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Journal of Hydrology 262 (2002) 177–192

Journal of Hydrology

www.elsevier.com/locate/jhydrol

A weather-type approach to analysing water resource drought in the Yorkshire region from 1881 to 1998

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Received 20 March 2001; revised 22 January 2002; accepted 14 February 2002

Abstract

Water resource droughts in the UK have occurred with regularity over the last 20 years. In Yorkshire, the most severe of these was from 1995 to 1996, with a return period estimate of over 200 years. 'Severe' drought events since 1881 in the Yorkshire region are classified using two drought severity indices based on 3- and 6-monthly cumulative precipitation anomalies. Atmospheric circulation contrasts associated with the droughts are analysed and a methodology developed to identify water resource droughts in Yorkshire using historical weather-type information rather than precipitation data.

Using a weather-type index to extend drought series and revise estimates of drought return periods is a potentially useful technique. The methodology is applied from 1881 to 1998 and highlights a large number of severe drought events between 1884 and 1896 which can be substantiated using anecdotal evidence. However, the drought events of the 1880s and 1890s have not generally been used when calculating return periods for recent drought events due to scarcity of long-term daily precipitation data. The validity of return period estimates of recent drought events must therefore be questioned. This research confirms the need for the reassessment of return period estimates for contemporary drought events particularly given current climatic trends, the rapid onset of recent droughts and rising water demands. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Drought; Rainfall; Weather types; Return periods; Water resources

1. Introduction

The 1988–1992 drought underlined the sensitivity of water resources in the UK to climatic variations. The years 1988–1990 were, taken together, the warmest 3 years in the Central England Temperature record since 1659 (Brugge, 1992) and were exceptionally dry. The drought also showed exaggerated hydrologic seasonality and was highly regionalised with north-west Scotland being very wet (Marsh and Monkhouse, 1993), whereas parts of eastern England showed the most extreme runoff deficits for 150 years (Bryant et al., 1994). The juxtaposition of wetter winters and drier summers continued from the 1980s into the 1990s, culminating in the serious drought of 1995, which affected mainly the north and west of the country. An extension of these climatic variations and trends will have serious implications for water resource systems in the 21st century.

Drought events in the UK have been investigated by many researchers. Jones and Lister (1998) used riverflow reconstruction to assess the incidence of hydrologic drought at 15 catchments across England and Wales since 1865. Low flow events are evident on

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PII: S0022-1694(02)00034-3

the River Wharfe in Yorkshire in 1887/88, 1900/01, 1933/34, 1937/38, 1975/76 and 1995/96. Although trends are negligible, there is some decadal scale variability, with drier periods occurring in the 1890s, 1940s and 1990s (Jones and Lister, 1998). Jones et al. (1997) suggest that the six most extreme short-duration droughts that primarily affected the north of the country occurred in 1887, 1921, 1929, 1959, 1984 and 1995. In the context of the past century, however, recent drought episodes have been severe locally but not extraordinary. Although the period from 1987 to 1996 included a large number of severe droughts, so did 1967–1976 and 1947–1956 (Goldsmith et al., 1997).

This paper examines historical drought events since 1881 in the Yorkshire water resource region using two drought severity measures based on cumulative monthly precipitation anomalies. Annual precipitation receipts in Yorkshire range from just 600 mm in the eastern lowlands to over 2000 mm at high western 'Pennine' sites and much of Yorkshire is dependent upon a large number of single-season upland reservoirs located in the Pennine hills. These fill during winter months and are drawn-down in summer months, with relatively little carry-over from one year to the next. These resources can be drawn-down rapidly during very dry spring and summer months and become increasingly vulnerable if autumn and winter months are also dry. In March 1995, following the wettest 32-month sequence this century, reservoirs were at capacity. However, by the beginning of August 1995 reservoirs in some areas were at below 20% of capacity; a rapid drawdown rate. The 1995–96 drought resulted in severe stress to the Yorkshire region, necessitating the emergency measure of bringing water in by road tanker from outside the region, and was caused by an unusual pattern of weather and precipitation.

Mawdsley et al. (1994) suggest that weather patterns could theoretically be a good indication of drought severity, and provide an explanatory measure. Although many researchers have linked weather types to 'precipitation amount' (e.g. Sweeney and O'Hare, 1992), no attempt has been made to define drought events using weather-type information. The rainfall return period in Yorkshire from April to August 1995 was estimated to be more than 200 years, and from April to October 1995, 120–170 years (see Marsh, 1996; Table 2). However, there has been some concern that the rarity of the 1995 drought event may be less unusual than the analysis of historical records would imply (e.g. Lees, 1997) as estimates of return periods for recent drought events have been generally based upon short precipitation records. This paper aims to characterise drought events that cause stress to water resources in Yorkshire using a synoptic weather-type index. This will enable the delineation of possible drought events, and their severity, back into the 19th century, and allows revised estimates of return period for recent drought events.

Recent patterns of rainfall, evaporative losses and water demands suggest that the type of water supply stress experienced in 1995–96 may now occur with greater frequency. Defining the characteristics of drought using synoptic weather patterns will also provide information on the resilience of water resource management under future climate change.

2. Using a drought severity index to assess drought risk

2.1. Methodology

Several drought severity indices (DSIs) have been developed to assess drought risk but these are not necessarily consistent and reliable. Indices have been based upon precipitation, temperature, evapotranspiration, groundwater levels and river flows. The index used in this study was developed from the accumulated monthly precipitation deficit concept of Bryant et al. (1992), and is the same as that used by Phillips and McGregor (1998) in an analysis of drought risk in southwest England. Mawdsley et al. (1994) recommend the use of this type of index as it requires little data and can be easily interpreted by users.

The monthly precipitation anomaly, defined in terms of the 1961–1990 mean, provides the only input to the DSIs, of which there are two: DSI_3 and DSI_6. DSI_3 uses a 3-monthly initiation and termination sequence, after Bryant et al. (1992, 1994) and Mawdsley et al. (1994). DSI_6 uses a 6-monthly rule (after Marsh et al., 1994) and can be thought of as more of a measure of hydrological drought than DSI_3 as

Table 1
Sites in Yorkshire used in analysis. Mean-annual precipitation (MAP) and mean proportion dry days (PD) given for the 1961–90 time-period. NGR = national grid reference

Site code	Location	NGR	Start year	Altitude (m)	MAP (mm)	PD
HR	Hury Reservoir	NY 967193	1929	263	909	0.42
LR	Lockwood Reservoir	NZ 668141	1873	193	803	0.45
SC	Scarborough	TA 031883	1911	52	660	0.52
MC	Moorland Cottage	SD 807923	1936	343	1939	0.41
KB	Kirk Bramwith	SE 618114	1891	7	593	0.58

precipitation totals over the preceding 6 months are considered. Drought termination rules can be adapted to suit the dominant water resource of an area by varying the critical duration for which precipitation is aggregated. It is suggested (Goldsmith et al., 1997) that for the northeast region, which includes Yorkshire, a 3-month termination rule is appropriate for surface water resources, with a 6-month rule for groundwater resources.

The formulae used to calculate DSI_3 are given as an example. Those used for DSI_6 are the same only using a 6-month period. The precipitation anomaly in month t is denoted as X_t. If X_t is negative and precipitation in the preceding 3-month period, i.e. X_{t-1}, X_{t-2}, X_{t-3}, is

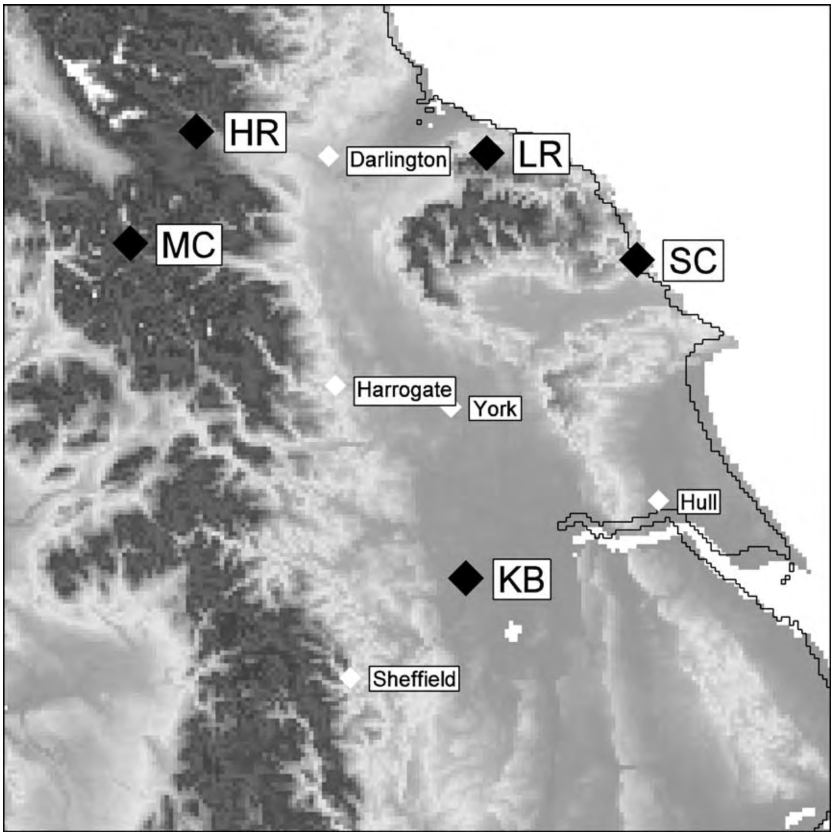

Fig. 1. Location of the five Yorkshire rainfall gauges used in the drought analysis with an underlay elevation map (dark areas show highest elevation).

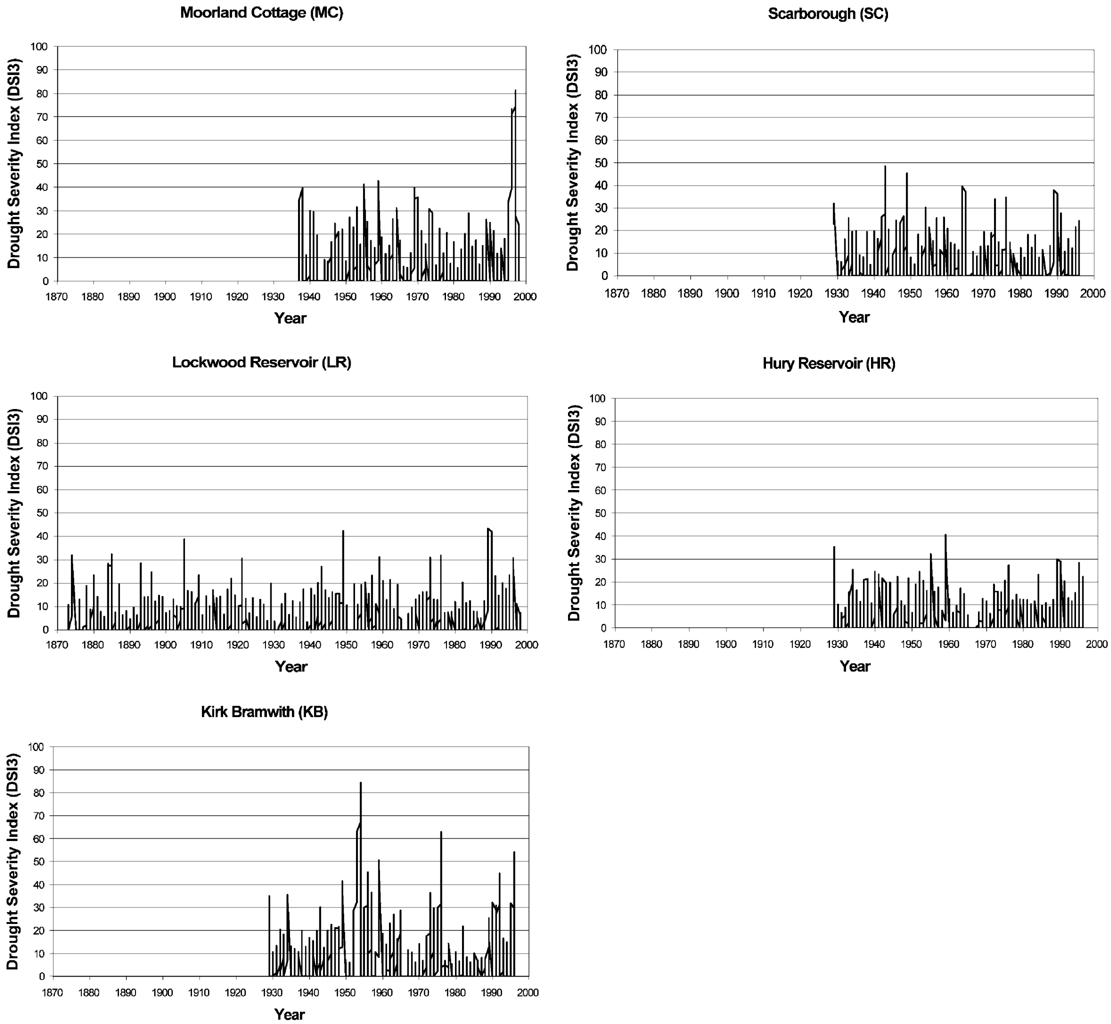

Fig. 2. Spatial comparison of drought behaviour at the five sites using DSI_3.

also lower than its mean, then a drought sequence is initiated. DSI_3 is assigned a positive value proportional to the precipitation deficit in month *t*. If the month $t+1$ is then considered and the precipitation deficits in months t and $t+1$ are $-X$ and $-Y$ mm, respectively, then DSI_3 for month $t+1$ will be $X+Y$ if the mean monthly precipitation total for the preceding 3 months has not been exceeded. If the precipitation anomaly is positive in month $t+1$ then the drought can continue only if the 3-monthly mean total has not been exceeded, with $DSI_3 = X - Y$ (after Phillips and McGregor, 1998).

Termination of a drought occurs when the 3-monthly mean total has been exceeded, and DSI_3 is assigned a value of zero. DSI_3 and DSI_6 are standardised by dividing the absolute deficit (mm) by the site mean-annual precipitation, and then multiplying by -100 to enable inter-station comparisons. The final index value expresses the accumulated deficit as a percentage of mean-annual precipitation (after Phillips and McGregor, 1998).

2.2. *Spatial comparison of drought severity indices*

The DSIs, DSI_3 and DSI_6, were used to assess drought risk at the five stations detailed in Table 1

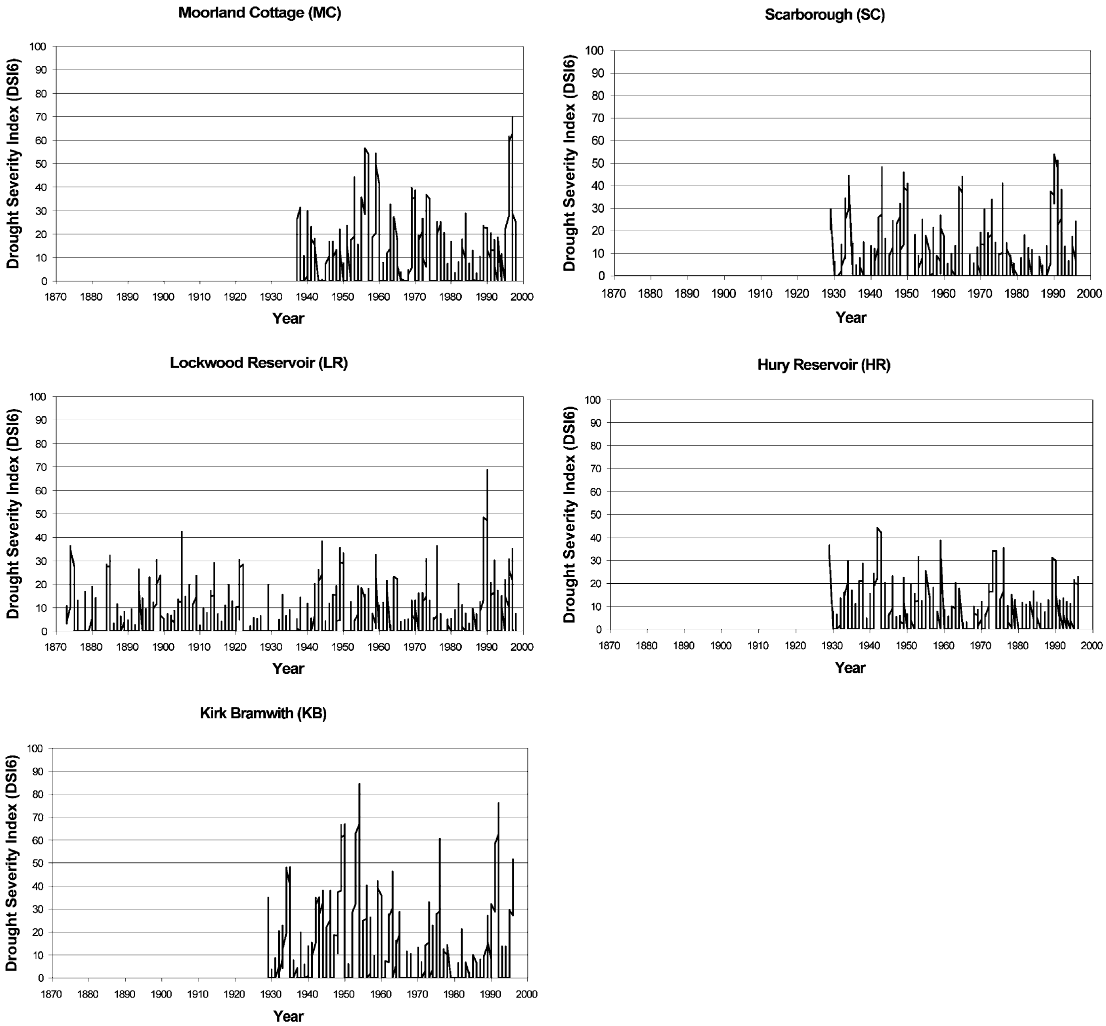

Fig. 3. Spatial comparison of drought behaviour at the five sites using DSI_6.

and Fig. 1: Hury Reservoir, Lockwood Reservoir, Scarborough, Moorland Cottage and Kirk Bramwith. At these stations continuous daily records of more than 50 years are available. The DSIs were compared using the Spearman rank-order correlation coefficient (after Phillips and McGregor, 1998) as about one half of the DSI values are zero (Figs. 2 and 3). Coefficients were calculated using the 718 months common to all seven sites and can be found in Table 2. All coefficients shown are statistically significant at the 95% level.

When a comparison is made of the DSI_3 time series, the largest correlation in drought behaviour is found between Scarborough and Lockwood Reservoir (both located in east Yorkshire) and Moorland Cottage and Hury Reservoir (both in the Pennines). The lowest associations are found between Moorland Cottage and the sites of Lockwood Reservoir and Kirk Bramwith. For the DSI_6 index, the strongest associations are again between Scarborough and Lockwood Reservoir, and Moorland Cottage and Hury Reservoir. This suggests a consistency in drought behaviour, and splits the sites into two groups; a Pennine group and those sites to the east of the Pennines. This division of Yorkshire into two climatogically distinct regions can be substantiated by a more rigorous analysis using 150

Table 2
Cross-correlation between the drought severity indices DSI_3 and DSI_6 at five sites, using the 718 month period common to all locations (October 1936–December 1998). All coefficients shown are significant at the 95% confidence level. Blank cells represent non-significant correlations

	DSI_3				DSI_6				
	MC	HR	SC	KB	LR	MC	HR	SC	KB
DSI_3									
LR	0.22	0.37	0.61	0.43	0.16	0.07	0.13	0.18	0.16
MC		0.53	0.22	0.27		0.19	0.13		
HR			0.44	0.38			0.15	0.14	0.11
SC				0.47	0.16	0.08	0.14	0.27	0.19
KB					0.17	0.12	0.19	0.21	0.35
DSI_6									
LR						0.10	0.24	0.50	0.35
MC							0.47	0.19	0.19
HR								0.32	0.32
SC									0.42

sites in Fowler et al. (2000). The correlations between sites in Yorkshire are nowhere near as high as those determined for locations in Cornwall (Phillips and McGregor, 1998) however, and this suggests that the climatology of Yorkshire is more spatially variable.

Of the five sites shown in Fig. 1, precipitation deficits are least likely to occur at Lockwood Reservoir. Over 46% of months at Lockwood Reservoir were assigned a DSI of zero. Interestingly, the site where a precipitation deficit is most likely to occur is Moorland Cottage. This site is located in the Pennines and is a useful representative site for estimating water supply to Pennine reservoirs.

2.3. Identifying and characterising significant drought events in Yorkshire

To be classed as a severe drought, both indices at all five locations must exceed 10, and these months are then termed the 'core' months of the drought (after Phillips and McGregor, 1998). The 14 severe droughts that have occurred since 1900 and the circulation anomalies associated with each of these droughts are presented in Table 3 and Fig. 4. The objective Lamb weather types (LWTs) (Jones et al., 1993) were aggregated into eight groups using the classification method of Phillips and McGregor (1998), but omitting the unclassified group. This classification is considered ideal for distinguishing drought patterns in Yorkshire, as northerly and easterly winds will generally bring rain to the eastern part of the region, whereas westerly and southerly winds will precipitate mostly in the west.

Droughts in the Yorkshire region are highly spatially variable in impact, in both severity and duration and can be classified as 'western', 'eastern' or 'regional' in nature. All droughts show an increase in the anticyclonic weather type, although this may be small. Another common feature is a decrease in the

Table 3
Percentage anomalies for each of the aggregated objective Lamb weather types for severe droughts occurring this century in Yorkshire when compared to the average for the period from 1861 to 1998 (after Phillips and McGregor, 1998)

Drought	Duration	A	C	N and E	S and W	A (N and E)	A (S and W)	C (N and E)	C (S and W)
1905/6	Jan 1905–Dec 1906	0.4	−19.3	2.1	8.3	−36.2	21.5	11.8	−22.1
1913/4	Jun 1913– Dec 1914	−3.5	−21.0	−19.0	13.4	−6.4	15.9	−32.3	−5.4
1933/5	Apr 1933–Apr 1935	−0.1	4.4	−6.0	−2.3	−14.0	5.4	−14.4	15.3
1941/4	Jul 1941–Oct 1944	31.6	−7.8	2.3	1.5	−7.8	3.2	−37.6	2.9
1948/9	Jul 1948–Apr 1950	14.0	−39.0	−38.9	17.9	−19.8	2.1	−23.1	19.7
1952/4	May 1952–Oct 1954	−10.2	−6.4	−7.3	9.0	6.6	22.5	−31.7	−1.7
1955/7	Apr 1955–Feb 1957	2.0	−26.1	−11.9	3.6	52.3	25.3	−9.9	−17.0
1959/60	Jan 1959–Feb 1960	15.3	11.4	−8.2	−8.7	−23.6	8.9	−9.7	−9.0
1962/3	Oct 1962–Dec 1963	−35.1	9.4	32.8	−5.2	67.7	−15.2	54.3	7.1
1963/65	Feb 1964–Oct 1965	−19.6	−24.1	5.7	20.7	−7.2	8.9	−13.9	13.4
1972/4	Sep 1972–Feb 1974	15.1	−19.5	−38.4	12.8	−33.3	17.6	−28.0	−14.7
1975/6	Apr 1975–Dec 1976	15.4	−21.6	0.1	4.0	−0.4	2.4	−7.5	−16.7
1988/92	Dec 1988–Dec 1992	4.8	−23.1	−15.4	15.3	−10.7	−7.7	−19.4	7.5
1995/6	May 1995–Feb 1997	9.8	−6.5	39.7	−14.1	35.2	1.6	5.1	−30.0

(a)

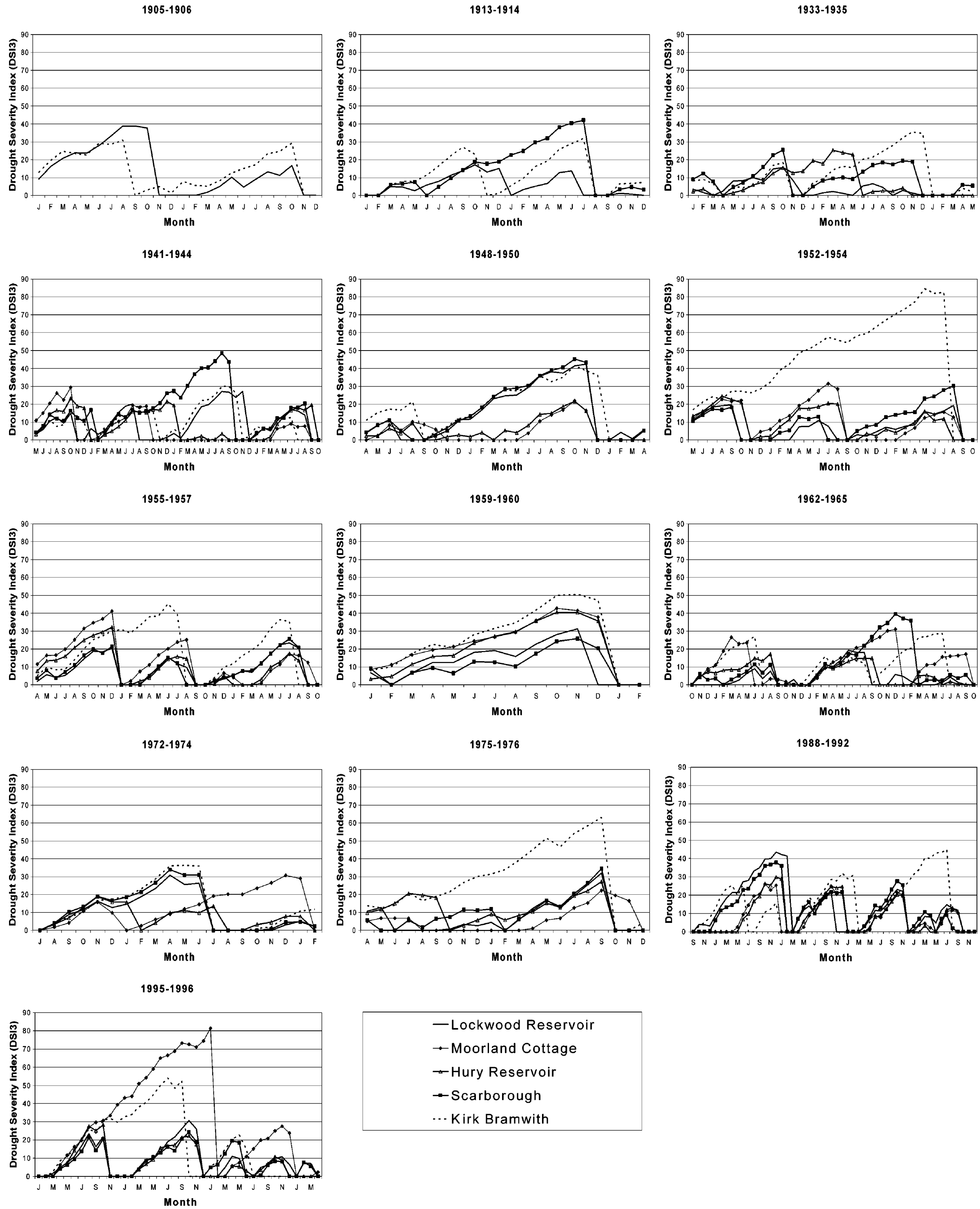

Fig. 4. Comparison of characteristics of the Class I drought events in Yorkshire since 1900 using: (a) DSI_3, (b) DSI_6.

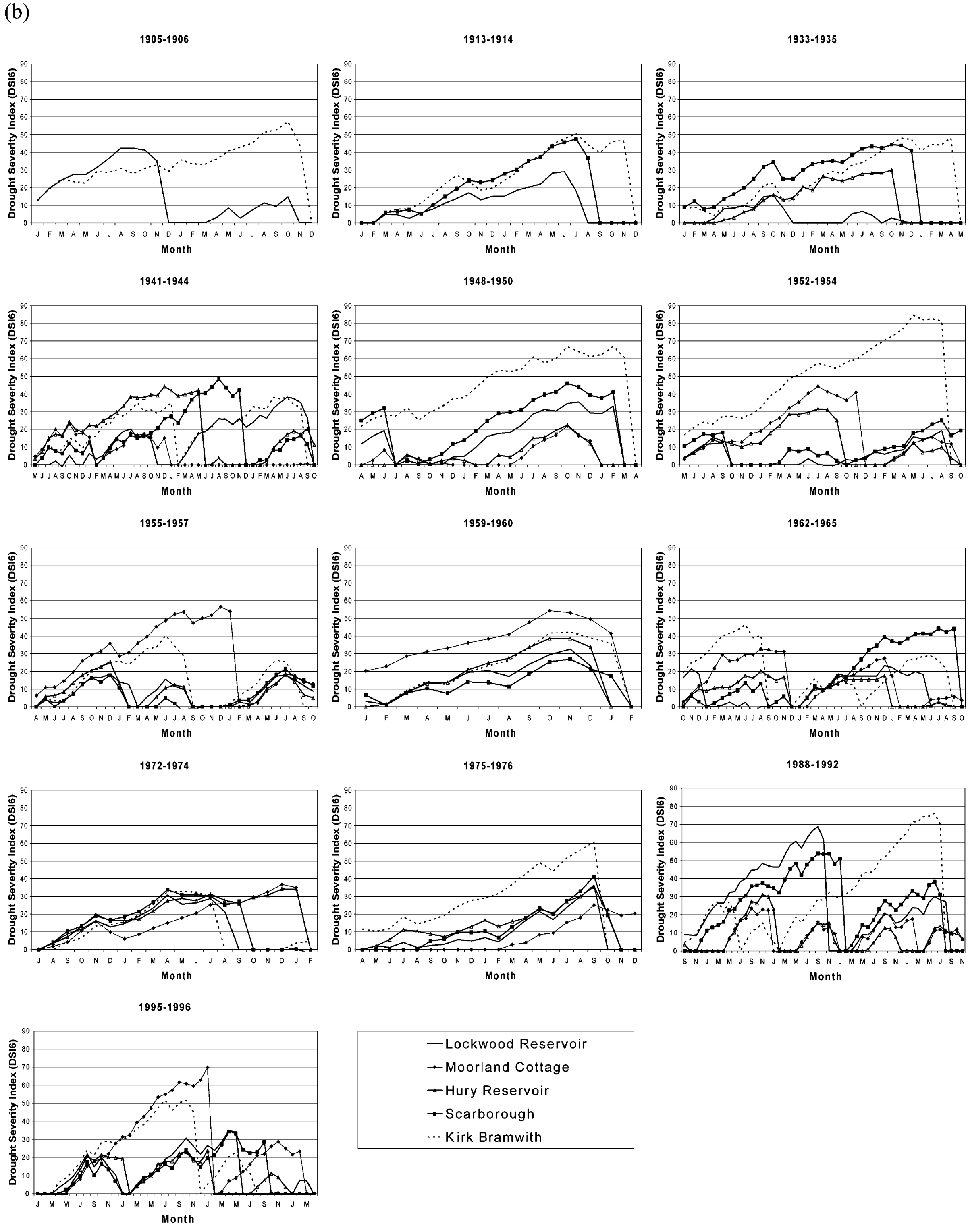

Fig. 4. (*continued*)

occurrence of cyclonic types. However, there is likely to be a larger decrease in cyclonic types during eastern droughts than western droughts. The eastern drought is generally classified by a decrease in the occurrence of easterly and cyclonic easterly weather types. This may also be accompanied by a decline in the frequency of anticyclonic easterlies. Most commonly, these decreases are countered by an increase in frequency of the westerly types (S and W, A (S and W) and C (S and W)). This accounts for the focus of the drought on the east of Yorkshire, while the west enjoys average precipitation conditions. A western drought generally exhibits opposing trends to that of an eastern drought. The drought is characterised by large decreases in the westerly and cyclonic westerly aggregated weather types. The easterly and northerly weather types generally increase in incidence during these events, although cyclonic types also show a rapid decline in frequency. A good example would be the drought of 1995. A regional drought can be characterised by many different factors. The main feature is a large decrease in rain bearing weather types across the region, usually cyclonic types (C, C (S and W) and C (N and E)). This is accompanied by an increase in anticyclonic types; sometimes just the anticyclonic type itself (as in 1975/76) but often in the form of the 'hybrids' (A (S and W) and A (N and E)). The directionals (S and W, and N and E) also exhibit large decreases during regional droughts, although the magnitude of the decrease will depend upon the drought being examined.

3. Development of a weather-type drought classification

3.1. Water resource droughts in Yorkshire

The north of England is very reliant on surface water resources. Much of Yorkshire, in particular, is dependent upon a large number of single-season upland reservoirs in the Pennine hills. These fill during the winter months and are drawn-down during the summer months, with relatively little carry-over from one year to the next. If low precipitation totals persist into autumn and winter these resources become increasingly vulnerable. Single-season reservoirs are especially sensitive to droughts lasting through one summer season, i.e. 6–9 months.

Most of the major water resource droughts in Yorkshire during the last century have involved a very dry spring and summer, with the preceding winter precipitation being less important. This can be seen in the drought of 1995. The 32-month period up to the late winter of 1994–95 constituted the wettest on record. Reservoirs were at capacity and groundwater levels were close to seasonal maxima. However, by mid-July there was a notable decline in reservoir levels in the Pennines, to below 20% of capacity. This implies that severe drought in the Pennines is as much a function of very dry spring and summer weather as a dry winter, due to the reliance upon single-season reservoir resources (Fowler, 2000). As most of Yorkshire's water resources are located in the Pennines then western droughts will be the most important in water resource terms and must be examined further.

3.2. Examining the weather-type characteristics of drought

The automated method of weather-type classification, based on Lamb's weather types (Lamb, 1972), and developed by Jenkinson and Collinson (1977) was used to define water resource drought events within Yorkshire. The objective Lamb weather types (Jones et al., 1993) provide a complete classification of daily atmospheric flow over the British Isles from 1880 and continue to be updated (http://www.cru.uea.ac.uk/cru/data/lwt.htm). The scheme contains eight directional weather types; north (N) northeast (NE), east (E), southeast (SE), south (S), southwest (SW), west (W), and northwest (NW), and two non-directional types; anticyclonic (A) and cyclonic (C). The directional and non-directional types can also be combined to define more complex hybrids, for example the cyclonic easterly (CE). In addition, an unclassifiable (U) type is defined. This gives 27 possible weather types within the scheme.

The 14 severe droughts were re-analysed using two weather-type cluster classification systems based on: (a) precipitation amount and, (b) direction of source. The precipitation amount classification was based on a *k*-means clustering analysis at Moorland Cottage, which is located in a region that was badly affected by the 1995 drought. LWTs were clustered using the

Table 4
Cluster definitions for the Pennine region in summer—precipitation classification. MDP is mean daily precipitation

Weather state	Characteristics	Objective Lamb weather types
Dry/light	MDP = 0.7–1.7 mm; PD = 0.7–0.8	A, ANE, AE, ASE
Medium	MDP = 1.9–4.3 mm; PD = 0.4–0.7	U, AS, ASW, ANW, AN, NE, E, SE, N, CNE, CN, AW
Heavy	MDP = 3.0–9.1 mm; PD = 0.2–0.5	S, SW, W, NW, C, CE, CSE, CS, CSW, CW, CNW

seasonal statistics of mean daily precipitation and PD. Three clusters, arbitrarily termed 'Dry/light', 'Medium' and 'Heavy', were found to adequately describe the precipitation regime at the Pennine site (Table 4).

The k-means algorithm is based on Hartigan and Wong (1979) and its objective is to find group memberships that minimise the total within-cluster sum of squares over all k of the clusters. The objective function, ϕ, can be represented by (Corte-Real et al., 1998):

$$\phi = \sum_{k=1}^{K} \sum_{j=1}^{M} \sum_{i=1}^{N_k} (x_{ijk} - \bar{x}_{jk})^2 \quad (1)$$

where K is the total number of classes, M is the number of variables used, N_k is the number of samples in the kth cluster.

A sample is assigned to a cluster by minimisation of the Euclidean distance between the vector of observed values (variables) and the mean of all the variables within a cluster. The k-means algorithm regroups data until the optimal cluster membership combination is achieved and the samples no longer change clusters.

Table 5
Cluster definitions for the directional classification

Weather state	Objective Lamb weather types
Anticyclonic (A)	A, AE, ASE, AS, ASW
Easterly (E)	AN, ANE, N, NE, CN, CNE, E, SE, CE, CSE
Westerly (W)	AW, ANW, S, SW, W, NW, C, CS, CSW, CW, CNW

In the 'directional' classification, weather types were clustered according to direction of source. In Yorkshire, the major sources can be split into two: the easterly and westerly weather states, with an additional weather state that is dry across the region and encompasses the majority of the anticyclonic types (Table 5) (after Fowler et al., 2000). It may be noted that in meteorological terms these may roughly be defined as blocking (anticyclonic), zonal (westerly) and meridional (easterly). The weather types within the westerly state supply the Pennines with precipitation, whereas the easterly state provides precipitation to the north and east. In the Pennines, both the easterly and anticyclonic states will produce little precipitation, and a prolonged increase in incidence of these would be expected to produce a water resource drought in the single-season Pennine reservoirs.

The 14 major drought events were examined using these measures, to allow the characterisation of the western or Pennine droughts that cause water resource deficits in Yorkshire. The characteristics of regional and eastern droughts were also determined. Droughts highlighted in bold in Table 6 refer to western or regional droughts. Two types of western drought can be discerned. The first type is caused by a dry winter followed by an average or dry summer. This type of drought occurs due to a lack of winter replenishment of water resources. The second type occurs due to the drawdown of resources during a very dry summer.

It can be observed in Table 6 that western droughts are characterised by a significant increase in the easterly weather state. This may also be accompanied by an increase in the occurrence of the anticyclonic weather state. The severity of drought depends upon the magnitude of increase of the two weather states. Most western droughts also show a decrease in the number of westerly days, although this may not be severe. The extreme drought of 1995 is highlighted by this analysis. An increase in easterly and anticyclonic occurrence of 28.4 and 17.7%, respectively, was accompanied by a large decrease of 15.3% in westerly weather state frequency. The drought of 1959–1960 also shows the same pattern of change, although nowhere near as severe. The 1962–1963 western drought records a large increase in easterly weather state occurrence of 30.6% accompanied by declines in both the westerly and anticyclonic states. This explains the drought to the west of the

Table 6
Percentage anomalies for each of the precipitation and directional classifications for severe droughts occurring this century in Yorkshire when compared to the average for the period from 1861 to 1998. Those droughts highlighted in bold refer to western or regional droughts

Drought	Duration	Precipitation classification			Directional classification		
		Dry	Medium	Heavy	A	E	W
1905/06	Jan 1905–Dec 1906	−5.6	12.2	−3.1	−1.9	3.1	−0.5
1913/14	Jun 1913–Dec 1914	−4.0	−4.5	1.3	−1.3	−19.9	3.2
1933/35	**Apr 1933–Apr 1935**	**−2.4**	**−1.3**	**1.7**	**−1.7**	**0.2**	**1.1**
1941/44	Jul 1941–Oct 1944	25.3	−1.1	−1.4	19.2	−3.0	1.5
1948/49	**Jul 1948–Apr 1950**	**8.7**	**−17.6**	**3.3**	**18.0**	**−33.6**	**0.7**
1952/54	**May 1952–Oct 1954**	**−7.5**	**5.9**	**1.8**	**−6.8**	**−11.6**	**6.8**
1955/57	**Apr 1955–Feb 1957**	**10.1**	**4.1**	**−6.6**	**−0.2**	**3.2**	**−0.6**
1959/60	**Jan 1959–Feb 1960**	**8.9**	**−0.2**	**−4.0**	**11.2**	**7.5**	**−7.2**
1962/63	**Oct 1962–Dec 1963**	**−18.6**	**12.0**	**1.7**	**−11.0**	**30.6**	**−4.4**
1964/65	Feb 1964–Oct 1965	−17.6	10.5	5.5	−12.7	12.6	3.9
1972/74	**Sep 1972–Feb 1974**	**7.5**	**−12.2**	**0.7**	**14.2**	**−31.7**	**0.8**
1975/76	**Apr 1975–Dec 1976**	**12.8**	**−0.2**	**−5.6**	**10.8**	**−4.5**	**−3.4**
1988/92	Dec 1988–Dec 1992	2.3	−11.4	3.6	−0.8	−13.4	4.1
1995/96	**May 1995–Feb 1997**	**13.8**	**15.8**	**−13.0**	**17.7**	**28.4**	**−15.3**

region, but normal precipitation totals to the east. Regional droughts, on the other hand, are generally characterised by an increased frequency of anti-cyclonic weather types. This can be seen clearly in the droughts of 1941–1944, 1949, 1972–1974 and 1975–1976. Eastern droughts are characterised by a decreased occurrence of easterly types, as in the drought of 1988–1992. These may also be increased in severity by an increased frequency of anticyclonic types.

If the 'precipitation' classification system is used then other features of drought within Yorkshire become apparent (Table 6). Unsurprisingly, western droughts are characterised by an increased number of days classified as 'dry' at western sites. A decrease in the occurrence of heavy precipitation days is also apparent for the more severe droughts. The 1995 drought shows a decrease of 13% in the occurrence of heavy weather types, coupled with a 13.8% increase in the frequency of dry types. Another strong feature of the 1995 drought was a large increase in the occurrence of medium weather types. In summer months, when evapotranspiration demands are high, these weather types may provide no effective precipitation. This may have contributed to the severity of drought felt in 1995 in many upland areas of the Pennines.

An analysis was made of summer (JJA) weather

Table 7
Percentage anomalies for each of the precipitation and directional classifications for western water resource droughts occurring this century in Yorkshire when compared to the average for the period from 1861 to 1998

Drought	Duration	Precipitation classification			Directional classification		
		Dry	Medium	Heavy	A	E	W
1928/29	Summer 1928	−23.4	−22.5	20.2	−25.9	−40.6	20.7
1937/38	Summer 1937	12.9	32.9	−15.6	17.1	1.9	−5.7
1948/9	Summer 1949	113.7	−50.2	−36.7	91.2	−23.6	−35.9
1959/60	Summer 1959	69.3	−16.9	−32.5	79.5	−66.0	−26.5
1962/3	Summer 1963	−51.6	29.3	4.1	−52.1	83.0	−2.9
1975/6	Summer 1975	65.3	5.2	−34.6	60.0	27.4	−34.0
1995/6	Summer 1995	57.2	16.3	−36.7	52.2	35.8	−34.0

Table 8
Percentage anomalies for each of the precipitation and directional classifications for western water resource droughts occurring this century in Yorkshire when compared to the average for the period from 1861 to 1998

Drought	Duration	Precipitation classification			Directional classification		
		Dry	Medium	Heavy	A	E	W
1928/29	Apr–Sep 1928	−10.6	26.1	−6.4	−21.6	60.6	−7.8
1937/38	Apr–Sep 1937	−2.7	−7.4	5.8	−4.3	−12.7	6.2
1948/9	Apr–Sep 1948	54.9	−43.4	−9.7	49.2	−40.6	−12.9
1959/60	Apr–Sep 1959	43.0	13.2	−28.4	53.0	−12.7	−23.9
1962/3	Apr–Sep 1963	−52.3	13.2	21.2	−48.3	18.7	17.2
1975/6	Apr–Sep 1975	33.0	−7.4	−15.2	33.9	4.7	−19.9
1995/6	Apr–Sep 1995	13.2	36.4	−24.0	9.0	39.7	−17.9

during recent water resource droughts (western droughts) using the droughts previously identified and those additionally identified by Yorkshire Water. This can be found in Table 7. It can be seen that drought in western Yorkshire is, in general, as much the function of a dry summer as a dry winter. Most water resource droughts involve the increased incidence of anticyclonic and easterly weather types during summer months, coupled with a decreased frequency of westerly types. Percentage changes can be very large and reach over 90% for anticyclonic types in 1949. However, the summer of 1928 was very wet in the west, although a drought occurred from 1928 to 1929. An analysis of weather types shows that this was due to the dry winter of 1928–1929. The summer of 1963 is also unusual as there was no increase in the anticyclonic type but instead a huge increase in the occurrence of easterly weather types. It can be noted, however, that the 1995 drought was no more severe than any other drought, and particularly similar to the 1976 drought, in terms of the 'precipitation' or 'directional' classification systems.

An examination was also made of dry day sequences and 1976 was found to contain longer runs. The longest dry day sequences (by weather cluster) in 1976 were pinpointed as 12 days, from June to July, and 19 days from July to August. In 1995, there was a 14-day dry sequence from June to July, a 10-day sequence in August, another 8-day sequence in August and a 9-day sequence in June. However, in summer months the medium weather-type cluster may also be dry, as evapotranspiration demands are so high. A 34-day 'dry and medium' sequence can be found in 1976 from the 20th July to the 23rd August. This suggests that the summer months of the 1976 drought were as severe as the 1995 drought, although water demand may have been lower.

Another useful measure of drought in Yorkshire, given that the incidence of drought is related to hot, dry summers, is the frequency of weather types during the period from April to September. Water-years run from October to October each year. The half-year from October to March is considered the recharge period, whereas from April through to September is the drawdown period. A severe drought would be expected to show marked change from normal conditions during the drawdown period. It can be seen in Table 8 that severe droughts can be characterised by an analysis of weather-type frequency. The summer droughts of 1948–1949, 1959–1960, and 1975–1976 were characterised by a large increase in the incidence of anticyclonic or dry weather types. In contrast, the 1995 drought exhibited a large increase in the occurrence of easterly types.

3.3. Weather-type index for drought severity classification

A classification system was developed to assess water resource drought severity in Yorkshire based upon weather typing. For each water-year (i.e. October to October), the number of anticyclonic, easterly and westerly weather types in the summer and winter half-years were calculated. For each summer and winter, the number of anticyclonic days was added to half of the number of easterly days (as approximately half can be expected to be dry), and this total

Table 9
Ranked severity of drought events occurring from 1881 to 1998 using the directional classification for western water resource droughts (all years signify the start of the time-period of drought—i.e. for winter (W) = October, and for summer (S) = April). Drought years during the 1880s and 1890 are italicised.

Ranking	Summer	Winter	W + S	S + W	S + W + S
1	*1887*	1963	*1886/87*	*1887/88*	*1887/88*
2	1921	*1891*	*1887/88*	1968/69	*1894/95*
3	1984	1969	1946/47	1955/56	1995/96
4	*1893*	1944	1958/59	*1894/95*	1968/69
5	*1884*	1938	*1894/95*	1995/96	*1886/87*
6	1968	1996	1995/96	1941/42	*1884/85*
7	1955	*1895*	1943/44	*1885/86*	*1895/96*
8	1976	*1888*	*1895/96*	*1896/97*	*1885/86*
9	1959	1934	1910/11	1921/22	*1893/94*
10	*1896*	1956	1940/41	1947/48	1983/84
11	*1894*	1940	1948/49	1939/40	1941/42
12	1977	1953	1968/69	*1884/85*	1940/41
13	1949	*1886*	1983/84	1996/97	*1888/89*
14	1947	*1898*	1939/40	1984/85	*1896/97*
15	1982	1942	*1885/86*	1945/46	1939/40
16	1941	1965	*1892/93*	*1895/96*	1975/76
17	1906	1992	*1898/99*	*1886/87*	1976/77
18	1995	*1887*	*1884/85*	*1888/89*	1905/06
19	1911	1947	1905/06	*1897/98*	1910/11
20	*1885*	1932	1941/42	*1889/90*	1944/45
21	1975	1986	*1888/89*	*1890/91*	*1892/93*
22	1989	1946	*1890/91*	1991/92	1958/59
23	1973	1923	1954/55	*1893/94*	1971/72
24	1901	1959	*1883/84*	1933/34	1955/56
25	*1888*	1964	*1893/94*	*1881/82*	1947/48
26	1957	1911	1944/45	1959/60	1982/83
27	1983	1929	1970/71	1944/45	1908/09
28	1915	*1882*	1920/21	1915/16	1972/73
29	*1895*	1941	1937/38	1937/38	1915/16
30	1971	*1899*	1908/09	1940/41	1948/49

was divided by the incidence of westerly types. Therefore, an index greater than one implies a high incidence of anticyclonic and easterly types and provides an indication of drought. Water half-years from 1881 to 1998 were ranked according to the above index and the top 30 summer, winter, summer–winter, winter–summer, and summer–winter–summer droughts can be found in Table 9. This kind of index is very useful as it allows the identification of drought events where precipitation records are scarce or lacking in either temporal or spatial extent.

This analysis clearly shows a large number of drought events during the 1880s and 1890s which are italicised in Table 9. The period from 1885 to 1898 contains a number of severe drought events if the 'directional classification' is used. The period 1886–1888 ranks as the most severe drought on record in all categories, excepting winter. Jones and Lister (1998) also reveal this drought as the most severe on record in the Wharfe river catchment, in terms of the runoff deficit index of Bryant et al. (1994) (see Jones and Lister, 1998; Fig. 7). The Wharfe drains the Pennine west of Yorkshire and will be highly affected by western water resource drought. This categorisation of drought can also be substantiated by many statements made about the 1880s and 1890s.

For 1884:

An observer at Hull (Derringham) noted,

> The water supply continued deficient to the end of the year, the wells, streams and district drains being all low. (Symons, 1884; p. 111)

During autumn 1884 in Leeds,

> The water supply at Horsforth (in the hands of a private company) failed, and was limited, from August 22nd until December 21st, to two hours per diem, and sometimes was not turned on at all…several open streams dried up, but the wells were not exhausted. (Symons, 1884; p. 111)

For 1887:

> The least rainfall [for any calendar year from 1868 to 1924 inclusive] was recorded in 1887 over much of the English Lake District and the Pennines…the catchment areas for the supply of Halifax, Bradford and Keighley join on the moors overlooking Howarth…while the water draining to the west of Howarth supplies the towns of Colne, Nelson or Burnley. The capacity of those schemes which were in operation during 1887 was more severely taxed than in those of forty subsequent years…the level of Lake Derwentwater fell on July 9th to a lower level than ever previously recorded, being 8 in. below low water mark. (Brooks and Glasspoole, 1928; pp. 135–136)

For 1893:

> The drought which prevailed over England and

> the neighbouring parts of the Continent during the spring and summer of 1893 was so exceptional, both as regards severity and duration, that little apology is needed for submitting the main facts of the case to the notice of the [Royal Meteorological] Society on this, the earliest available opportunity. The drought itself was followed, after a long showery interval in July, by another spell of fine weather in August and September, so that one was at first tempted to extend the limits of the present inquiry up to Michaelmas. On reflection, however, it seemed quite evident that a wide distinction must be drawn between a drought and a mere deficiency of rain; and as the former characteristic ended with the close of June it was decided to confine this investigation to the weather of the four months commencing with March. (Brodie, 1894)

In September 1893, an observer at Thixendale in the Yorkshire Wolds noted,

> Great scarcity of water, springs very low (Symons and Wallis, 1893; p68)

It can be noted that the summer droughts of 1884, 1887 and 1893 are, respectively, ranked fifth, first and fourth in severity using this classification system. The summer of 1995 is ranked at only 18th. However, the drought of 1995–96 ranks as the fifth most severe summer–winter drought during the period from 1881 to 1998. This is raised to the third most severe summer–winter–summer drought, starting in April 1995 and ending in September 1996. This long duration, severity, and unusual nature of the drought, being driven by increased occurrence of easterly weather types rather than anticyclonic types, may have led to the water supply crisis in western Yorkshire during 1995–96.

The 1984 summer drought is also highlighted by this analysis. Previous analyses (Goldsmith et al., 1997) failed to find a reason for the water supply shortages in 1984. An analysis of weather types has however, pinpointed the cause as increased anticyclonic and easterly weather conditions that led to decreased precipitation in western Yorkshire. The period from April 1983 to September 1984 ranks as the 10th most severe drought period on record, in terms of weather types. Therefore, the 1984 drought can be defined as an amalgamation of two dry summers with an intervening dry winter.

This analysis shows that the severe drought events of the late 1980s and 1990s are not unique within the context of the historic record. Indeed, evidence suggests that the 1880s and 1890s may have had more severe drought events than during recent years. Therefore, in the context of the historical past the 1995/96 drought is not a rare event. However, the drought events of the 1880s and 1890s have generally not been taken into account when return periods for recent drought events have been calculated due to a scarcity of daily precipitation data prior to the 1900s, although much undigitised monthly data exist.

A crude return period estimate of the 1995–96 drought can be made, using the information given in Table 9. The drought from April 1995 to March 1996 is ranked as the fifth most severe drought in a 118-year period. This gives a return period estimate of 1 in every 24 years for the water-year. Using this estimation system, the 18-month drought from April 1995 to September 1996 can be classed as a 40-year event. These return period estimates are much less severe than those generally quoted for the 1995–96 drought. However, since the clustering of dry and wet years is a prominent feature of climate in Europe, as can be seen during the 1880s and 1890s and recently during the 1980s and 1990s, return periods may not be the best way of classifying drought or flood events.

4. Discussion and conclusions

An examination has been made of 14 severe drought events in Yorkshire using two DSIs based on 3- and 6-monthly cumulative precipitation anomalies. The aggregated objective LWT patterns associated with the 14 drought events suggest that there are three main types of drought in Yorkshire; the eastern drought, the Pennine or western drought, and one where the whole region is similarly affected to a lesser or greater degree. A subjective classification of the 14 severe droughts can be found in Table 10.

Using a weather-type approach to extend drought sequences and hence revise estimates of drought return periods is a potentially useful technique. However, there are limitations within the method

Table 10
Classification of the 14 severe droughts in Yorkshire occurring since 1900

Drought classification	Drought years
Eastern	1905/06, 1913/14, 1941/44, 1964/65
Western/Pennine	1952/54, 1955/57, 1962/63
Regional	1933/35, 1948/50, 1959/60, 1972/74, 1975/76, 1988/92, 1995/96

that must be acknowledged. Firstly, that there may be a non-stationary relationship between weather type and its associated meteorological properties. For example, Wilby (1994) found inter-decadal variability in both mean wet day precipitation amount and probability of precipitation associated with the three dominant LWT classes of A, C and W. This calls into question whether relationships determined between contemporary weather patterns and contemporary drought events are also valid for the earlier period. However, anecdotal evidence reveals that severe droughts predicted using the weather-type indexing methodology actually occurred in the earlier period from 1880 to 1900. Secondly, weather patterns alone may not determine water resource drought. This was certainly the case in 1995, where a severe drought event in Yorkshire was exacerbated by poor management decisions. Further, droughts can be highly localised phenomena and the same weather pattern can yield very different responses in space.

It must also be remembered that it is not necessarily the number of days of occurrence of a particular weather type that may be important for drought initiation, but instead the sequencing and persistence of a weather type may play an equally prominent role. Although recent droughts have not been unusual occurrences in a historical sense, their rapid onset has also been noted by other researchers (e.g. Walker, 1998). There has been a very quick build up of precipitation deficits in recent drought events. This is in contrast to earlier droughts where large water deficiencies took much longer to develop. In this sense, recent droughts have followed a different pattern to that of previous historical drought events, both the 1992 and 1995 sequences taking only 3 months to develop. The 1995 drought was additionally unusual, as the controlling factor was a large increase in the incidence of northerly and easterly weather types, whereas normally a larger increase in anticyclonic conditions would be expected.

There has been much interest in recent drought events and, particularly, the 1995 drought. The changing pattern of recent drought events, with greater intensity of onset, calls into question the validity of giving equal weight in return period estimation to modern and historical hydrometric data (Marsh, 1996). However, there has always been concern that the rarity of the 1995 drought event may be less unusual than the analysis of historical records would imply (e.g. Lees, 1997). The large number of drought events in the late 1980s and early 1990s is not unusual in a historical sense, as similar events are likely to have occurred in the last two decades of the 19th century. These events may have also had a rapid onset; anecdotal evidence certainly seems to suggest a quick build-up of large precipitation deficits. Using a weather-type approach to index the rarity of historical and contemporary drought events provides important additional information on historical drought events where precipitation records are either scarce or lacking. Although not strictly quantitative, this may offer enough data to allow water resource managers to alter return period estimates of recent drought events.

Another advantage of the weather-type approach is the link to large-scale atmospheric circulation. Classifying water resource drought severity in this way provides the opportunity to examine the impacts of future climate change using weather-type frequency changes from GCM predictions. This can either be achieved via a simple indexing approach as taken in this research, or a more complex downscaling methodology where rainfall series are generated stochastically using conditioning by weather types clustered according to regional patterns of precipitation that cause water resource drought (Fowler et al., 2000). This advance will allow the return period estimation of drought events of similar severity of magnitude to the 1995–96 drought for future climate change scenarios.

Even if the events of the 1880s and 1890s were similar to recent drought events, climatic change coupled with the increasing demand for water and enhanced variability of the hydrological system means that water resource contingency planning in the UK needs to concentrate on significantly increased periods of water supply deficit and the rapid diminution of resources.

Acknowledgements

This work was undertaken as part of a PhD thesis funded jointly by the Engineering and Physical Sciences Research Council (EPSRC) and the Environment Agency (Yorkshire and Northumberland Region). Precipitation data were supplied by Mike Stokes (York EA), and LWT data by Phil Jones (Climate Research Unit, UEA). Supervision and encouragement from Enda O'Connell is also gratefully acknowledged.

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