple linear regression models. These differences imply that such models should be used with caution, and that models which have more physical meaning are more useful. The estimation procedure in the Low Flow Studies Report has some physical basis, although the relationship between actual and potential evapotranspiration in a catchment is empirical.

8.3.4 Spatial implications of climate change

Section 8.3.3 has demonstrated how the estimated sensitivity of average annual runoff to changes in average annual precipitation and potential evapotranspiration is very dependent on the form of model assumed. This

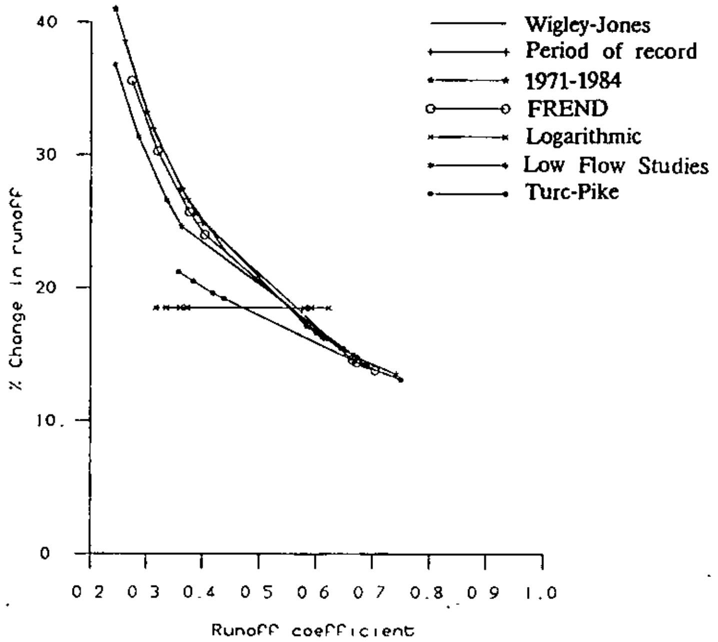


Figure 8.1 Effect on average annual runoff of a 10% increase in average annual rainfall

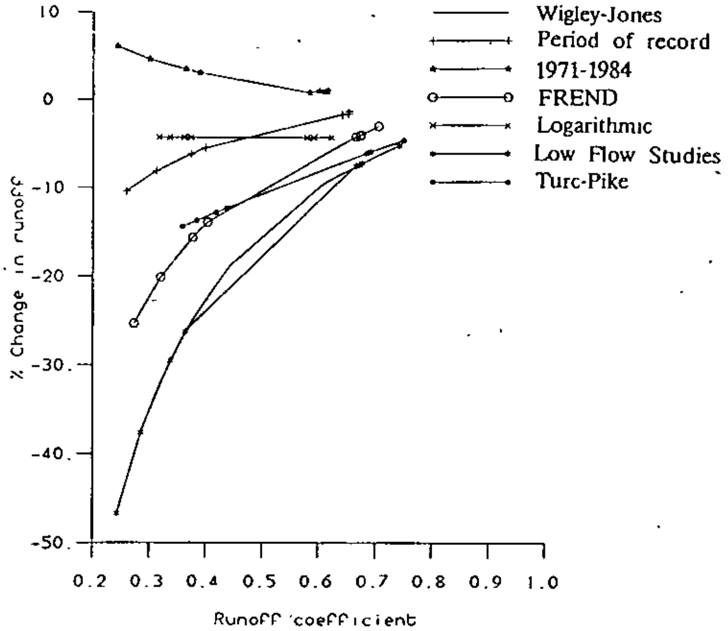


Figure 8.2 Effect on average annual runoff of a 15% increase in average annual potential evapotranspiration

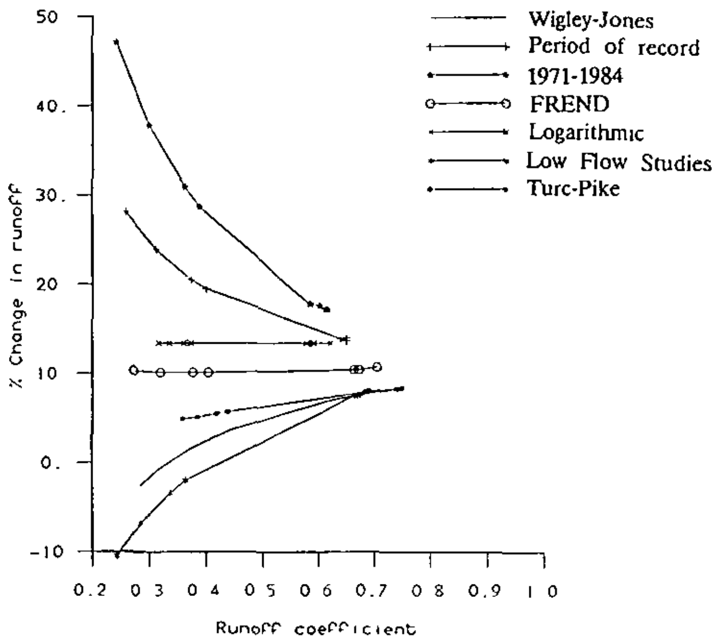


Figure 8.3 ***Effect on average annual runoff of a 10% increase in rainfall and a 15% increase in potential evapotranspiration***

section considers, for one model, the spatial implications of given changes in precipitation and potential evapotranspiration. How, for example, would a 10% change in average annual precipitation affect runoff across Britain? The Low Flows Study method is used in the examples given: it must be emphasised again that the results are dependent on model form.

The 1941-1970 average annual rainfall SAAR and potential evapotranspiration PE are stored on the Surface Water Archive on a 1km x 1km grid. Average values over a 20km x 20km grid were constructed from these 'point' values, and the Low Flow Studies method was applied to each grid square to estimate changes in average annual runoff. In order to apply the seasonally-variable scenarios, it is necessary to know the distribution of precipitation and evapotranspiration through the year. This information is not held on the Surface Water Archive, but MORECS grid data (Thompson *et al.*, 1983) were used to calculate the mean monthly precipitation and potential evapotranspiration over the period 1961-1980 for each 40km x 40km MORECS grid box. The seasonal change scenarios were applied to each of the 188 MORECS boxes to determine changes in annual precipitation and potential evapotranspiration, and these changes were then applied to the 20km x 20km scale SAAR and PE data from the Surface Water Archive (these data were used to give a greater spatial resolution and clearer indication of variations over space).

Figure 8.4 shows the effect across Britain of rainfall scenario PA4 (i.e. wetter in winter and drier in summer, with around 5% extra over the year as a whole) with unchanged evapotranspiration. It is clear that the greatest increase in annual runoff - over 35% - is in the south east, whilst considerably smaller increases appear in the more humid north and east (although increases are large in absolute terms). Water resources in the south east appear most sensitive to changes in climate, and assessments of possible change are most sensitive to the assumed change scenario.

Figure 8.5 adds to scenario PA4 the effect of an increase in annual potential evapotranspiration following scenario EVP2. This scenario results in an increase of potential evapotranspiration of between 6 and 8% across Britain, and the spatial distribution of change is very different to that where potential evapotranspiration is assumed to be unchanged. Average annual runoff decreases in south east England, and the greatest relative increase in runoff is in the wet north west where potential evapotranspiration is the smallest proportion of annual precipitation. A similar, but more extreme, pattern is produced with scenario EVP1, which assumes a greater change in evapotranspiration. Rather different patterns are produced using models which imply less sensitivity to changes in potential evapotranspiration, and show increases in runoff throughout Britain.

This section has shown how a single scenario of change can have a very different impact in different parts of Britain, depending primarily on the current runoff coefficient. The importance of evapotranspiration is shown clearly, and one set of maps which incorporate an increase of annual potential evapotranspiration of the order of 6 to 8% implies that over much south east Britain an increase in precipitation of around 10% would still lead to a reduction in annual runoff. It should be strongly emphasised, however, that these results are stongly dependent on the form of the assumed model: the results in Figures 8.4 and 8.5 are based on the application of the Low Flows Study procedure, which shows a relatively high sensitivity to changes in potential evapotranspiration.

8.4 MEASURES OF FLOW REGIME

8.4.1 Introduction

The previous section has indicated how generalised methods can be used to define possible changes in average annual runoff (showing how sensitive these assessments are to both model form and the assumed scenario of change). This section considers how similar generalised procedures can be used to explore the possible changes in other aspects of flow regime. Beard and Maristany (1979) attempted to estimate changes in seasonal runoff totals due to changes in seasonal precipitation using a regression model, but there have been no other published studies. The investigations described in this section concentrate on the flow duration curve. This shows the proportion of time that flows exceed different values. The flow exceeded 95 per cent of the time is frequently used to determine licences for abstractions and returns.

8.4.2 Regional regressions

The same type of approaches used in the estimation of changes in average annual runoff can in principle be used to determine sensitivities of indices of flow regime to change. Many regression relationships have been developed to estimate indices such as the mean annual minimum D-day flow or the flow exceeded X per cent of the time (see Gustard *et al.*, 1989, for example),

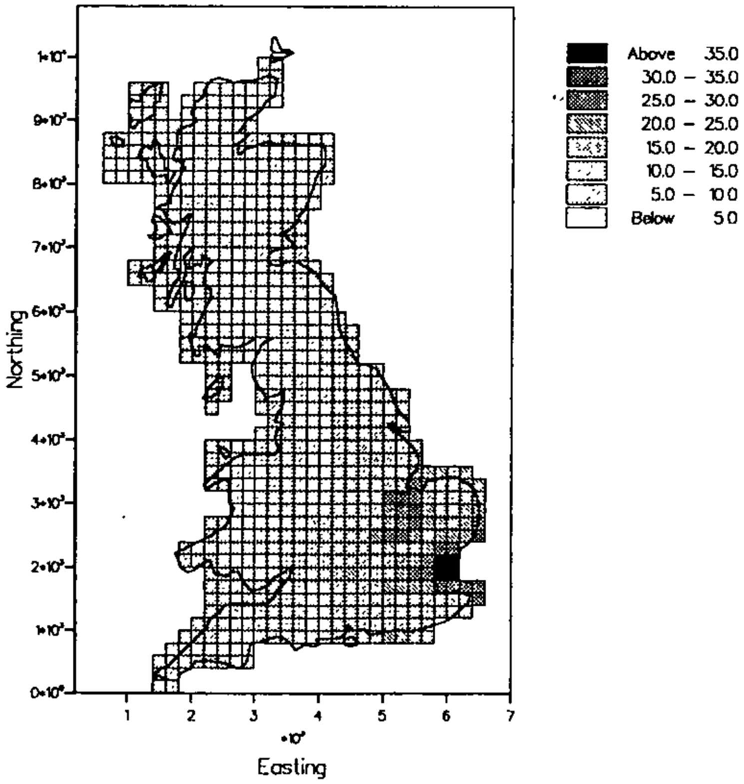


Figure 8.4 Percentage change in average annual runoff under scenario PA4+EVPO: Low Flow Studies estimation procedure

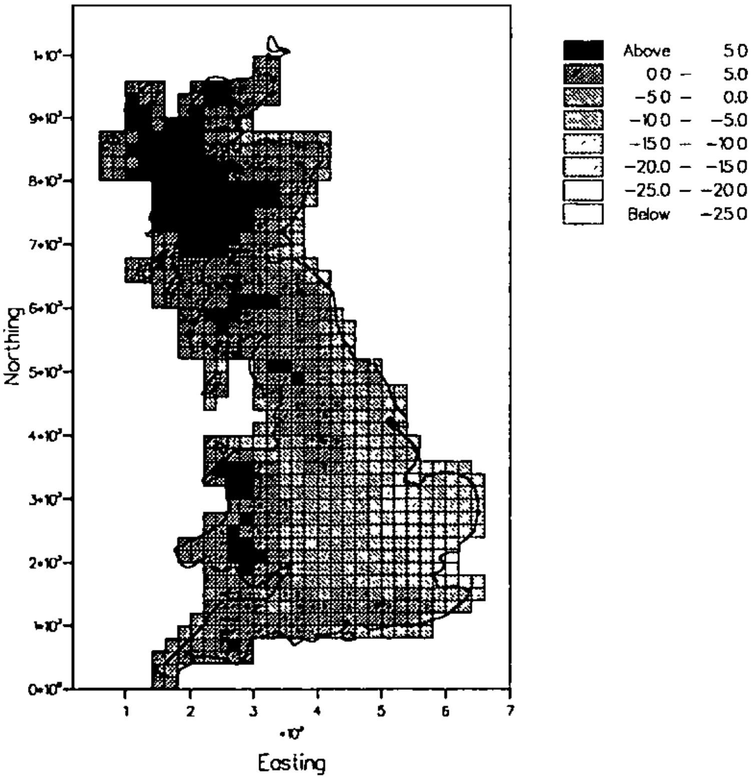


Figure 8.5 Percentage change in average annual runoff under scenario PA4+EVP2: Low Flow Studies estimation procedure

although few have expressed the climatic indices used in terms relevant to climate change assessments.

The Low Flow Studies Report (Institute of Hydrology, 1980) presents a series of regression-derived relationships to estimate the flow duration curve at sites with no flow data. The 10-day mean flow exceeded 95 per cent of the time (Q95(10)) - expressed as a percentage of the mean flow - is estimated from standard average annual rainfall (SAAR) and the Base Flow Index (BFI), and this value determines the member of a family of dimensionless flow duration curves appropriate at the site of interest. The Base Flow Index is essentially an index of catchment geology (but it is affected to a degree by climatic conditions) and is highest for catchments with large amounts of storage. Flow duration curves of different periods (from 1 day, for example, to 30 days) can be derived from the 10-day curve, again using SAAR and BFI. This procedure could be used with estimated changes in SAAR to determine the sensitivity to change of flow duration curves and flows exceeded with a given frequency. However, a change in the seasonal distribution of rainfall could have very significant implications for variations in flow over time - a reduction in summer rainfall and increase in winter rainfall would be expected to yield a steeper flow duration curve - and such a change cannot be examined using the relationships derived during the Low Flows Study.

A regression model was therefore developed to relate Q95(10) to the base flow index (BFI), SAAR and the ratio of winter (December to February) to summer (June to August) rainfall (SEASON). Data from 383 catchments with more than 10 years of record were used, and the following model derived to predict Q95(10), expressed as a percentage of mean flow:

$$\begin{aligned} \mathrm{Q95(10)}^{1/2} &= -0.262 + 8.389\ \mathrm{BFI}^{1/2} \\ &\quad + 0.027\ \mathrm{SAAR}^{1/2} - 2.151\ \mathrm{SEASON}^{1/2} \quad \ldots.\ (8.15) \end{aligned}$$

$$R^2 = 0.658$$
$$\mathrm{se} = 0.704$$

All the coefficients except the intercept are significantly different from zero at the 5% level. The predictive power of the equation is rather poor, but the coefficients have the expected signs: an increase in rainfall seasonality, for example, is associated with a reduction in Q95(10). It is important to note that BFI, SAAR and SEASON are themselves highly inter-correlated. Nevertheless, the equation can be used to get some indication of the possible effects of changes in total annual rainfall and rainfall seasonality on flow variation over time.

Table 8.2 shows the estimated Q95(10) and percentage change with respect to the current value (in both percentage of mean flow and m^3/sec) for seven precipitation scenarios (as defined in Chapter 7) and the eight catchments listed in Table 8.1. The effects of the scenarios on mean flows are estimated using the Low Flow Studies equation. Although Q95(10) decreases as a proportion of the mean flow at all sites, implying that dimensionless flow duration curves become steeper, increases in mean flows result in increases in the absolute magnitude of Q95(10) in four of the eight catchments. The sensitivity of Q95(10) to change is related to the Base Flow Index (as expected from the form of equation 8.15). Impermeable catchments, with the lowest BFI, show the greatest relative change in flow duration shape as rainfall seasonality increases, and the steepening may be sufficient to outweigh the effect of the increased mean: scenario PA2, for example, would result in a reduction of 20% in the absolute magnitude of the 10-day average flow exceeded 95% of the time, even though the mean flow would increase by nearly 40%. In catchments with a higher BFI, the reduction in the absolute magnitude of Q95(10) is considerably less.

8.4.3 Spatial transfer of information

'Popular' accounts of climate change frequently claim that the climate of a region will in the future be similar to the climate currently enjoyed by another area. The climate of southern Britain, for example, could become more 'Mediterranean' (see Gribbin and Kelly, 1989, for example). If climate can be transferred in such a way, it may be possible for the current hydrology of one region to be used as an analogue for the future hydrology of another region. The basic principles and drawbacks of such a spatial analogue were introduced in Chapter 7. In essence, it is assumed that local controls on climate are of less importance than larger scale regional controls. Local topography and the positions of water bodies, for example, are assumed to have little effect on the broad climatic characteristics of an area.

The selection of an appropriate analogue region for Britain is complicated by the particular combination of local and regional controls which determine Britain's weather and climate. It is most unlikely that Britain would in the future enjoy a 'classic' Mediterranean climate due to its westerly maritime situation. A more likely analogue may be provided by south west France or north west Spain. Both regions have strong maritime influences, but are generally milder than Britain due to their more southerly location. The south west of France was selected as an analogue region in the current study primarily because flow data were already available at IH from the FREND project (Gustard *et al*, 1989), but also because the variation in topography and geology provides greater opportunity for the selection of appropriate analogue catchments.

Summers in south west France tend to be more settled and have longer dry spells than in Britain (Arlery, 1970). Precipitation is more concentrated in winter and spring, although summers are not dry. In the south of the region, precipitation patterns are influenced by the proximity of the Pyrenees. Table 8.3 summarises the mean monthly temperature and precipitation for south west France (data from Willmott *et al*, 1985), and shows for comparative purposes average climatic data for several sites in southern Britain.

Once an analogue region has been selected it is necessary to define the way in which hydrological information is transferred. The hydrological characteristics of a basin are strongly dependent on the physical properties of that basin, and in particular its geological characteristics. The Base Flow Index (BFI) has been shown in both the Low Flows Study (Institute of Hydrology, 1980) and during the FREND project (Gustard *et al.*, 1989) to be of value in discriminating amongst different types of flow regime. However, although the BFI appears to be primarily related to catchment geology - a catchment with a high storage component and subdued response has a high Base Flow Index - it may also be influenced by climatic characteristics such as the duration of dry spells. A BFI of

Table 8.2 The effect of changes in SAAR and rainfall seasonality on Q95(10)

Q95(10) is expressed as a percentage of mean flow.

	0	PA1	PA2	PA3	PA4	PB1	PB2	PB3
25006	4.08	4.43	2.77	4.26	3.42	4.39	3.82	2.82
% CHANGE		8.78	-32.09	4.44	-16.15	7.66	-6.31	-30.91
32003	17.74	18.29	15.23	18.02	16.51	17.96	17.01	15.32
% CHANGE		3.10	-14.14	1.58	-6.92	1.27	-4.11	-13.63
39019	41.52	42.43	37.38	41.99	39.51	42.11	40.45	37.40
% CHANGE		2.19	-9.98	1.12	-4.86	1.40	-2.58	-9.92
76005	10.82	11.41	8.60	11.12	9.73	11.33	10.40	8.69
% CHANGE		5.42	-20.51	2.75	-10.11	4.72	-3.88	-19.68
12001	18.93	19.69	16.01	19.32	17.51	19.52	18.36	16.19
% CHANGE		4.01	-15.41	2.04	-7.52	3.13	-3.03	-14.45
84004	19.13	19.93	16.28	19.54	17.74	19.72	18.53	16.33
% CHANGE		4.19	-14.91	2.13	-7.28	3.09	-3.13	-14.62
34004	30.17	30.92	26.81	30.55	28.54	30.52	29.21	26.85
% CHANGE		2.47	-11.15	1.26	-5.42	1.15	-3.19	-11.00
43005	36.95	37.83	32.76	37.40	34.91	37.71	36.05	32.95
% CHANGE		2.37	-11.33	1.21	-5.53	2.04	-2.43	-10.84

Q95(10) is expressed in m^3/sec

	0	PA1	PA2	PA3	PA4	PB1	PB2	PB3
25006	0.080	0.114	0.064	0.097	0.073	0.100	0.087	0.064
% CHANGE		43.14	-19.54	20.94	-8.36	24.66	8.49	-19.99
32003	0.067	0.118	0.078	0.092	0.074	0.092	0.087	0.079
% CHANGE		75.44	16.04	37.22	9.57	36.78	29.53	16.67
39019	0.771	1.204	0.894	0.985	0.840	0.988	0.949	0.878
% CHANGE		56.21	16.03	27.84	8.97	28.19	23.17	13.89
76005	1.604	2.211	1.503	1.902	1.572	1.938	1.779	1.486
% CHANGE		37.81	-6.29	18.54	-2.02	20.80	10.89	-7.34
12001	6.681	8.864	6/531	7.757	6.662	7.840	7.371	6.503
% CHANGE		32.69	-2.24	16.11	-0.27	17.35	10.34	-2.66
84004	3.737	5.052	3.716	4.384	3.759	4.425	4.159	3.665
% CHANGE		35.20	-0.56	17.33	0.59	18.43	11.29	-1.91
34004	1.033	1.700	1.208	1.363	1.133	1.362	1.303	1.198
% CHANGE		64.50	16.93	31.91	9.64	31.75	26.11	15.94
43005	1.070	1.631	1.212	1.347	1.152	1.358	1.299	1.187
% CHANGE		52.43	13.26	25.96	7.65	26.98	21.43	10.97

Table 8.3 The climate of south west France in comparison with that of some climate stations in Britain

a) mean monthly temperature (°C)

South west France (data from Willmott et al. (1985)). The table shows the median and quartiles from 37 climatological stations.

	J	F	M	A	M	J	J	A	S	O	N	D
25%	6.2	7.2	9.6	12.0	15.7	18.9	21.2	21.1	18.6	14.2	9.3	6.8
median	5.0	6.7	9.0	11.6	15.4	18.4	20.5	20.7	18.3	13.7	8.8	6.3
75%	4.3	6.0	8.5	11.4	14.8	18.0	20.0	20.0	17.8	13.1	8.3	5.5

Central England (Manley, 1970)

3.4	3.9	5.9	8.4	11.4	14.6	16.2	16.0	13.7	10.1	6.7	4.7

b) The percentage of annual rainfall which falls in each month

South west France (data from Willmott et al. (1985))

	J	F	M	A	M	J	J	A	S	O	N	D
25%	8.8	8.1	9.1	10.1	9.9	9.2	6.6	7.3	8.0	11.0	11.4	10.8
median	8.2	7.4	8.7	9.2	9.04	8.1	6.0	6.4	7.5	9.1	10.0	10.1
75%	7.4	7.1	8.2	8.3	7.8	6.8	5.4	6.0	7.0	8.6	9.1	9.3

Central England (Manley, 1970)

9.3	6.9	6.3	7.0	8.0	6.9	9.7	9.6	8.3	10.0	9.6	8.6

0.6 in one area may not therefore have the same geological interpretation as in another region with a rather different climate, but given the lack of other discriminatory indices, the BFI was used to select catchments for comparison. Any differences in hydrological behaviour between catchments with similar physical characteristics - as indexed in this instance by BFI - are assumed to be due to differences in climate.

Figure 8.6 shows the locations of the catchments in south west France on the FREND archive with more than ten years of daily flow data. The station characteristics are summarised in Table 8.4. A pooled regional average 10-day flow duration curve was calculated from the 15 catchments with a BFI between 0.5 and 0.6, and is shown in Figure 8.7. The curve shows flows expressed as a percentage of the mean flow: standardisation by area alone would not correct for differences in the absolute amount of rainfall. Figure 8.7 also shows a flow duration curve calculated from 28 catchments with areas less than 500 km2 in south and east England (Hydrometric areas 28 to 54) with the same range in BFI. The curve for south west France is slightly steeper, but the French curve is within the limits defined by individual English site curves. If it is assumed that the Base Flow Index does represent the most important catchment controls on flow regime, the differences in flow duration curve shape must reflect differences in the distribution of rainfall through the year and the length of dry spells. The French curve can be expected on climatological grounds to be the steepest, but the difference between the two curves is small. It is important to note that the French catchments tend to be higher and in more mountainous regions than their British counterparts with similar BFIs. This difference may complicate the comparison of the two sets of catchments.

This section has attempted to estimate possible changes in flow regimes in Britain using a spatial analogue. Even if a suitable analogue region can be found - and it is not clear at present whether south west France really is an appropriate analogue for future British conditions - it may be very difficult to find catchments with similar key characteristics. Catchments in south west France, for example, appear to have higher Base Flow Indices than catchments in similar upland locations in Britain, and the range of geological conditions which exists in south west France is considerably less than that in southern Britain. The tentative spatial analogue attempted indicates that if climate in southern Britain in the future were to resemble that of south west France at present, changes in the relative variability of flows over time could be rather small (the mean flow, however, could be rather different with implications for the frequency of occurrence of particular discharge values).

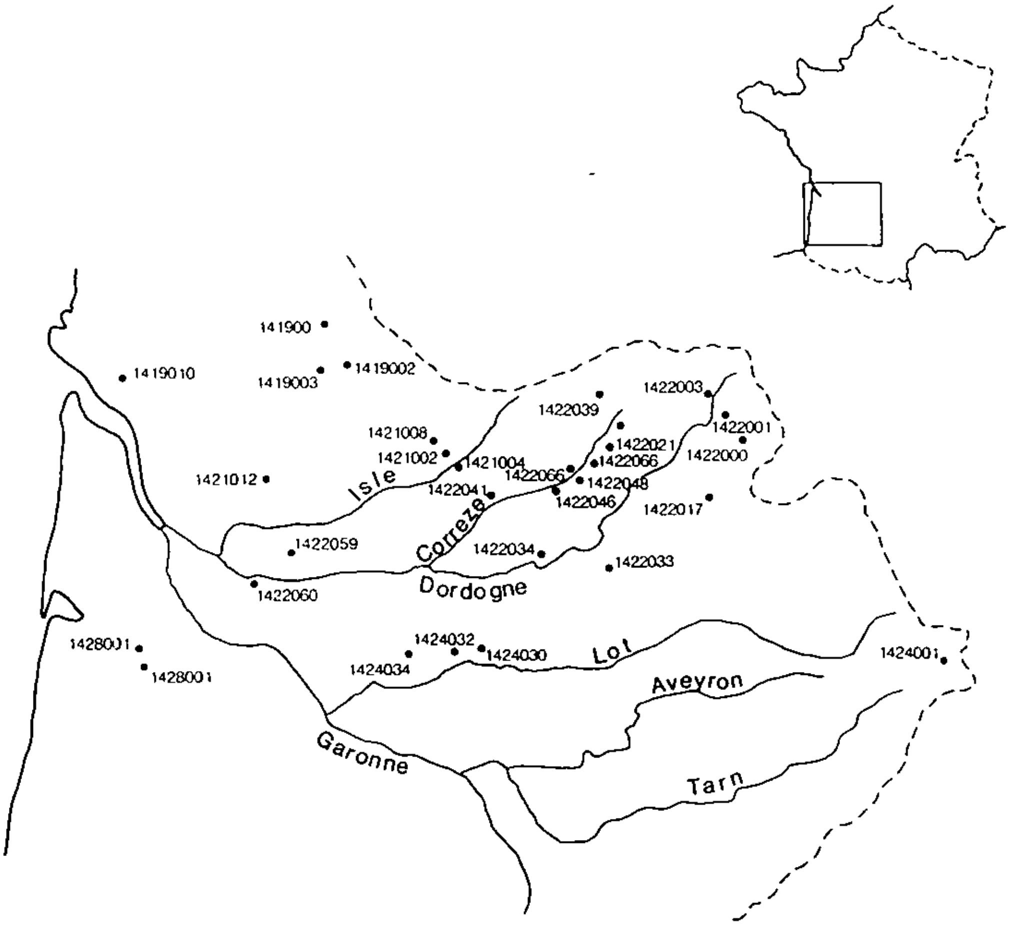


Figure 8.6 Location of catchments in south west France

8.5 SUMMARY AND CONCLUSIONS

This chapter has attempted to take a range of generalised empirical approaches to estimate the sensitivities of flow regimes in Britain to changes in climate. Such approaches rely on regional relationships between climate and hydrological response, and are quicker to apply than procedures based on hydrological modelling. They can also be applied at many sites to give an indication of the spatial implications of a change in climate.

Several simple models were used to estimate the sensitivity of average annual runoff to changes in annual precipitation and potential evapotranspiration. In general, the results showed a greater sensitivity to changes in precipitation than potential evapotranspiration, and that sensitivity increases as the proportion of annual rainfall which runs off decreases. These findings are consistent with those of the few other generalised studies that have been published. The current study, however, has shown how the implied sensitivity to changes in potential evapotranspiration is very dependent on the form of the model used.

Table 8.4 Characteristics of the catchments in south west France used for the spatial analogue

FREND number	Name	area (km^2)	BFI	Annual rainfall (mm)
1419001	Bonnieure at Villebette	203	0.566	910
1419002	Tardoire at Montbron	389	0.635	988
1419003	Bandiat at Feuillade	333	0.661	962
1419010	Seudre at St Andre de Lidon	236	0.787	803
1421002	Isle at Corgnac	432	0.582	1032
1421004	Loue at St Medard	196	0.532	1056
1421008	Dronne at Le Manet	140	0.618	1014
1421012	Tude at Pont de Corps	318	0.594	850
1422001	Dordogne at St Sauves	87	0.628	1689
1422003	Chavanon at La Cellette	362	0.582	1192
1422009	Rhue at Egliseneuve	40	0.597	?
1422017	Mars at Vendes	117	0.385	1387
1422019	Triouzoune at St Angel	78	0.614	1309
1422021	Luzege at Pont de Maussac	84	0.600	1344
1422033	Bave at St Cere	183	0.582	1049
1422034	Tourmente at St Denis	202	0.433	915
1422039	Vezere at Maisonnial	52	0.586	1555
1422041	Brezou at Pt de Blaygeat	104	0.613	1163
1422045	Correze at Correze	167	0.558	1418
1422046	Vimbelle at Moulin du Bos	147	0.592	1312
1422048	Montane at Pont du Jay	43	0.573	1307
1422059	Eyraud at Bitarel	74	0.459	800
1422060	Corral at Ruch	4	0.405	700
1422066	Soudeille at Ventadour	122	0.592	1341
1424001	Bramont at Les Fonts	116	0.582	991
1424030	Vert at Les Campagnes	117	0.455	785
1424032	Lemance at Cuzorn	224	0.769	802
1424034	Lede at Casseneuil	411	0.372	686
1428001	Grave at Biganon	108	0.547	898
1428002	Bouron at Moulin du Moine	36	0.758	909

Maps have been prepared showing the differential spatial impact across Britain of several climate change scenarios. Even a constant percentage change in average annual rainfall has a very different impact in different parts of Britain - due to variations in the runoff coefficient - and the south east of England is shown to be most sensitive to a given change in precipitation and potential evapotranspiration. This is particularly significant because pressures on resources here are greatest: estimates of future resource availability are most needed but at the same time most uncertain. Very different spatial patterns of impact are produced when changes in potential evapotranspiration are added. Under some scenarios, average annual runoff is predicted to decrease over large areas of south and east England,

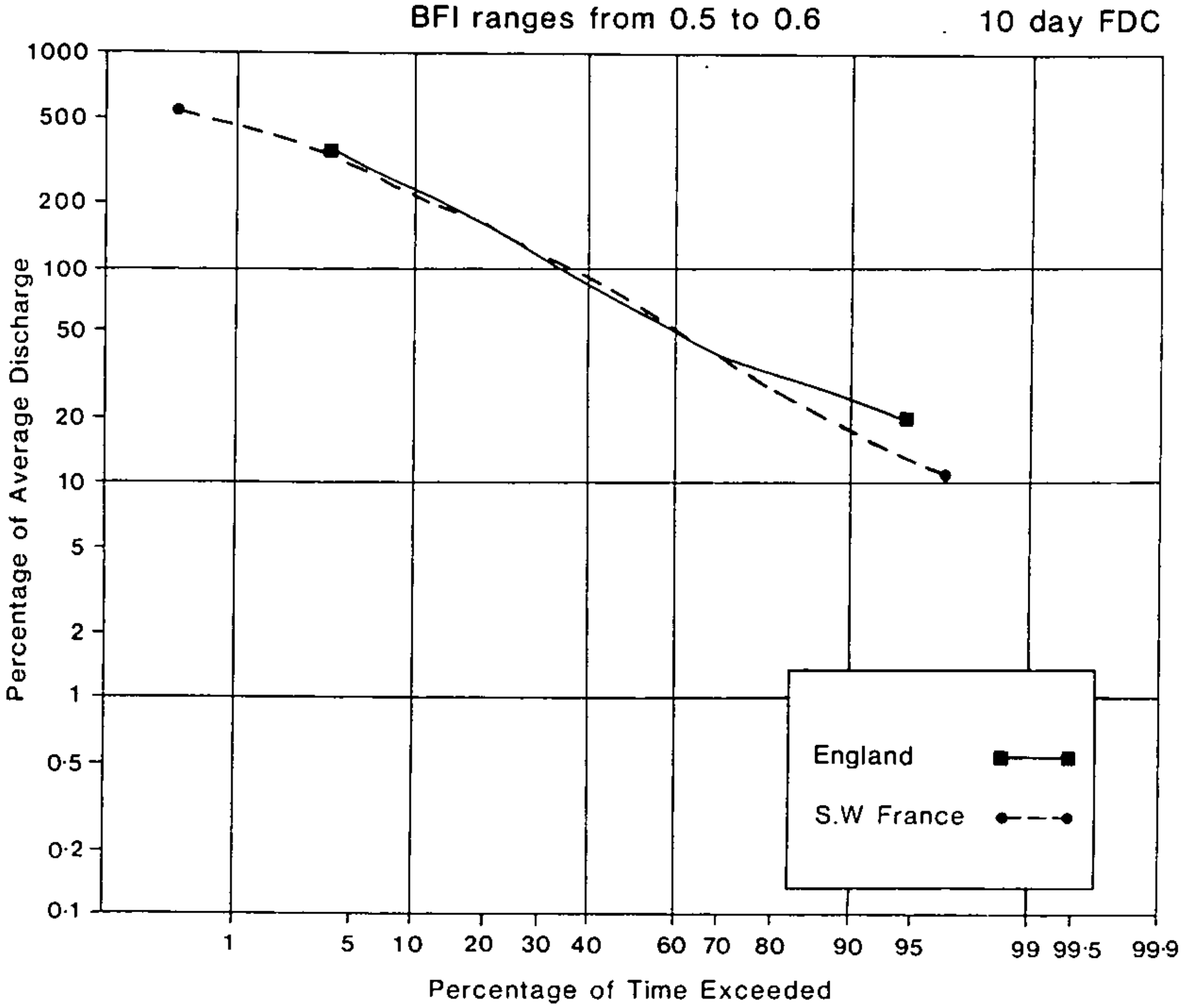


Figure 8.7 Flow duration curves for south west France and central and southern England: BFI ranges from 0.5 to 0.6. The curves show flows as a percentage of mean flow.

despite an increase in precipitation. Estimates of the effect of changes in potential evapotranspiration are, however, very dependent on model form, and some analyses show much lesser sensitivities.

Some more tentative assessments of possible changes in flow regime have also been made. Regression analysis was used to explore the effect of changes in rainfall seasonality on the shape of flow duration curves (indicative of variability of flow over time), and showed the importance of catchment geology on sensitivity to change. Flow duration curves would become steeper as rainfall seasonality increased, but this steepening would in many catchments be offset by the increase in mean flow. In more impermeable catchments, the increase in mean flows would not be sufficient to offset the very large changes in flow duration curve slope, and the frequency of exceedance of given discharges would reduce.

Finally, an attempt was made to infer possible changes in flow regime characteristics in Britain by transferring information from south west France, a region assumed to be an analogue for future British conditions. The problems in defining a suitable analogue region were reviewed once more, and the additional problem of the selection of appropriate analogue catchments was considered. The average flow duration curve for catchments in south west France was shown to be slightly steeper than that for catchments with similar physical characteristics in Britain (as indexed by the Base Flow Index), implying that flows would be more variable over time in a changed Britain. However, the differences between the two regions were small, and the two regional flow duration curves were well within the limits defined by individual site curves in the other region.

The next chapter takes a more conventional approach to impact assessment, and employs hydrological models to estimate changes in mean flows and flow regimes. The results are compared with those obtained by the more simplified and empirical methods used in this chapter.

9. Impact assessment using hydrological models

9.1 INTRODUCTION

The previous chapter considered the application of a range of generalised procedures for the estimation of the impacts of climate change on some aspects of. flow regime. The objective of this chapter is to use simple hydrological models applied in several catchments to explore further the sensitivities of different catchments to change. In particular, attention is directed to the influence of the nature of the scenario and the importance of catchment type in determining the impact of a given scenario.

A simple water balance model is used to examine changes in average annual runoff and monthly flow regimes. The model, data and methodology are outlined in Section 9.3, and Sections 9.4 and 9.5 present the results.

9.2 BACKGROUND

A great many studies have recently used rainfall-runoff models of varying degrees of complexity to estimate the effects of a change in climatic inputs on flow regimes and water resources. Beran (1986) provides a comprehensive review to 1986, and summarises the types of models that are used. This section does not attempt to review all the studies that have been published, but draws attention instead to some key papers.

The first study of possible changes in flow regimes and water resources in a changed climate was published by Schwarz (1977). He generated synthetic monthly flows for a catchment in the north east United States, and compared the effects of different climatic perturbations on mean monthly flows and reservoir yield reliability. Another early study was made by Nemec and Schaake (1982). They used the Stanford Watershed Model to model daily river flows in two American catchments under a range of arbitrary changes in annual rainfall and potential evapotranspiration, showing changes in average annual runoff and the reliability of a hypothetical reservoir with a specified target yield. Their results showed that the catchment in the semi-arid south west USA was much more sensitive to change than the catchment in the more humid north west USA, and that catchments were more sensitive to changes in precipitation than potential evapotranspiration.

These pioneering studies have been followed by many case studies in several regions, notably the Great Lakes area (Cohen, 1986), the Sacremento basin in California (Gleick, 1987) and several parts of Australia (Nathan *et al.,* 1988). Most of these studies have used monthly water balance models, and have concentrated on few catchments and on a small number of change scenarios derived from GCM results. In. Europe, Bultot *et al.* (1987) used a daily model in three different Belgian catchments, but employed only one change scenario. Very few attempts have been made to generalise the results of impact studies, in order to determine the effect of differences in scenario and different catchment characteristics, although Schaake and Chunzhen (1989) applied a simple water balance model - with 'typical' parameters - across the south eastern USA to show the spatial implications of a given change in precipitation: they did not, however, consider the effect of catchment type on sensitivity to change.

There have also been very few attempts - despite Schwarz (1977) and Nemec and Schaake's (1982) early leads - to go beyond studies of changes in flow regimes to explore changes in, for example, reservoir reliability or irrigation feasibility, and practically the only published examples come from Australia (Nathan *et al.*, 1988, Fitzgerald and Walsh, 1988). Again, the studies have been very site-specific.

This chapter represents the first attempt to estimate the potential changes in flow regimes in the UK following changes in climate, and also attempts to generalise the results: the chapter does not aim to determine possible changes at a specific location, but is concerned instead with identifying the sensitivity of estimated changes to the form of the assumed climate change scenario and the characteristics of the catchment.

9.3 METHODS AND MODELS

In the most general terms, the determination of the effects of climate change on flow regimes and water resources involves the following stages:

(i) define a hydrological model which converts climatic inputs into hydrological response, and calibrate under the current climatic conditions;

(ii) create a 'perturbed' climatic time series, representing the climate under the defined scenario;

(iii) run the model with the perturbed climate inputs, and compare indices of flow regime (such as mean monthly runoff or flow duration curve) under the perturbed climate with those under the current climate.

There are therefore three key elements in an impact study, namely model specification, the definition of climate input data and the selection of appropriate case study catchments.

A wide variety of hydrological models has been used for climate change impact studies, ranging from simple monthly water balance models with no calibrated parameters to daily models with a large number of optimised parameters. Gleick (1986) identified six criteria for evaluating the applicability of hydrological models for climatic impact assessments.

Firstly, the model must have some inherent accuracy. The model does not need to be able to reproduce exactly the flow series at the site of interest - the aim of the exercise is to look at sensitivities to rather coarse changes in climate not to calibrate a model for its own sake - as long as it does reproduce the basic characteristics of the catchment flow regime. Secondly, the model accuracy must not depend too much on the conditions under which it was calibrated. If the model parameters are very closely related to current climatic conditions, land cover or soil characteristics, they cannot be expected to remain constant as climate changes. This criterion discriminates against very highly parameterised models, whose parameters are derived directly from such variables as the percentage of the catchment under particular vegetation covers or the current physical properties of soil. Thirdly, input data for model calibration must be readily available, and fourthly they must be accurate. Long records are important for model calibration, but long records of variables other than river flows, catchment average rainfall and temperature are rarely available. Fifthly, the model must be easy to use, and capable of rapid repeated application. The model should be sufficiently robust to be used - with calibration - at sites with different characteristics. Finally, the model should be able to use the types of information provided in climate change scenarios, and in particular the types of output which can be obtained from GCMs. This last criterion is extremely important, and limits the types of models which can meaningfully be used at present in impact studies. It was reported in Chapter 7 that it is currently very difficult to define climate change scenarios at time scales shorter than one month - GCM estimates of day-to-day variability in climate are not particularly reliable - and that changes in factors such as windspeed, humidity and cloud cover are currently very uncertain. The ideal hydrological model for impact studies would therefore (under the current 'state-of-the-art') use as inputs monthly values of precipitation and temperature or evapotranspiration.

Gleick (1986) suggested that simple water balance models fulfilled all these criteria, and such a model was used in the current study. A monthly model was adopted partly because it was simple to apply, but primarily because of the difficulties in defining meaningful climate change scenarios at time scales shorter than a month. Perturbed climate input series were defined, as outlined in Chapter 7, by adjusting historical time series of precipitation and potential evapotranspiration in accordance with the defined scenarios. Some studies (e.g. Nathan *et al.*, 1988) have used synthetic series generated from monthly parameters, but this approach was not adopted in the current study.

Before describing the model applied in the study, it is necessary to summarise the data set upon which the analysis was based. A total of fifteen catchments were used, distributed across England and Wales as shown in Figure 9.1 and Table 9.1. The catchments were selected to represent a wide range of geological conditions, as represented by the Base Flow Index (BFI), and climate characteristics, as represented by the long-term average runoff coefficient. All the catchments had at least 25 years of good quality data with few gaps, and minimal artificial influences on flow regimes. The river runoff and catchment average monthly rainfall data were taken from the Surface Water Archive. Time series of catchment monthly potential evapotranspiration were not available, so monthly long-term average values were taken from the agricultural zone averages presented in MAFF (1976), and corrected for altitude differences between the average zone altitude and the catchment using the long-term average annual potential evapotranspiration taken from the Surface Water Archive. The monthly average potential evapotranspiration values were applied in each year: it is recognised that this oversimplifies variations in climate between years.

Figure 9.1 Location of catchments used in impact modelling study

Table 9.1 List of catchments used in the monthly modelling

Number	Catchment name	Area (km^2)	BFI	runoff coeff.	record used
25006	Greta at Rutherford Bridge	86.1	0.21	0.652	1961-1988
26003	Foston Beck at Foston Mill	57.2	0.95	0.470	1960-1988
28008	Dove at Rocester Weir	399.0	0.61	0.563	1954-1988
32003	Harpers Brook at Old Mill Bridge	74.3	0.49	0.288	1939-1988
34004	Wensum at Costessy Mill	536.1	0.73	0.374	1961-1988
37005	Colne at Lexden	238.2	0.53	0.262	1959-1988
39019	Lambourn at Shaw	234.1	0.96	0.324	1963-1988
40007	Medway at Chafford Weir	255.1	0.50	0.416	1960-1988
42003	Lymington at Brockenhurst	98.9	0.36	0.416	1960-1988
43005	Avon at Amesbury	323.7	0.91	0.415	1965-1988
47001	Tamar at Gunnislake	916.9	0.46	0.589	1957-1988
54008	Teme at Tenbury	1134.4	0.57	0.480	1957-1988
54016	Roden at Rodington	259.0	0.61	0.379	1962-1988
57004	Cynon at Abercynon	106.0	0.42	0.673	1957-1988
76005	Eden at Temple Sowerby	616.4	0.37	0.618	1965-1988

Many monthly hydrological models have been proposed and, excepting those using stochastic data generation, can be conveniently divided into empirical and water balance models. Empirical models use empirically-derived relationships between the runoff in a month and the climate and runoff in that and preceding months, whilst water balance models are based on some form of monthly accounting. Water balance models differ in how they express the relationship between actual and potential evapotranspiration, and allocate the effective rainfall in a month to runoff in that and succeeding months. Several water balance models were considered in the current study, including a number of variants of Thornthwaite and Mather's 'bucket' model (Thornthwaite and Mather, 1955; Alley, 1984), Schaake and Chunzhen's (1989) linear and non-linear models, the Thomas *abcd* model (Alley, 1984) and the Palmer model (Alley, 1984). The models were implemented on a PC, and calibrated and evaluated using the IH interactive model calibration package MIMIC (Bonvoisin and Boorman, 1990). The comparison - which was not intended as a definitive evaluation of the relative merits of each model or as an exercise to construct a new model - was based on a subset of the 15 study catchments, and involved both a visual evaluation of the goodness of fit and an attempt at parameter interpretation. A three-parameter Thornthwaite water balance model appeared to perform most consistently, and had parameters which could be interpreted (loosely) in terms of catchment characteristics. The model (from Alley, 1984) uses monthly precipitation (P_i) and potential evapotranspiration (PE_i) as input, and has the following stages:

(i) Remove a fraction of the monthly precipitation which contributes directly to runoff in that month:

$$P_i' = \left(1 - \alpha\right) P_i$$

α is a model parameter.

(ii) Calculate the change in storage (S_i) in a month from:

$$\text{if } P_i' > PE_i \qquad S_i = P_i' - PE_i + S_{i-1}$$

$$= \text{SMAX if } S_i > \text{SMAX}$$

$$\text{if } P_i' < PE_i \qquad S_i = S_{i-1} \exp\left[-(PE_i - P_i')/\text{SMAX}\right]$$

SMAX is a model parameter, notionally reflecting the storage capacity of the soil. The calculations are started when it is assumed S_i = SMAX (i.e. in January).

(iii) Calculate the change in the water available for runoff:

$$\text{if } P_i' > PE_i \text{ and } S_i = \text{SMAX} \qquad dQ_i = P_i' - PE_i - S_i + S_{i-1}$$

$$\text{otherwise} \qquad = 0$$

(iv) Compute the amount available for runoff and the actual amount of runoff in that month:

$$\text{amount available} = V = dQ_i + Q_{i-1}$$

$$\text{RUNOFF}_i = (1 - \lambda)\ V + \alpha\ P_i$$

$$\text{surplus} = Q_i = \lambda\ V$$

λ is the third model parameter, representing catchment lag. The calculations are started when it is assumed that $Q_{i-1} = 0$ (in September).

Model parameters were estimated by least-squares using a Rosenbrock procedure in the MIMIC package. The model does not include an allowance for snowmelt, due to a lack of readily available data. Monthly temperature data are too coarse for estimating when precipitation falls as snow in Britain, and time series of daily temperature and precipitation could not be assembled for all the study catchments in the time available. Although snowmelt is rarely an influence on monthly flow regimes in Britain, it is recognised that the omission of snowmelt may lead to a poor fit in extreme winters and may cause problems in estimating runoff in some of the upland study catchments.

The model was fitted to a proportion of each sample, and model fit was validated by comparing observed and estimated flows for a five-year test period at the end of each record. Model parameters are shown in Table 9.2, which also shows the correlations between observed and simulated flows in both the calibration and validation period. The fits are adequate rather than good, but the characteristics of the simulated flows were generally similar to those of the observed flows. The poorest fits were found with the catchments with a high base flow component, particularly Foston Beck. The parameter λ was closely related to catchment geology as indexed by BFI - as expected - and increased as BFI increased (λ represents the portion of a month's available water which is held over for succeeding months). There was also a tendency for α to reduce as BFI increased, but SMAX, the notional soil moisture storage, appeared to be more of a local calibration factor.

Table 9.2 ***Parameters of the monthly water balance model, and the correlation between observed and simulated flows in the calibration and validation (1983-1988) periods***

		SMAX	λ	α	correlation coefficient	
					calibration period	validation period
25006	Greta	34.7	0.171	0.086	0.887	0.886
26003	Foston Beck	30.7	0.810	0.000	0.794	0.730
28008	Dove	77.8	0.598	0.227	0.923	0.935
32003	Harpers Brook	175.5	0.531	0.115	0.882	0.777
34004	Wensum	97.8	0.741	0.140	0.882	0.863
37005	Colne	158.5	0.561	0.098	0.886	0.851
39019	Lambourn	500.0	0.888	0.000	0.864	0.873
40007	Medway	146.1	0.513	0.284	0.922	0.814
42003	Lymington	60.4	0.561	0.470	0.895	0.930
43005	Avon	133.6	0.776	0.000	0.937	0.915
47001	Tamar	149.4	0.274	0.130	0.966	0.952
54008	Teme	210.1	0.465	0.172	0.932	0.929
54016	Roden	78.5	0.537	0.198	0.888	0.917
57004	Cynon	183.4	0.234	0.340	0.945	0.975
76005	Eden	21.8	0.303	0.307	0.943	0.954

9.4 CHANGES IN AVERAGE ANNUAL RUNOFF

It was shown in Chapter 8 how simple generalised procedures can give some insights into the sensitivity of average annual runoff to changes in climate, but more sophisticated analyses can be based on hydrological models. Such models allow the investigation of the effect of different seasonal distributions of change and the importance of catchment characteristics. This section presents results from the application of the monthly model described above to estimate average annual runoff under the range of scenarios outlined in Chapter 7 to the 15 catchments in Table 9.1. Results are compared with those obtained from the generalised procedures developed in Chapter 8.

9.4.1 Effect of changes in total annual precipitation: potential evapotranspiration constant

Table 9.3 shows the percentage change in average annual runoff for the four higher rainfall scenarios PA1 to PA4, with potential evapotranspiration unchanged. Scenarios PA1 and PA3 assume a 20% and 10% change respectively throughout the year, whilst the annual effects of PA2 and PA4 - which have drier summers - depend on the seasonal distribution of rainfall. The ratio of change in average annual runoff to change in average annual precipitation can be termed the 'elasticity' (Schaake and Chunzhen, 1989), and ranges from around 1.2 to nearly 3 in the catchments studied (assuming no change in evapotranspiration). The effect of a change in average annual rainfall of 20%, however, is slightly more (up to 3.3%) than twice the effect of an increase in average annual rainfall of 10%. This implies that inferred elasticities depend on the amount of change introduced, although the effect is rather small. A reduction in rainfall of 10% was found to have a similar magnitude effect on average annual runoff as a 10% increase (but in the opposite direction, of course).

Table 9.3 Percentage change in average annual runoff under precipitation change scenarios PA1 - PA4. Potential evapotranspiration is unchanged.

		PA1	PA2	PA3	PA4
25006	Greta	28.9	18.4	14.4	9.2
26003	Foston Beck	35.0	25.3	16.9	12.5
28008	Dove	31.3	19.3	15.5	9.6
32003	Harpers B.	54.2	34.8	26.5	17.4
34004	Wensum	39.5	29.0	19.2	14.3
37005	Colne	57.5	40.7	27.8	20.0
39019	Lambourn	57.9	34.2	28.7	17.1
40007	Medway	35.1	25.8	17.3	12.8
42003	Lymington	28.4	22.7	14.1	11.3
43005	Avon	41.6	29.6	20.4	14.8
47001	Tamar	31.6	21.2	15.7	10.6
54008	Teme	37.8	24.1	18.8	12.0
54016	Roden	37.6	28.0	18.3	13.8
57004	Cynon	26.5	17.5	13.2	8.8
76005	Eden	26.7	18.3	13.2	9.1

The elasticity of runoff to rainfall is very strongly related to the current runoff coefficient, as shown in Figure 9.2: the smaller the runoff coefficient, the more sensitive the catchment to changes in average annual rainfall, and the differences in sensitivities between catchments are large. Catchment geology, as indexed by the Base Flow Index (BFI) appears to have no influence on the sensitivity of annual runoff to change.

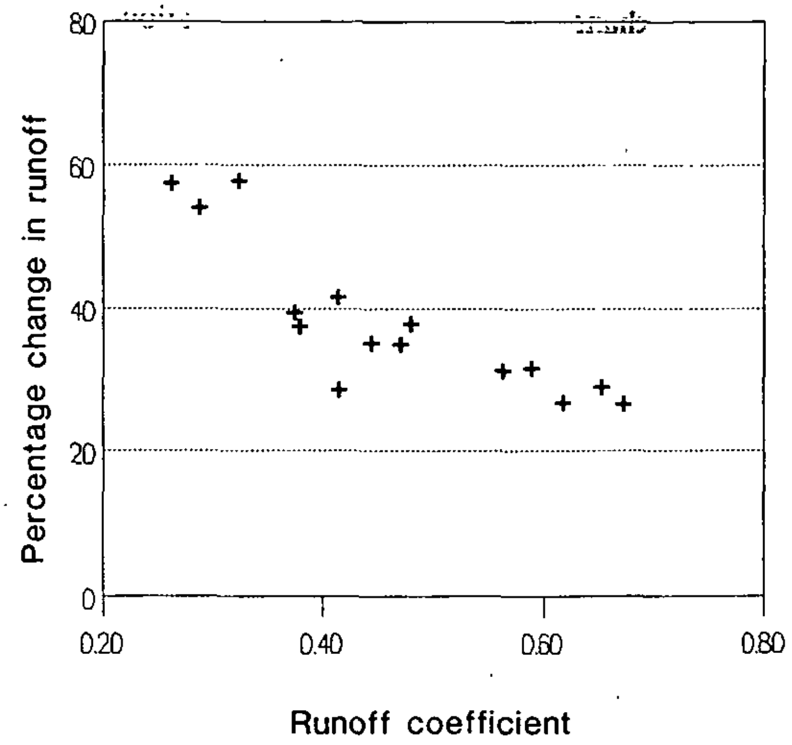


Figure 9.2 Change in average annual runoff under scenario PA1. Potential evapotranspiration is unchanged.

Figure 9.3 compares the estimated change in average annual runoff derived from the monthly model with estimates based on four of the generalised approaches from Chapter 8 (results for PA1 and PA2 only are shown: those for PA3 and PA4 are qualitatively similar). When the increase in rainfall is proportionally the same each month (scenarios PA1 and PA3), the monthly model results imply a considerably lesser sensitivity to change in average annual precipitation than implied by the regression model in equation (8.8), the Low Flows Studies model and the Wigley and Jones (1985) model. The Turc-Pike formulation (Dooge, 1989) appears to give the closest fit. However, Turc-Pike equation underestimates the sensitivity to change when change varies through the year, whilst the other procedures give much closer estimates. It is clear that the relative precision of the generalised procedures - assuming of course that the monthly model gives the 'correct' answers - depends on how the rainfall increase is applied through the year. If the increase is concentrated in winter, the regression, Low Flows Studies and Wigley-Jones methods give close estimates: if the increase applies throughout the year, the Turc-Pike formula appears better. The differences between the estimates is greatest in the catchments with the lowest runoff coefficients.

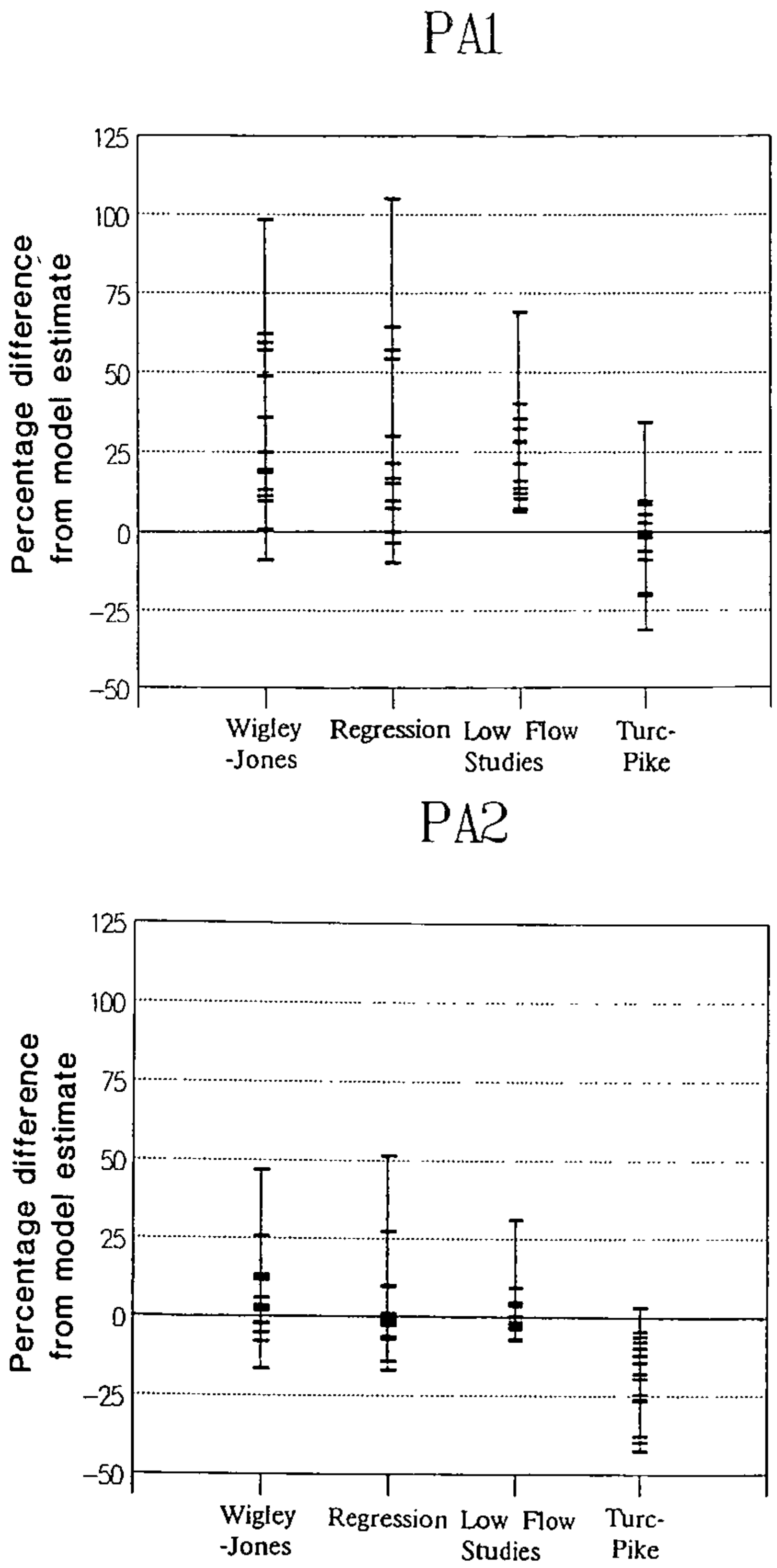


Figure 9.3 Percentage difference between modelled change in annual runoff and change estimated from five empirical procedures from Chapter 8: Scenarios PA1 and PA2

9.4.2 Effect of changes in potential evapotranspiration: rainfall constant

Average annual runoff reduces as potential evapotranspiration increases, but a given change in potential evapotranspiration has a lesser effect than the same proportional change in rainfall (Table 9.4). Elasticities range from 0.35 to 1.8: an elasticity of less than one implies that a given change in annual potential evapotranspiration has a lesser proportional change on runoff. As is the case with rainfall, the sensitivity of average annual runoff to changes in potential evapotranspiration is determined by the runoff coefficient, and this is shown in Figure 9.4. Catchments with the lowest runoff coefficient are most sensitive to a given change in potential evapotranspiration.

Table 9.4 Percentage change in average annual runoff under potential evaporation change scenarios EVP1-EVP3. Precipitation is unchanged.

		EVP1	EVP2	EVP3
25006	Greta	-6.4	-3.2	-6.6
26003	Foston Beck	-9.4	-4.9	-10.0
28008	Dove	-.72	-3.7	-7.4
32003	Harpers Brook	-19.1	-10.2	-19.9
34004	Wensum	-10.6	-5.6	-11.5
37005	Colne	-21.2	-12.5	-22.3
39019	Lambourn	-25.0	-12.6	-25.3
40007	Medway	-8.7	-4.6	-9.3
42003	Lymington	-5.9	-3.0	-6.7
43005	Avon	-13.2	-6.9	-13.8
47001	Tamar	-8.0	-4.0	-8.3
54008	Teme	-11.8	-6.0	-12.0
54016	Roden	-7.6	-3.3	-6.3
57004	Cynon	-4.4	-2.2	-4.5
76005	Eden	-4.5	-2.3	-4.8

A comparison between estimated sensitivities derived from the monthly model and four generalised procedures is given in Figure 9.5 (EVP3 results are very similar to the EVP1 results). Modelled sensitivity is somewhat less than that implied by the Low Flows Studies equation or the Wigley-Jones (1985) formula (which was applied with the possible unrealistic assumption that changes in actual evapotranspiration would be proportionately the same as changes in potential evapotranspiration), but is rather higher than implied by the simple linear regression developed in the current study. The Turc-Pike formula appears to estimate most closely the sensitivity of average annual runoff in Britain to changes in potential evapotranspiration.

Finally, a comparison between the effects of scenarios EVP1 and EVP3 implies that differences in changes in winter potential evapotranspiration are

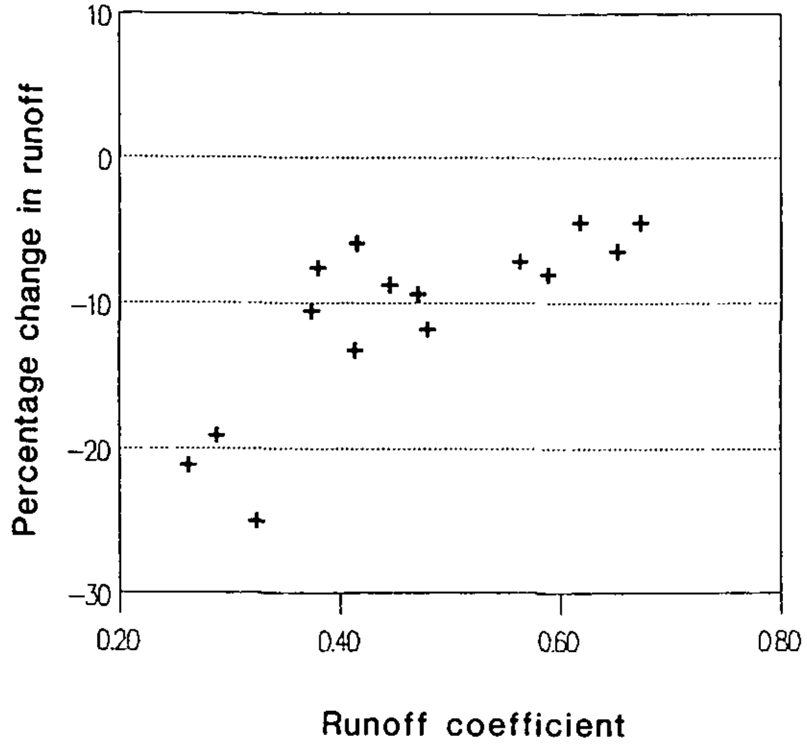
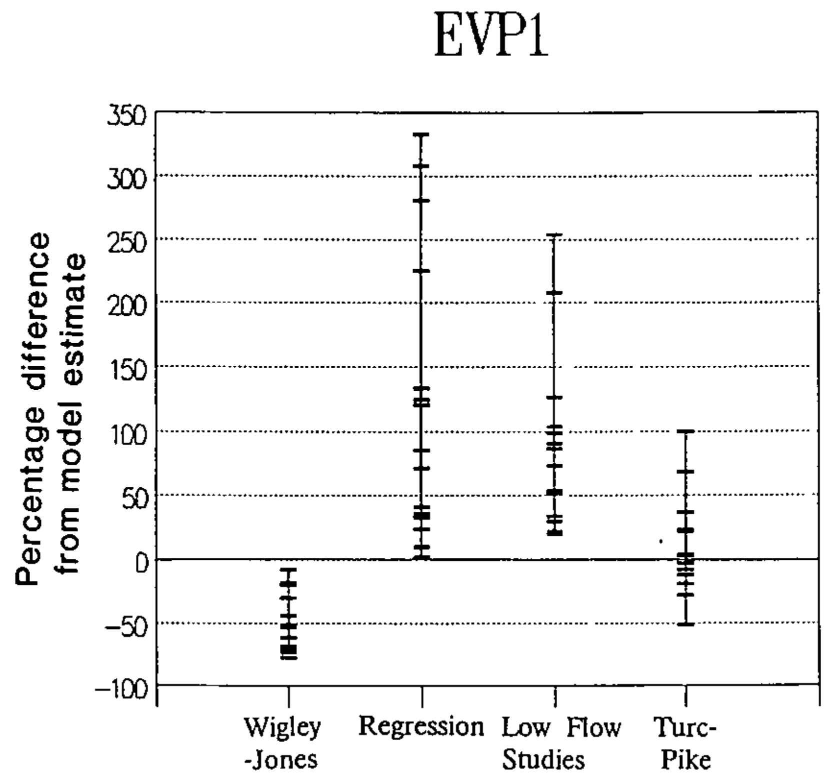


Figure 9.4 Change in average annual runoff under scenario EVP1. Precipitation is unchanged.

unimportant. Scenario EVP3 includes an increase in winter potential evapotranspiration double that of EVP1 (see Chapter 7), but because the absolute totals of winter potential evapotranspiration are low, the net results are very similar. Changes in the duration of the recharge season - when rainfall exceeds potential evapotranspiration - are very important for groundwater resources, but cannot be defined at the monthly time-scale used in the current study.

9.4.3 The effect of the seasonal distribution of changes in rainfall

The effect on average annual runoff of a given increase in average annual rainfall can be expected to depend on the distribution of that change through the year. Scenarios PB1, PB2 and PB3 all assume an increase in average annual rainfall of 10%, with the increase being increasingly concentrated in winter from PB1 to PB3. In PB3, summer rainfalls are reduced (see Chapter 7). Table 9.5 shows the effect on average annual runoff of the different scenarios (including PA3, which assumes a 10% increase in each month), and it is clear that average annual runoff increases more as the extra rainfall is more concentrated in the winter season. The greatest difference is between PB2 and PB3, where summers change from becoming wetter to becoming drier.



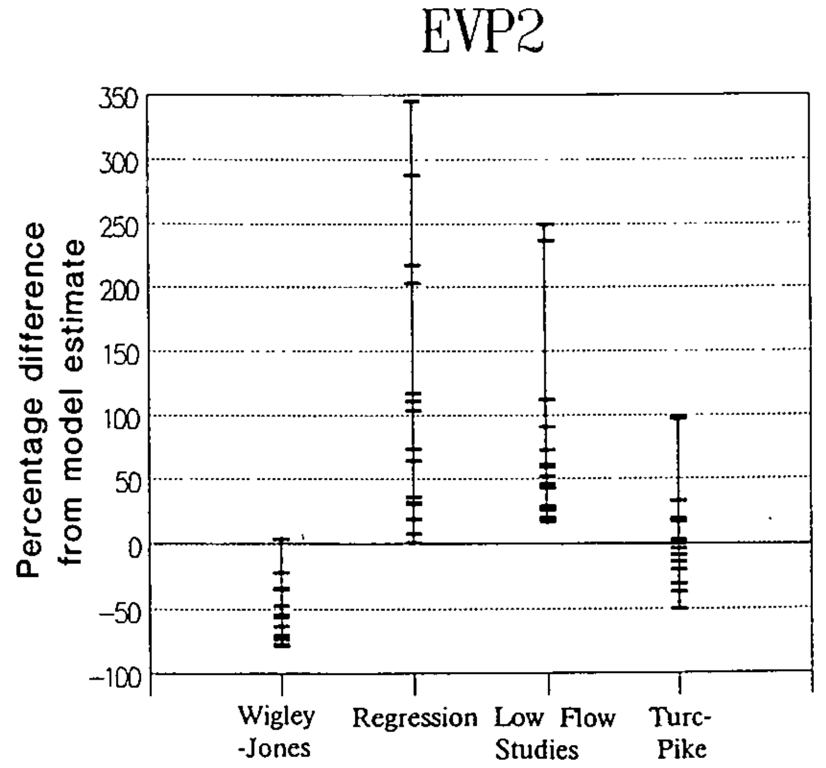


Figure 9.5 Percentage difference between modelled change in annual runoff and change estimated from five empirical procedures from Chapter 8: Scenarios EVP1 and EVP2

Table 9.5 Percentage change in average annual runoff under precipitation change scenarios PB1-PB3. All show a 10% increase in average annual rainfall, with the addition increasingly concentrated in winter from PB1 to PB3. Evapotranspiration is unchanged.

		PB1	PB2	PB3
25006	Greta	14.2	14.6	15.8
26003	Foston Beck	16.6	18.3	22.6
28008	Dove	15.4	16.0	17.5
32003	Harpers B.	26.4	29.1	34.3
34004	Wensum	18.9	21.7	27.2
37005	Colne	27.5	31.3	38.8
39019	Lambourn	28.5	29.5	31.4
40007	Medway	16.5	18.3	21.8
42003	Lymington	13.0	15.1	18.9
43005	Avon	19.9	21.8	26.0
47001	Tamar	15.4	15.9	17.3
54008	Teme	18.6	19.4	21.2
54016	Roden	18.2	21.0	26.6
57004	Cynon	13.2	13.3	13.8
76005	Eden	12.8	13.6	15.6

Table 9.6 shows the increase in average annual rainfall which would, if applied in the same proportion in each month, give the same increase in average annual runoff as scenarios PB1, PB2 and PB3. Scenario PB2, for example, gives the same change in average annual runoff as an increase in each month's rainfall of between 10 and 11.5%, depending on the catchment, whilst scenario PB3 is equivalent to constant annual increases ranging from 10.3% to 14.5%. The implications of changing the seasonality of a given increase in rainfall vary between catchments for two reasons. Firstly, each scenario has a different impact on seasonal rainfall changes in each catchment: the proportional change in winter rainfall in catchment A will be different to that in catchment B under scenario PB3, for example. The greater the proportion of rainfall that occurs in winter, the smaller the effect a given scenario (for example PB3) has on increasing winter rainfall totals, and hence total annual runoff. Secondly, different runoff coefficients amplify the effects of increased rainfall in different ways. The assessment of the relative importance of the two influences is hindered by the strong correlation between runoff coefficient and the proportion of rainfall that occurs in winter. Catchments in the dry south east tend to have both lower runoff coefficients and a higher proportion of their annual rainfall in winter.

Further insights into the effect of seasonality can be gained by comparing scenarios PA1 and PA2 (or indeed PA3 and PA4). PA1 assumes an increase in rainfall of 20% in each month, whilst PA2 assumes that although winter rainfall increases by 20%, summer rainfall reduces. Unlike in the previous experiments, the proportional change in rainfall in the runoff generating season - winter - is constant between catchments. The change in average annual

Table 9.6 The percentage change in average annual rainfall which, if applied in each month, would give an increase in average annual runoff equivalent to scenarios PB1, PB2 and PB3. Scenarios PB1, PB2 and PB3 all imply a 10 per cent increase in average annual rainfall.

		PB1	PB2	PB3
25006	Greta	9.86	10.19	11.00
26003	Foston Beck	9.80	10.82	13.34
28008	Dove	9.93	10.34	11.32
32003	Harpers Brook	9.97	10.96	12.92
34004	Wensum	9.89	11.33	14.20
37005	Colne	9.90	11.26	13.94
39019	Lambourn	9.94	10.27	10.94
40007	Medway	9.55	10.56	12.56
42003	Lymington	9.18	10.70	13.43
43005	Avon	9.76	10.69	12.73
47001	Tamar	9.82	10.15	11.00
54008	Teme	9.89	10.31	11.27
54016	Roden	9.96	11.49	14.53
57004	Cynon	9.95	10.08	10.42
76005	Eden	9.70	10.28	11.82

runoff from PA1 and PA2 in different catchments was found by correlation analysis to be unrelated to the runoff coefficient and catchment geology (as indexed by the Base Flow Index). However, a weak relationship was found between the impact of seasonality and the size of the excess of summer potential evapotranspiration deficit over rainfall, and is shown in Figure 9.6. The addition of rainfall seasonality has the greatest effect (i.e. PA2/PA1 is lowest) in catchments where there is currently a surplus of rainfall over potential evapotranspiration in summer: a reduction in rainfall in these areas transforms the surplus into a deficit, and runoff is reduced accordingly. In catchments where summer rainfall is already considerably less than potential evapotranspiration, reductions in summer rainfall have less effect on summer runoff and hence total annual runoff. In practice, soil moisture deficits will be replenished in such catchments later than at present and autumn flows would be lower, but the monthly models used are too coarse to detect an influence on annual runoff. This subject will be considered further in Section 9.5.

9.4.4 Changes in annual runoff: a summary

Figure 9.7 draws together the results discussed in the previous three sections, and summarises the sensitivity of average annual runoff to change in average annual rainfall and evapotranspiration in two catchments, one with a low runoff coefficient (and hence high sensitivity to change: Harpers Brook), and the other - the River Greta - with a high proportion of rainfall going to runoff. Several points are emphasised by the graphs.

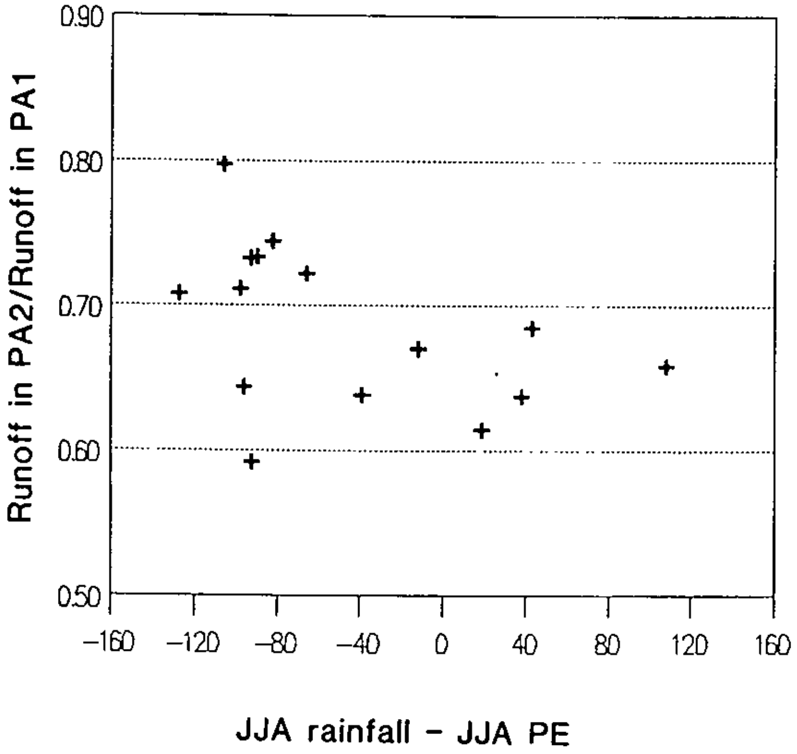


Figure 9.6 Influence of summer water balance as the effect of rainfall seasonality on change in average annual runoff: scenarios PA1 and PA2

Firstly, the different slopes of the relationships between changes in rainfall and runoff represent the different sensitivities to change: the lower the runoff coefficient, the steeper the lines. The relationship between percentage change in rainfall and percentage change in annual runoff is shown to be very nearly linear, as indicated in Section 9.4.1.

Secondly, the vertical bars at 10 and 20% extra annual rainfall show the effect on changes in average annual runoff if the increase in annual rainfall is concentrated in winter. Similar vertical bars could be defined at other points along the relationship, and if the extra rainfall were concentrated in summer, the bars would extend below the line: the relationship between changes in average annual rainfall and average annual runoff is therefore best seen as covering a region rather than describing a single line. The greater the concentration in winter of a given increase in annual rainfall the greater the increase in average annual runoff, but it is considered that the most extreme scenarios used in this study (PB3 and PB6 for 10 and 20% extra rainfall respectively) provide a realistic upper limit: they do represent a considerable increase in rainfall seasonality. As discussed in Section 9.4.3, the size of this region depends on both the runoff coefficient (increasing as the runoff coefficient reduces) and the summer water balance (with a larger spread in catchments where summers are currently wet).

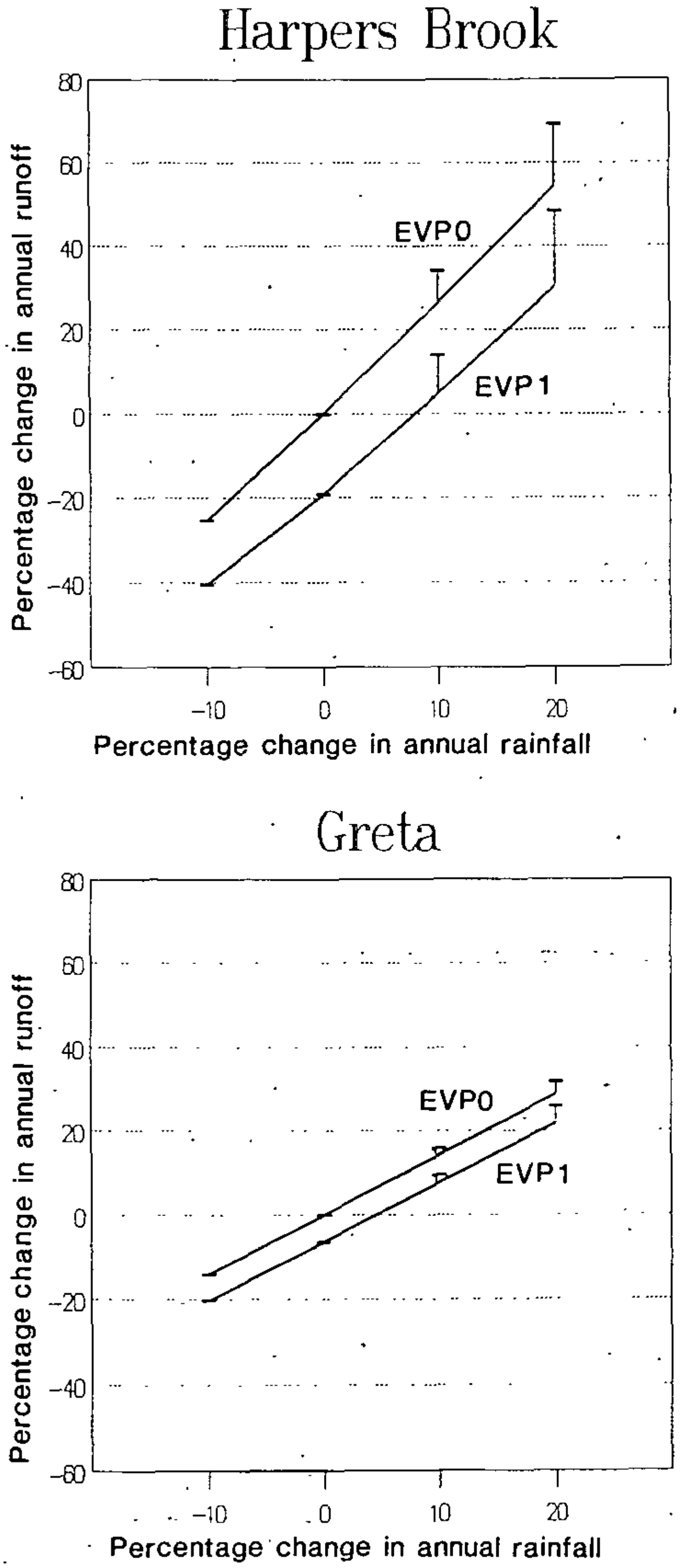


Figure 9.7 Effect of change in average annual precipitation and potential evapotranspiration for two example catchments

Thirdly, Figure 9.7 shows the effect of increased potential evapotranspiration on the relationship between changes in annual rainfall and annual runoff. The greater the distance between the lines representing the different evapotranspiration change scenarios, the greater the sensitivity of average annual runoff to changes in potential evapotranspiration. The approximately equal spacing between the lines representing the different scenarios indicates that the relationship between changes in runoff and evapotranspiration - holding rainfall constant - is nearly linear.

Changes in evapotranspiration complicate considerably the relationship between changes in rainfall and changes in runoff. When evapotranspiration is assumed not to alter, a 20% increase in rainfall produces approximately twice as much extra runoff as a 10% increase in rainfall. This is not the case when evapotranspiration is assumed to increase, and a 20% increase in rainfall will give rather more than twice the extra runoff than would a 10 per cent increase: the relative difference appears to be greatest in catchments with the lowest runoff coefficients. For example, an increase in rainfall of 10 per cent would, if associated with an increase in evapotranspiration according to scenario EVP1, give approximately 5% extra runoff in Harpers Brook, whilst a 20% increase in rainfall would result in 30% extra runoff. In the more humid Greta catchment, however, 10 and 20% increases in rainfall would give increases in runoff of 7.5 and 21% respectively. Note that, when evapotranspiration is assumed to increase, a 10% increase in rainfall gives a greater percentage increase in runoff in the humid, rather than the dry, catchment. The effect of a given change in annual rainfall on annual runoff depends therefore not just on the runoff coefficient, but also on the change in evapotranspiration: the relative impact in two catchments of 10% extra rainfall, for example, would be different if the extra rainfall was associated with higher evapotranspiration, with that difference depending on the runoff coefficients of the two catchments.

Diagrams such as those presented in Figure 9.7 constitute important and useful summaries of the sensitivity of a catchment to change in climatic inputs. Their form is quite general, being controlled largely by the ratio of average annual runoff to average annual rainfall: Figure 9.7 represents examples from close to the two extremes in Britain. They can be used to estimate the effects of a particular change scenario, and can also be used to determine how much extra rainfall, for example, would be needed to compensate for an increase in potential evapotranspiration of 17% (from Figure 9.7 it can be seen that average annual rainfall would need to increase by approximately 8% in the Ise catchment, but by only 5% in the more humid Greta catchment: lesser increases would suffice if the extra rainfall were concentrated in winter).

9.5 CHANGES IN FLOW REGIMES

Different climate change scenarios have different implications for flow regimes, and the same scenario can have a very different impact in different catchments. This section considers the effect of scenario type and catchment characteristics on monthly and seasonal flow regimes, the frequency at which particular flows are exceeded and the rate of occurrence of extreme low flow conditions. The final subsection considers the effect of change on some hypothetical storage-yield diagrams.

9.5.1 Changes in monthly flow regimes

The effect on mean monthly runoff of scenario PA1, which specifies a 20% increase in rainfall in each month, was found to vary considerably between the fifteen catchments modelled. Two basic patterns were identified: some catchments showed the greatest percentage increase in flow in summer, whilst others showed the lowest percentage increase in summer and the largest increase in autumn. Most catchments fitted between these two extremes. Figure 9.8 shows changes in average monthly flow in four catchments, including the two showing the most extreme differences (Greta and Harpers Brook). The differences in behaviour are primarily due to differences in the amount of surplus rainfall in summer. In the Greta catchment, where the greatest percentage increase in runoff is in summer, summer rainfall is very close to summer potential evapotranspiration. An increase in summer rainfall therefore increases by a large proportion the amount of surplus rainfall available for runoff, and hence runoff increases by a correspondingly large amount. In catchments with a considerable summer rainfall deficit, increases in rainfall are still not sufficient to generate summer rainfall surpluses, so summer flows are little affected. Autumn flows are increased, however, because smaller deficits build up over summer. For example, November flows in the Harpers Brook catchment are increased by approximately 120% (i.e. more than doubled), and this reflects both the extra autumn rainfall and the lower summer deficits. The size and timing of the autumn (and indeed spring) peak increase depends on the timing of the transition from a monthly rainfall deficit to a monthly surplus. Harpers Brook shows a particularly large increase in autumn runoff because rainfall in September is currently very close to potential evapotranspiration: an increase in rainfall has a large relative impact on effective rainfall. In other catchments, early autumn rainfall is rather greater than potential evapotranspiration. The monthly timescale used in the analysis perhaps tends to exaggerate the differences in peak changes between catchments.

The Lambourn catchment has a very even increase in runoff through the year, and this is typical of the catchments with high groundwater components. The extra winter rainfall feeds through only slowly to river flows, and compensates for the relatively lower increases in summer effective rainfall.

Figure 9.8 also shows the effect of the seasonally variable scenario PA2 on changes in mean monthly runoff for four catchments. The differences between the catchments depend on catchment geology and the summer water balance. In the Lambourn, a reduction in summer rainfall results in an increase in summer flows, and indeed flows are increased under scenario PA2 by over 35% in each month. This is because the catchment responds very slowly to rainfall, and summer river flows are maintained by the higher winter and spring rainfall inputs. The Greta catchment shows a very different response, with large reductions in summer flows associated with lower summer rainfall. As indicated above, this catchment currently has a summer rainfall surplus, and a reduction in summer rainfall tips the water balance into deficit: flows are therefore reduced considerably, with the responsive nature of the catchment exaggerating the effect of the change still further. Figure 9.9 shows that the percentage change in summer runoff (June, July and August) in each catchment is very closely related to catchment Base Flow Index when PA2 is applied, but there is no apparent relationship when PA1 is used. For

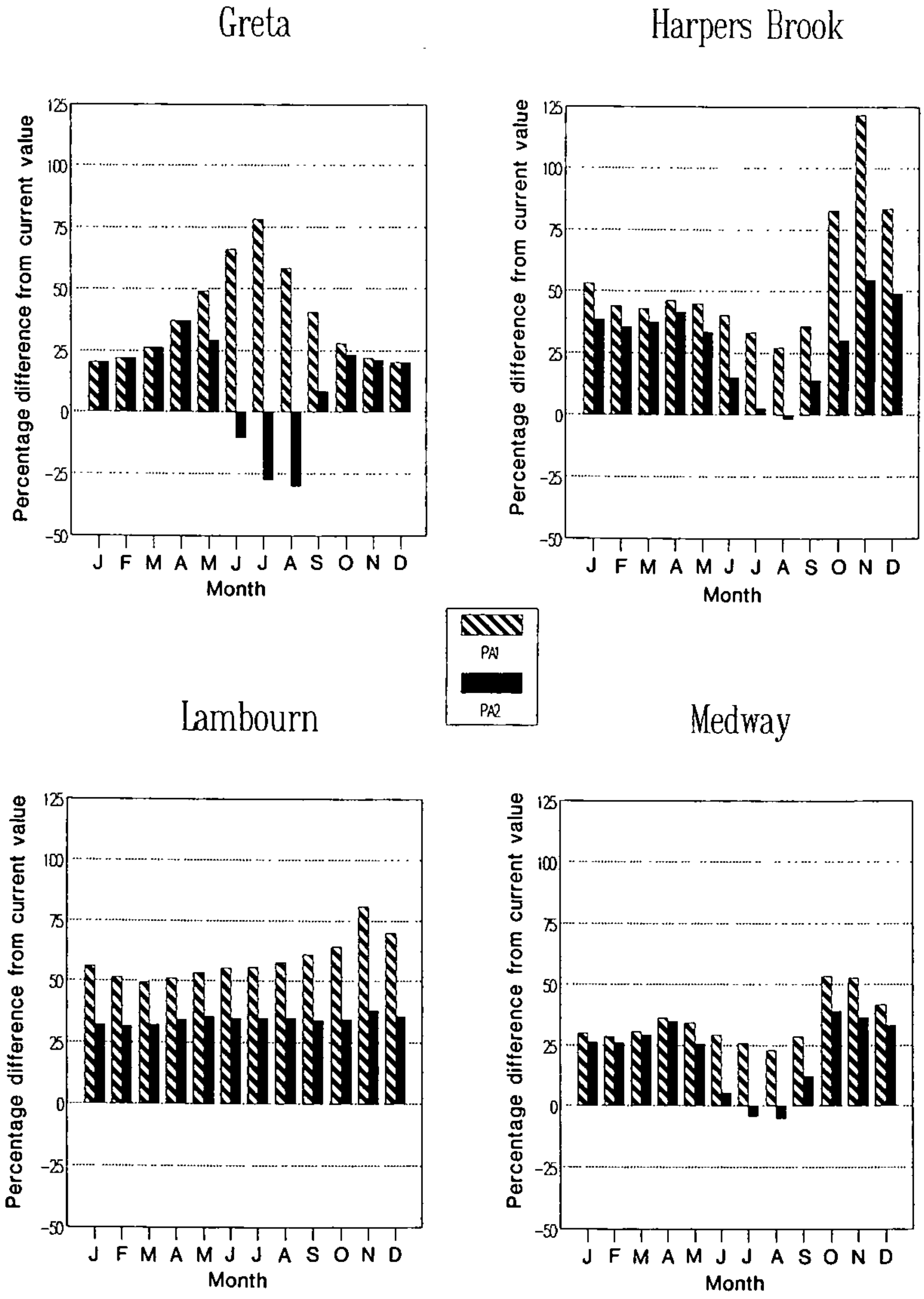


Figure 9.8 Change in mean monthly flows under scenarios PA1 and PA2 for four example catchments. Potential evapotranspiration is unchanged.

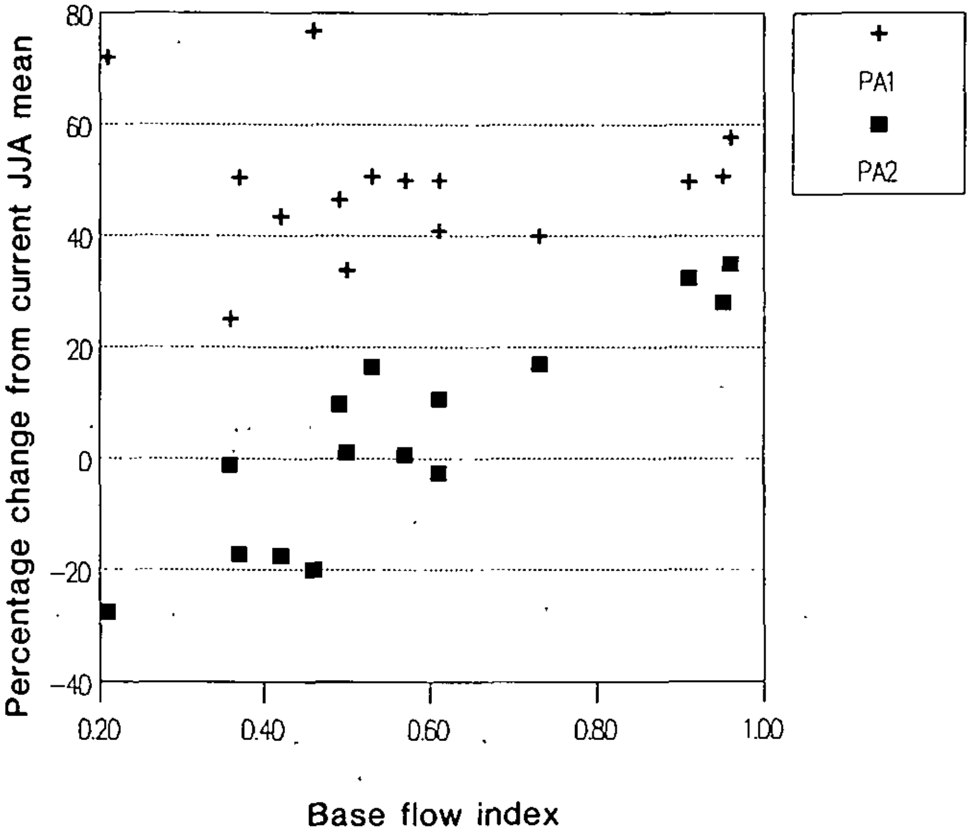


Figure 9.9 Percentage change in summer (JJA) runoff under scenarios PA1 and PA2, against catchment BFI

catchments with a Base Flow Index greater than 0.5, summer runoff increases even though summer rainfall is less in PA2 (this refers to the average across all three months: flows may decline in individual months, particularly August). In such catchments, summer flows are maintained by the higher rainfall inputs in winter and spring. The interpretation of the relative effect of catchment geology and summer water balance is hindered by the strong association between the two (the catchments with the very lowest base flow index are also those with the largest summer rainfall relative to potential evapotranspiration), but the signal from catchment geology seems strongest.

The comparison between the effects of scenarios PA1 and PA2 reveals that changes in summer flows in catchments currently experiencing a near balance between summer rainfall and potential evapotranspiration are extremely sensitive to the assumed changes in summer rainfall. In the Greta catchment, for example, flows in summer may either increase by over 60% or reduce by over 30%, depending on whether summer rainfall increases or reduces. More generally, winter and spring flows are least affected by the assumed changes in summer rainfall - except in catchments with very slow response times - but estimated increases in autumn flows are rather lower if it is assumed that summer rainfall declines.

The effect of a change in potential evapotranspiration (with no change in rainfall) is indicated in Figure 9.10. Again, the different patterns reflect differences in catchment geology and summer water balance. If summer currently has a small rainfall surplus, an increase in potential evapotranspiration will possibly lead to a deficit, and hence a large reduction in summer runoff: this is illustrated by the Greta catchment. In drier catchments, an increase in potential evapotranspiration serves to increase an already large summer deficit, and hence has limited effect on summer flows but considerable effect on autumn runoff. In the Medway catchment, for example, summer deficits are currently so large that an increase in potential evapotranspiration of around 40% has minimal effect on summer runoff, but autumn runoff is reduced by around 10%. This catchment represents a rather extreme example of the behaviour of most of the fifteen catchments, which showed the greatest reduction in runoff due to increases in potential evapotranspiration in spring and autumn. As with the rainfall changes, this reflects alterations in the season when rainfall exceeds potential evapotranspiration. The effect of changes in winter potential evapotranspiration is generally small (because winter potential evapotranspiration is currently very low), but can be important in catchments with relatively small current winter rainfall surpluses. Catchments with slow response to rainfall (such as the Lambourn) are affected rather differently by changes in potential evapotranspiration. Reductions in runoff are much more consistent throughout the year, reaching their maximum in late autumn, and this is because flows are influenced more by the sum of the climate over several months than the net rainfall in any one month.

A reduction in monthly rainfall of 10% (scenario PA5) was found to have qualitatively similar effects to an increase in potential evapotranspiration, but with a slightly greater magnitude.

The major conclusion from this section is that different catchments can respond in very different ways to the same climate change scenario. This response is related to the summer water balance and catchment geology, with geology in particular controlling the response of a catchment to reductions in summer rainfall. In slowly responding catchments, summer flows are more influenced by winter and spring rainfall than summer rainfall, and reductions in summer rainfall have the most important impact on autumn flows. The greatest relative - but not of course necessarily absolute - changes in runoff tend to occur in spring and autumn, and represent changes in the length of season when rainfall exceeds potential evapotranspiration. The coarse time interval of the monthly models used in this study may tend to exaggerate the difference in spring and autumn response between catchments. Winter and spring runoff appears to be relatively unaffected by the assumed changes in summer climate, and this makes the task of defining possible changes in the volumes of water available for winter reservoir replenishment rather easier.

9.5.2 Changes in flow seasonality

The previous section has considered the effects of change on monthly flow regimes in percentage terms. Changes in the distribution of flow through the year, however, reflect the application of percentage changes to absolute amounts of runoff. This section explores the effect of change scenarios on runoff seasonality, defined as the ratio of winter (December, January and February) runoff to summer (June, July and August) runoff.

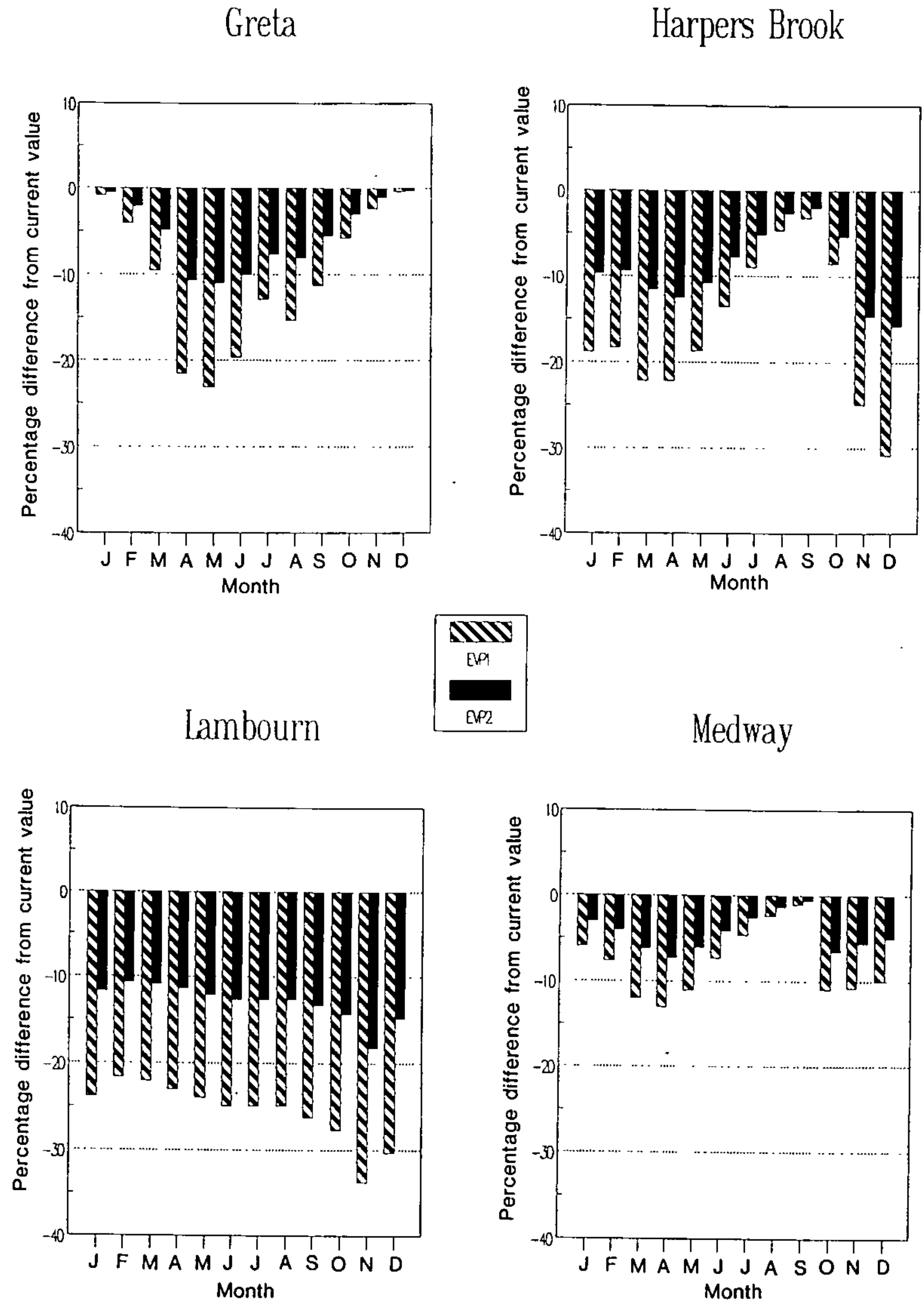


Figure 9.10 Change in mean monthly flows under scenarios EVP1 and EVP2. Precipitation is unchanged.

Under scenario PA1, flow seasonality is increased in seven catchments and reduced in the remaining eight. In the catchments showing an increase in seasonality the extra winter rainfall is more effective than the extra spring and summer rainfall, which is depleted by the seasonally higher potential evapotranspiration. The lower the runoff coefficient the greater the magnification of the rainfall changes by winter runoff, and hence the greater the increase in seasonality. In the remaining catchments, seasonality is reduced because summer runoff is increased by more - in volumetric terms - than winter runoff. These catchments are the ones currently with the greatest surplus or smallest deficit of summer rainfall over potential evapotranspiration, and increases in summer rainfall create or increase further summer rainfall surpluses. All the catchments with an increased seasonality have summer water balance deficits in excess of 70mm: only one of the catchments with a reduced seasonality has such a deficit, and that is a chalk catchment showing only a slight change in seasonality.

The effect of increased summer dryness, however (scenario PA2) is determined by catchment geology (Figure 9.11) and is uninfluenced by runoff coefficient. The lower the Base Flow Index (and hence more responsive the catchment), the greater the effect of a dry summer on summer flows and hence the greater the increase in the range of flows through the year. In less responsive catchments, the effects of the drier summer are counteracted by the higher rainfall in the preceding winter and spring.

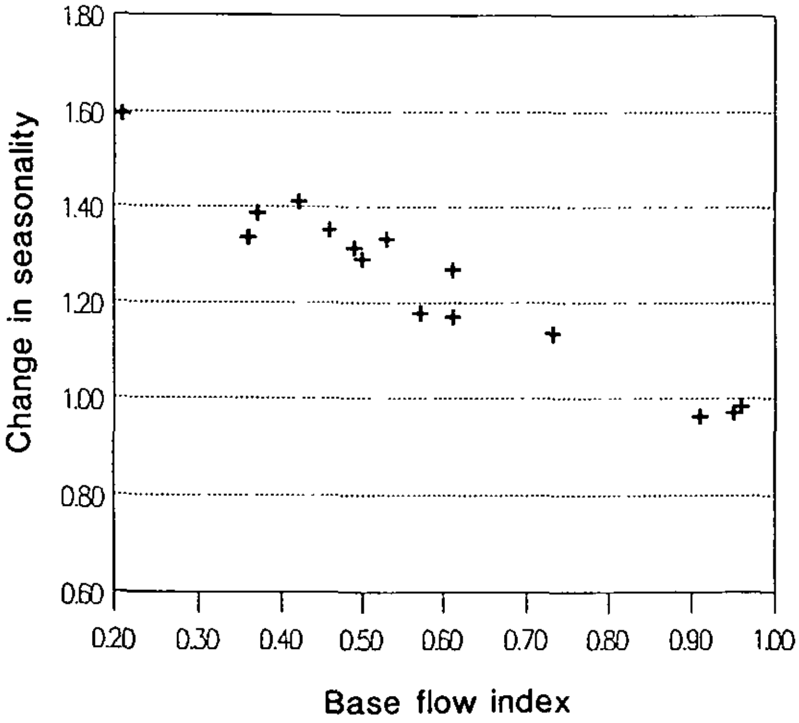


Figure 9.11 Change in runoff seasonality (winter runoff/summer runoff) under scenario PA2. The graph shows the seasonality index under scenario PA2 divided by the index under current climate.

Absolute amounts of potential evapotranspiration in winter are low, and it is therefore expected that an increase in annual potential evapotranspiration according to scenario EVP1 would have a greater effect on spring and summer flows and hence increase flow seasonality. Only two catchments in fact show a substantial decrease in seasonality (implying a relatively greater effect in winter), and most show either very little change or an increase. The catchments with reductions or little change in seasonality are those with the greatest current potential evapotranspiration in winter.

This section has shown that the effect of a change scenario on flow seasonality - as crudely indexed by the ratio of average winter to summer flows - varies considerably between catchments, and is strongly influenced by both catchment geology and current climatic conditions. If summers become wetter, for example, the greatest increase in seasonal variation is expected in catchments with a low runoff coefficient and a current summer water balance deficit, as is found in the south and, particularly, the east of England. If summers become drier, the geology of the catchment exerts a greater influence on changes in seasonal variation, with the most noticeable increases in variability in responsive catchments. Changes in evapotranspiration will cause the greatest increase in seasonality where winter potential evapotranspiration is currently low.

9.5.3 Changes in the frequency of low flows

The rate of occurrence of low flows has important implications for water resources management. The flow exceeded 95% of the time (Q95), for example, is frequently used as a guide when controlling discharges from sewage treatment works and assessing licences for abstraction. A reduction in the frequency of occurrence of the current Q95 would mean that the potential for such discharges and abstractions would in turn be reduced. Three aspects of the rate of occurrence of low flows were considered in this study: the variation in low flows over time, as indexed by the slope of the flow duration curve; changes in the magnitude of the flow exceeded 95% of the time; and changes in the rate of exceedance of the current Q95. All the studies used monthly flow data, so the percentages refer to months.

If rainfall is increased by 20% in each month (scenario PA1), the catchments are evenly divided between those which show a steeper flow duration curve and those showing less relative variation over time. The greatest reduction in the slope of the flow duration curve is found in the catchments with the highest Base Flow Index. Under scenario PA2, however, 10 of the 15 catchments have steeper flow duration curves, although again the catchments with the largest groundwater component show a reduction in the slope of the flow duration curve. Ten catchments also show an increasing range of flows over time when climate changes according to scenario EVP1.

Even with the dry summers in scenario PA2, the absolute magnitude of Q95 increases in 12 of the 15 catchments studied, and in the remaining three the reduction is small. The amount of change is related to both the change in mean runoff and the catchment base flow index. A simple regression relationship shows that the increase in the magnitude of the flow exceeded 95% of the time is greatest when the mean flow increases the most (of course), and where the Base Flow Index is highest:

$$\frac{Q95_{PA2}}{Q95_{P0}} = -88.2 + 1.42 \text{ \% change in mean runoff} + 42.9 \text{ BFI}$$

$$N = 15$$
$$R^2 = 0.762$$

All the coefficients are significantly different from zero at at least the 99 per cent level. The Q95 in high BFI catchments was found to be up to 60 per cent larger under scenario PA2, even though summers were assumed to be drier. Similar relationships, although with lower R^2 and less significant coefficients, were found using both EVP1 and PA1.

Changes in the rate of exceedance of the flow currently exceeded 95% of the time were found to be closely related to catchment Base Flow Index. Even under scenario PA2, the current Q95 was generally found to be exceeded more frequently, as shown in Figure 9.12. Under scenario EVP1, the current Q95 was exceeded less frequently in all catchments, and in the highest BFI catchments would only be exceeded 88 to 90% of the time in future. The effects of higher evapotranspiration, however, tend to operate in the opposite direction to the effects of an increased concentration of rainfall in winter, and when the two scenarios are combined there is less change in the rate of exceedance of Q95. A reduction in rainfall of 10% (scenario PA5) was found to have a greater effect than EVP1, with the duration of time with flow less than the current Q95 nearly doubling.

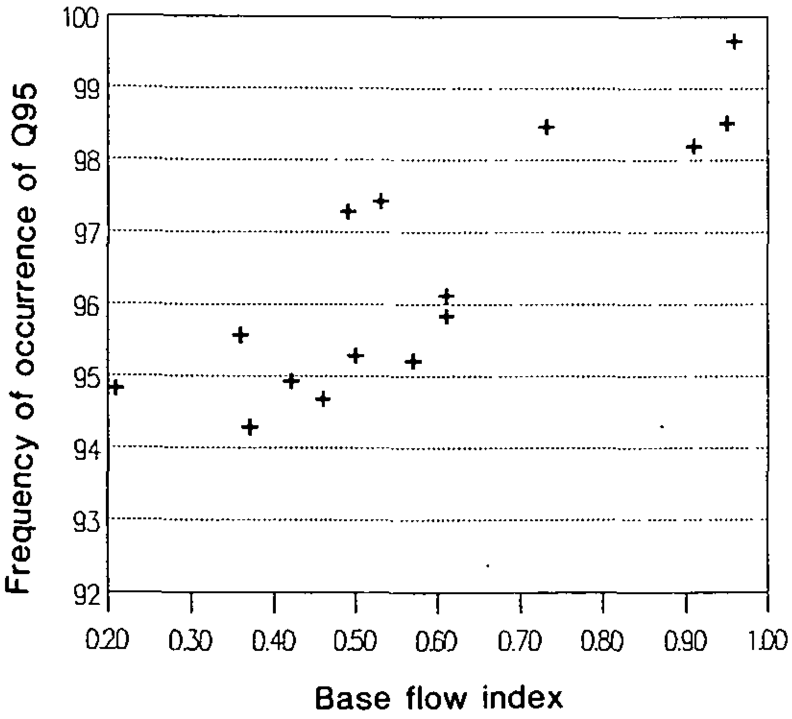


Figure 9.12 The percentage of the time the current Q95 is exceeded under scenario PA2

Taken together, these results imply that changes in the magnitude of low frequency flows are influenced more by changes in the mean flow than changes in flow duration curve steepness, and this supports the conclusions from the generalised procedures used in Chapter 8.

9.5.4 Changes in the rate of occurrence of extreme low flows

Water resource managers are perhaps even more interested in possible changes in the rate of occurrence of very extreme low flows. How frequently, for example, would droughts as experienced in 1976 occur in the future? The methods used in the current study, however, are much more suited to an assessment of changes in average rather than extreme flows. The most extreme summer flows on record were experienced at the vast majority of the 15 study catchments in 1976, and were considerably lower than in the next driest summer. An assessment method based on the perturbation of a relatively short instrumental record cannot give a meaningful indication of possible changes in the rate of occurrence of such low flows simply because the 1976 drought was so much more extreme than others in the short record available. The lowest flows in the other summers would have to be altered to a very large degree to result in an implied change in frequency of the 1976 drought. The most appropriate way of estimating changes in the frequency of very extreme droughts would be to generate very long time series from different populations which might incorporate changes in variability: this was not possible within the limits of the current study.

Instead, the rate of occurrence of a lesser drought - that experienced in 1984 - was examined under the various climate change scenarios. Table 9.7 shows the number of years of record containing a June, July and August runoff total less than or equal to that experienced (as modelled) in 1984, under current conditions and scenarios PA2 (a dry summer) and EVP1. The table shows that even if summer rainfall is reduced, the rate of occurrence of '1984 droughts' is reduced, and this is due to the effect of the wetter winter and spring. An increase in evapotranspiration, however, leads to an increase in the rate of occurrence of the 1984 drought in 11 of the 15 catchments. When the two scenarios are combined, the effect of the increased evapotranspiration generally has a greater influence than the reduced summer rainfall, and the frequency of the 1984 drought therefore increases.

9.5.5 Reservoir storage-yield relationships

What effect would the hypothesised changes in climate have on reservoir reliability? The precise effect on an individual reservoir would depend of course on the reservoir operating rules, the responses of the operators to evolving conditions and changes in demands. Nevertheless, some insights into sensitivities to change and the potential magnitudes of change can be obtained with the aid of storage-yield diagrams calculated for some hypothetical reservoirs.

The brief analysis in this study used the simulated data from five of the study catchments: Harpers Brook, the River Colne, the River Tamar, the River Dove

Table 9.7 The rate of occurrence of the summer (June, July and August) 1984 runoff under current climate and three change scenarios

		current	PA2	EVP1	PA2 + EVP1	years
25006	Greta	2	3	3	5	28
26003	Foston Beck	18	7	20	11	29
28008	Dove	4	3	6	3	35
32003	Harpers Brook	2	1	6	5	50
34004	Wensum	12	3	18	10	28
37005	Colne	5	2	9	7	30
39019	Lambourn	10	4	23	7	26
40007	Medway	3	2	5	5	29
42003	Lymington	2	1	2	2	29
43005	Avon	5	2	12	2	24
47001	Tamar	2	2	2	2	32
54008	Teme	4	3	8	7	32
54016	Roden	4	2	5	5	27
57004	Cynon	2	2	2	2	32
76005	Eden	3	4	3	4	24

and the River Greta. Yields were assumed constant throughout the year and not to vary as storage contents reduced, and evaporation losses from the reservoir surface were ignored (this assumption obviously omits the effect of increased evaporative demand on reservoir contents). Storage-yield relationships were estimated by first defining a series of critical storage volumes using a semi-infinite analysis and subsequently assessing the risk of failure of these storages using a simple behaviour analysis. This procedure ensures that the behaviour analysis is performed on storages which would just fail. The risk of failure was defined as the proportion of years the hypothetical storage was insufficient to meet the desired yield. The duration of reservoir failure was not considered. Storage performance under two scenarios, PA2+EVP1 and PA4+EVP1, was evaluated: both assume wetter winters and drier summers, the first with twice as great an increase in rainfall as the second.

Table 9.8 shows the storage required to maintain a given absolute yield under the two climate change scenarios as a percentage of the storage which currently provides that yield with a 5% probability of failure (the tabulated values are interpolated from storage-yield diagrams and hence imprecise). 'Low' and 'High' yields, corresponding to yields equal to 30% and 70% respectively of the current mean flow, were considered.

Under the wetter of the two change scenarios (PA2+EVP1), a smaller storage would in the future be sufficient to maintain both the 'low' and 'high' yields in four of the five catchments. There are indications that a greater reduction would be possible in catchments with a lower runoff coefficient, where a given increase in rainfall gives a greater increase in runoff. Greater reductions would also be possible in storages supplying low yields. In the fifth catchment,

Table 9.8 The storage needed to supply constant yield with 5 per cent risk of annual failure, expressed as percentage of the current storage requirement

		Yield=30% of current mean flow		Yield=70% of current mean flow	
		PA2+ EVP1	PA4+ EVP1	PA2+ EVP1	PA4+ EVP1
25006	Greta	108	113	101	106
38008	Dove	99	103	88	102
32003	Harpers Brook	71	85	89	106
37005	Colne	68	99	85	105
47001	Tamar	97	101	97	105

however, a drier summer with higher potential evapotranspiration leads to a considerable reduction in summer runoff (see Section 9.5.1), and hence an increase in the storage required to maintain a given yield.

A rather different picture emerges with scenario PA4+EVP1, which assumes rather smaller increases in winter season rainfall. The storage required to maintain a low yield could be reduced in some catchments (possibly those with lower runoff coefficients) and would need to be increased in others, but the storage necessary to maintain a high yield would need to be increased in all the catchments.

The results serve to emphasise that high yield reservoirs are likely to be most affected by future climate change, and also that the degree of impact is quite dependent on the degree of change in rainfall: the examples here imply that a 20% increase in winter season rainfall would allow a smaller reservoir, whilst a 10% increase would require a larger one to maintain the same yield. Catchments with the greatest potential for reductions in summer runoff - responsive catchments with a current excess of summer rainfall over evapotranspiration - would need larger reservoirs to maintain yields even if winter rainfall were to increase by 20%, and many reservoired catchments fall into this group. Increased evaporation from reservoir surfaces would increase the need for larger reservoirs.

These rather limited studies with a 'naive' reservoir model have indicated the potential sensitivity of reservoir sizes (and, by inference, yields) to future climate change, and showed that even though annual runoff may increase, larger reservoirs may be necessary where high yields are required. Further studies would incorporate explicitly possible increases in reservoir evaporation, would use longer input time series (the storage-yield diagrams in the current study were based on between 30 and 50 years of data, and were consequently far from smooth), would consider more indices of reservoir performance (such as time to drawdown and date of replenishment), and would apply realistic operational rules to model the change in yield during a dry summer.

9.6 SUMMARY AND CONCLUSIONS: POSSIBLE CHANGES IN FLOW REGIMES IN A WARMER UK

Since 1977 a great many case studies of the possible effects of climate change on river regimes and, less frequently, water resources potential have been published. The studies all combine input series of climate data under a range of change scenarios with a rainfall-runoff model. Models range in complexity from simple water balance calculations to complicated many-parameter daily simulation models. However, there have been very few studies in humid temperate areas such as western Europe which are of direct relevance to Britain (the most notable exception being Bultot *et al.'s* (1988) study in Belgium), and there have been no attempts to determine which aspects of a catchment's current physical and climatic attributes control its sensitivity to a given climate change scenario. The current study marks the first attempt to define potential changes in flow regimes in Britain, and to identify factors which control catchment sensitivity to change.

Before summarising the conclusions and suggesting possible changes under what are currently believed to be the most feasible scenarios, it is necessary to sound a few notes of caution. The analysis used a very simple model of catchment response to climate, and assumed that the parameters of this model would not change as climate evolved (all other studies have of course had to make this assumption). A different model might, however, produce slightly different results. The current study has implied that increased winter and spring water surpluses would help to maintain summer runoff, and variations in the treatment of increased surpluses between models could therefore lead to important differences in estimated summer runoff. Indeed, Wright's (1978) model predicts a rather greater reduction in summer flows in a few test catchments than the monthly water balance model, and hence implies a greater change in the risk of summer shortages. The use of a daily, rather than monthly, accounting model might lead to greater high flows during winter and less water stored and available for maintenance of summer flows. The climate change scenarios were defined by applying constant perturbations to observed, relatively short, records, and therefore retain most of the characteristics of the original series, in particular their distribution of extremes. Finally, the results represent conditions under a new equilibrium climate: the route to this new equilibrium might pass through some periods with very different behaviour.

Although it is difficult to predict with certainty the future climate of Britain, a consensus is emerging that whilst winters might be warmer and wetter, summers are likely to become warmer and drier, except perhaps in the most humid western regions (Chapter 8; Rowntree, 1990b). Accordingly, the 'most feasible' scenarios selected for this final section are a combination of EVP1 - which gives an annual increase in potential evapotranspiration of the order of 15 to 16% and an increase in growing season evaporation in the south and east of England of around 50mm - and either PA2 - an average annual increase in rainfall of the order of 15%, with a decrease in summer and an increase in all other seasons - or PA4 (as PA2 but with just a 7% annual increase in rainfall). The changes are illustrated with the aid of four catchments which represent a range of conditions in England and Wales: the Greta is a rapidly responding upland catchment with a close summer balance between rainfall and evapotranspiration; Harpers Brook is a lowland catchment in eastern England, with a low runoff coefficient; the Medway has similar response characteristics, but a larger runoff coefficient; the Lambourn is a chalk catchment with very slow response to rainfall.

9.6.1 Average annual runoff

The response of different catchments to a given change in both average annual rainfall and potential evapotranspiration depends strongly on the runoff coefficient (the ratio of average annual runoff to average annual rainfall), as shown in Figure 9.7. The lower the runoff coefficient - and hence the larger the evaporative losses as a proportion of rainfall - the greater the sensitivity of catchment average annual runoff to change, assuming no change in potential evapotranspiration. In the driest catchments in Britain, for example, a given percentage change in average annual rainfall gives a three-times higher change in average annual runoff whilst in the most humid regions there may be only 20% amplification. The addition of changes in potential evapotranspiration complicates the relationship between changes in rainfall and changes in runoff, and simple amplification factors cannot be quoted. The relative effects of 10 and 20% increases in rainfall, for example, depend on the change in evapotranspiration (and hence therefore on runoff coefficient, which controls the effect of a change in evapotranspiration: the implied amplifications at 10 and 20% increases in rainfall become more different as the runoff coefficient reduces). With some combinations of changes in average annual rainfall and increases in potential evapotranspiration, humid catchments with high runoff coefficients show a greater relative change in runoff than drier catchments.

Table 9.9 shows the percentage change in average annual runoff for the four example catchments under the two scenario combinations PA2+EVP1 and PA4+EVP1. Changes in average annual runoff are very small under PA4+EVP1 - the increase in evapotranspiration compensates for the extra rainfall - and are well within current variability (but see Section 9.6.2 for a discussion on changes in flow seasonality, which may have very important practical implications). Changes in average annual runoff under the wetter PA2+EVP1 are rather higher, but are still less than the difference in average runoff between the 1980s and the 1970s (see Table 4.8).

The effect of a given annual increase in precipitation, however, depends on how that increase is distributed during the year, and the greater the concentration in winter, the greater the effect on average annual runoff.

Table 9.9 Percentage change in average annual runoff for four catchments

		PA2+EVP1	PA4+EVP1
25006	Greta	12.2	2.8
32003	Harpers Brook	14.5	-2.7
40007	Medway	16.3	3.7
39019	Lambourn	8.6	-8.2

Sections 9.4.1 and 9.4.2 showed that no one generalised empirical model provided 'accurate' estimates of changes in average annual runoff (relative to the water balance model) across all scenarios. Maps of the spatial implications of scenarios PA2+EVP1 and PA4+EVP1 were therefore produced by applying the monthly water balance model with 'representative' parameters to the mean monthly rainfall and potential evapotranspiration data held for each 40km x 40km MORECS box. Values of 150 and 0.1 were used for SMAX and α respectively: the value of the 'routing' parameter λ has no effect on annual totals. Figure 9.13a and 9.13b show how the two scenarios combinations would impact upon average annual runoff (remembering that one set of parameters was used throughout). Very large areas of the UK show a reduction in average annual runoff under scenario PA4+EVP1. The differences between the two maps emphasise the considerable uncertainties involved in estimating further changes in water resources.

9.6.2 Average monthly runoff

Most other published case studies show large changes in the seasonal distribution of runoff under warmer climates, which is attributed to an earlier snowmelt season (Gleick, 1987; Lettenmaier and Gan, 1990, for example). Although changes in snowmelt do not figure in the current study, large changes in seasonal runoff are simulated, with the percentage change in monthly flow depending closely on catchment geology and summer water balance. In slow responding catchments, higher spring and winter rainfalls could maintain higher river flows even during drier, warmer summers. Bultot *et al.* (1988) found the same in Belgium. In more responsive catchments, the extra winter rainfall runs off more rapidly, and drier summers lead to lower summer runoff totals. The greatest percentage changes in summer flows are found in responsive catchments which currently have a close balance between summer rainfall and evapotranspiration: a change in one or the other may lead to a very substantial relative change in available water. In catchments with a large summer deficit, an increased deficit has little relative effect on summer runoff but leads to lower autumn flows as storages take longer to replenish.

Figure 9.14 shows the percentage change in mean monthly flows under scenarios PA2+EVP1 and PA4+EVP1 for the four example catchments. In all catchments river flows under PA2+EVP1 are higher from autumn to spring, and despite the lower summer rainfall and higher potential evapotranspiration, summer flows are generally little affected. Only in the Greta catchment, which has rapid response to rainfall and a close balance between summer rainfall and evapotranspiration, are summer flows considerably reduced, with August flows reduced to nearly half of their current value. In the Lambourn, average flows are increased throughout summer. Rather different results appear with the less wet scenario PA4+EVP1. Increases in flow in winter are less, of course, and in Harpers Brook increases in evapotranspiration eliminate increases in runoff between autumn and spring. Flows are reduced throughout the year on the Lambourn. The results emphasise how sensitive implied changes in monthly runoff are to the nature of the climate change scenario, and that two equally feasible scenarios can give very different changes in flow regime: unfortunately it is currently not possible to chose between scenarios PA2 and PA4. Even though the changes in average annual runoff under PA4 are small, the modelled changes in the seasonal distribution of runoff could have important implications. It may not be possible, for example, to store the extra winter runoff for use when flows are lower during summer.

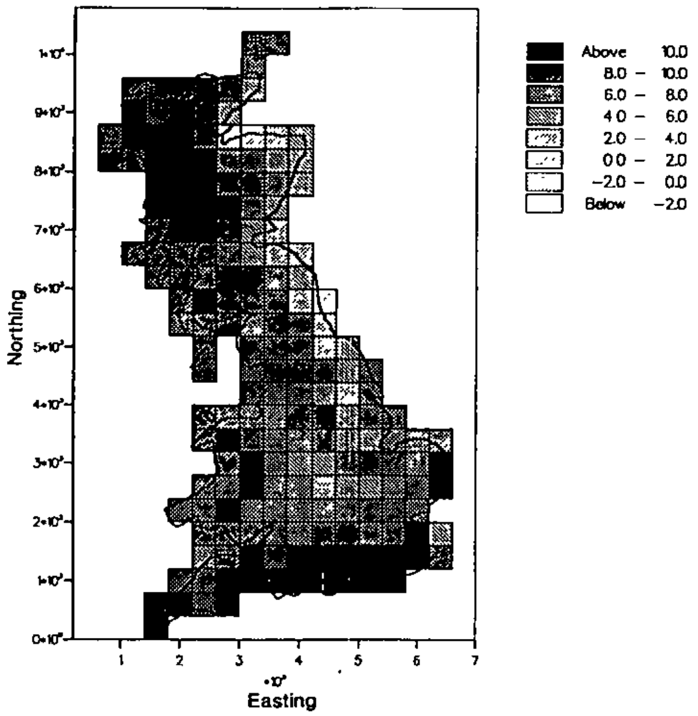


Figure 9.13a Percentage change in average annual runoff: scenario PA2+EVP1

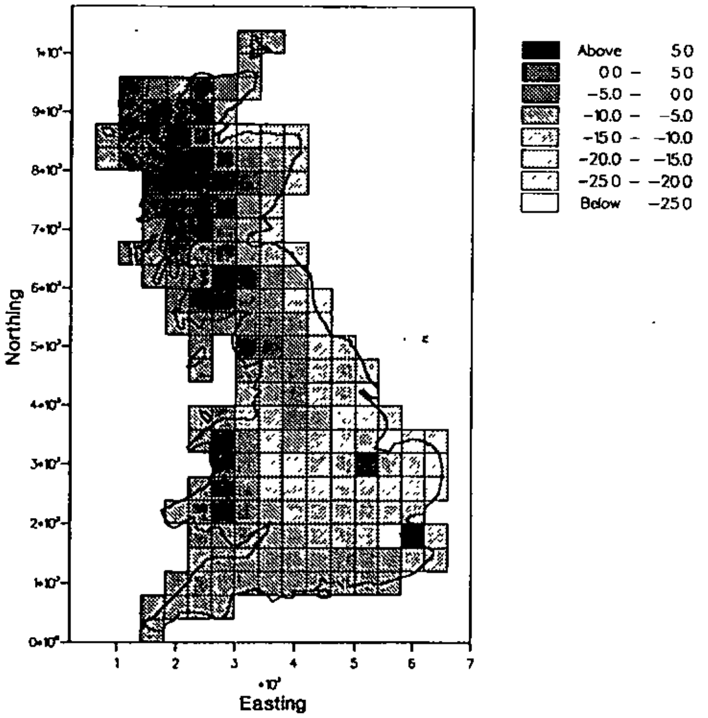


Figure 9.13b Percentage change in average annual runoff: scenario PA4+EVP1

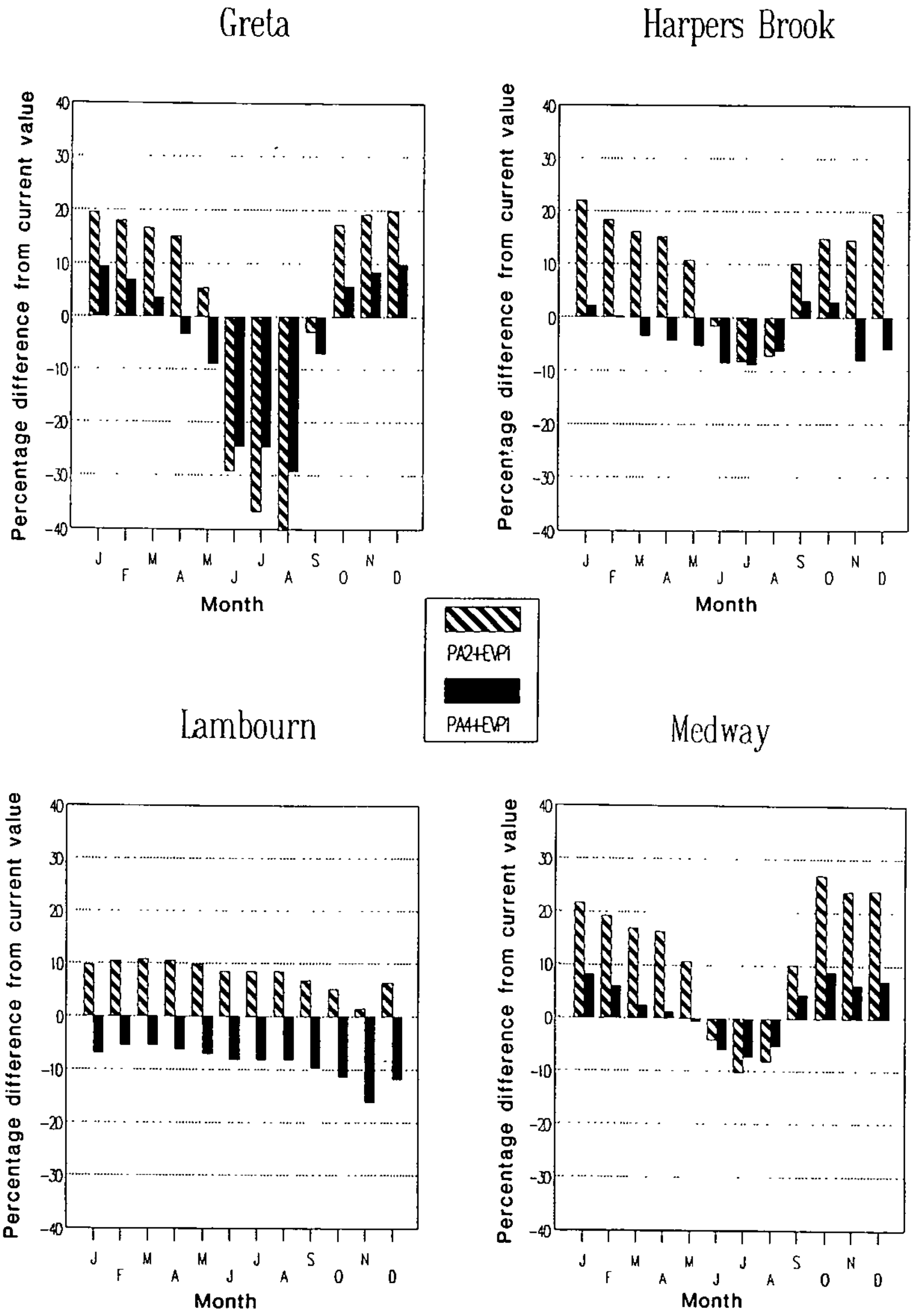


Figure 9.14 Percentage change in mean monthly flows under scenarios PA2+EVP1 and PA4+EVP1, for four example catchments

9.6.3 The frequency of low flows

The examination of the frequency of occurrence of low flows was hindered in the current study by the monthly timescale, the relatively short records (mostly less than 30 years) and the extreme nature of the 1976 drought. However, some conclusions about changing frequencies of low flows can be drawn.

Firstly, the change in slope of the flow duration curve is related to catchment geology, with slowly-responding catchments showing a flattening of the flow duration curve (implying less variability between months) and responsive catchments showing steeper curves. The change in the magnitude of flows exceeded with a given frequency was found to be related more to the change in mean flow than to changes in the steepness of the flow duration curve (as found in Chapter 8). Under scenario PA2+EVP1, the current flow exceeded in 95% of months would be exceeded more frequently in some catchments - e.g. Harpers Brook and the Lambourn - but less frequently in those catchments with lower summer flows - e.g. the Medway and the Greta. However, the differences are small. Over 10 years, monthly runoff would be less than the current 95 percentile value in six months: under scenario PA2+EVP1 the number of occurrences of such a runoff would change by at most plus or minus two months, depending on catchment geology and summer water balance.

Although it was not possible to estimate changes in the frequency of low flows experienced in 1976, because flows in that year were so much lower than those experienced in other years and very large reductions in runoff would be needed to create events that approached it in size, it was possible to assess changes in the frequency of the lesser drought as experienced in many of the catchments in 1984. Summer runoff was less than or equal to the summer 1984 runoff in two years in the Greta and Harpers Brook catchments, for example, and in three years in the Medway (in 28, 50 and 29 years respectively). Under scenario PA2+EVP1, such a low runoff would be experienced five times in the same number of years: the frequency would more than double. Summer 1984 runoff was not particularly low in the chalk catchment 39019.

9.6.4 Reservoir reliability

The current study has undertaken only a brief investigation of reservoir reliability, ignoring changes in operating rules and reservoir evaporation. Although evidence is limited, it appears that the same yield could be supplied with the same risk of failure from smaller reservoirs if rainfall were to increase according to scenario PA2, but that if the increase followed scenario PA4, larger reservoirs would be needed, particularly at higher yields. Larger reservoirs would also be needed - even under the relatively wet PA2 scenario - in catchments most prone to reductions in summer runoff, and many reservoired catchments in Britain are of this type: summers are characterised by an excess of rainfall over potential evapotranspiration, and the catchments respond rapidly to rainfall. Once again, however, it is important to emphasise that the possible change in reservoir yield and reliability is very strongly dependent on the assumed change in climate inputs.

This chapter has attempted to estimate sensitivities to change and predict possible future river flow characteristics using various scenarios of future climate. The next chapter considers what hints about the future might be contained in past records.

10. Estimating future river flows from past experience

10.1 INTRODUCTION

The studies described so far have attempted to define future flow regimes in Britain on the basis of the application and extrapolation of models predicting flow characteristics. Is it possible, however, to use past experience to provide directly information on potential future conditions? There are basically two ways in which recorded information can be exploited without the need to apply a hydrological model. In the first, past recorded data are used to define a future climate scenario, whilst in the second a pre-defined climate scenario - based perhaps on physical reasoning or GCM simulations - is used as a basis for a search for relevant information from similar periods in the past.

Chapter 7 has indicated the problems involved in using past instrumental data to define a climate change scenario (see also Lough *et al.,* 1983). Firstly, the differences between extreme warm and cool periods may be rather smaller than the changes anticipated under global warming, and unless some method is applied to scale up differences in hydrological characteristics, only qualitative assessments can be made. Secondly, the use of local, regional, hemispherical or global temperature data sets can identify different warm and cool periods. Thirdly, it is assumed that the differences in hydrological characteristics between two periods are not influenced by the reasons for the differences in temperatures between the two periods: all warming, from whatever cause, is assumed to have a similar impact. It is also assumed that the order of the warm and cool periods is not important. Finally, it is assumed that circulation patterns, rainfall and hydrology have adjusted within each warm and cool period to the warm and cool conditions.

The second approach - to look in the past for periods when climate was similar to that expected in the future - does not appear to have been used widely, but may be particularly useful in estimating impacts of particular extreme events.

Both approaches to estimating the hydrological impacts of climatic change are considered, rather briefly, in this chapter.

10.2 USING THE PAST TO DEFINE A POSSIBLE FUTURE

Lough *et al.* (1983) defined seasonal climate change scenarios for Europe and North America by comparing seasonal temperatures and rainfalls in the coolest and warmest decades between 1900 and 1980, using Northern Hemisphere average annual temperature data. The coolest 20-year period was 1901-1920, whilst the warmest, over the Northern Hemisphere as a whole, was from 1934 to 1953. Subsequently, Hulme and Jones (1987) compared 1901-1920 with the 20-year period with highest global mean temperature, 1968-1987 (1901-1920 was also a cool period in global time series).

Table 10.1 Differences in rainfall across England and Wales between warm and cool periods (from Hulme and Jones, 1988)

	1934-1953 cf 1901-1920	1968-1987 cf 1901-1920
DJF	-0.06	-0.03
MAM	-0.37	0.11
JJA	-0.27	-0.44
SON	-0.41	0.29
annual	-0.05	-0.02

The differences are expressed in standard deviation units.

Table 10.1 shows the difference in rainfall over England and Wales between the cool and two warm periods. Over the year as a whole, average rainfall was slightly lower in both warm periods. The warmer 20-year periods also both had wetter autumns, drier summers and slightly drier winters: in contrast, spring was wetter when 1968-1987 defined the warm period, and drier when the warm period ran from 1934 to 1953.

Palutikof (1987) compared the monthly river flows in Britain in 1901-1920 and 1934-1953, using reconstructed river flows from several catchments. Her analysis was repeated in the current study, using eight reconstructed flow series (there are too few long-record flow gauging stations) and several different warm and cool periods. Two comparisons used Lough *et al.*'s (1983) and Hulme and Jones's (1989) warm and cool periods:

(i) 1901-1920 compared with 1934-1953: based on Northern Hemisphere data;

(ii) 1901-1920 compared with 1968-1987: based on global temperatures;

A third comparison used Northern Hemisphere temperatures from 1880 to 1988 (data supplied by P.D. Jones, Climatic Research Unit), and defined a different cool period:

(iii) 1880-1899 compared with 1934-1953: note that the temperature data prior to 1900 are less reliable.

The final comparison used the Central England temperature series (also supplied by P.D. Jones), which showed the greatest contrast between:

(iv) 1885-1904 compared with 1942-1961.

Table 10.2 shows the differences in average annual runoff between each of the four sets of cool and warm years. The differences between catchments reflect not just differences in rainfall changes, but also the catchment runoff

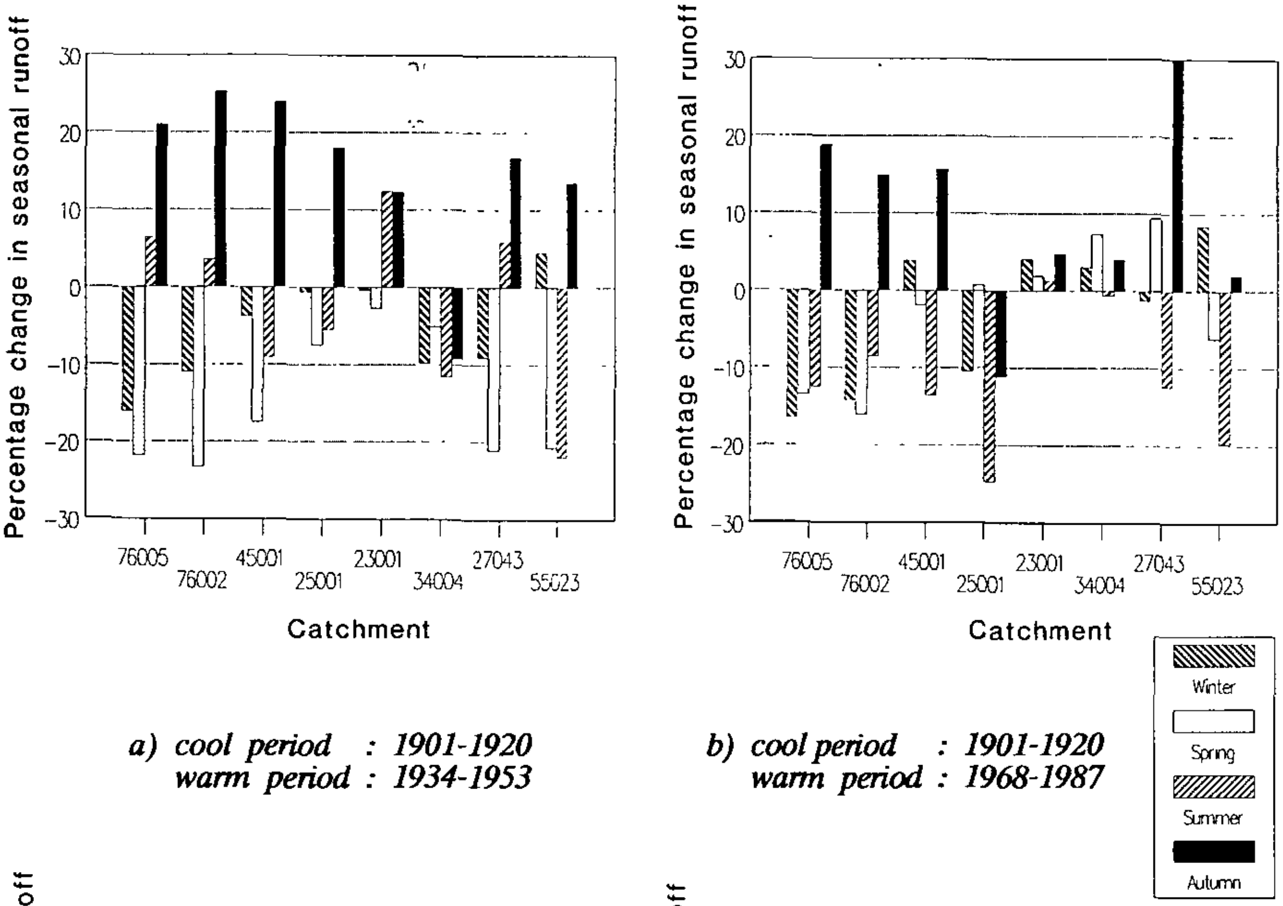
Table 10.2 Differences in average annual runoff

warm:		1934-1953	1968-1987	1934-1953	1942-1961
cool:		1901-1920	1901-1920	1880-1899	1885-1904
76005	Eden	-5	- 7	-4	-6
76002	Eden	-3	- 6	-2	-2
45001	Exe	-1	3	10	16
25001	Tees	2	- 10	0	0
23001	Tyne	4	4	9	4
34004	Wensum	-8	- 8	4	-1
27043	Wharfe	-3	8	-1	7
55023	Wye	-3	0	2	9

coefficient - which determines the amplification of rainfall changes - and differences in the inter-annual variability. However, it is the differences between the different warm and cool periods that is of interest here: in some catchments, these differences may be very large. Although some show consistent patterns across all the comparisons, others do not, and indeed show markedly different responses.

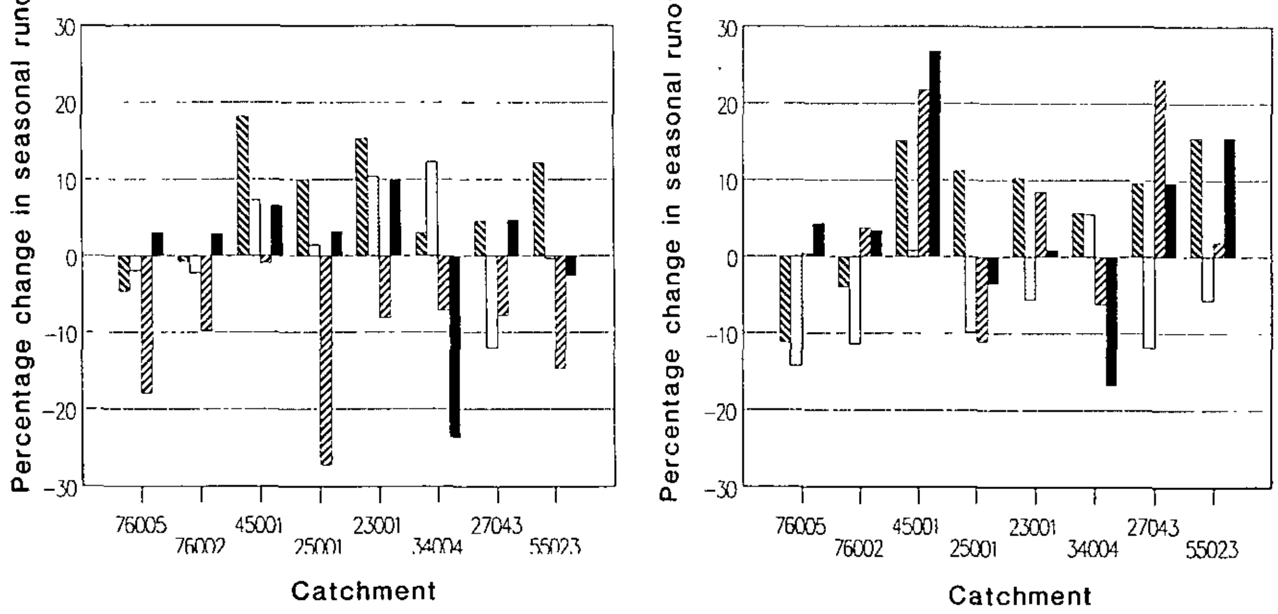
Figure 10.1 shows the change in average seasonal flows from the cool to the warm period for all four comparisons. Figure 10.1a basically reproduces Palutikof's (1987) results: autumn runoff was higher in the warm periods in virtually all the catchments, with winter, spring and summer runoff generally lower. Summer runoff was higher in the northern catchments in the warm period. Similar patterns are seen in the comparison between 1968-1987 and 1901-1920, with some exceptions. The higher summer runoff in northern catchments shown in 1934-1953 is less clear - one catchment shows just a slight increase - and the Wensum experienced increased flows in winter, spring and autumn. A similar pattern is found when 1880-1899 is compared with 1934-1953, although again there are exceptions. The increases in autumn flows in the warm period are less marked, and the Wensum shows a large reduction in summer and autumn flows. More strikingly, flows in the Thames are shown to increase considerably in each season. Under the earlier two comparisons they were lower during the warmer period. Different results again are seen when Central England temperatures define the warm and cool periods. Increases in runoff are more frequent, although five catchments show reduced spring flows, and autumn flows are again lower in the Wensum.

The different results from the different comparisons make it difficult to draw conclusions about possible future flow regimes from simple analogies with the past. The differences basically reflect differences in rainfall patterns in each of the test periods, and correlations between global and hemispherical temperatures and local rainfall are weak: autumn rainfall, is particularly poorly correlated with annual temperatures. Relationships do exist between local temperatures and local rainfall in some seasons - warmer winters in Britain tend to be wetter, for example, and warmer summers tend to be drier - but some years depart from the general trend (such as the mild but dry winter of 1988/89) and relationships in spring and autumn are weak. Karl and Riebsame



a) cool period : 1901-1920
warm period : 1934-1953

b) cool period : 1901-1920
warm period : 1968-1987



c) cool period : 1880-1899
warm period : 1934-1953

d) cool period : 1885-1904
warm period : 1942-1961

Figure 10.1 Change in seasonal runoff between warm and cool periods (expressed as a percentage change over the cool period)

(1989) showed that once differences in rainfall between different time periods were removed, differences in temperature had virtually no effect on differences in annual or seasonal flows. Chapter 3 similarly shows that annual variations in seasonal flows are much more strongly related to differences between years in rainfall than temperature. The value to hydrological investigations of temperature-based analogues which do not take into consideration rainfall differences is therefore rather limited.

10.3 INFERENCES FROM PAST EVENTS

In principle, one way of determining the effect of a trend towards wetter winters and springs and drier summers is to look for examples from past recorded data. For how long, for example, were summer flows maintained by the extra rainfall stored in winter and spring? However, it is difficult to find individual years that fulfill all the desired criteria. In no recent individual years have winter and spring both been consistently wetter than average or summer drier than average, and the occasional below- or above-average month is enough to confuse any patterns.

More potential is perhaps offered by individual extreme events. In a warmer Europe, for example, it is possible that the frequency of stable anticyclonic conditions affecting Britain in summer would increase, and an assessment of the impacts of such an event on river flows - and indeed demands for water resources - could be based on the 1976 drought. 1984 provides an example where a wet winter was followed by a dry spring and summer, with a subsequent summer drought. Information from extreme events can also be used the other way round: are the conditions which led to particular types of events - such as dry winters - likely to become more or less frequent in the future?

The application of the method requires, of course, both that the types of events expected in the future can be determined (from either physical reasoning or GCM simulations) and that similar events have been experienced in the past.

10.4 CONCLUSIONS

This rather brief chapter has indicated how information from the past may be used to estimate possible changes in flow regimes in the future. One method uses past data to define past analogues for future conditions, whilst the other searches in the past for examples of particular climatic behaviour.

It was suggested that the comparison of hydrological behaviour in warm and cool periods was not particularly helpful, because most of the difference in behaviour was due to differences in rainfall, and relationships between rainfall and, in particular, regional and global temperatures are weak (Chapter 3 has also shown how the variations between years in seasonal flows are strongly related to rainfall but poorly related to temperature). It is possible in principle, however, to define analogue periods on the basis of assumed changes in rainfall characteristics (or indeed on assumed changes in atmospheric circulation characteristics). Chapter 4 has indicated, for example, that the 1980s were wetter than the 1960s, with a tendency in some areas for summers to be drier in the 1980s. In broad terms, this difference is consistent with the climate change scenarios outlined in Chapter 7, and the difference in hydrological behaviour between the 1960s and 1980s can be taken as indicative of possible changes in the future. This has not been attempted formally, but some inferences are possible: winter and spring flows are increased, by a greater proportion than rainfall, and flows through the drier summer are maintained by the extra winter and summer rainfall. These conclusions support those derived from the hydrological modelling described in Chapter 9. The 1980s also seem to have been characterised by more variability, particularly in summer, than the 1960s, although whether this year-to-year variation can be expected in the future is uncertain.

11. Climate change and flow regimes in the UK: a summary

11.1 INTRODUCTION

Chapters 8, 9 and 10 have applied a variety of approaches to estimate the sensitivity of flow regimes in UK catchments to changes in climate. Detailed conclusions are drawn at the end of each chapter, and this chapter presents an attempt at a synthesis. Several points need to be emphasised at the outset, reiterating Chapter 6. Firstly, the results cannot be taken as definitive predictions of future flow regimes in Britain: current forecasts of future climate are extremely imprecise, particularly with regard to rainfall which is of course critical for any hydrological assessment. The studies aimed instead to define the factors controlling sensitivity to change, and the differences associated with different assumed future climates. Secondly, the studies represent sensitivities to changes in equilibrium conditions. Hydrological behaviour *en route* to a new equilibrium (if such a phenomenon exists) may be very different to initial or ultimate behaviour, and the hydrological characteristics of 30 years hence will not necessarily be only half as different from present conditions as the characteristics expected 60 years in the future. Thirdly, no attempt has been made to define possible changes in short-term aspects of flow regime such as floods or short-period flow duration curves. Fourthly, possible changes in the relative variability of climatic events have not been considered. Finally, emphasis has been placed on river flows: water resources have not been addressed explicitly, and changes in water resource management will have to reflect a variety of changes along with possible climate change.

This chapter summarises the methods used, indicating some methodological problems encountered, reviews the conclusions concerning changes in flow regimes, and finally attempts to consider - despite the caveats in the previous paragraph - the implications of changes in flow regimes for water resources.

11.2 METHODS USED

Three basic methods have been used to estimate possible future flow regimes.

The first analyses used simple empirical methods relating various indices of flow to climate and catchment characteristics. The approach relies on the assumption that variations across space between catchments can represent changes over time in one particular catchment, but has the advantage that assessments can be made at many sites. Included within this broad heading were attempts to estimate variations over time in flows in the UK using data from catchments in south west France.

Most other studies have used hydrological models of one form or another to estimate the effects of changing time series of climatic inputs, and the bulk of the effort in the current study was directed towards the application of a simple monthly water balance model at a range of 'typical' catchments in the UK. Unlike other studies, the current investigations attempted to define the aspects of the catchment and its current climate which controlled its response to a given climatic change scenario. Scenarios were defined by perturbing a time series of recorded monthly rainfall and potential evapotranspiration. Although such a procedure is simple, it does not allow an assessment of changes in the rate of occurrence of particularly extreme events. Even after rather extreme perturbations, minimum flows did not reach the extremely low levels experienced during the 1976 drought at most catchments, and the implied frequency of the event did not change. Future analyses should use longer input time series, which means that stochastic data generation techniques must be adopted.

The third approach adopted used recorded data from various periods in the past to define possible changes in flow regime. It was concluded that temporal analogues selected on the basis of temperature alone were of little direct relevance to hydrological impact studies, because the hydrological differences between two periods were controlled by the rainfall differences: these tend to show little relation to temperature. However, it may be possible to define past periods as analogues for future climates on the basis of rainfall patterns, and it appears that the contrast between the 1960s and 1980s in Britain might give some indications of possible changes in British flow regimes.

11.3 CHANGES IN FLOW REGIMES

In general, it was found that changes in flow regimes are very sensitive to the nature of the assumed change scenario, with some catchments far more sensitive than others.

Changes in catchment water balance were found to be more sensitive to changes in catchment rainfall than to changes in evapotranspiration (in many other studies changes in temperature were shown to be of extreme importance, as they determined the date of the onset of snowmelt: this is not as significant in Britain). Rainfall changes are amplified in changes in runoff, by factors ranging from 1.2 to 3 (assuming no change in evapotranspiration), with the greatest amplification in drier catchments where runoff is a low proportion of rainfall. The greater the concentration of the rainfall increase in winter, the greater the increase in average annual runoff. Results from the monthly models indicated that an increase in annual rainfall of 10% could, if concentrated in winter to a realistic degree, be equivalent to a 15% increase in rainfall in each month: it is the increase in average winter rainfall which determines the increase in average annual runoff. It was found that none of the various generalised procedures for estimating changes in average annual runoff performed particularly well across all possible combinations of scenario (assuming the monthly model results represented truth), with sensitivity to potential evapotranspiration change particularly different both between generalised procedures and between generalised and modelled. A regression model estimating changes in average annual runoff from the seasonal distribution in changes in rainfall and potential evapotranspiration was developed, and although it has some drawbacks, does enable estimation at many sites of the effect of seasonally-variable climatic changes. Using the model, it was found that, under one climate change scenario, average annual runoff would increase by between 12 and 30% (the greatest increase in the north and west where the effect of the increased evaporation is least), or between 20 and well over 200mm. Although this increase is only slightly greater than the change in runoff experienced in many catchments between the 1970s and the 1980s, it represents an average over a longer duration. An increase in average annual runoff over 30 years of approximately 20% would be without precedent in the last 60 years (although recorded flow data over this duration are rather sparse). In parts of the south east it is possible that the effect of increased evapotranspiration will outweigh the extra winter rainfall, and runoff totals could reduce: if evapotranspiration increased by 15%, annual rainfall would need to increase by at least 10% for runoff to increase in the drier regions of south east England.

Changes in summer river flows under drier summer conditions were found to be related to catchment geology and summer water balance. If summer is currently characterised by a considerable excess of potential evapotranspiration over rainfall, reductions in rainfall would have little effect on summer flows, but would delay the rise in flows in autumn. In contrast, a reduction in summer flows would occur if summer currently has a fine balance between rainfall and evapotranspiration - as is the case in many upland catchments. Catchment geology influences the effect of drier summers, by controlling the release of the extra winter and spring rainfall. Responsive catchments are more likely to experience reduced summer flows, particularly if the catchment currently has a close summer water balance. In catchments with a greater baseflow component (approximately half of the catchments studied), the extra winter and spring rainfall would maintain flows during summer. If evapotranspiration were to remain unchanged, summer flows would be increased in a future dry summer, but if evapotranspiration were to increase, summer flows would only increase in the most slowly responding chalk catchments. The importance of catchment geological conditions in controlling the response to wetter winters and drier summers was also shown in the comparison of flow behaviour in the 1960s and 1980s.

Changes in the variability in flow between years were not assessed, because of the difficulties in defining a meaningful scenario incorporating changes in the annual variability of climate.

11.4 SOME TENTATIVE IMPLICATIONS FOR WATER RESOURCES

It has been emphasised throughout this report that the studies have concentrated on potential changes in river flow regimes, and that the assessment of impacts on water resource management requires a more site-specific treatment. However, it is appropriate to conclude by considering some of the most general implications for water resource management. These implications can be considered as hypotheses for further study:

* Although average hydrological conditions in a changed climate are likely to be rather different than current conditions averaged over a few years, there will be a considerable overlap between the characteristics of individual years

under current and changed climates.

* The implications of increased winter and spring rainfall for increased supply depend on reservoir characteristics. Small reservoirs in particular are unlikely to be able to store the additional winter and spring runoff for use in the drier summers, and more (or bigger) reservoirs would be required if the extra winter and spring runoff needs to be exploited.

* Run-of-river abstractions in responsive, upland catchments may provide a lower yield during summer, even if the annual total runoff increases. Current yields may, however, be less affected in high baseflow catchments.

* Increased winter and spring rainfall implies an increase in groundwater recharge, and hence groundwater resources available through the summer, but drier and warmer summers will probably mean the recharge season begins later. Increased rainfall intensities could also mean that the extra winter rainfall would not contribute to additional recharge, although this depends on how winter rainfall changes (would it rain more frequently or more heavily?) and aquifer characteristics.

* Wetter winters and springs imply an increased risk of flooding. Not only might storm rainfalls increase in frequency, but catchments may be generally wetter. Drier and warmer summers, however, could mean that there is less opportunity for summer flooding, although this will depend on how summer rainfall characteristics change: warmer, more stable summers could produce more intense localised storms.

Additional implications of climate change for reservoir safety, power generation (hydro and thermal), navigation and urban drainage are considered in Beran and Arnell (1989), whilst Jenkins and Whitehead (1989) review possible implications for water quality.

It is clear from Chapters 8, 9 and 10 that any estimate of the possible effects of climate change on water resources in the UK will be extremely uncertain. The degree of climatic change assumed influences strongly the inferred change in resource availability, and in south east England in particular, slight variations in the assumed change in rainfall can make the difference between an increase in runoff or a decrease. However, site-specific studies using a range of scenarios will provide information about the sensitivity of a water management system to change. How much of a reduction in summer rainfall, for example, would result in sustained yields falling below some critical threshold? Is such a reduction in rainfall likely? As estimates of possible future climates become more refined, the range of scenarios considered can be narrowed.

12. Some suggestions for future research

12.1 INTRODUCTION

It is clear from the preceding chapters that much is still unclear about the nature of past variability in flow regimes and the impacts of possible future changes. The studies have highlighted many areas which merit further research.

12.2 CLIMATOLOGICAL INPUTS INTO HYDROLOGICAL STUDIES

* How do climatic characteristics vary over time? Is there a tendency for groups of years with similar characteristics to cluster, and if so, why?

* The vast majority of climate change impact studies conclude with a plea for better climate change scenarios. For hydrological purposes, answers are required to the following questions in particular:

- What could happen to seasonal and shorter-term rainfall in Britain?

- How can evapotranspiration be expected to change?

- How might short-term climate characteristics - such as the interval between rain events and event intensities - change?

- How might variability change? Is there a risk, for example, that whilst winters become on average warmer or wetter, occasional winters might be unusually cold or dry?

- How might change over the British Isles evolve as global climate changes?

Such questions can be addressed with the aid of general circulation models, but increased effort needs to be placed on the use of direct physical reasoning to construct indications of feasible changes and the differential impact of change across the UK. The construction of scenarios appropriate for hydrological impact studies should have a very high priority.

12.3 STUDIES OF PAST AND RECENT HYDROLOGICAL VARIABILITY

An understanding of current patterns of variability and their impact enables estimates of possible future changes to be placed in context. Research is needed into several areas:

- It is essential that long hydrological time series are maintained, and that efforts are made to assemble more long records. This involves the naturalisation of long gauged flow series, the compilation of long records from, for example, springs and reservoir inflows, and the reconstruction of flow series from past climatic records.

- How can the apparent non-random nature of hydrological time series be characterised? This is important for the generation of synthetic time series which attempt to maintain the characteristics of real data, and is vital for the assessment of risk over the next few years (irrespective of possible climate change).

- How does weather in the broadest sense - as defined by weather types, for example - relate to hydrological behaviour? What types of 'weather' tend to lead to particular types of events?

- What is the most appropriate standard period for the calculation of hydrological characteristics?

- What does the concept of a 'wandering' climate, with no stable long term mean, imply for the estimation of return periods of extreme events (again, irrespective of possible future climate change)?

- Can the effects of global climate change be seen in British rivers? Although records in British rivers are short, it may be possible to derive a test for the global warming hypothesis which uses information from rainfall, temperature and flow data from a range of sites - perhaps from all of Europe. The test would consider the spatial distribution of change, and compare it with that expected - from theoretical grounds - under global warming.

The highest priority tasks under this heading are to examine the implications of a 'wandering' climate for water resource assessment, and to define the most appropriate standard preference period for analysis.

12.4 THE IMPACT OF CLIMATE CHANGE ON HYDROLOGICAL PROCESSES AND REGIMES

A great deal has already been accomplished by many groups of researchers, but considerable uncertainties - other than those associated with the development of scenarios - remain.

- How might evapotranspiration change at the catchment scale? This requires some procedure for scaling up studies made at the plant or plot scale.

- How does the time-scale of modelling influence the implied sensitivity of a catchment to change? Daily-scale hydrological models need to be applied with daily-scale climate change scenarios to examine the importance of possible changes in short-term climate characteristics. How sensitive is the change in slope of a flow duration curve, for example, to the way a reduction in monthly rainfall occurs (i.e. whether daily rainfall totals reduce or the number of raindays declines)? It is possible that daily models will produce more rapid response to extra winter rainfall and hence imply less maintenance of flows during drier summers than do the monthly models used in the current study.

- Stochastic data generation techniques should be used to define scenarios for hydrological impact studies. Simply perturbing short recorded climate time series does not provide much information about changes in the rate of occurrence of extremes, and the implied changes are quite sensitive to the characteristics of the input series. The use of stochastic data generation would allow the construction of longer input time series, the incorporation of changes in variability, and the derivation of short-term 'nested' time series.

- Most studies currently use empirical rainfall-runoff models, and it is assumed that model calibrations would remain appropriate in a changed climate. Future studies need to consider more realistic physically-based models whose parameters both reflect the hydrological processes involved and can be modified in line with assumed changes in catchment characteristics.

- Attention has been concentrated so far on river flows, and needs to be shifted towards other hydrological characteristics such as soil moisture and, most importantly, groundwater.

- The changes in hydrological regimes associated with climate change need to be compared with those resulting from other changes. What are the relative effects of climate change and, for example, afforestation or increased abstraction?

The highest priority tasks under this heading are to develop stochastic climate change scenarios and apply daily time-scale hydrological models. The comparison of the effects of climate and other changes has the lowest priority.

12.5 THE IMPACT OF CLIMATE CHANGE ON WATER RESOURCES MANAGEMENT

The practical consequences of future climate change depend on how that change is managed by water resources systems. This is of course difficult to generalise, but despite the uncertain nature of climate change scenarios, it is not too early to embark upon a series of case studies or methodological investigations:

- How might different climate change scenarios impact upon selected water management schemes? What, for example, would be the effect on the frequency of restrictions on hosepipe use rather than on summer flow regimes? How could operating rules mitigate - or enhance - the effects of a climatic change? Many operational water management models now exist which may be used as the basis for such studies.

- How is it possible to estimate the performance of a scheme over the next, say, 30 years as climate evolves? Water resource planners are interested not just in new equilibrium conditions. One approach would be to develop a stochastic generation model which constructed synthetic input time series following some defined trend and exhibiting the characteristics (such as the tendency to cluster) of observed data. It would be possible to examine the sensitivity of assessments of future scheme performance to different evolutionary scenarios.

- How might changes in demand influence changes in resource availability, relative to changes in climatic inputs? Demand for water is sensitive to some aspects of climate, but is also determined by external, non-climatic, pressures.

- How can information on the implications of different scenarios best be presented to water planners? What degree of 'certainty' is needed before planners are prepared to respond to a threat of climate change?

Studies of the impact of climate change on particular water resources management issues are best delayed until more progress has been made with the application of short-time scale scenarios and hydrological models.

All aspects of water management are sensitive to possible climate change, and it is possible to contrive a multitude of research projects. It is appropriate to conclude by emphasising two points. Firstly, estimates of climate change are currently extremely uncertain, although they are expected to become better defined, and results of individual impact studies using a narrow range of detailed scenarios should not be taken too seriously. Secondly, however, more general climate change impact assessments provide extremely important information on the sensitivity of a system to change and the potential consequences.

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