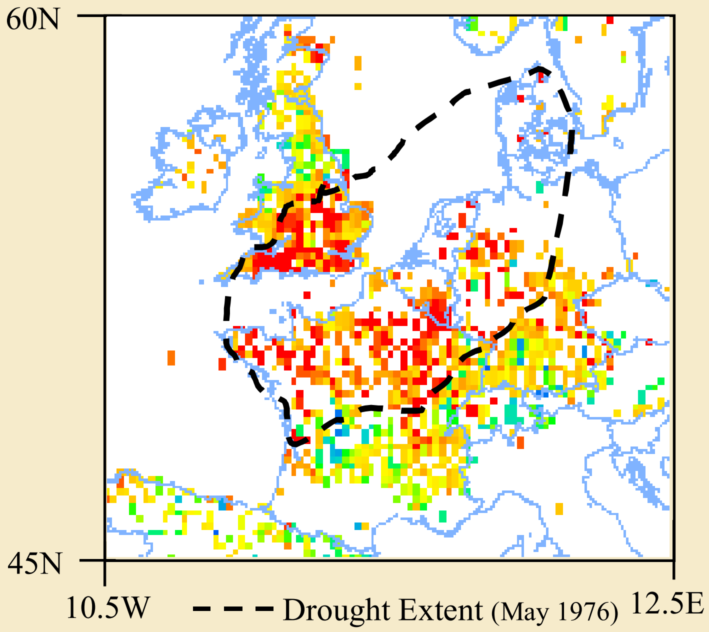
ARIDE

Assessment of the Regional
Impact of Droughts in Europe

Technical Report 8

Spatial Patterns of Streamflow Drought in Western Europe 1960 - 1995



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Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

Technical Report to the ARIDE project No.8

Spatial Patterns of Streamflow Drought in Western Europe 1960-1995

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Supplement to Work Package 3: Drought Visualisation

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Executive Summary

This technical report documents a study conducted as part of the ARIDE (Assessment of the Impact of Droughts in Europe) Project's third work package, *Drought Visualisation*. The study examined spatial and temporal aspects of the growth and decay of historical drought events in Europe, drawing upon daily river flow data stored on the FRIEND European Water Archive (EWA).

Flows in rivers located in Northwest Europe (including UK, Ireland, Belgium, the Netherlands, Denmark, France, Switzerland, Austria, Czech and Slovak Republics and Germany) were examined. Gauging stations not having data in the 1960-1995 period were excluded from the study. A methodology for mapping the spatial distribution of the flow deficit on each day was developed. Firstly each river flow was expressed as a standardised departure from the 1960 to 1995 mean daily flow. Standardised anomaly values for each station were then transferred onto an 18km resolution grid spanning the north west region of Europe (from 10.5^{o}W to 15.0^{o} E and from 45.0^{o}N to 60^{o}N).

A sensitivity analysis was used to determine the anomaly level most representative of the onset of drought conditions. A series of areal drought descriptors were developed to quantify variations in drought in terms of extent, severity and growth rate over time based on the grid data sets. Using a flow anomaly of 2 standard deviations as the drought threshold, the daily drought descriptors were determined for a number of drought events, including the 1976 and 1989/90 droughts.

The analysis showed a number of patterns common to both the 1976 and 1990 droughts. In both cases drought conditions began to appear during winter, but did not become widespread until the following summer. These observations show that antecedent streamflow, soil moisture and groundwater conditions are likely to have a strong influence on the severity and longevity of drought events. Each drought developed gradually with conditions spreading from west to east across northern Europe. Periods where large changes in flow levels occurred on a day by day basis were superimposed on this steady trend of drought growth, and were probably caused by short-term variation in the synoptic weather situation over Europe. The maximum spatial extent of drought was observed toward the end of the drought period and the area affected decreased rapidly once the flows started to recover.

Acknowledgements

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The analysis was based on daily flow data stored on the FRIEND European Water Archive. The authors gratefully thank and acknowledge those organisations that have contributed to the Archive over the past two decades.

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1 Introduction

1.1 Background

The ARIDE Study (Assessment of the Regional Impact of Droughts in Europe) is aimed at improving current understanding of hydrological aspects of widespread European droughts. The project is subdivided into five 'work packages', focussing either on physical processes that influence droughts (e.g. meteorology, hydrogeology), or on methods for monitoring, assessing and predicting droughts. Each work package is further subdivided into a number of specific activities, described in detail in the ARIDE Work Programme (Demuth (ed.), 1998).

Work Package 3, *Drought Visualisation*, focuses on understanding the mechanisms controlling areal aspects of drought development in Europe. As part of Work Package 3 a study of the spatial and temporal distribution of historic river droughts within Europe during the period from 1960 to 1995 was undertaken. Firstly visualisation techniques were used to create animations of streamflow data and to illustrate the chronological sequence of drought growth and decay. These techniques are described in ARIDE Technical Report 7 (Zaidman *et al*., 2000). In parallel with the visualisation, and documented in *this* report, a series of analyses of flow data stored on the FRIEND European Water Archive (EWA) were undertaken and used to quantify variations in extent, severity and growth rates during historic drought events

1.2 Aim of Study

Although likely to be triggered by lack of rainfall, drought is unique among atmospheric and other environmental hazards in that it creeps up gradually on the afflicted area. For example, during a prolonged dry spell runoff to small tributaries may cease some time before flow in the main channel falls to drought levels. Therefore characterising the spatial behaviour of past drought events could help us to predict how river drought conditions might spread during future events. This would lead to improved early warning and mitigation of droughts, and better management of integrated water resources during drought events (the UK Drought Mitigation Working Group (UK DMWG, 1996) highlighted the need for improved early warning of potential drought events).

Day to day changes in flow conditions across Europe can be linked to the synoptic weather situation in Europe and the North Atlantic, and can affect the short-term growth of a drought. The long-term development of each drought is, however, constrained by geography (e.g. the distribution of geology and soil types) and by the antecedent condition of groundwater and surface water systems. For instance flows in groundwater-fed streams are unlikely to decrease during a period with no rainfall, unless the groundwater table has dropped because of reduced recharge. Therefore is it possible to make a general characterisation of the behaviour of droughts in Europe?

The aim of this study was to improve our understanding of the dynamics of streamflow drought development in Europe from the catchment scale upwards. The main objective was to devise a method for defining the time-varying spatial extent and rates of drought growth of each drought event, and to apply this method to discern the repeatability of spatial patterns from year to year.

1.3 Methodology

The study was based upon flow data from rivers in north west Europe stored on the FRIEND European Water Archive (EWA), including those in the UK, Ireland, France, Germany, Netherlands, Belgium, Denmark, Switzerland, Austria and the Czech Republic. Gauging stations having less than 15 years data in the 1960-1995 period were excluded from the study, so about 2000 stations were used in all. Inevitably these were not uniformly distributed in space; the highest data density was in the UK and northern France.

As *streamflow* or river drought can be thought of as a period in which flows are critically depleted, an index that would indicate the size of the flow depletion on a daily basis, was developed. Each gauged daily flow was expressed as a standardised departure from the 1960-1995 mean daily flow for that day of the year. In this way when a flow is higher than the mean flow the flow anomaly is negative, likewise when the flow is lower, the flow anomaly is positive. Time series of daily flow anomaly values were derived for each station. These were then pooled to form spatial data sets based on a 18km resolution grid spanning the north west region of Europe (from 10.5°W to 15.0° E and from 45.0°N to 60°N). A sensitivity analysis was conducted to determine which flow anomaly level could be used as a critical value, representing the onset of drought conditions. The affects of using different threshold levels to define droughts in eleven different catchments were investigated. This analysis suggested that a flow anomaly of 2.0 standard deviations would be a suitable threshold level.

The time series of flow anomaly values for each station were analysed in order to gain an idea of their spatial coherency. For instance the number of drought events observed at each gauging station were identified, and from this drought frequency determined. A series of areal drought descriptors were then developed in order to quantify variations in drought in terms of extent, severity and growth rate over time based on the grid data sets. Using an anomaly level of 2 standard deviations from the mean as the drought threshold, the daily drought descriptors were determined for a number of drought events, including the 1976, 1989/90 and 1992 droughts.

1.4 Layout of Technical Report

Following this introduction, the methodology used for deriving the flow anomaly time series and grid data sets is described in Chapter 2. The sensitivity analysis used to determine the most suitable threshold to indicate the onset of a drought is reported in Chapter 3, whilst the temporal analysis conducted on the flow anomaly time series are described in Chapter 4. Chapter 5 is split into four parts. Firstly a review of previous studies of spatial aspects of drought development is given, followed by the derivation of the spatial descriptors developed in this study. The third and fourth parts of Chapter 5 describe how these descriptors were applied to the grid data sets. The results are focussed on two case studies; the 1976 drought and the 1989/90 drought.

2. Data

2.1 Standardised Flow Anomaly Data

2.1.1 Methodology

A standardisation procedure, in which gauged daily flows were expressed as a standardised departure from the normalised 1960-1995 mean daily flow, was adopted. In order to deseasonalise the data, each day of the year was considered separately. Firstly, the station flows for each particular day were drawn from the period of record flows to form a new data set. Each data set was log-transformed (flows generally conform to a log-normal distribution because of erratic high magnitude events), producing a normally distributed data set, and was then normalised to a mean of zero and standard deviation of one (by subtracting the mean and dividing by the standard deviation). A daily 'flow' value drawn from such a population therefore provides a numeric measure of departure (in standard deviations) from the mean flow. For any given day of the year (d) this departure, or flow anomaly, is given by

$$A_d = \frac{\overline{\ln Q_d} - \ln Q_d}{\sigma(\ln Q_d)} \qquad (2.1)$$

Where A_d, is the flow anomaly on day d, Q_d is the flow on day d, $\overline{\ln Q_d}$ and $\sigma(\ln Q_d)$ are the mean and standard deviation respectively, of the series of log transformed flows for day d. Where the flow is close to 'average' levels, A_d is close to zero, where conditions are drier than usual the anomaly is positive, and where it is wetter than average the anomaly is negative. In normal conditions the flow anomaly is likely to range between –1 to 1 (i.e. falling within one standard deviation of the mean) but would become increasingly positive as flows fall below the mean, and vice versa. Extreme values may be as little as –3 or as much as +3. Extreme low flows occur as the anomaly values become larger. For instance, an anomaly value of 1.65 is approximately equivalent to the 95th percentile flow (Q95), an anomaly of 2.0 to the Q98 flow and an anomaly of 3.0 to the Q99.87.

2.1.2 Data Quality

Here data quality relates to three specific issues: spatial density of gauging stations, period of record and accuracy of gauged flows. As this study examines spatial variability of droughts over time, a data set of high spatial density is essential.

Although a large amount of data from all over Europe has been collected together in the FRIEND European Water Archive, data availability differs from country to country. The spatial density of data and average record length is much lower in Iberian, Adriatic, Baltic and Eastern Regions than in western and central regions of Europe (data available on the EWA is listed in Appendix 1). To ensure an adequate spatial density of data points the study was limited to rivers in the north-western part of Europe, and only catchments located in UK, Ireland, France, Germany, The Netherlands, Belgium, Denmark, Switzerland, Austria, Czech Republic and Slovakia were included.

A common period of record is also essential when comparing standardised data sets, because although there is always some variability in total catchment runoff from year to year, this variability may be influenced by climatic trends if considered over long periods. Here data availability was in fact the main constraint on the choice of common record period. To ensure temporal coherence, a common period of 1961 to 1995 (35 years) was to be applied. As the number of gauging stations with a full record for the period from 1961-95 is small, those with fifteen or more years of gauged data between 1961 and 1995 were also considered. This assumed that changing the record length did not unduly affect the long term mean and standard deviation of each set of flows (and the flow anomaly values derived from them). A full list of catchments used in the study is given in Appendix 2.

The accuracy of the gauged measurements can also vary widely from region to region. The reliability of each discharge value depends on the accuracy of the level recording and on the accuracy of the stage-discharge relation used to determine the flow. Errors in stage measurement, for instance, often result from algal growths occurring on weir crests. Gustard *et al.* (1992) show that when flows are very low, a small percentage error in the stage measurement can produce a large flow error. Low flows are therefore often overestimated. In this study there has been no accounting for the reliability of data and no checks for artificial influences in any of the catchments from which data has been used.

2.2 Data Sets

Three distinct data sets were derived for use in this study, each having been derived from gauged daily flow records held on the European Water Archive (EWA) Oracle database and the UK National River Flow Archive (NRFA) Oracle database.

2.2.1 Station Time Series

Time series of daily flow anomaly values for the period 1960-1995 were derived for all UK stations using a PRO*FORTRAN program. The program consisted of two parts; in the first a call to Oracle was used to extract the gauged daily flow (GDF) records (period of record 1960-1995) from the NRFA database. Once the historic records for each gauging station had been downloaded, the second part of the program executed an algorithm that determined their mean and standard deviation and from this determined the standardised flow anomaly value (flow exceedance) for each day on record. At this point stations with less than 15 years equivalent of data in the 1960-95 period were disregarded. Those stations remaining were grouped into those stations with a full complement of values in the 1960-95 period, and those with between 15-35 years equivalent of data. The daily flow anomaly values for each station for all days in the record period were then output to file. A similar method was used to derive time-series for the selected catchments based on data stored in the EWA database.

2.2.2 NW Europe 18km (0.2^o) Resolution Grids

A time series of daily flow anomaly grids was developed. Each grid covered an area from 10.5^oW to 15.0^o E and 45.0^oN to 60^oN, with each cell representing an 18km by 18km area.
The gauged daily flow records (period of record 1960-1995) for selected stations on the EWA and NRFA Archives were used to derive the standardised flow anomaly value for each day on record. The daily flow anomaly values for each station for all days in the years 1975-77, 1983-84,1988-90 and 1992-95 were then output to file. Latitude and longitude co-ordinates were assigned to each station, the position of which was then mapped onto the 0.2^o resolution grid template. For each daily time-step the number of data points falling within each grid square was determined and the average anomaly value of those data points was calculated. This value was then attributed to the grid cell. Grid squares for which there were no data points were assigned null values. The grid cell values were systematically output to file, with a separate file for each

daily time step. Finally the grids were re-sampled in Lambert Azimuth projection with a cell dimension of 18km.

2.2.3 UK 2.5 km x 2.5 km Resolution Grids

Deriving grids by the method described in 2.2.2 takes no account of the size and shape of the catchment sampled at each gauge. As a result grid squares that do not contain gauging stations are assigned null values, even though they may be part or wholly contained within a catchment boundary. In the UK catchment polygons form an interlocking pattern, much like a patchwork quilt. If each polygon has an anomaly value associated with it, and a grid is overlain, each grid cell can be assigned a value according to the polygon(s) it overlays.

The ARC/INFO Graphical Information System (GIS) was used to convert flow anomaly values associated with digitised UK catchment polygons to grid cell format. The time series of flow anomaly data were first used to form ARC/INFO 'attribute' tables, in which the daily flow anomaly at each gauging station is considered as an attribute, or characteristic, of the digitised catchment area. However a particular problem was encountered when determining how to represent catchments that are nested within a larger catchment. After some consideration a simple approach was adopted, and the downstream catchment's value was assigned only according to the anomaly at the downstream gauging station, whilst the upstream catchment's value was assigned only according to the flow anomaly at the upstream gauging station. The attributes were then used to generate grids using Lambert Azimuth projection and with a cell size of 2.5km x 2.5 km. The grids covered the whole of mainland UK, and Northern Ireland. As this method is relatively labour-intensive daily grids were generated only for the 1975/1976 drought event.

3 Identification of Drought Periods

3.1 Defining Drought Events

In order to identify where and when a drought occurs, it is necessary to set a critical threshold at which the flow descriptor determines the on-set of a drought. Hisdal *et al*. (2000) assess the range of different methodologies that may be used to define this onset. Santos (1983), for example, proposed a time-varying threshold that accounts for the natural seasonal variation in flow, whilst others, such as Yevyevich (1967), have used constant threshold methods. In general the type of threshold used should depend on which numeric index is used as the flow descriptor. Whether constant or dynamic methods are used, both index and threshold level can strongly influence perceived spatial patterns of drought duration and frequency (Soulé, 1992).

In this study a constant anomaly level is used to define the threshold. As the standardised flow anomaly already accounts for seasonal variation in flow, using a constant anomaly threshold is actually equivalent to using a variable flow threshold (i.e. the absolute flow level corresponding to a particular flow anomaly will change throughout the year). Henceforth the term threshold refers only to an anomaly threshold, and the onset of drought is said to occur if the Standardised Flow Anomaly within a catchment, Z, is higher than the threshold level, Zo (i.e. Zo <= Z).

3.2 Threshold Selection

3.1.1 Sensitivity Analysis

As the threshold had to be set arbitrarily, a sensitivity analysis was conducted to assess the effect of using different threshold levels. An initial analysis of the time series data showed that the peak values of flow anomaly range between 1.3 and 5.3, with 99% above the 2.0 level, 88% above the 2.5 level and 48% above the 3.0 level. It is important not to set the threshold level so high that droughts are only observed at a few of the stations (if a threshold of 3.0 was used, drought conditions would never be observed in 52% of the stations, whereas if a threshold of 2.0 was used at least one drought event should be observed in 99% of stations during the study period). Based on these observations three different threshold levels (Z_o, Z_1, Z_2) were proposed; 1.75, 2.0 and 2.25. The 2.0 threshold represents the level at which the flow is two standard deviations lower than the mean flow, and is broadly equivalent to a flow exceedance of 98%, the 1.75 and 2.25 levels are broadly equivalent to flow exceedances of 95 and 98.5 % respectively.

3.2.2 Sensitivity of Drought Frequency

The analysis was conducted on eleven example catchments representing a variety of hydrological regimes, and geographic locations within Northwest Europe. The catchment details are given in Appendix3. The flow anomaly time series for each example catchment was examined, and periods of drought occurrence identified.

Table 3.1 *Summary of drought occurrences in the example catchments.*

Station	Threshold Used	Frequency of Drought	Max. Observed Duration of Drought Period (days)	Frequency of drought lasting > 14 days
27061	1.75	2.21	7	0
27061	2	1.11	3	0
27061	2.25	0.29	2	0
37005	1.75	1.56	31	0.17
37005	2	1.2	22	0.08
37005	2.25	0.89	21	0.03
40020	1.75	1.85	12	0
40020	2	1.29	6	0
40020	2.25	0.28	3	0
45003	1.75	1.27	23	0.03
45003	2	0.65	12	0
45003	2.25	0.21	10	0
53008	1.75	1.94	34	0.19
53008	2	1.12	24	0.06
53008	2.25	0.56	19	0.03
95001	1.75	2.55	24	0.38
95001	2	1.85	15	0.11
95001	2.25	0.92	9	0
422014	1.75	3.39	42	0.17
422014	2	2.04	32	0.03
422014	2.25	1.17	7	0
519021	1.75	1.52	19	0.03
519021	2	0.55	4	0
519021	2.25	0.12	2	0
1001009	1.75	1.44	42	0.25
1001009	2	0.87	34	0.09
1001009	2.25	0.44	17	0.06
1422071	1.75	2.68	39	0.25
1422071	2	1.79	27	0.11
1422071	2.25	1.29	18	0.04
1610946	1.75	1.99	36	0.20
1610946	2	1.21	25	0.04

Table 3.1 summarises how drought frequency varies in each catchment as each of the three different threshold values is used to define the onset of drought conditions. Table 3.1 also shows how the length of the drought periods varied as the threshold was changed. Although there is a wide variation is drought frequency in the different catchments, the choice of threshold has a strong influence on the number of drought events. In all cases observed frequency is at least two times greater when a threshold of 1.75 is used than when a threshold of 2.25 is used. The duration of each event also changes, droughts become distinctly of shorter duration as the higher thresholds are used. Changing the threshold from 1.75 to 2.0 has less effect than changing the threshold from 2.0 to 2.25.

3.2.3 Sensitivity of Drought Area

The analysis was conducted on twelve spatial data sets (flow anomaly grids) representing different seasonal regimes (3 each of summer, winter, spring and autumn). Using each of the thresholds, the areal extent of drought was determined. Table 3.2 summarises how drought area varies as each of the three different threshold values is used to define the onset of drought conditions.

Table 3.2 *Variation in measured drought area when different thresholds are used*

	1976				*1983*				*1990*			
Days *a*	*70*	*160*	*250*	*340*	*70*	*160*	*250*	*340*	*70*	*160*	*250*	*340*
1.75	211	478	447	19	3	4	25	33	39	42	130	46
2.0	116	305	285	13	3	0	10	16	22	23	75	21
2.25	73	172	180	9	2	0	5	7	7	13	41	7

In some cases drought area was four times smaller when a threshold of 2.5 was used compared to a threshold of 1.75. This effect was most evident during the spring and winter (days 70 and 340). Again the 2.0 threshold level is intermediate.

3.3 Proposed Threshold Level

The sensitivity analysis shows that when the threshold level is dropped from 2.25 to 1.75 the observed frequency of ‘drought events’ doubles, and the areal extent of drought quadruples. Between 2.25 and 2.0, these ratios fall to 1.2, -1.8 and ~1.5 respectively. Drought parameters are extremely sensitive to the precise threshold value, when the threshold is relatively low, but less sensitive to changes in the threshold as the threshold increases. As the 2.0 threshold represents the level at which the flow is two standard deviations lower than the mean flow and is roughly equal to the Q98 flow it was chosen as the threshold for this study.

4 Analyses of Time Series of Flow Anomaly

4.1 Drought Frequency

4.1.1 Method

The total number of days on which the threshold level was exceeded (N_d) was determined for each station using a threshold level of 2.0. From this the mean number of days per year or drought frequency, F_d, was determined. A number of other parameters were derived:

- The number of drought events occurring in the record period, N_e.
- The average number of drought events per year, or event frequency, F_e.
- The frequency of drought events lasting longer than a fortnight and a month (F_{14} and F_{30} respectively).

A distinction is made between a day during which streamflow drought is observed and a *drought event*. A drought event is a period of one or more consecutive days over which drought conditions are continually observed. Each event has a distinct start and end, and duration

4.1.2 Observations

As way of illustration of the types of variable observed, Table 4.1 shows the drought frequency parameters for the same eleven stations used in Chapter 3.

Table 4.1 *Drought and Event Frequency Parameters for eleven example catchments*

ID	River	N_d	F_d	N_e	F_e	N_d/N_e	F_{14}	F_{30}
27061	Colne	22	1.28	19	1.11	1.16	0	0
37005	Colne	172	4.78	43	1.2	4.00	0.08	0
53008	Avon	156	4.88	36	1.12	4.33	0.06	0
45003	Culm	54	1.59	22	0.65	2.45	0	0
40020	Eridge Stream	42	2.36	23	1.29	1.83	0	0
95001	Inver	172	9.34	34	1.85	5.06	0.11	0
422014	Nagelstedt	184	6.17	61	2.04	3.02	0.03	0.03
519001	Hronec	33	1.01	18	0.55	1.83	0	0
1001009	St. Hippolyte	163	5.09	28	0.87	5.82	0.09	0.03
1422071	Enchanet	206	7.36	50	1.79	4.12	0.11	0
1619046	Kappelrodek	121	4.72	31	1.21	3.90	0.04	

The rivers shown in Table 4.1 represent a range of hydrological regimes. The number of droughts observed per year ranged from 1 to 10, but the number of drought events observed per year was smaller, ranging between 0.5 and 2 events. Seven of the eleven catchments had experienced droughts lasting over two weeks, but the frequency of such events was much lower, between 1 in 10 and 1 in 20 years.

Figure 4.1 shows range of drought frequencies (in drought days per year) observed for all stations. The stations are grouped into FRIEND hydrometric regions. A map showing how Europe is divided into hydrometric regions is given in the Appendix.

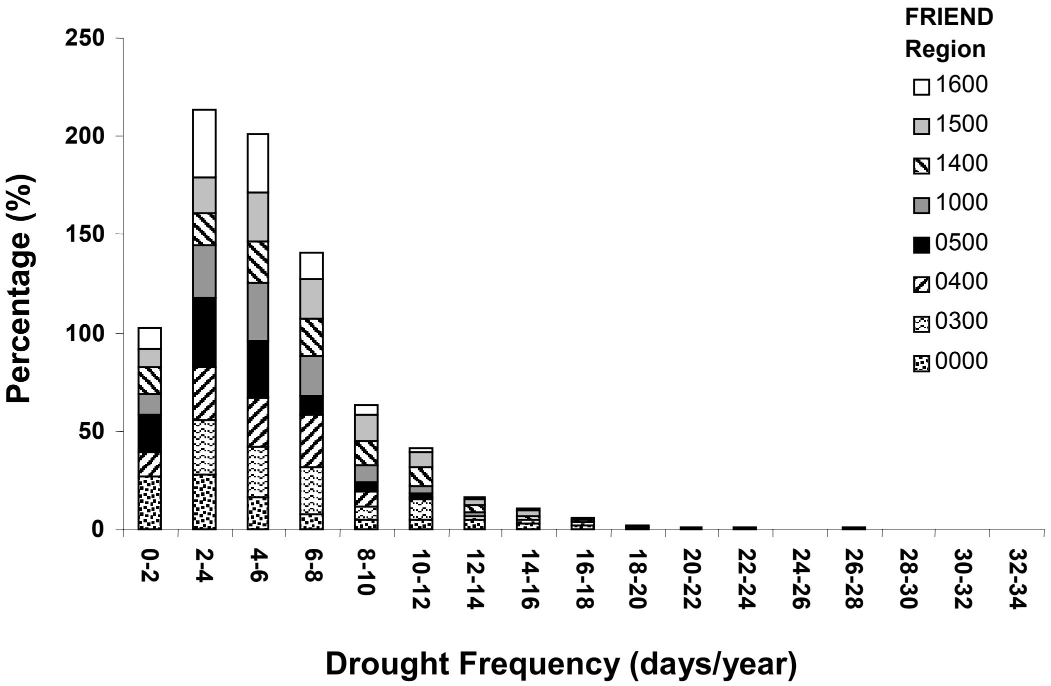


Figure 4.1 *Frequency of drought events in the different FRIEND hydrometric regions of Europe.*

Figure 4.1 shows that for most rivers in Europe, flow levels did not fall below the drought threshold for more than twelve days per year. In over half of the stations examined drought occurred on between two and six days per year, and for an eighth of stations there were less than two days per year. In a small number of stations the average drought frequency was quite high, up to 32 days/yr. The distribution of drought frequency is not, however, geographically uniform throughout Europe. For example the average frequency of drought tends to be low in Ireland (region 0300), and East Europe (0400,0500) but is skewed towards higher values in the UK (0000), northern France (1500), and Germany (1600).

Figure 4.2 shows the distribution of drought frequency in different areas of the England and Scotland.

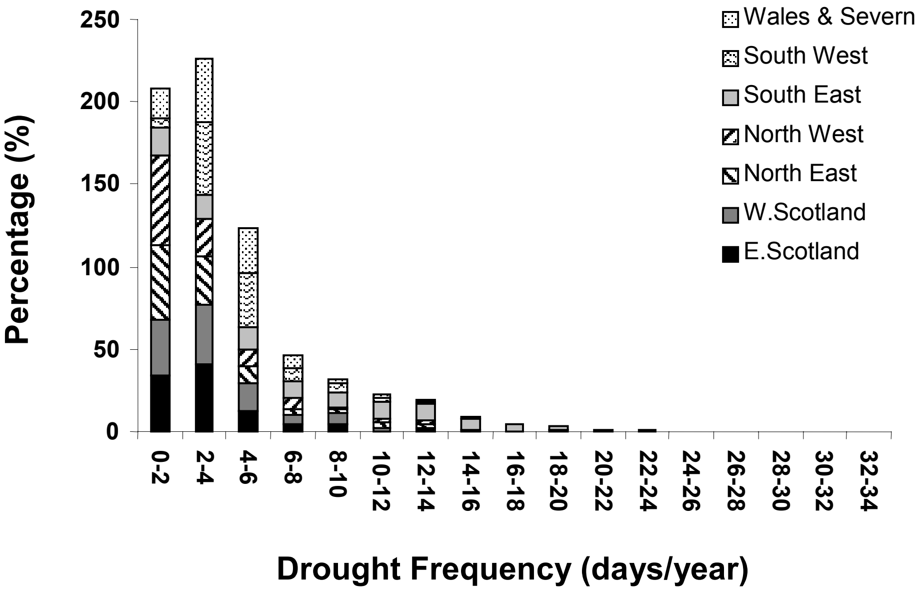


Figure 4.2 *Frequency of drought events in different areas of England and Scotland*

Figure 4.2 shows that most of the UK stations with high drought frequencies are located in the Southeast and East Anglia. Drought frequencies were lower for stations in Scotland and Northern England. This pattern may reflect rainfall distributions over Great Britain; high rainfall in Ireland, Scotland and the Northwest, and low rainfall in south easterly areas.

Figure 4.3 shows the N_d/N_e ratios for stations located in Europe, and Figure 4.4 those only for catchments located in the UK. This ratio indicates whether the catchments are more likely to experience short-lived droughts (lasting around 1 day in duration), or multi-day droughts. Where the number of events is much smaller than the number of days, the Nd/Ne ratio is high, indicating that most droughts are fairly prolonged events. The ratio also represents the average duration (in days) of a drought event. In both Europe and Great Britain, the Nd/Ne ratio for most catchments is less than 6, indicating relatively flashy behaviour. In Southeast England a large proportion of catchments had very high ratios, as much as 40 in some cases, indicating a high susceptibility to prolonged droughts.

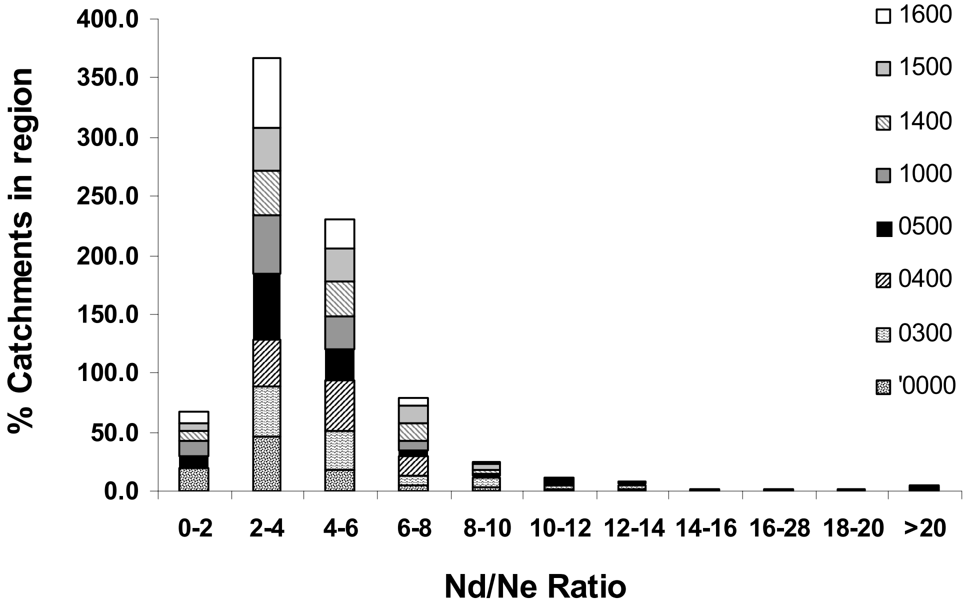


Figure 4.3 *Distribution of Nd/Ne ratios for mainland Europe*

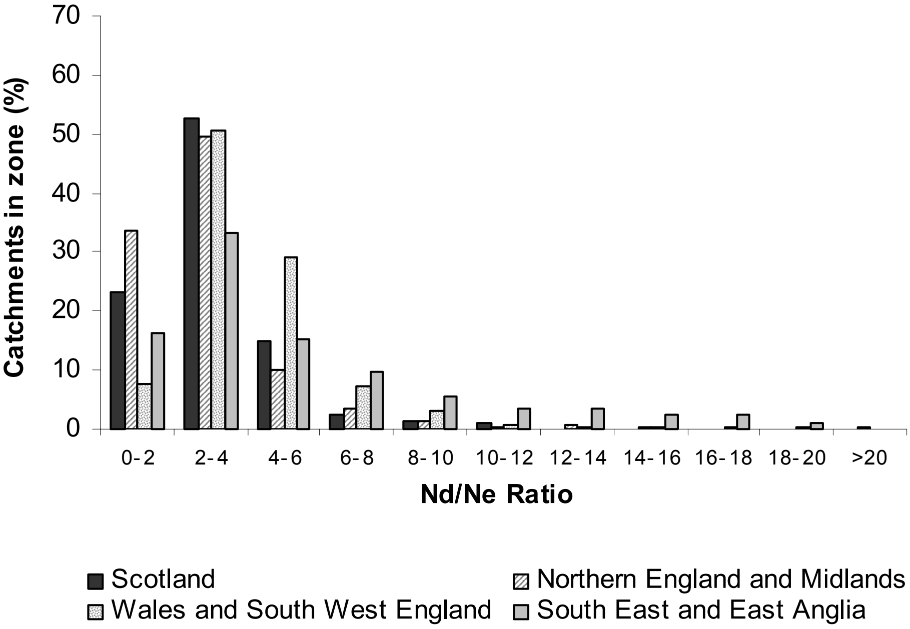


Figure 4.4 *Distribution of Nd/Ne ratios in different areas of the UK*

4.2 Duration, magnitude and timing of drought (events)

4.2.1 Method

The duration, magnitude and timing of drought events were investigated. A number of parameters were derived from each time series:

- The maximum event duration (in days), D_{max}.
- The maximum flow anomaly observed during the period of record, $Z_{max.}$
- The date on which the maximum flow anomaly was observed.
- The starting date of each drought event.
- The duration (in days), D_e, of each drought event.
- The average flow anomaly observed during the drought period, Z_A.

The first three parameters where used to characterise the behaviour of different catchments, the latter three compare different conditions during different drought events occurring within the same catchment.

4.2.2 Observations

Table 4.2 illustrates the duration and magnitude parameters determined for the eleven example stations. The frequencies of drought events lasting longer than 14 and 30 days are also shown.

Table 4.2 *Drought Duration and Magnitude indicators for 11 example stations*

ID	**River**	Z_{max}	**Date of** Z_{max}	D_{max}	F_{14}	F_{30}
27061	Colne	2.59	09/06/90	3	0	0
37005	Colne	3.89	08/07/76	22	0.08	0
53008	Avon	2.8	16/08/76	24	0.06	0
45003	Culm	3.39	15/08/76	12	0	0
40020	Eridge Stream	3.05	01/07/76	6	0	0
95001	Inver	2.86	23/09/93	15	0.11	0
422014	Nagelstedt	3.18	13/06/77	32	0.03	0.03
519001	Hronec	2.37	03/09/83	4	0	0
1001009	St. Hippolyte	3.19	19/07/64	34	0.09	0.03
1422071	Enchanet	4.24	27/11/78	27	0.11	0
1619046	Kappelrodek	2.74	19/02/63	25	0.04	0

A wide range of D_{max} values are determined for the different stations, ranging from a maximum duration of 3 days for 27001 (UK) and a maximum duration of 34 for 1001009 (France). Only two of the stations had droughts occurring longer than 30 days, in each case the F_{30} value indicates that this occurred only once during the record period. Seven of the stations recorded drought events lasting longer than 14 days, these events occurring about once every ten - twenty years. Z_{max} values ranged from 2.37 to 4.24. These events also occurred on a variety of dates.

To identify patterns in the duration, magnitude and timing of droughts, the parameters obtained for all stations were analysed. Figure 4.5 shows the distribution of D_{max} values observed.

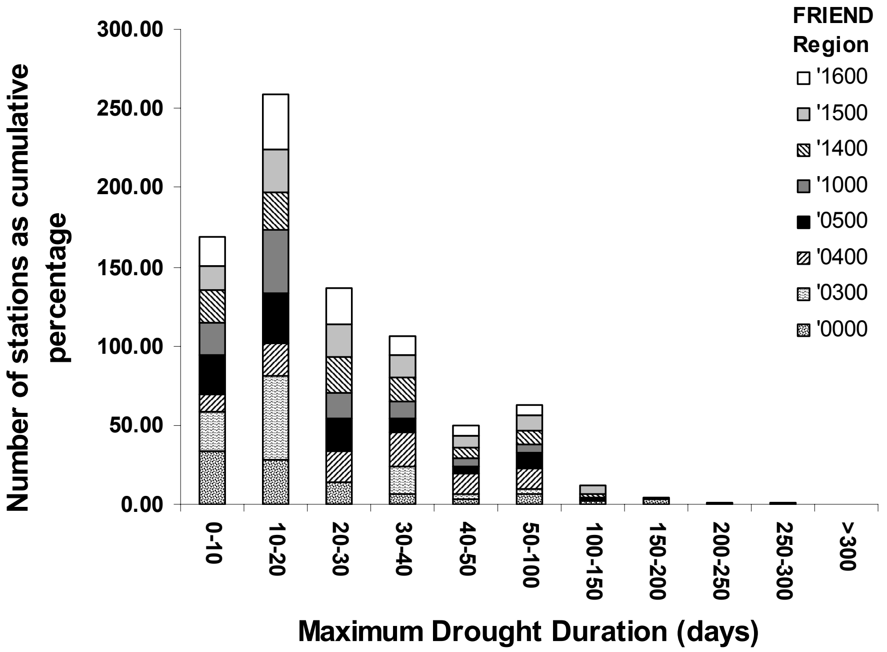


Figure 4.5 *Distribution of maximum drought event duration values for stations in Europe.*

The most frequently observed range of maximum duration (D_{max}) values was between ten and twenty days. A fairly large proportion of catchments also had durations ranging from one to ten days. This indicates that, during the study period, many of the stations in Europe did not experience droughts lasting longer than 20 consecutive days. However D_{max} values as high as 250 were observed at one or two gauging stations, implying that, in some locations, drought conditions lasted for nine or ten months.

Figures 4.6 and 4.7 illustrate the distribution of maximum flow anomaly values for different regions in the Europe and the UK respectively.

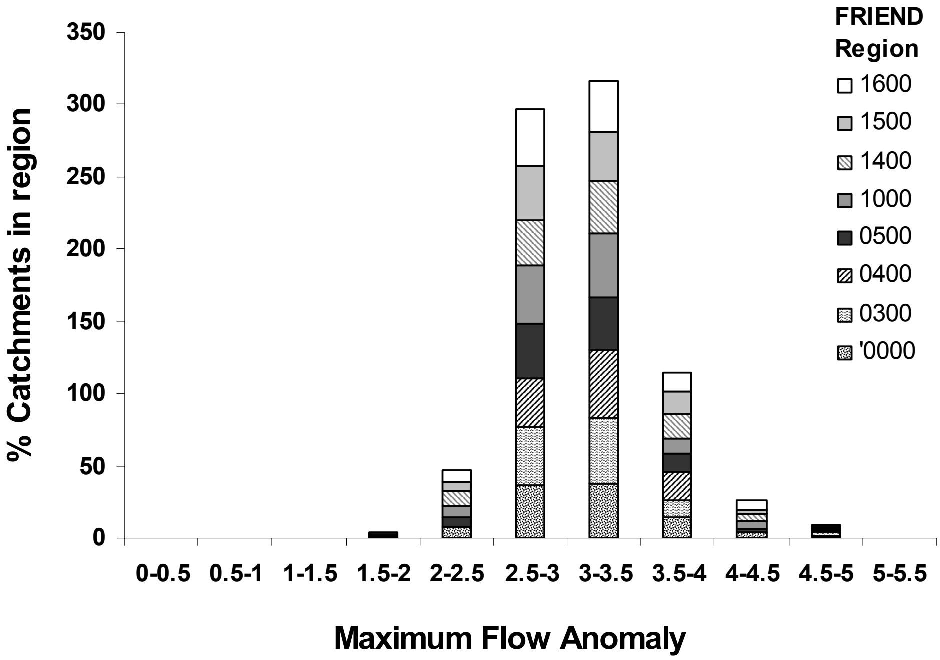


Figure 4.6 *Distribution of maximum flow anomaly value for drought events recorded at stations in Europe.*

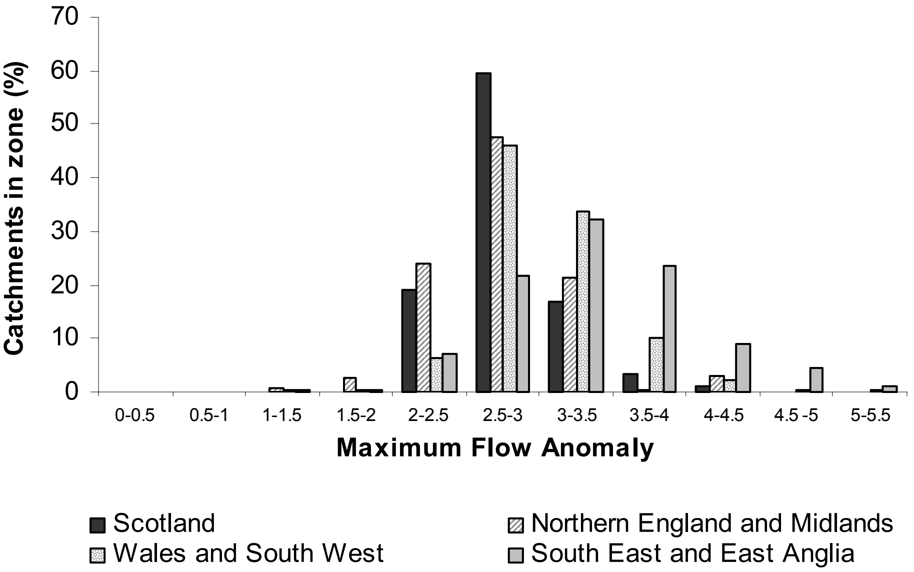


Figure 4.7 *Distribution of maximum flow anomaly value for drought events recorded at stations in UK.*

Figure 4.6 indicates that there seems to be little regional control on the severity of drought events, with over three quarters of the stations in Europe having maximum flow anomaly values falling in the range 2.5 to 3.5. All hydrometric regions had a small proportion of stations at which flow maximum flow anomaly values in the range 3.5 to 4.5 were observed. However most of the stations for which the flow anomaly was above 4.5 were located in central Europe (region 0500).

Figure 4.7 illustrates that on a country-wide scale there can be a large spatial variation in the maxmium flow anomaly. In the UK, high maximum flow anomalies were observed for stations Southeast England (upto anomalies of 5.5), whilst the stations in Scotland and northern England tended to have much lower maximum anomaly values. This means that the droughts that have been observed in southern England during the last 40 years have been more severe than those observed in the north.

The dates on which the maximum flow anomaly was recorded at each station were also identified, as shown in Figure 4.8.

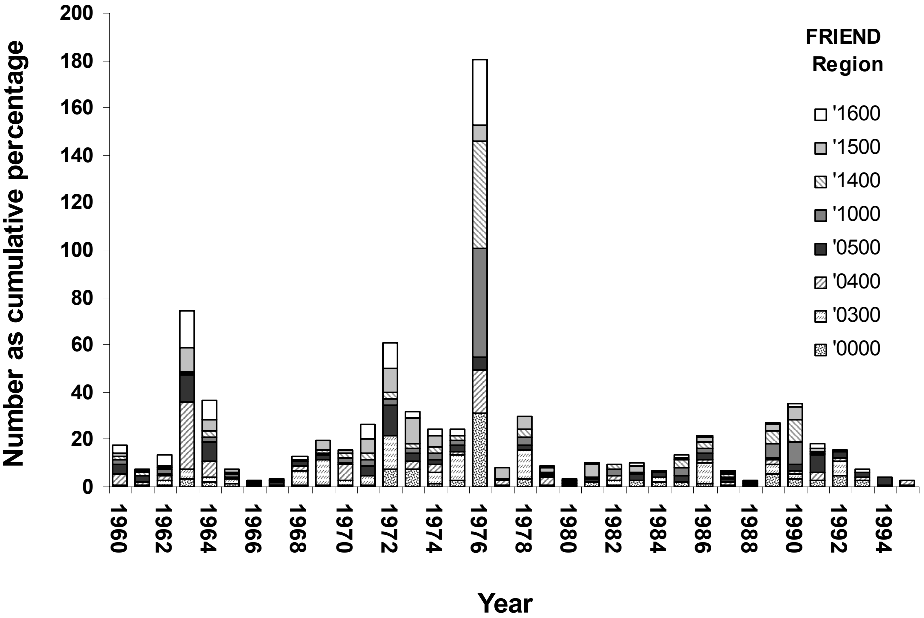


Figure 4.8 *Occurrence of maximum flow anomaly records for stations across Europe.*

Figure 4.8 shows that even in non-drought years a small number of gauging stations experience their lowest-ever-flows (highest flow anomalies). However there have been distinct episodes during which the number of stations experiencing their lowest-ever-flows has been very large. These episodes include the years of 1963, 1964, 1972, 1976, 1978, 1989 and 1990. Figure 4.8

shows that a widespread and severe drought took place during 1976. Nearly a quarter of all the stations examine Europe experienced their lowest-ever-flow during that year, this percentage being almost three times greater than observed during the next severe most year (1962). Distinct periods of drought occurred in the early 1970's and early 1990's. The distribution of lowest-ever-flows over time varies from region to region. For instance only a small proportion of stations in central Europe (region 0500) recorded low flows in 1976.

The dates at which the most severe daily flow anomalies, Amax, were observed for each of the example catchments are also shown in Table 4.2. Five of the eleven catchments suffered their greatest flow deficits during the summer of 1976, the remaining taking place during 1963, 1964, 1978, 1983, 1990 an 1993, thus reflecting the distribution observed in Figure 4.8. Although some indication of the susceptibility of a catchment to drought may be gained by calculating average drought frequencies, an indication of the distribution of drought events through time cannot. In any one catchments drought events are not usually evenly distributed through time; they usually occur in clusters. Appendix 4.1 gives details of the drought events occurring at station 37005. The duration and average flow anomaly for each event is also given. Of the 43 drought events that took place, seventeen occurred in 1965, five occurred in 1973, five occurred in 1974 and sixteen occurred in 1976. Similarly of the twenty events occurring at station 27061 (Appendix 4.2) over half occurred during the early 1990's.

4.3 Conclusions

Pan-European scale droughts occurring in the study period were characterised in terms of drought frequency, duration and anomaly. For most stations in Europe the average drought frequency was between two and six days per year. Only a very small percentage of stations experienced, on average, more than 12 days of drought per year. The average duration of a typical drought event was between two and four days, whilst the longest-ever-duration recorded was, on average, between ten and twenty days. In extreme droughts flow anomalies usually ranged from 2.5 to 3.5.

The analysis presented in this chapter did not show any marked variation in the drought frequency in different hydrometric regions in Europe. However the analysis of the data from the UK showed that at national scale, there were regional differences in the drought characterstic. For instance droughts occurring in the south east of England were more severe and of longer duration than those occurring in other parts of the UK.

5 Spatial Development of Streamflow Droughts

5.1. Review of Previous Studies

Areal aspects of drought development have received much less attention than temporal trends. In most previous studies drought distribution has been considered in terms of regions; characteristics of different regions have been compared and contrasted. Whilst a number of different meteorological indices have been studied, for example the Palmer Drought Severity Index (Briffa *et al*., 1984; Soulé, 1992; Karl, 1993), climatological indices (Bogardi *et al*., 1994) and rainfall (Oladipo, 1986), few have considered streamflow drought.

These studies have generally also fallen short of describing dynamic aspects of drought development. However Tase (1976), Santos (1983) and Sen (1998) made some progress in defining useful indices to describe and quantify areal drought characteristics. Tase (1976) used a polynomial method to produce area-intensity relationships for an interpolated grid of rainfall measurements. He then investigated the areal characteristics of the grid, using three indices; deficit area, total deficit and deficit intensity. He looked at the relationships between these variables for a large number of droughts and using a range of thresholds. Using predefined regions, Santos (1983) used an areal threshold value, to differentiate between local and regional rainfall drought events. She then used probability theory to make a stochastic characterisation of a number of random variables (such as duration, areal deficit) associated with regional rainfall droughts. Sen (1998) suggested two different models for drought growth, identifying that a localised area that becomes stricken by drought either i) remains in that state until the whole region is covered by drought (regional persistent drought) or ii) recovers and experiences 'wet' conditions in the course of time, even though drought is still experienced in other parts of the region (multi-seasonal drought). He then described this behaviour stochastically. Sen's work showed that the overall size and density of a drought depends on the proportion of catchments within a given area that are entering a cycle of recovery, and thus on the size of the flow deficit in each catchment. Mapping the spatial distribution of the flow deficit at each time step is therefore crucial to understanding the dynamics of drought development.

5.2 Methods of Analysing Spatial Behaviour

5.2.1 Introduction

Using the work of Tase (1976) and Sen (1998) as a starting point, a number of numeric descriptors were developed to characterise the spatial characteristics of a drought at any given moment in time. The descriptors, including drought extent, drought growth, rate of change of drought growth, total deficit and drought intensity, are presented in sections 5.2.2 through 5.2.5.

A series of Fortran programs were written to calculate each descriptor at each daily time step based on the grid data sets of flow anomaly described in Chapter 2. Time series of each descriptor were then derived, allowing each stage in the spatial development of a drought to be analysed. The development of droughts during 1976 and 1989/90 are presented as case studies in section 5.3.

5.2.2 Drought Extent

A grid cell is said to be in a drought condition if the flow anomaly value, Z, is higher than the threshold level (i.e. if $Z_o <= Z$). At any time interval a certain number of grid squares are likely to meet this criteria. This can be described mathematically by

$$A_d = \sum_{i=1}^{N_d} A_I \tag{5.1}$$

Where A_d is the total areal extent of the drought

N_d is the number of grid squares within the drought entity (i.e. for which ($Z<=Z_o$)

A_i is the area of the i^{th} grid square

As the grid is uniform $A_1=A_2=A_N$ and so on. Therefore, denoting the size of each grid cell simply as A, the area of the drought can be defined as

$$A_d = A. N_d \tag{5.2}$$

With A_d, A and N_d defined as before.

5.2.3 Drought Growth

The rate of change of drought area, or the rate of spatial growth, is given by

$$\frac{dA_d}{dt} = \mathrm{A}\,\frac{d(N_d)}{dt} = \frac{\mathrm{A}\,(\mathrm{N_d(t2)} - \mathrm{N_d(t1)})}{\Delta\mathrm{t}} \tag{5.3}$$

Where $N_d(t_1)$ is the number of cells under the drought condition at time t_1

$N_d(t_2)$ is the number of cells under the drought condition at time t_2.

Δt is the time interval between subsequent data sets.

If a time unit of one day is used the spatial growth rate in km^2 per day, G, is given by

$$G = \mathrm{A}\,(N_{d2} - N_{d1}) \tag{5.4}$$

where d1 and d2 are two consecutive days.

5.2.4 Rate of Change of Growth

The rate of change of growth shows whether the rate at which the drought extent is growing is increasing or decreasing, and is given by

$$\frac{dG}{dt} = \frac{d^2 A_d}{dt^2} = \mathrm{A}\,\frac{d^2(N_d)}{dt^2} \tag{5.5}$$

Where time is measured in discrete units this may be simplified to

$$\frac{dG}{dt} = \frac{\mathrm{A}}{\Delta\mathrm{t}}\,(\mathrm{N_d(t3)} - 2\mathrm{N_d(t2)} + \mathrm{N_d(t2)}) \tag{5.6}$$

Where $N_d(t_1)$ is the number of cells under the drought condition at time t_1

$N_d(t_2)$ is the number of cells under the drought condition at time t_2.

$N_d(t_3)$ is the number of cells under the drought condition at time t_3.

Δt is the time interval between subsequent data sets.

If a time unit of one day is used the spatial growth rate in km^2 day^{-2}, H, is given by

$$H = A\,(N_{d3} - 2N_{d2} + N_{d1}) \quad (5.7)$$

where d1, d2 and d3 are three consecutive days.

5.2.5 Total Deficit and Intensity Index

Some areas within the drought will be affected more severely than others. In these areas the cell condition will surpass the threshold level by a wide margin. There are two approaches to mapping the distribution of drought severity within the drought. Firstly the difference between the cell value and threshold value can be determined for each cell, giving an indication of the flow deficit of that cell and allowing isolines of deficit to be drawn.

$$S_I = Z_I - Zo \quad (\text{ where } Z_o <= Z_I) \quad \text{or} \quad (5.8)$$
$$S_I = 0 \quad (\text{where } Z_o > Z_I)$$

Where S_I is the flow deficit/ anomaly deficit of the ith cell

Z_I is the flow descriptor at the ith cell

Z_o is the threshold value

The total deficit of the drought, S_d, can therefore be derived from

$$S_d = \sum_{i=1}^{N_d} S_I \quad (5.9)$$

In the second approach a secondary and tertiary thresholds (Z_1 and Z_2) are set, each being incrementally higher than the original threshold. Each cell can then be categorised into one of three zones. The number of squares within the first zone, N_o, is defined by the condition

$$Z_o < Z \le Z_1 \quad (5.10)$$

where Z is the descriptor magnitude.

The number of squares within the second zone, N_1, is defined by the condition

$$Z_1 < Z \leq Z_2 \tag{5.11}$$

and the number of squares within the third zone, N_2, is given by the condition

$$Z_2 < Z \tag{5.12}$$

Likewise values for area, growth and rate of change of growth can be determined for each zone i.e. by determining (A_0, A_1, A_2, G_{Z0}, G_{Z1} and $G_{Z\,2}$ and so on.
An intensity index can be assigned to each drought based on the fraction of squares in the most severe contour interval.

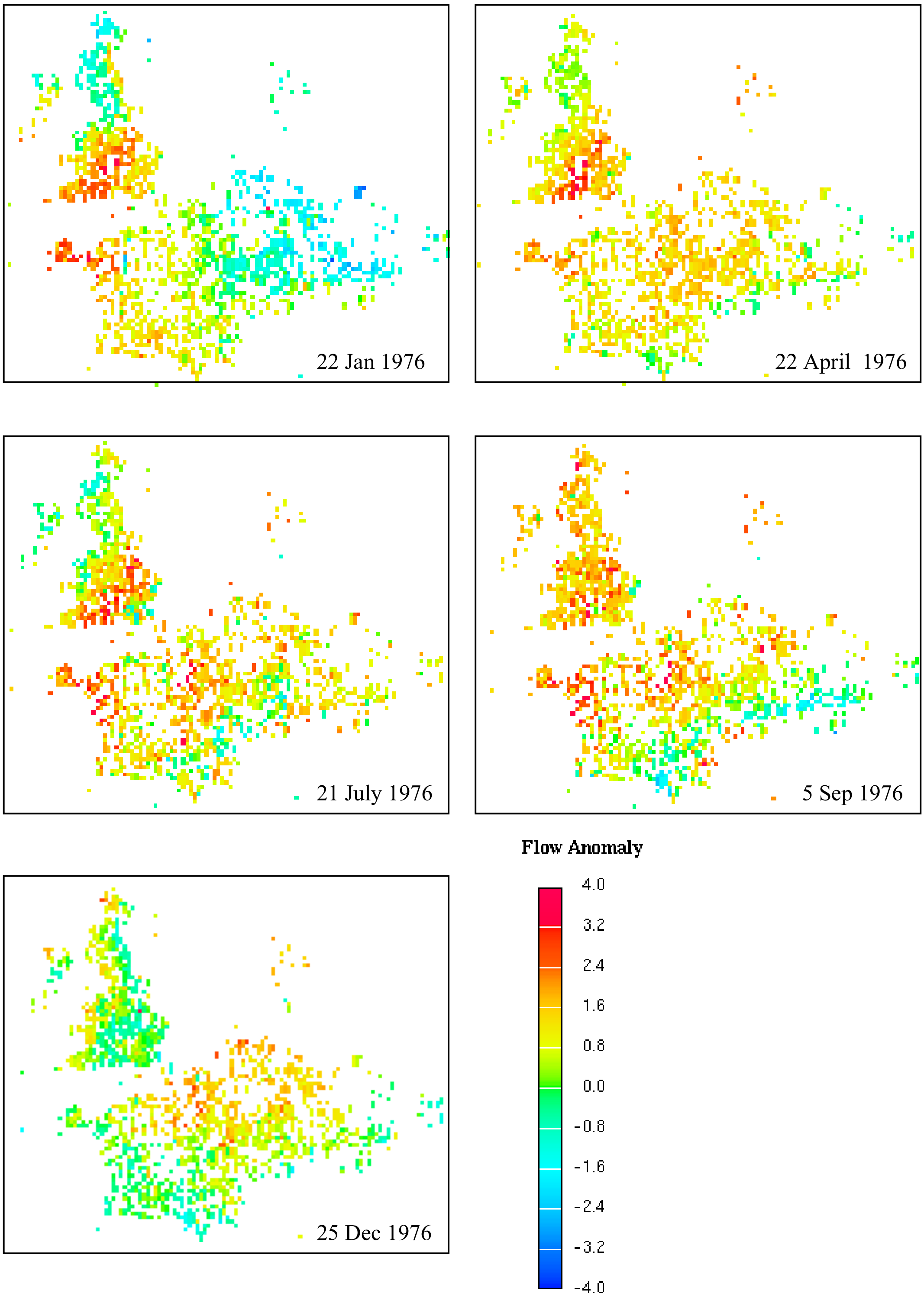
$$I = \frac{N_2}{N_d} \tag{5.13}$$

Where I is the drought index, N_2 is the number of squares of the most extreme magnitude and N_d is the total number of squares making up the drought.

5.3 Case study I) The 1975/76 Drought in Europe

5.3.1 Pan European Development

Figures 4.8 and 4.9 showed that many gauging stations across Europe experienced their lowest recorded flow levels during the year of 1976. The electronic atlas, ElectrA, was also used to show that there was a pan-European drought event in 1976 (Zaidman *et al.*, 2000). The 1976 drought was therefore selected as a case study.
Figure 5.1 illustrates key changes in the spatial distribution of flow anomaly magnitudes over north west Europe during the 1976 drought. Figure 5.1 shows that the drought mainly affected the northern part of Europe. Drought conditions appeared first in south western England and north western France during the 1975/1976 winter season. Drought conditions subsequently spread eastwards into mainland Europe. Most parts of Germany were affected by spring 1976, but flow conditions remained relatively normal in the Alpine and Mediterranean regions for most of the 1976 period.



5.1 *Key changes in the spatial distribution of drought conditions over north west Europe during the 1976 drought*

Figure 5.1 indicates that those regions experiencing low flows in winter 1975/76 also appear to suffer the severest drought in the summer of 1976. This was probably caused by the low amount of winter recharge received by aquifer systems in these areas. Flow conditions returned to normal by October 1976, although recorded flows were still relatively low in Germany until the end of the year.

Figure 5.2 shows how the areal extent of drought changes throughout 1976 using a threshold flow anomaly (Z_o) of 2.0. Also shown are the areal extents of those cells with anomaly values falling between Zo and Z1 (Z1 is set here as 2.5) and the areal extent of those cells with anomaly values greater than Z1. Figures 5.3a and 5.3b show the corresponding growth and rate of change of growth plots. Figure 5.3c shows how intensity index and total deficit varied over the same period.

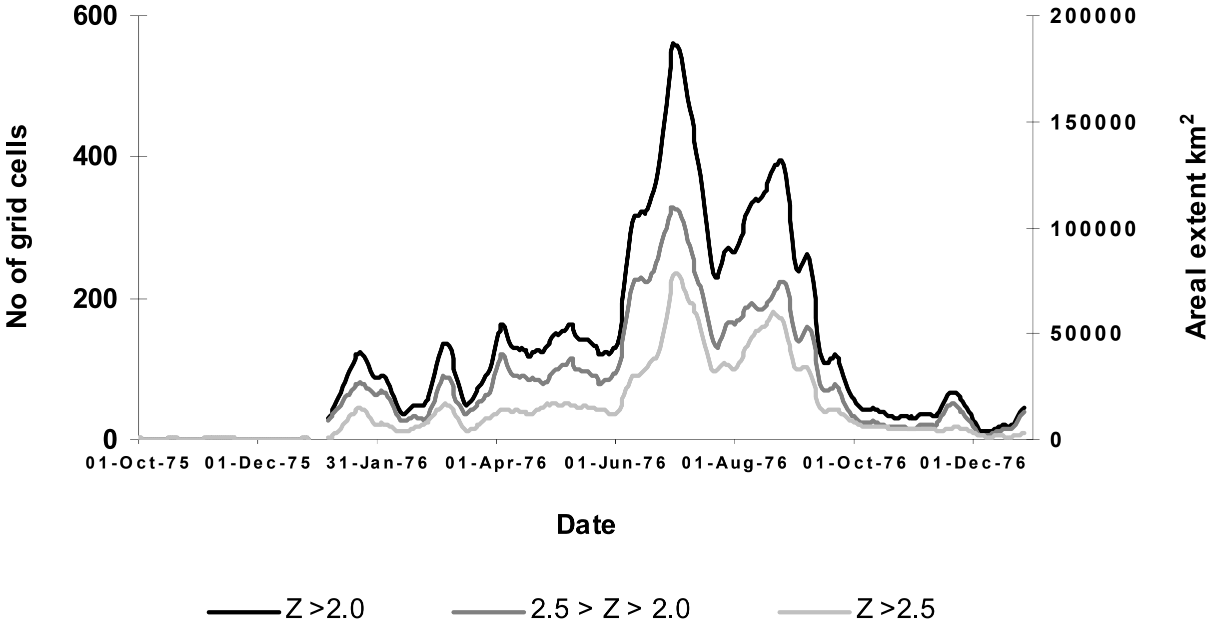


Figure 5.2 *Variation in drought area during the 1976 drought*

Figure 5.2 shows that the drought started to form in January 1976 (i.e. as a winter drought). The areal extent increased exponentially reaching its maximum seven months later during July 1976. The drought dissipated very quickly and the end of the drought occurred in October, three months after the maximum extent was record. The extent of areas of higher flow anomaly (i.e. where Z is greater than 2.5) changes proportionally with the overall extent of the drought.

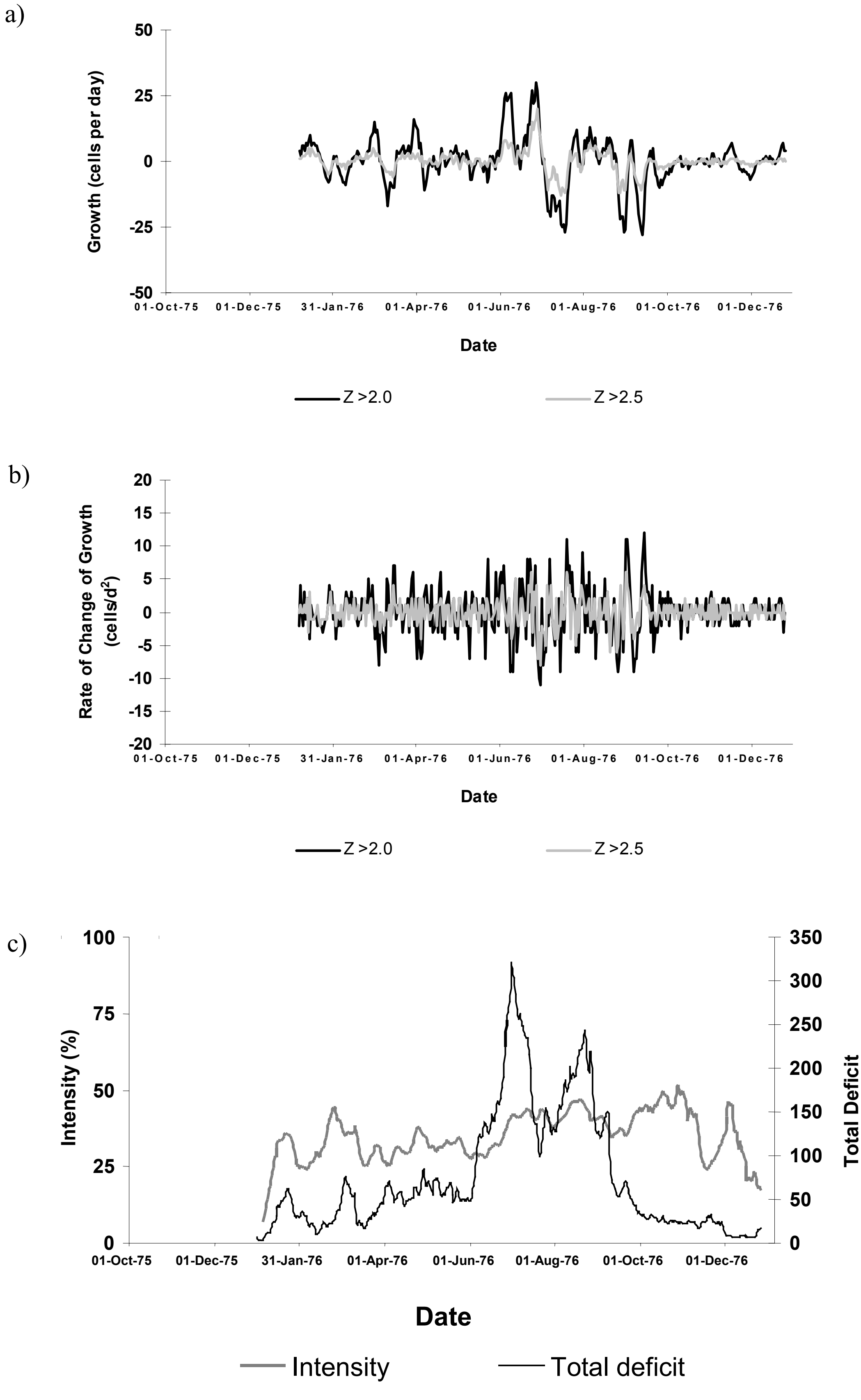


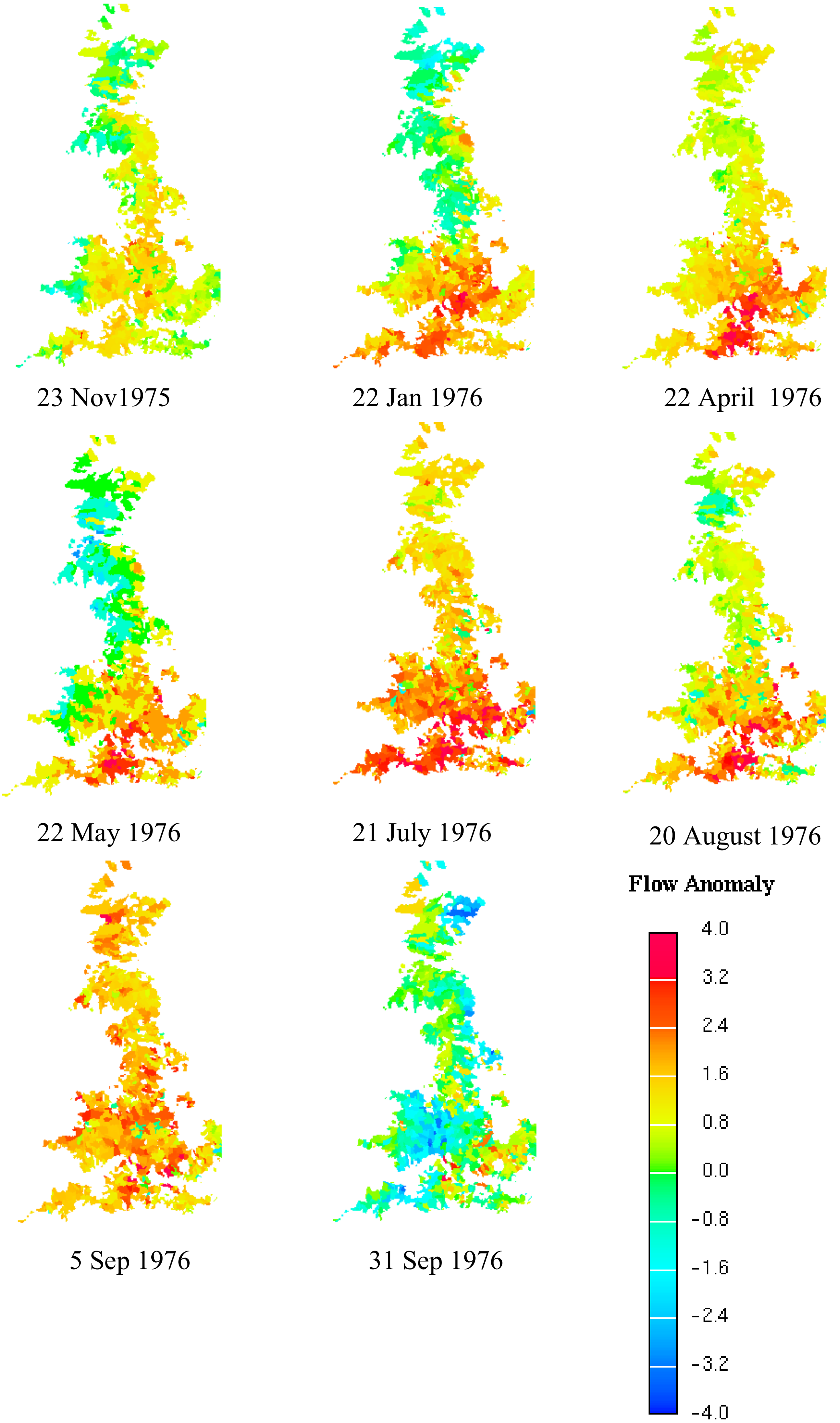
Figure 5.3 *Variation in a) drought growth, b) rate of change of drought growth and c) drought intensity and total deficit during the 1976 drought*

The drought did not grow steadily; periods in which there were rapid changes in the size of the drought occurred in January, March and July. These may have been caused by localised rainfall events that increased river flows for short periods. At the end of July 1976, the drought halved in size, which probably resulted from a period in which there was widespread rainfall in Europe. The maximum drought extent (gauged area 200,000 km^2) occurred on July 1976, with a second event on 20 August 1976. These variations in drought size are also reflected in the intensity index and total deficit plots (Figure 5.3c). Apart from the latter part if 1975, where it reached 100% because there were only one or two grid cells in the drought condition, the intensity index varied between 25 and 50% (intensity represents the proportion of the drought extent for which the flow anomaly exceeds 2.5). Intensity was at its highest toward the end of the drought period. In the early stages of the drought there was a lag between increase in drought intensity and increase in total deficit. This indicates that increase in drought intensity was due to existing parts of the drought becoming more severely affected, and not because of new areas becoming affected by drought conditions. The increase in drought extent in June-September was caused by an increase in drought cells in the 2.0 –2.5 range. Changes in total deficit over time are closely related to the variation in drought extent over time. The total deficit was very high (compared to the drought intensity) during two short periods - June/July 1976 and August/September 1976, but very low at other times. This indicates that the drought was at both its worst and most widespread from June to September 1976. The average cell deficit (not shown) ranged from 0.1 in January to 0.6 in October and closely mirrored the shape of the intensity curve.

5.3.2 The 1976 Drought Event in the UK

As shown in Figure 5.1 drought conditions occurred in South West England during winter 1975/1976. This area continued to act as a focal point for subsequent drought initiation. behaviour of the pan-European drought. The 2.5km resolution grid derived for the UK (Section 2.2.3) were used to study in more detail the development of drought in the UK during the 1975/76 drought event.

Figure 5.4 shows how drought conditions developed across the UK during 1976. Most areas were affected by drought, with the exception of the north-west coast of Scotland and Wales where the flow anomalies were moderate or zero. The drought appears to have been most widespread during the months of July and August.



23 Nov1975

22 Jan 1976

22 April 1976

22 May 1976

21 July 1976

20 August 1976

5 Sep 1976

31 Sep 1976

Figure 5.4 *Key changes in the spatial distribution of drought conditions over Britain during the 1976 drought*

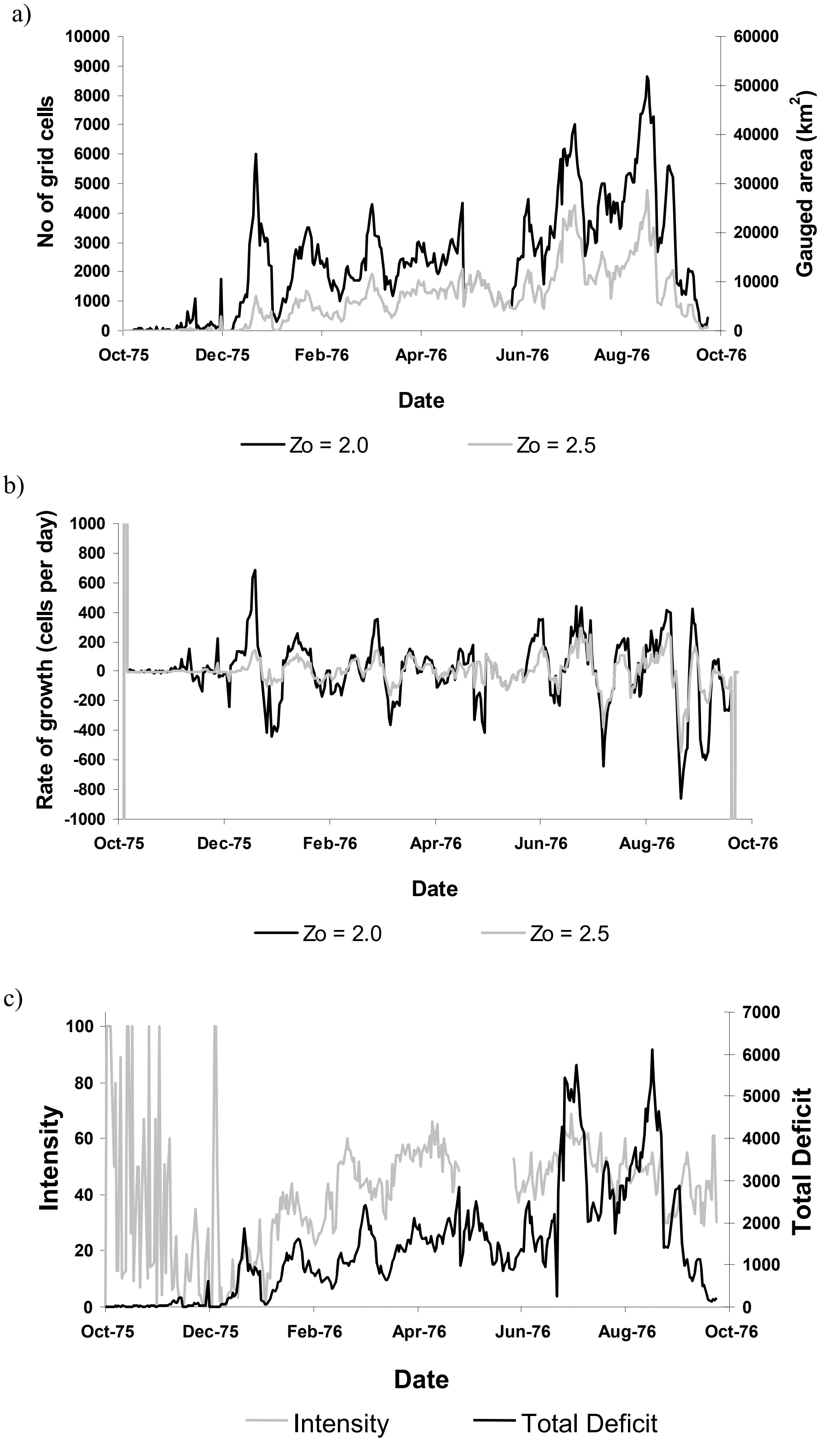


Figure 5.5 *Variation in a) drought extent, b) growth, c) intensity and total deficit*

Figure 5.5a shows the variation in drought area for the UK over the 1975/76 period. As observed for Europe as a whole, the drought area increased gradually throughout the lifetime of the drought, reaching its maximum extent near the end of the drought period. Similarly, there were a number of periods in which expansion and contraction cycles occurred. This cyclic behaviour is reflected in the intensity index (Figure 5.5c), and in the rate of growth plot (Figure 5.5b), and may be related to weather systems coming in from the Atlantic.

During the initial stages of the drought its growth was fairly steady, but was this much more variable in the latter stages of the drought. The growth rate was higher for cells in the Z=2-2.5 range than for cells above 2.5. The intensity index was also generally higher in Britain than in Europe as a whole, suggesting that the drought conditions were more severe in Britain. In contrast to the situation in Europe, in Britain, the highest intensity coincided with the period of greatest total deficit (July 1976).

Figures 5.6a and 5.6b show the variation of flow anomaly values at two gauging stations in England between January 1975 and April 1976 (the catchment characteristics are given in Appendix3). These illustrate the development of drought conditions at the catchment scale – for two different types of regime. Both series are characterised by a prolonged period between July 1975 and September 1976 in which the flow anomaly is predominantly positive (lower than average flows). For the River Colne (Figure 5.4a) the threshold (Zo = 2.0) was surpassed only between May and August 1976, whereas for the Avon, the threshold was exceeded periodically between October 1975 and September 1976. The peak event in both catchments occurred in the first week of July 1976. The onset and end of the drought occurred relatively rapid on the R.Avon, whilst conditions developed and abated more gradually on the R.Colne.

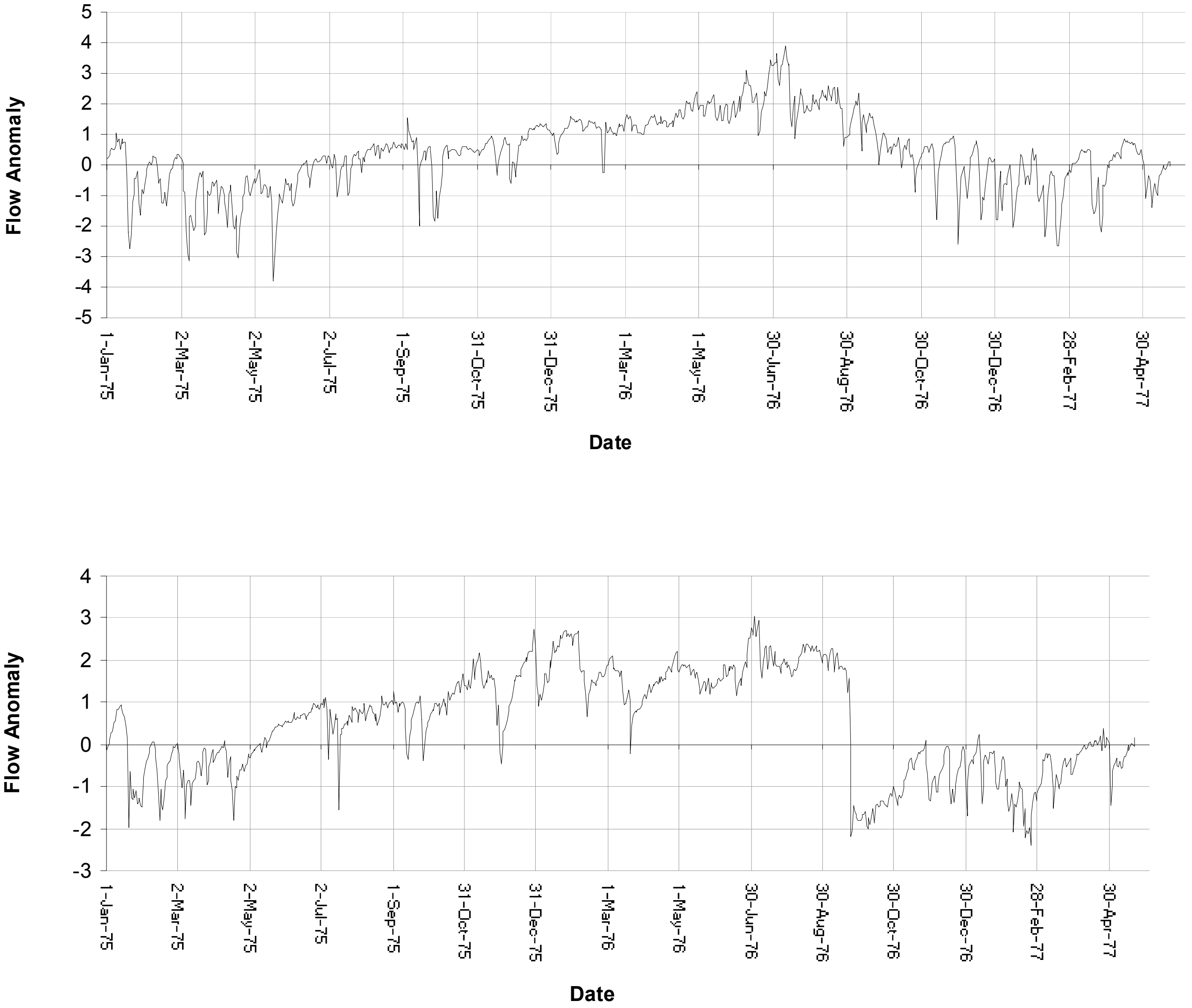


Figure 5.6 Variation in flow anomaly throughout 1975 and 1976 at a) –Colne at Lexden and b) *Avon at Great Somerford*

Table 5.1 shows how droughts developed on a week by week basis for a number of catchments in the UK. Where 4 out of 7 days per week were affected by drought, the week is given a drought status of ‘1’. If three or less days per week were affected by drought the week is given a drought status of zero. Although there was a large of degree spatial and temporal variability in drought status throughout 1975 and 1976, there was a distinctive start and end to the drought period – these occurred at week 50 (1975) and week 40 (1976) respectively.

Table 5.1 *Weekly drought status for some UK catchments during 1975 and 1976*

Week		1975 1 10 20 30 40 50	1976 1 10 20 30 40 50
		JAN75 AUG75	JAN76 AUG76
8005	North East	0000000000000000000000000000000000000000000000000000	0000000000000000000000000000000000010000000000000000
10001		0000000000000000000000000000000000000000000000000000	0000000000000000000000000001000000110000000000000000
16004		0000000000000100000000000000000000000000000000000001	0000000000000000000000000000000000000000000000000000
17004		0000000000000100000010000000100000000000000000000111	0000000000000000000000000000000000000000000000000000
21034		0000000000000000000000000010000000000000000000000000	0000000000000000000000000000000001110000000000000000
25019		0000000000000000000000000000000000000000000000000000	0000000000000000000000000000000000000000000000000000
27040		0000000000000000000000000000000000000000000000000000	0000000001000100000000000000110100111100000000000000
28009		0000000000000000000000000000000000000000000000000011	0000000000000000000000000011011111010000000000000000
30001	Southern England	0000000000000000000000000000000000000000000000000000	0001111111111111111110111111111111110000000000000000
33002		0000000000000000000000000000000000000000000000000000	0011111111001110111100010111111111111100000000000000
37008		0000000000000000000000000000000000000000000000000000	0000000000000000000000111111010011000000000000000000
38018		0000000000000000000000000000000000000000000000000000	0000000000001100111100111111111111110100000000000000
39001		0000000000000000000000000000000000000000000000000000	0111111111111111111111111111111111111111100000000000
42008		0000000000000000000000000000000000000000000000000000	0000000000111111111111111111111111111100000000000000
43019		0000000000000000000000000000000000000000000000000000	0111100011000111111111100110000000000000000000000000
44006		0000000000000000000000000000000000000000000000000000	1111111111111111111111111111111111111100000000000000
46002		0000000000000000000000000000000000000000000000000011	0111000000000000000000000010011111000000000000000000
48004	North West	0000000000000000000000000000000000000000000000000000	0011000000000000000000000000000000000000000000000000
52004		0000000000000000000000000000000000000000000000000000	0010000000000000011001100110110111000000000000000000
53002		0000000000000000000000000000000000000000000000000000	0011100001001111111110111111111111000000000000000000
60006		0000000000000000000000000000000000000000000000000010	0000000000000000000000000000000000000000000000000000
62001		0000000000000000000000000000000000000000000000000000	0000000000000000000000000000000001110000000000000000
64002		0000000000000000000000000000000000000000000000000000	0000000000000000000000000000000001110000000000000001
67017		0000000000000000000000000000000000000000000000000000	0000000000000000000000000000000000000000000000000000
72001		0000000000000000000000000000000000000000000000000000	0000000000000000000000000000000001000000000000000000
79003		0000000000000000000000000000000000000000000000000000	0000000000000000000000000000000000010000000000000000
83002		0000000000000000000000000110000000000000000000000000	0000000000000000000000000000000000000000000000000000
84001		0000000000000100000000000000000000000000000000000000	0000000000000000000000000000000000000000000000000000
94001		0000000000000000000000000000000000000000001100000000	0000000000000000000000000000000000010001000000000000
97002		0000000010100000000000000000000000000000000000000000	0000000000000000000000100000000000000000000000000000

Table 5.1 shows that in the permeable aquifer systems of southern UK the drought was probably already widely established during the 1975/76 winter. This implies that groundwater levels would have been much lower than usual at the end of the winter recharge period. As a result rivers usually maintained by base flow would have received little or no contribution from groundwater in the following summer.

Animations of the drought conditions within the UK showed intense drought activity in Southwest England, especially around the counties Wiltshire, Gloucestershire, Somerset, Hampshire and Berkshire. Droughts tended to appear first in these areas and spread outwards into the rest of the UK. There were also locallised 'hotspots' in other areas of the UK. The growth of locallised drought zones was measured using a condition to specify the boundaries of the contiguous drought area. Figure 5.7 shows how the size of an isolated event changes over time.

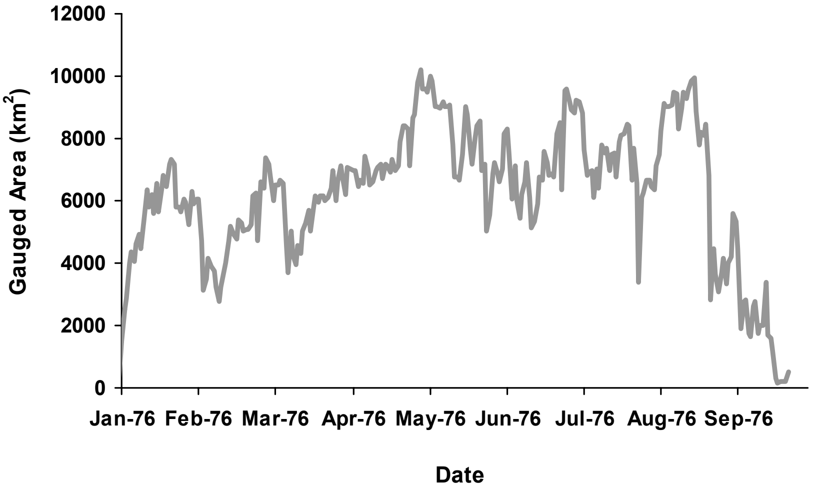


Figure 5.7 *Variation in the size of an isolated drought area in Southwest England*

The nucleus of the drought appeared in December 1975. Initially the drought grew rapidly, but there was a decrease in size during February and again in March. From then on the drought grew steadily, reaching a size of 9000km^2 in early June. During high-summer the drought contracted and expanded quite rapidly, before began to die off in late August.

The behaviour of this isolated event reflects the development of drought conditions in UK as a whole, implying some countrywide influence, probably atmospheric, on drought development.

5.3.3 Summary of Drought Behaviour during the 1976 Event

Figure 5.8 illustrates the three main stages of drought development that were observed in western and central Europe during 1976.

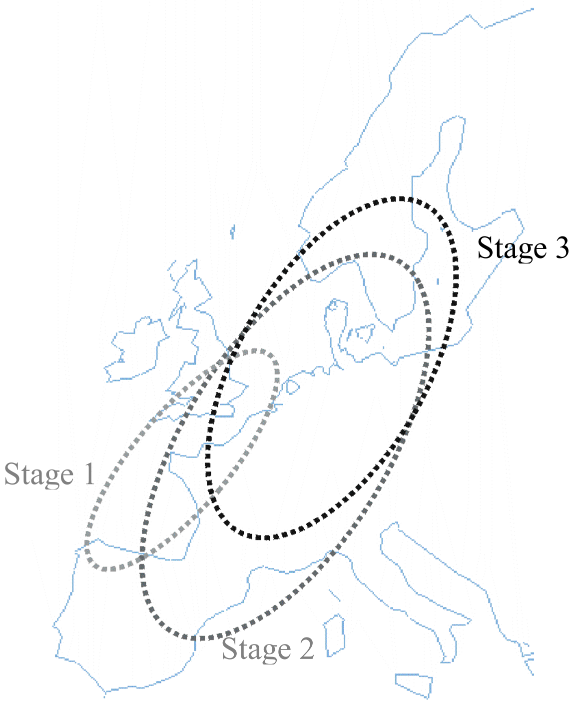


Figure 5.8 *Stages in the spatial development of drought conditions in Europe during 1976*

Between winter 1975 and spring 1976 flow anomalies were at the threshold level in southern regions of England and north-western regions of France (Stage 1). By early summer 1976, drought conditions started to be observed in other regions in Europe, including Germany and southern France. The drought area increased as shown by the boundary for Stage 2. During Stage 2, drought conditions persisted in the UK and northern France. Although the drought continued to affect mainland Europe, by September 1976, conditions had started to improve along the western Atlantic coast, resulting in a sharp decrease in the total drought area (Stage 3). Drought conditions had abated throughout most areas of north western and central Europe by late autumn.

5.4 Case Study II) The 1989/90 Drought in Europe

Drought conditions affected Europe between summer 1989 and summer 1990. A fairly large number of rivers across different hydrometric regions recorded their lowest-ever-flows during this period (section 4.2). Figure 5.9 (next page) shows the spatial distribution of drought during the 1989-1990 period (the images were obtained using the Electronic Drought Atlas, ElectrA (Zaidman *et al.*, 2000)). The percentage flow exceedance observed for each grid cell is shown, blue colours representing high flows and orange and red colours representing low flows and drought conditions.

Figure 5.9 suggests that flows in many rivers were persistently low from late summer 1989 through the following autumn and winter. Although river flows recovered somewhat during the early part of 1990, dry conditions were quickly established again during late spring. Again these conditions persisted through the summer months, with flows finally returning to normal levels during autumn 1990.

Figure 5.10 shows how the drought area varied throughout 1989 and 1990. The areal extent calculated using two different thresholds (Z = 2.0 and Z = 2.5 are shown). Figures 5.11 and 5.12 show the variation in total deficit and intensity and rate of drought growth respectively.

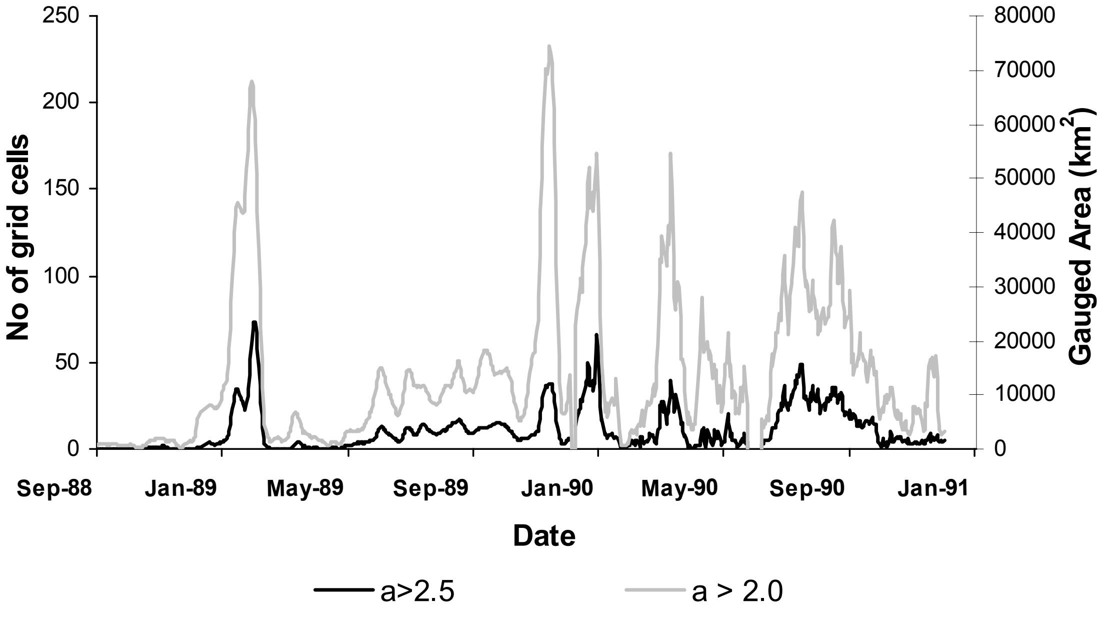
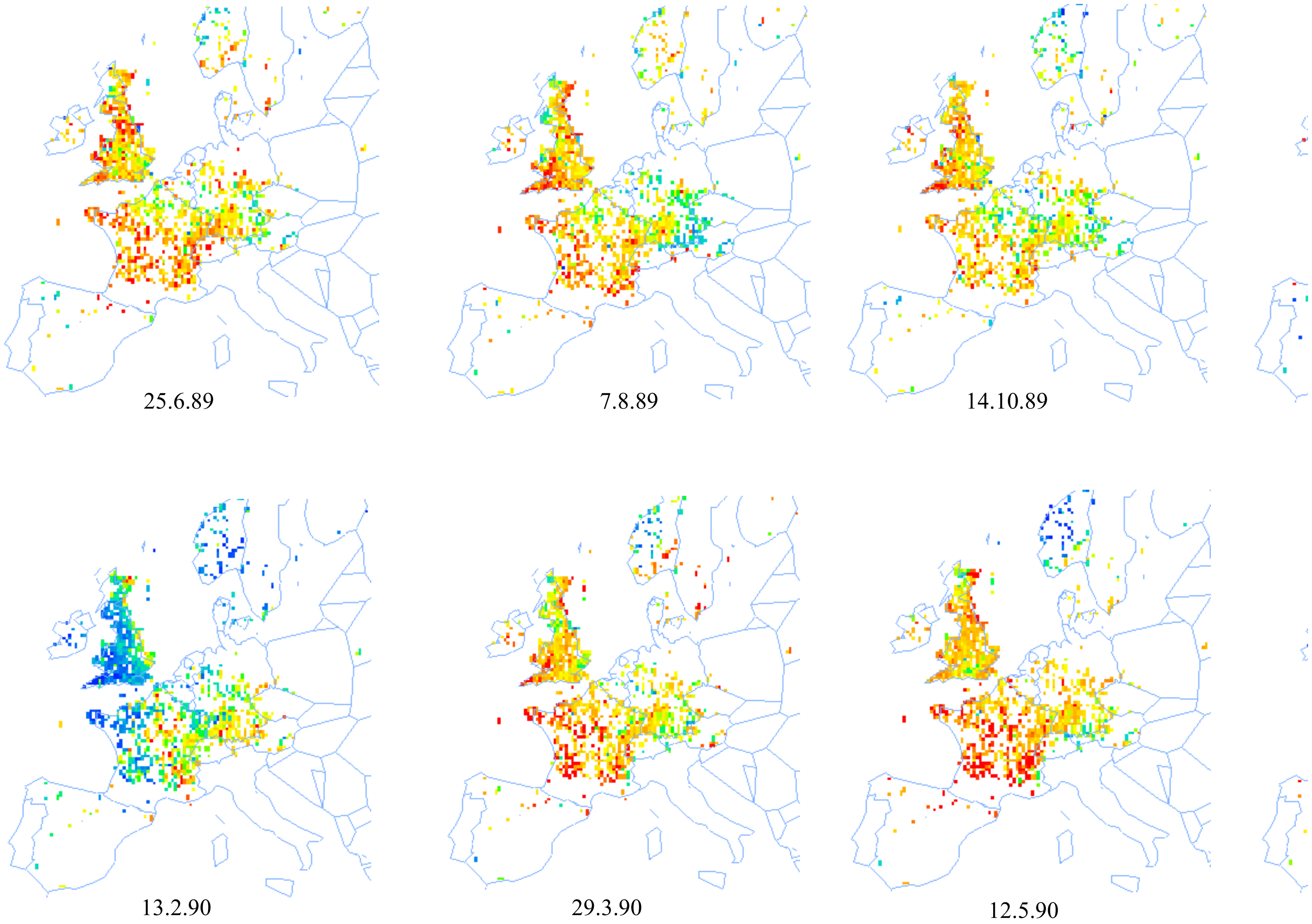


Figure 5.10 *Variation in areal extent of drought in Europe, 1989-1990.*



25.6.89

7.8.89

14.10.89

13.2.90

29.3.90

12.5.90

Figure 5.9 *Key changes in the spatial distribution of drought conditions over Europe during 1989/1990*

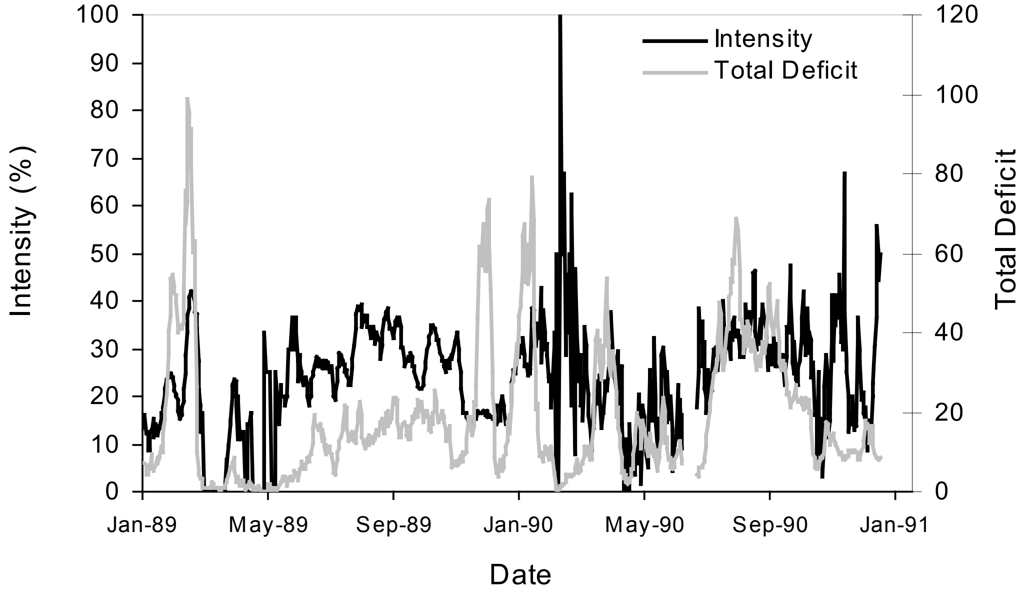


Figure 5.11 *Changes in drought intensity and total deficit during the 1989/90 drought*

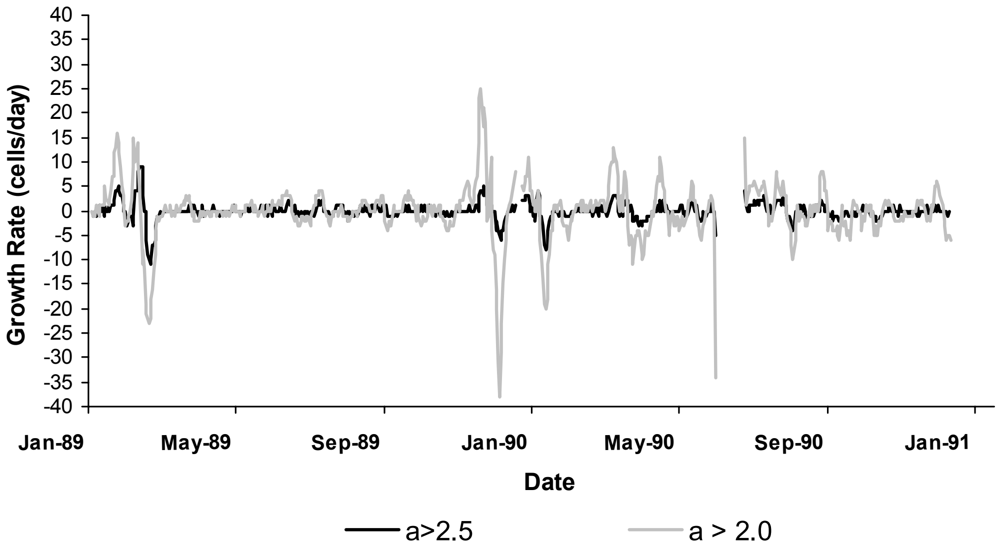


Figure 5.12 *Changes in the growth of drought area during the 1989/90 period*

The drought can be separated into two periods. The first, winter-spring 1989-1990, was characterised by several short-lived drought events. In the second period, during summer and autumn 1990, drought conditions were more persistent. The analysis showed that, using a flow anomaly of 2.0 standard deviations to mark the onset of drought condition, the most extensive drought in the 1989/90 period occurred during November 1989 and reached a gauged area of 70,000km^2 (i.e. only a third of the maximum size of the 1976 drought). It was followed by two other events of similar magnitude, and duration in December 1989 and March 1990. Notably these were all winter drought events, perhaps reflecting precipitation being held for short periods as unmelted snow, or occurring as a result of high pressure over Europe. Up to May 1990 the drought intensity was relatively low compared to the total deficit, indicating that the anomaly values of many of the cells constituting the drought were only just over the threshold. Thus although the drought was widespread in these periods, it was not particularly severe. The three peaks may not have been observed if a higher threshold had been used.

From May 1990 onwards a drought of substantial size (gauged area = 50,000 km^2) occurred lasting around 3 months. The spatial extent began to increase in June 1990. The drought then grew fairly rapidly reaching the maximum extent with one month. During this time, both total deficit increased and intensity rose to fifty percent, indicating a widespread increase in deficit size, i.e. the drought condition worsened in many of the existing drought areas, whilst at the same time the drought extent also increased. After reaching the peak extent the drought's extent decreased steadily throughout August and September 1990. The total deficit and intensity also decreased at a similar rate.

6 Conclusions & Discussions

6.1 Conclusion

6.1.1 Drought Events during the 1960-1995 Period

Drought conditions were widespread in the study area on several occasions during the 1960-1995 period. These episodes include the years of 1963, 1964, 1972, 1976, 1978, 1989 and 1990. Comparison of different drought events was hampered by a lack of available data for some parts of the study area. Two drought events were studied in detail, the 1976 event and the 1989/90 event, and are described in sections 6.1.3 and 6.1.4.

6.1.2 Techniques Used

The temporal and spatial variations in river droughts across Europe were studied in order to identify any spatial patterns common to the growth and decay cycles of different drought events. Chronological sequences of the variation of flow anomaly across Western Europe were examined, both qualitatively and quantitatively. A number of indices were developed to describe the spatial extent and severity of the drought on each day. Time series of these indices were developed and used to study trends in the rate of growth of each drought event.

6.1.3 Spatial Behaviour of the 1976 Drought

Drought conditions appeared first in the south western corner of England and north western France during the 1975/1976 winter season, subsequently spreading eastwards into mainland Europe. Most parts of Germany were affected by spring 1976, but flow conditions remained relatively normal in the Alpine and Mediterranean regions for most of the 1976 period. Finally drought conditions began to recover in Britain and France during September 1976, and from most other regions in Europe by November 1976.

6.1.4 Spatial Behaviour of the 1990 Drought

The development of the 1989/90 drought was broadly similar to that of 1976. Flow deficits appeared simultaneously in England and France during the winter of 1989. These became widespread in early summer 1990 and were relatively persistent in England and France and western parts of Germany throughout the summer months. However drought conditions were observed much later in Scandinavia, Scotland and Alpine regions. These areas also showed, on the whole, more variable flow conditions throughout the drought period. The drought ended in late summer/autumn 1990, with high flows being observed again across most areas during September 1990.

6.1.5 Drought Frequency

For most stations in Europe the average drought frequency was between two and six days per year. Only a very small percentage of stations experienced, on average, more than 12 days of drought per year. The average duration of a typical drought event was between two and four days, whilst the longest-ever-duration recorded was, on average, between ten and twenty days. In extreme droughts flow anomalies usually ranged from 2.5 to 3.5.

6.1.6 Regional Aspects

The analysis showed some variation in the drought frequency in different hydrometric regions in Europe. However the analysis of the data from the UK showed that at national scale, there were regional differences in the characteristics of the droughts observed. For instance droughts occurring in the south east of England were more severe and of longer duration than those occurring in other parts of the UK.

6.2 Discussion of Results

Although the development of each drought was distinct, a number of patterns common to both events were observed. In both the 1976 and 1989/90 droughts, low-flow conditions began to appear, in localised areas, during winter, but did not become widespread until the following summer. Winter droughts may be related either to precipitation being held as snow, or to lack of rainfall. As the drought conditions were first observed in lowland areas of England and France, they are more likely to have been triggered by low rainfall, rather than by snow. As most recharge takes place during autumn and winter, a winter drought also implies that low water table levels will become manifest during the following summer. In areas where streams are predominantly groundwater fed, such as in the chalk plains of southern England and northern France, this means that a winter drought is also likely to be followed by a summer drought. These predictions were born out by the subsequent behaviour of the droughts over the summer months; Southeast England and Northwest France suffered from persistent drought conditions both in summer 1976 and summer 1990. The analysis also showed droughts in these regions were more prolonged than those in regions, such as Scotland or Alpine Europe, where the flow regime is generally responsive to rainfall. These observations show that antecedent streamflow, soil moisture and groundwater conditions can have a strong influence on the severity and longevity of drought events.

That the droughts spread from west to east across northern Europe indicates that North Atlantic weather systems influence the development of droughts in Europe. Changes in flow levels on a day by day basis were probably caused by short-term variations in the synoptic weather situation over Europe.

6.3 Limitations of the study

An important limitation of the method employed to study the spatial distribution of drought conditions in the catchments was the resolution of the spatial data sets. Each grid square represented an area of 18km by 18 km, that is, almost 350km^2. Although some catchments in Europe exceed this in size, many are much smaller. The grid resolution may therefore be too coarse for examining the spatial variation on a basin or regional basis.

Characterisation of past drought events is also of little operational use unless definitive patterns in the development of droughts can be identified, and used to predict future spatial development of droughts at a near real time scale. Given the availability of data to this study, it was very difficult to make a complete assessment of such patterns on a Pan European scale.

6.4 Suggestions for further work.

Further work is recommended to confirm whether there is a spatial and temporal pattern common to the development of other streamflow drought events in Europe. The areal indices described could be related to other hydro-meteorological parameters For example one option could be to relate streamflow drought indices and rainfall time series, to provide a sound basis for drought forecasts. Comparison of drought behaviour with physiographical catchment characteristics could also help to predict future spatial development of droughts. As touched upon in this study, catchments with different river regimes react differently in dry periods. Catchments with flashy regimes have high short-term vulnerability, whereas the impact of reduced recharge is more important for groundwater catchments. Furtherwork might focus on whether the geographical distribution of different catchment types influences the growth of drought.

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Appendix 1

A1.1 Availability of gauged daily flow data for stations on the FRIEND European Water Archive

Table A1.1 *Number of gauging stations and station years of data per country*

Country	*Number of Stations*	*No Stations with Daily Flow Records*	*Earliest Record*	*Latest Record*	*Station Years*	*Av. Record Length*
Austria	139	139	1922	1996	4520	33
Belarus	40	33	1919	1995	1383	42
Belgium	80	74	1929	1992	803	11
Bulgaria	3	3	1978	1986	27	9
Czech Rep.	34	27	1887	1993	1468	54
Denmark	43	35	1917	1997	2115	60
Finland	71	68	1847	1997	3674	54
France	1476	1333	1863	1992	29734	22
Germany	717	625	1884	1998	22918	37
Greece	2	2	1978	1980	6	3
Hungary	26	25	1935	1996	825	33
Iceland	8	8	1932	1994	386	48
Ireland	130	77	1940	1997	1908	25
Italy	252	252	1925	1990	3969	16
Netherlands	30	25	1901	1994	581	23
Norway	213	204	1871	1998	7756	38
Poland	61	29	1955	1992	738	25
Portugal	73	73	1920	1994	1092	15
Romania	35	33	1838	1990	1155	35
Russia	217	146	1928	1995	6094	42
Slovakia	23	23	1930	1992	1441	63
Slovenia	12	12	1945	1990	300	25
Spain	239	239	1912	1989	3317	14
Sweden	71	66	1907	1992	2583	39
Switzerland	132	75	1904	1992	2775	37
Turkey	12	12	1958	1991	201	17
UK	1112	1014	1879	1998	29961	30
Ukraine	67	58	1960	1990	1798	31
Yugoslavia	5	5	1978	1990	63	13
SUMMARY	**5325**	**4715**	**1838**	**1998**	**133591**	**28**

Table A1.2 *Data availability for hydrometric regions in Europe showing percentage of stations that have over 60% non-null data during time period from 1951-1995*

Hydrometric Region	1951-1995 (45 yrs)	1971-1995 (25yrs)	1968-1992 (25yrs)	1960-1995 (36 yrs)
	%	%	%	%
0300		37.66	58.40	54.55
0400	75.31	83.95	83.33	79.63
0500	72.00	85.25	85.00	79.25
0600				
0700				
0800				
0900				
1000	22.15	58.86	63.92	42.72
1100	17.27	17.27	21.82	20.00
1200	23.88	24.63	25.37	24.63
1300	15.89	15.89	16.82	16.82
140A	6.34	48.64	54.98	34.14
140B	21.32	64.47	74.62	47.21
1500	13.27	48.89	55.09	33.19
160A	62.79	70.64	75.58	70.93
160B	42.06	66.04	79.13	64.49
1700	42.42	69.70	74.24	59.85
1800	52.1	85.4	87.5	79.2
1900	45.83	66.67	66.67	62.50
2000	51.85	92.59	94.44	64.81
2100	53.85	61.54	76.92	61.54
2200	92.96	94.37	95.77	94.37
2400	91.66	100	100	100
2500	50	100	100	60
UK1	43.9	79.2	76.2	68.3
UK2	28.8	58.0	54.6	47.1
Mean	**44.08**	**66.28**	**69.62**	**57.65**

A1.2 Hydrometric Regions of Europe

The FRIEND Hydrometric Regions are shown in Figure A1. Table A1.3 gives details of the hydrometric regions from which gauging station data were used in this study.

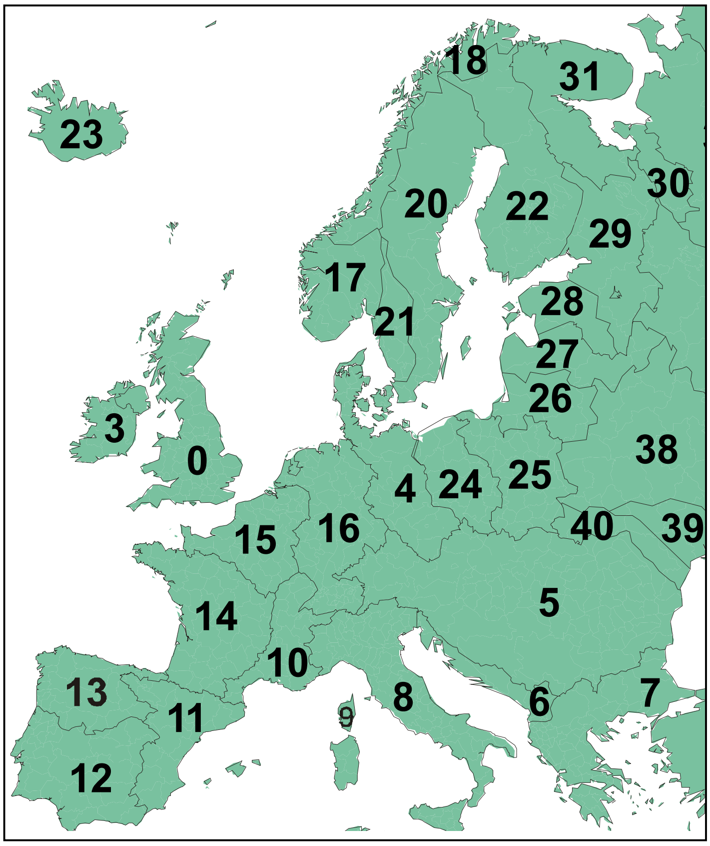

Figure A1. *Locations of Hydrometric Regions in Europe*

Table A1.3*Hydrometric Regions from which gauging station data were used in this study*

Code	Map Region	Countries Included
0000	0	England, Scotland & Wales
0300	3	Republic of Ireland
0400	4	Austria, Czech Republic, Germany, Denmark
0500	5	Austria, Switzerland, Czech Republic, Germany, Slovakia
1000	10	Switzerland, France
1400	14	France
1500	15	Belgium, France, Netherlands, Germany
1600	16	Austria, Belgium, Switzerland, Germany, France, Netherlands

Appendix 2

Table 2. Gauging Stations used in this study

Wales, Scotland and Republic of Ireland

2001	11001	18001	21013	55028	58008	66005	80002	84018	101001	325006
3002	11002	18002	21014	55029	58009	66006	80003	84019	306013	325021
3003	11003	18003	21015	55031	58010	66008	81002	84020	306014	325022
3004	12001	18005	21016	55032	58011	66011	81003	84022	306021	325025
3005	12002	18008	21017	55033	58012	66802	81004	84023	306023	325027
4001	12003	18011	21018	55034	59001	67001	82001	84024	307002	325030
4003	12004	19001	21019	55035	59002	67003	82002	84025	307004	326005
4004	12005	19002	21020	56001	60002	67005	82003	84026	307005	326011
6007	12006	19003	21021	56002	60003	67006	83002	84027	307006	326012
6008	12009	19004	21022	56003	60004	67008	83003	84028	307010	326014
7001	13001	19005	21023	56004	60005	67009	83004	84029	307011	326019
7002	13005	19006	21024	56005	60006	67010	83005	84030	307012	330004
7003	13007	19007	21025	56006	60007	67011	83006	85001	309001	334001
7004	14001	19008	55002	56007	60009	67015	83007	85002	311001	335001
7005	14002	19009	55003	56010	60010	67017	83008	85003	312001	335011
8001	15003	19010	55004	56012	60012	67018	83009	85004	312002	336015
8002	15006	19011	55006	56013	61001	67025	83010	85005	314005	336018
8004	15007	20001	55007	56014	61002	67028	84001	86001	314019	336020
8005	15008	20002	55008	56015	61003	77001	84002	86002	315002	336021
8006	15010	20003	55010	57004	62001	77002	84003	87801	315006	336027
8007	15011	20004	55011	57005	63001	77003	84004	89002	316001	336028
8008	15012	20005	55012	57006	63002	77004	84005	89003	316002	336071
8009	15013	20006	55013	57007	64001	77005	84006	89004	316003	336073
8010	15016	20007	55014	57008	64002	78003	84007	89005	316004	336091
8011	16001	21003	55015	57009	64006	78004	84008	89006	316009	339003
8807	16002	21005	55016	57010	65001	78005	84009	89007	316010	
9001	16003	21006	55017	57015	65004	79001	84011	91002	316011	
9002	16004	21007	55018	57016	65005	79002	84012	93001	318002	
9003	17001	21008	55021	58001	65006	79003	84013	94001	320001	
9004	17002	21009	55023	58002	65007	79004	84014	95001	320002	
9005	17003	21010	55025	58005	66001	79005	84015	96001	323001	
10001	17004	21011	55026	58006	66003	79006	84016	96002	323002	
10002	17005	21012	55027	58007	66004	80001	84017	97002	324001	

England and Wales

21026	25018	27040	28020	28871	31026	33028	34811	37023	39011	39073	41006	43004	47010	53002	54038	69032
21027	25019	27041	28022	28872	31811	33029	35001	37024	39012	39074	41009	43005	47013	53004	54040	69033
21030	25020	27042	28023	28873	31813	33030	35002	37026	39013	39076	41010	43006	47014	53005	54041	69035
21031	25021	27043	28024	29001	31814	33032	35003	37028	39014	39077	41011	43007	47015	53006	54044	69040
21032	25023	27044	28025	29002	32001	33033	35004	37029	39015	39078	41012	43008	47016	53007	54046	69041
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22002	26004	27050	28030	29009	32006	33039	35013	37038	39020	39087	41016	43014	48004	53017	54057	70005
22003	26005	27051	28031	30001	32007	33040	35015	37039	39021	39088	41017	43017	48005	53018	54060	71001
22004	26006	27052	28032	30002	32008	33044	36001	37816	39022	39089	41018	43018	48006	53019	54063	71002
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22007	27001	27054	28035	30004	32015	33046	36003	38002	39024	39092	41020	43021	48009	53023	54086	71004
22008	27002	27055	28036	30005	32016	33048	36004	38003	39025	39093	41021	43811	48010	53024	54087	71005
22009	27003	27056	28037	30006	32018	33050	36005	38004	39026	39094	41022	44001	48011	53025	54088	71006
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Appendix 3

Table A3.1 *Catchment characteristics for eleven small catchments in Europe*

ID	Country	Station	River	Yrs	Area (km2)	Geology	Catchment Characteristics
27061	UK	Longroyd	Colne	17	72	Millstone Grit	Reservoirs in catchment
37005	UK	Lexden	Colne	36	238	Upper Chalk with surface cover of semi-pervious clay	Rural - agricultural
53008	UK	Somerford	Avon	17	53	Oolitic limestone with clays	Flows augmented by groundwater scheme
45003	UK	Wood Mill	Culm	34	226	Permo-triassic sandstone breccias and marls, headwaters drain Greensand and Gault Clay, with gravel and alluvium filling valley areas.	Moderate surface and groundwater abstractions which affect low flows.
40020	UK	Handal Bridge	Eridge Stream	32	3	Geology includes Tunbridge Wells Sands Wadhurst Clay and Ashdown & Hastings Beds.	Sussex Weald, Rural
95001	UK	Assynt	Inver	18	137		Moorland with many lochans
422014	Germany	Unstrut	Nagelstedt				
519001	Slovakia	Cierny Hron	Hronec				BFI= 0.63
1001009	France	Dessoubre	St. Hippolyte				BFI = 0.35
1422071	France	Maronne	Enchanet				BFI = 0.45
1619046	Germany	Acher	Kappelrodek				BFI = 0.55

Appendix 4

Table A4.1 *Low flow events above the a = 2.0 threshold for station 37005 (UK)*

Drought	Event Begins	Event Ends	Duration (days)	Lowest Anomaly	Highest Anomaly	Average Anomaly
1	08-Feb-65	08-Feb-65	1	2.14	2.14	2.14
2	11-Feb-65	13-Feb-65	3	2.05	2.66	2.45
3	15-Feb-65	18-Feb-65	4	2.01	2.49	2.27
4	26-Feb-65	26-Feb-65	1	2.07	2.07	2.07
5	04-Mar-65	05-Mar-65	2	2.06	2.37	2.21
6	13-May-65	13-May-65	1	2.06	2.06	2.06
7	15-Jul-65	20-Jul-65	6	2.41	3.22	2.86
8	31-Jul-65	01-Aug-65	2	2.11	2.37	2.24
9	06-Aug-65	22-Aug-65	17	2.04	3.56	2.94
10	27-Aug-65	01-Sep-65	6	2.77	3.81	3.26
11	20-Sep-65	24-Sep-65	5	2.22	2.59	2.38
12	28-Sep-65	29-Sep-65	2	2.37	2.38	2.38
13	05-Oct-65	05-Oct-65	1	2.01	2.01	2.01
14	17-Oct-65	18-Oct-65	2	2.03	2.09	2.06
15	20-Oct-65	20-Oct-65	1	2.04	2.04	2.04
16	22-Oct-65	30-Oct-65	9	2.03	2.45	2.23
17	04-Nov-65	10-Nov-65	7	2.01	3.15	2.56
18	17-Mar-73	17-Mar-73	1	2.05	2.05	2.05
19	19-Mar-73	29-Mar-73	11	2.01	2.4	2.2
20	12-Apr-73	13-Apr-73	2	2.15	2.16	2.16
21	06-Sep-73	06-Sep-73	1	2.05	2.05	2.05
22	08-Sep-73	10-Sep-73	3	2.23	2.37	2.3
23	13-Apr-74	13-Apr-74	1	2	2	2
24	28-May-74	28-May-74	1	2.14	2.14	2.14
25	01-Jun-74	01-Jun-74	1	2.05	2.05	2.05
26	03-Jun-74	03-Jun-74	1	2.02	2.02	2.02
27	19-Jun-74	20-Jun-74	2	2.07	2.08	2.07
28	18-Apr-76	18-Apr-76	1	2.09	2.09	2.09
29	20-Apr-76	20-Apr-76	1	2.05	2.05	2.05
30	24-Apr-76	27-Apr-76	4	2.1	2.38	2.22
31	05-May-76	10-May-76	6	2.02	2.3	2.12
32	20-May-76	20-May-76	1	2.02	2.02	2.02
33	26-May-76	27-May-76	2	2.08	2.1	2.09
34	31-May-76	31-May-76	1	2.25	2.25	2.25
35	02-Jun-76	14-Jun-76	13	2.06	3.11	2.45
36	20-Jun-76	11-Jul-76	22	2.15	3.89	3.12
37	15-Jul-76	15-Jul-76	1	2.26	2.26	2.26
38	19-Jul-76	22-Jul-76	4	2.03	2.52	2.29
39	30-Jul-76	31-Jul-76	2	2.17	2.28	2.22
40	02-Aug-76	02-Aug-76	1	2.13	2.13	2.13
41	05-Aug-76	21-Aug-76	17	2	2.6	2.28
42	04-Sep-76	04-Sep-76	1	2.08	2.08	2.08
43	06-Sep-76	06-Sep-76	1	2.33	2.33	2.33

Table A4.2 *Low flow events above the Z = 2.0 threshold for station 27061 (UK)*

Drought	Event Begins	Event Ends	Duration (days)	Lowest Anomaly	Highest Anomaly	Average Anomaly
1	09-May-84	09-May-84	1	2.14	2.14	2.14
2	11-May-84	11-May-84	1	2.07	2.07	2.07
3	26-Aug-84	26-Aug-84	1	2.14	2.14	2.14
4	02-Jan-85	03-Jan-85	2	2.26	2.46	2.36
5	05-Jan-85	05-Jan-85	1	2.34	2.34	2.34
6	07-Jan-85	07-Jan-85	1	2	2	2
7	04-May-85	04-May-85	1	2.04	2.04	2.04
8	28-Aug-89	28-Aug-89	1	2.01	2.01	2.01
9	28-Mar-90	28-Mar-90	1	2.07	2.07	2.07
10	18-May-90	18-May-90	1	2.43	2.43	2.43
11	30-May-90	30-May-90	1	2.13	2.13	2.13
12	07-Jun-90	07-Jun-90	1	2.13	2.13	2.13
13	09-Jun-90	09-Jun-90	1	2.59	2.59	2.59
14	13-Jul-90	13-Jul-90	1	2.17	2.17	2.17
15	25-Jul-90	25-Jul-90	1	2.35	2.35	2.35
16	26-Jul-91	26-Jul-91	1	2.08	2.08	2.08
17	23-Sep-91	23-Sep-91	1	2.11	2.11	2.11
18	16-Mar-93	16-Mar-93	1	2.22	2.22	2.22
19	22-Mar-93	24-Mar-93	3	2	2.23	2.09