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Naughty thoughts about drought rarity

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Drought rarity assessment from monthly rainfall data is suspect. Estimates are typically cherry-picked, with raingauge, starting month and duration chosen to maximise the inferred rarity of the drought that a Water Company is experiencing. Yet the water-resource system is sensitive to a spectrum of droughts: not just one of this specific duration and starting month. The paper forms part of a new approach to assessing and visualising the rarity of an ongoing drought based on long-term monthly rainfall records and characteristics of the resource system. Using records from 38 sites across Great Britain and Ireland, it is shown that even a century of data provides only a very small sample of long-duration extremes. Measures related to 98% reliable yield and inter-site dependence are investigated.

Keywords: *drought rarity, inter-site dependence, long duration, monthly rainfall data*

1. INTRODUCTION

1.1. Context

The paper is concerned with *water-resource drought*. This is taken to mean periods of several/many months of sufficiently low rainfall as to present Water Companies with difficulties in maintaining normal supplies. The author contends that – for the specific task of drought rarity assessment – the analysis of long-term monthly rainfall data is unfashionable. Reactions heard include:

- Why are you dredging up old data no longer representative of the current climate?
- You must study effective rainfall not total rainfall.
- Why are you using monthly rainfall depths rather than daily data?
- Catchments are complex entities. You must use hydrological models to link rainfall to the runoff/recharge that feeds your water resource.

There is an element of truth in these criticisms, and each is touched on in the closure to Reed (2015). It is correct to doubt the validity of many estimates of drought rarity made from monthly rainfall data. All too often, the assessment grossly exaggerates the rarity of an ongoing drought through cherry-picking the raingauge, starting month and duration over which historical comparisons are made. Yet the resource is sensitive to a spectrum of droughts: not just one of this specific duration and starting month.

Though many professionals know that event rarity is thereby grossly exaggerated, the poor practice is resumed when drought next puts water resources under strain. This detracts from professional as well as public understanding, and erodes trust in statistics. It is gratifying that Jones (2003) has explored at least part of the topic formally.

The degree of exaggeration of drought rarity is influenced by the character of the water resource. Those of limited storage are typically sensitive to short drought, while systems with large storage are sensitive to middling or long drought. Systems integrating surface water and groundwater resources – and those integrating local and regional resources – can be sensitive to an especially wide range of drought durations. This is accentuated by operating rules which exploit flexibility to over-draw low-cost local water in times of plenty, knowing that (in most scenarios) deficits can be made good by regional water should the drought deepen or persist. System complexity can make it difficult to confirm that quoted standards of reliability are being met. It is as well that undue emphasis on minimising operating costs is curbed by ecological, amenity and water quality constraints.

A typical approach to drought management planning is to simulate catchments and water-resource operations in considerable detail. Changes in land use occur even within catchments that form a major water resource. Features of the resource system itself – storage, aqueduct & treatment capacities and abstraction licenses & operating rules – evolve, as does the water demand placed on the system and the energy costs incurred in its operation. Whilst it is important to simulate how the currently configured system performs over the historic period of record, this can lead to a detachment between observations and modelling. The hydrometric records available for model calibration are seldom uniform. Given the concerns of climate and land-use change, it is tempting to focus on more recent data: data that (somewhat puzzlingly) are held *de facto* to be more reliable. But it is unacceptable to downplay important droughts simply because they occurred a long time ago.

For reasons captured in Section 3, we are much less well-endowed with information than we think we are. A century of data is of immense value in river flood estimation yet pitifully short if the underlying interest is in long-duration events: be these multi-year droughts or “wets”.

In a companion paper, Reed (2015) presents a method for assessing and displaying the rarity of an ongoing drought based on the stock simulation method introduced in Section 2.2 of the current paper.

1.2. Long-term rainfall series

Reed (1995) trialled drought analysis methods in a paper to a centenary conference. The period adopted for analysis was 1890-1989, with a further three years selected at either end to capture long-duration extremes that lie mainly within the century of analysis. These choices are maintained in the current research. Each data series studied has complete records of monthly rainfall across 1887-1992 (i.e. 1272 months). It can be helpful not to be too up-to-date. Rainfall records at nominally long-term sites are not always continued. Raingauge networks in the UK shrank notably in the 1980s, and the continuation of some long series is dependent on data transfer from nearby sites. The records analysed here come from datasets held by the UK Met Office (UKMO), the Climatic Research Unit (CRU) and the Centre for Ecology and Hydrology (CEH).

Though simple in principle, the measurement of rainfall can be problematic in the long term. Changes in observer, measurement technology and exposure (not least to trees and buildings) present difficulties even at prestigious sites, as Craddock and Smith (1978) illustrate.

Analysts sometimes differ in their interpretation of particular long-term rainfall series and not all changes made are recorded or recalled. New data checks were made as part of this research. It is especially helpful that copies of the *British Rainfall* (BR) yearbooks are available online up to closure of the series in 1991. These contemporary accounts assist checks on long-forgotten episodes.

All but one of the required 1272 rainfall depths were present in the monthly rainfall series for Braemar (labelled BRAE in Figure 1). The missing value was for Jan 1937. The BR yearbook highlights the exceptionally wet January in Braemar, Balmoral and district, presents confirmatory data and observes that the total of 13.41 inches was the wettest of any month since records began at Braemar in 1866. McEwen (1987) presents evidence that the 24 Jan 1937 flood on the upper Dee was the largest since August 1829. Yet at some stage, an analyst has rejected the monthly value as unreliable. It is good that the deletion was declared in the series by a missing value. If only that were always the case. The Oct 1960 value in the Southampton (SOUT) series had been reduced from the gauged value of 7.10 inches to 3.50 inches. Reference to the BR yearbook revealed nothing to support the reduction.

Out of obsession more than real need, minor differences in competing series for Armagh Observatory (labelled ARMA) prompted reference to the BR yearbooks. The two versions differed in only eight of the 1272 months, and none of the differences was greater than 10 mm. In this instance, the CRU series was favoured over the UKMO series. Bells rang more loudly during the drought analysis of Section 2.1. A long-duration drought in the early/mid 1950s was perplexing, given that this is not pronounced elsewhere. It transpired that monthly rainfalls in the UKMO and CRU series are in gross error from Aug 1952 to Mar 1955, with 1952-1955 rainfall totalling 91.00 inches in the BR yearbooks but only 51.05 inches in the UKMO and CRU series. A further version of Armagh monthly rainfall data was found in Butler *et al.* (1998), albeit presented as daily mean rates rather than monthly depths. These data reconfirmed the BR data for 1952-1955. Worryingly, the Butler *et al.* data are in gross error elsewhere in the long time-series. It would appear that the authors (based at Armagh Observatory) adopted readings of 9.06 and 6.27 inches for Jan 1911 and Feb 1934 through misreading handwritten entries of 1.06 and 0.27 inches, and failing to cross-check with annual totals.

The initial network of sites studied included Point of Ayre in the Isle of Man and a CRU series labelled Cork Airport. The BR yearbooks indicate non-standard instrumentation at the Point of Ayre in the early decades, likely leading to serious under-catching at this highly exposed site. It was not possible to remedy this within the current study, and the site was removed from the network. Inhomogeneity in the Cork series was found to reflect the shunting together of records from University College Cork with later records at Cork Airport, without adjustment for elevation differences. The Cork series was removed from the network and Roche Point (labelled ROCH) added in its place.

The final network comprises the 38 sites marked in Figure 1. The labels indicate the first four characters of the place-name. These are chiefly premier sites for long-term monthly rainfall; 25 of the 38 sites are amongst those studied by Wright and Jones (1982).

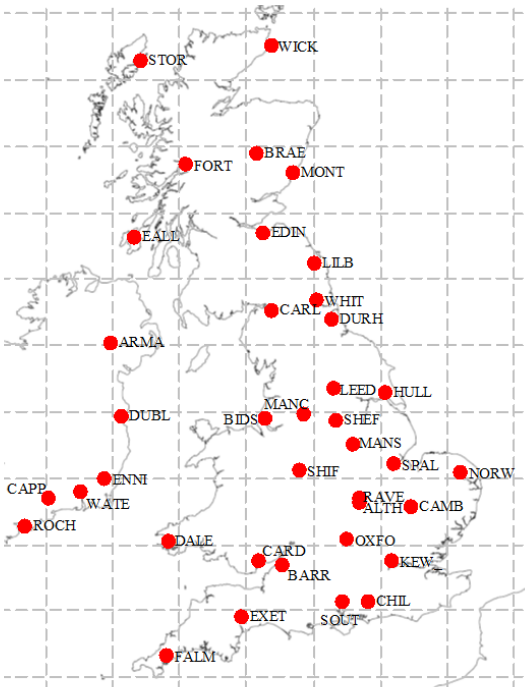


Figure 1 Location map (38 sites)

The LILB and RAVE series – Lilburn in Northumberland and Ravensthorpe in Northamptonshire – were newly worked up from decadal summary sheets held in the UKMO Archive. Other versions of the Lilburn record exist. The version constructed here represents Lilburn Tower Gardens, taking gauged values from that site for 1920-1980. Earlier data are estimated as 1.08 times Lilburn Tower (the original Lilburn Tower instrument was at a non-standard height) and later data as 1.11 times (3.2 km distant) Chillingham Barns. A correction marked on the 1950s decadal summary sheet was incorporated, increasing the Oct 1955 total from 2.47 to 3.27 inches.

The record for Ravensthorpe Reservoir is thought to be a new abstraction. The reservoir forms part of the Ruthamford North Resource Zone summarised in Anglian Water (2014). The long-term rainfall series gathered by the water undertaking appears in generally good order until cessation of measurements in June 1986. The final few years were patched as 1.045 times (8.2 km distant) Moulton Park. Ravensthorpe was selected as an alternative to the somewhat problematic Althorp Park (labelled ALTH). It transpired that CRU had done further work on the Althorp record, so both sites were retained in the study. Being only 5.2 km apart, the ALTHRAVE site-pair is an exception in an otherwise well distributed network.

2. ANALYSIS

2.1. Drought plots

Figure 2 marks droughts for two sites. These are based directly on the monthly rainfall data, without reference to any resource: real or hypothetical. The vertical axis marks drought duration from one to 48 months. For each duration in turn, the ten smallest aggregate rainfalls are selected from the century of record. The most severe drought is found first, and the relevant months of rainfall assigned default values of 9999 mm so that further droughts abstracted of that duration are independent and non-overlapping. Droughts are plotted as rectangles extending from start to end of the relevant period. The heights of the rectangles convey the rank of the drought, with the 10th ranking drought in the century of record given least visual impact. Reed (1995) favoured a square-root transform on the vertical axis to improve visibility of the droughts at short duration.

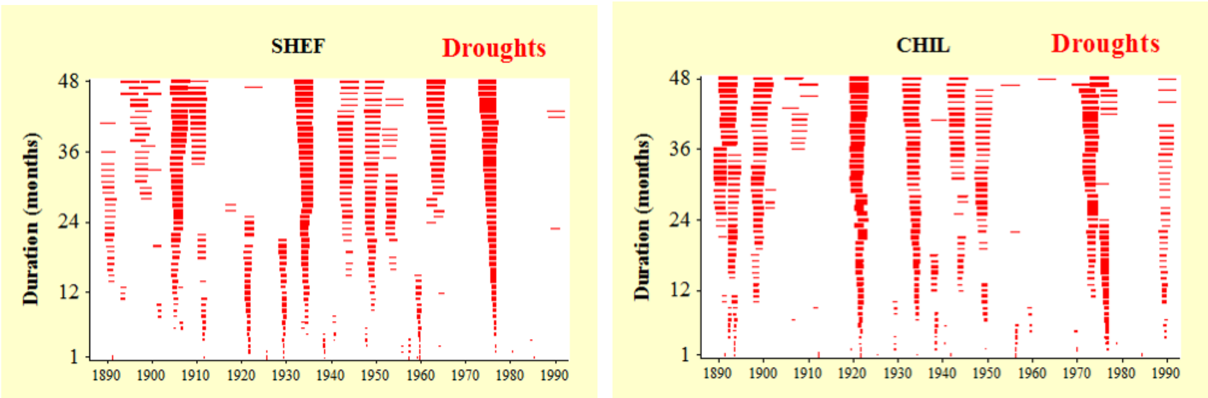


Figure 2 Drought plots for Sheffield and Chilgrove House

The plot for Sheffield (SHEF) is relatively coherent, with droughts in the mid-1930s and mid-1970s severe across a wide range of durations. Pronounced droughts of shorter duration are discernible in 1921, 1929 and 1959. The pattern of drought in the mid-1970s is more complex at Chilgrove House (CHIL), as is the drought at the onset of the 1890s. These sites are 277 km apart, with Sheffield having a less continental climate than Chilgrove. The coefficient of variation (CV) of the 1200 monthly rainfalls in the century of analysis is 0.56 at Sheffield but notably higher at Chilgrove (CV = 0.63). A happy by-product of such plots is their value in assessing the long-term consistency of neighbouring records. The drought plots provide much finer detail than is possible in a double-mass plot.

2.2. Stock simulations

A core aim of the research is to identify the distribution of drought durations to which a resource is sensitive. An approach based on *stock simulation* is adopted in which monthly rainfalls are fed into a hypothetical storage of given size. Excess rain is spilled when the storage fills. Ten storage sizes were considered in the main analysis. These have capacities of 0.05, 0.075, 0.10, 0.125, 0.15, 0.20, 0.25, 0.30, 0.35 and 0.40 of the centennial average annual rainfall (AARF). An eleventh storage size of SS = 0.111 was added following the inter-site dependence study reported in Section 2.4. Arbitrarily, the storages are initialised to be 100 (1 – SS) % full at the beginning of the warm-up period. Thus the small storage of 0.05 is assumed 95% full at the beginning of January 1887 while the large storage of SS = 0.25 is assumed 75% full.

Stock levels in the storage are simulated repeatedly, and the drawoff rate increased until a failure occurs within the century of analysis. This drawoff rate provides an estimate of the 99% reliable yield of the hypothetical resource. The drawoff is further increased and the rates leading to two, three, four, … ten failures in the century of analysis are noted.

The relevant drought periods are superposed on the drought plot, as is illustrated in Figure 3 for small, medium and large storages at Ravensthorpe. Although difficult to pick out in the figure due to over-plotting, the drought durations causing failure range from 2 to 6 months for the small storage, 3 to 15 months for the medium storage and 5 to 15 months for the large storage. This confirms that any resource is sensitive to a relatively wide spectrum of droughts of differing durations.

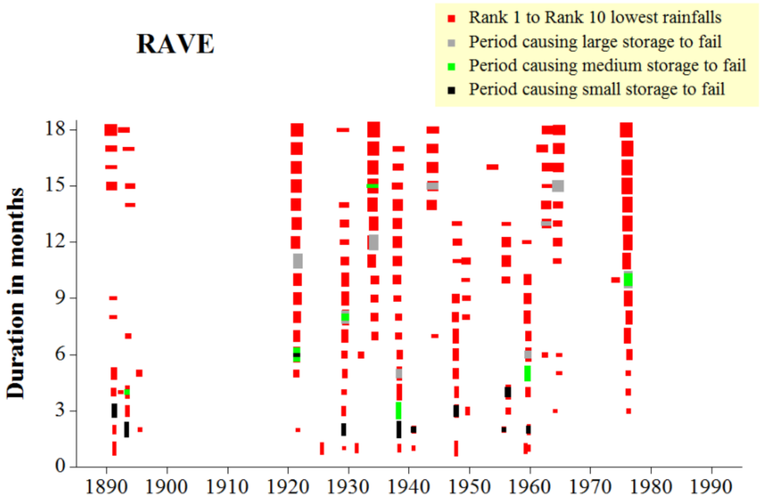


Figure 3 Droughts and storage failures for Ravensthorpe

The Water Resources Management Plan (Anglian Water, 2014) for Ravensthorpe and associated reservoirs recognises the sensitivity to droughts of differing length and severity. The plan highlights the 1-season 1929 drought, the longer 1975-76 event and the prolonged 1943-45 drought. Judging from Figure 3, a number of other droughts such as those of 1921 and 1934 may merit attention too.

Reed (1995) feared that drought durations inferred by stock simulation might underestimate the typical duration to which a resource is sensitive: arguing that a drawoff rate that allows more than two or three failures per century represents over-exploitation of the resource. The site (Norwich) and storage size (0.25) studied in that research confirmed that expectation. However, it transpires that this was an exceptional result. Taking the 38 sites and 11 storage sizes as a whole, no trend was found for lower-ranking droughts to be systematically shorter or longer than those in higher-ranking droughts. The relative frequency of different drought durations leading to failure of a storage of given size lies at the heart of the methods of assessing and visualising drought rarity presented in Reed (2015).

2.3. Yield-storage curves

The drawoff rates yielding two failures per century are illustrated in Figure 4 for a range of storage sizes. The examples are for hypothetical storages at Exeter (EXET) and Manchester (MANC). The 98% reliable yield, RY, is expressed as a fraction of the centennial average monthly rainfall (AMRF). Manchester has monthly rainfalls that are notably less variable (CV = 0.51) than at Exeter (CV = 0.64). Only Wick, Armagh, Eallabus (EALL) and Stornoway (STOR) have less variability than MANC, and only Southampton (SOUT) has greater variability than EXET.

A general model of yield-storage was derived by linear regression as:

$$RY = 1.549 + 0.229\ \ln SS - 0.785\ CV \qquad (1)$$

where RY denotes the 98% reliable yield (fraction of AMRF), SS is the storage (fraction of AARF) and CV is the coefficient of variation of monthly rainfalls. Explaining 96.0% of the variation in reliable yield across the 38 sites and 11 storage sizes, the model's performance is summarised in Figure 5.

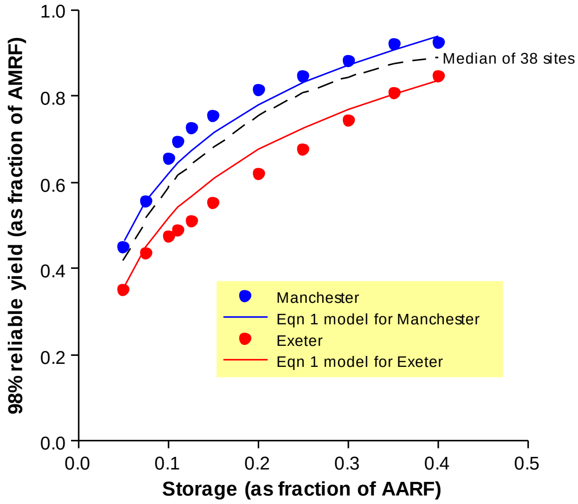


Figure 4 Sample yield-storage curves

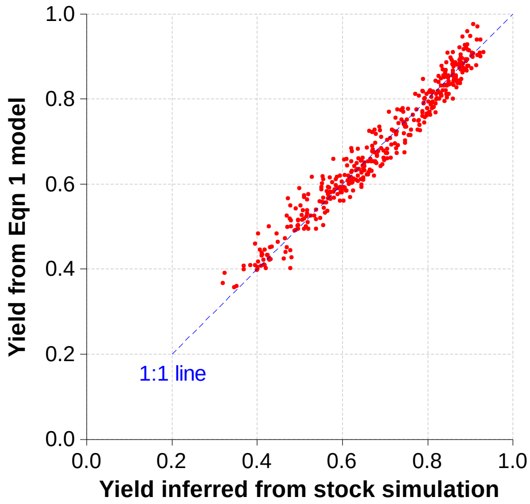


Figure 5 Performance of yield-storage model

2.4. Inter-site dependence in drought

Hannaford *et al.* (2013) refer to spatial coherence in drought. A theme here is to study inter-site dependence by assessing conjunctive gain. Each rainfall series is standardised to a mean AMRF of 50 units. Pairs of series are fed into a single storage, and failures studied as in Section 2.2. The factorial conjunctive gain (FCG) is taken as the ratio of the 98% reliable yield of the combined system to the geometric mean of the 98% reliable yields of the individual systems.

These conjunctive gains are hypothetical. One expects the gain to be greater for sites far apart or for sites for which the temporal distribution of rainfall is characteristically different e.g. in terms of variability or seasonality. A network of 38 sites permits the study of 703 site-pairs.

Inter-site distance was found to explain just over half the variation in FCG for a storage of size 0.111 (i.e. a ninth of AARF). The geographical structure is weaker for smaller storages and much weaker for the largest storages considered. Pairwise descriptors of site differences in rainfall variability and seasonality appeared to add little to the modelling of FCG.

The factorial conjunctive gains are relatively modest (see Figure 6). The median value is about 10% for small storages but less than 5% for the larger storages. This highlights that notable droughts tend to have a relatively large footprint across Great Britain and Ireland.

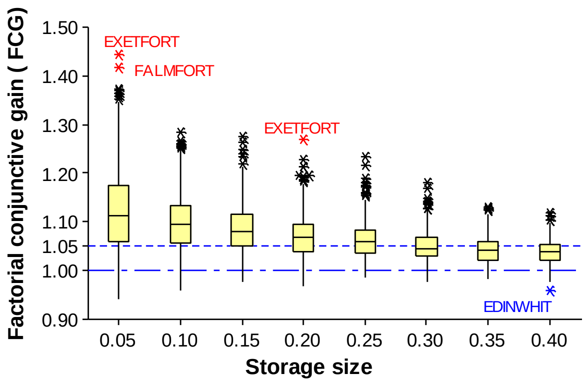


Figure 6 Boxplot of FCGs for a range of storage sizes

Using metric scaling (sometimes called classical scaling), and an inter-site dissimilarity distance of FCG-1, the gauge network is remapped in
Figure 7 for the 0.111 storage. That the geographical structure is recognisable is consistent with inter-site distance providing a fair description of inter-site dependence for this storage size.

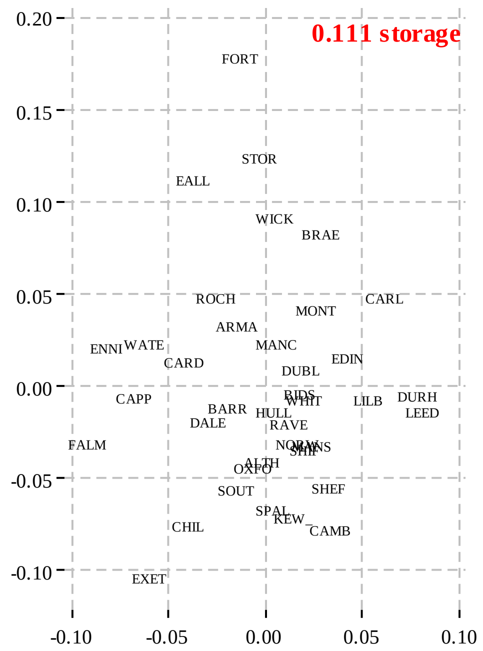
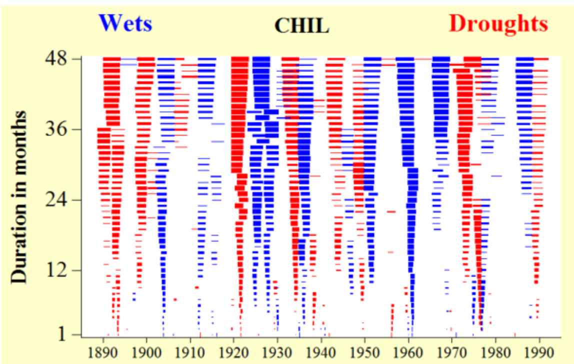


Figure 7 Mapping where distance reflects FCG-1

3. THE IMPORTANCE OF LONG RECORDS

Colloquially – and sometimes professionally – it is said that floods and droughts are opposite ends of the same spectrum. This is too casual a perspective. Water-resource drought is intrinsically a long-duration phenomenon. Its polar opposite is flooding in heavily regulated systems with exceptionally large lake, floodplain or groundwater storage: cases in which floods seldom arise but persist for many months when they do. These are referred to here as “wets”.

Figure 8 drives home the fundamental importance of long records when assessing long-duration phenomena. It shows droughts and wets for Chilgrove House. The red rectangles mark the ten driest periods in the analysis century. The blue rectangles mark the ten wettest periods. The rectangle’s height denotes its ranking: thickest = Rank1, thinnest = Rank 10. The wets have been abstracted by a procedure analogous to that used for droughts in Section 2.1. For each duration in turn, the ten greatest aggregate rainfalls are selected from the century of record. The most severe wet is found first, and the relevant months of rainfall assigned default values of -9999 mm so that further wets abstracted of that duration are independent and non-overlapping. It is seen that – for durations longer than about 24 months – the ten worst droughts from a century of record start to infringe on the ten worst wets. Such behaviour highlights that we are not analysing *extreme* long-duration droughts but merely those few for which we have data. See also Reed (2015).



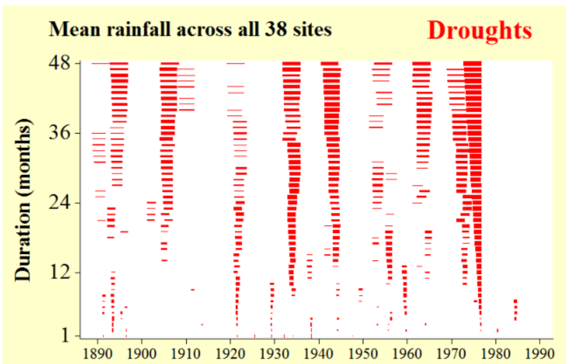


Figure 8 Droughts and wets at Chilgrove House

Figure 9 Drought across the 38 sites

Reed (1995) allowed the period of analysis to be dictated by the centenary of CIWEM. This fell somewhat inconveniently, given that 1988-1992 was a pronounced drought across much of southern and eastern Britain. This drought was centred on the very fringe of the analysis century 1890-1989.

Figure 9 presents the drought plot for monthly rainfall taken as the arithmetic mean of the 38 series. The extra weight allowed to wetter sites such as Fort William (FORT), Cappoquin (CAPP), Eallabus and Stornoway counters the SE bias in the gauge network. The prominence of the 1975-76 drought is evident at all durations. Based on stock simulations, the most notable droughts *at the scale of the British and Irish Isles* are (chronological order): Feb-Jun 1893, Dec 1904 to Sep 1911, Jun 1933 to Jul 1934, Jan-Apr 1938, and Sep/Nov 1975 to Aug 1976. All of these produced Rank 1 or Rank 2 failures for more than one storage size. Although outside the century of analysis, the period ending May 1888 was a further notable widespread drought, making the choice of Jan 1887 as the start of the warm-up period less than ideal. Brook and Glasspoole (1928) discuss the dry year of 1887 in some detail.

4. CONCLUSIONS

Amid our concerns about catchment and climate change, and our obsession with modelling, we must not ignore older data. There is a place for exploiting long-term rainfall records and empiricism in the analysis of droughts of long duration. Using fruits of the stock simulation approach, Reed (2015) presents methods for assessing and visualising the rarity of an ongoing water-resource drought.

5. ACKNOWLEDGMENTS

Phil Jones of the Climatic Research Unit (University of East Anglia) and Terry Marsh of the Centre of Ecology and Hydrology are thanked for providing additional rainfall series. Their work over many years has enhanced both the quality of long-term records and our understanding of why these data are to be treasured. Séamus Walsh of Met Éireann resolved the difficulty with records for Cork. Joan Self of the Met Office Archive helped in the abstraction of monthly rainfall series for Ravensthorpe and Lilburn. This research is unrelated to any client. I thank Neil Wellington for visiting 30 years ago and feeding my interest in inter-site dependence in extremes. I also thank the anonymous reviewers.

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