06 - HOW RARE THE ONGOING DROUGHT?

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Abstract
Drought rarity assessment from monthly rainfall data is suspect. Estimates are 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 resource system is sensitive to a spectrum of droughts: not just one of this specific duration and starting month.

These difficulties are resolved in a new approach. Using complete historic rainfall series for 1887 to 1992 for 38 sites across Great Britain and Ireland, methods are presented for assessing and visualising the rarity of an ongoing drought.

1 INTRODUCTION

1.1 Context

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 paper's closure. 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. But we shouldn't discard the resource of long-term monthly rainfall records simply because we are too lazy to develop *veritable methods*. The paper revives the role of long-term monthly rainfall series.

1.2 What's the problem?

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 difficulties to Water Companies in maintaining normal supplies. Typical practice is to cherry-pick comparisons of the ongoing drought with historical droughts. This has the happy by-product of maximising the inferred rarity of the drought that the company is experiencing. Yet the resource system 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 combining surface water and groundwater – 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 excessive emphasis on minimising operating costs is typically 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 5.4, 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".

Storage – engineered or natural – is fundamental to water-resource systems. In a companion paper, Reed (2015) presents a method of *stock simulation* by which to identify ten droughts per century that lead to a storage of given size failing. *Stock* is a shorthand name for the amount of water in store. The stock simulation method underpins identification of the typical *distribution of drought durations leading to failure*. The work lies at the heart of the new methods presented in Section 5 for assessing and displaying the rarity of an ongoing drought.

Extensive water-resource research is undertaken on many topics including the design, assessment, modelling and impact modelling of drought e.g. Tallaksen and van Lanen (2004). Research on assessing the rarity of an ongoing drought is less well advanced. As with real-time flood forecasting, it is critical for the researcher to adopt a real-time "operational" mind-set. While Hisdal and Tallaksen (2000) appear to tackle the important problems of drought definition and classification, this is largely based on retrospection rather than within an emulated real-time framework.

2 DATA NETWORK

The data network used in the research 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). The period adopted for analysis is 1890-1989, with a further three years selected at either end to capture long-duration extremes that lie mainly within the century of analysis. Each data series studied has complete records of monthly rainfall across 1887-1992 (i.e. 1272 months). Reed (2015) gives further details.

3 DROUGHT MONITORING

3.1 Why it matters

Drought is a threat that generally approaches slowly. Nevertheless, when rain fails to materialise, the need for decisive action can be pressing. Measures to restrict water use or relax abstraction conditions require approval. Procedures in England and Wales seek to determine applications for drought permits within 12 days and drought orders within 28 days. Drought permits are determined by the Environment Agency. Drought orders – which typically relate to higher-impact measures – are determined by the Secretary of State or by Welsh Ministers. Forecasting conditions one month ahead (see Section 6) may help the Water Company to apply for drought orders in timely fashion.

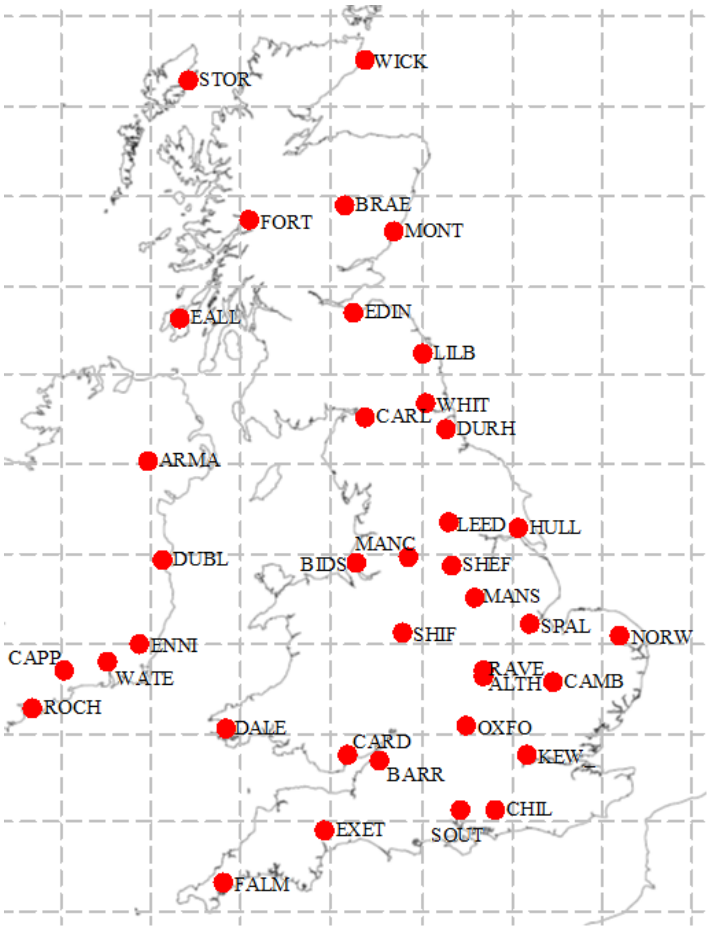

***Figure 1**: Location map (38 sites)*

3.2 Classification of drought rarity

Most parties – e.g. regulators, media, general public – value assessments summarisable in a single number. This makes an extreme amenable to classification. Greater clarity in summarising the rarity of an ongoing drought will assist both water-resource management and regulation. Whilst a classification system is desirable, it is important to achieve this without oversimplifying the problem. Reviews such as those by Mawdsley *et al.* (1994) and Prudhomme and Farquharson (2003) suggest that the indexing of drought rarity remains problematic.

A 4-category classification is proposed in Table 1.

Table 1: Proposed classification of drought rarity

Colour code	Category name	Expected frequency of drought
–	–	Ten or more times per century
Yellow	Drought	Six to nine times per century
Orange	Severe drought	Three to five times per century
Red	Very severe drought	Once or twice per century

The category *Unprecedented* is purposely omitted. In the UK and Ireland, there will nearly always have been a worse drought with at least a little documented history. Effective management is about anticipation and timely response. In marked contrast to storm and flood extremes, unprecedented drought cannot arise without warning. Management options in severe drought will be strongly influenced by the *spatial extent* of the deficit. Unprecedented is too loose a label to use without heavy qualification: qualification of a kind that does not lend itself to soundbite.

3.3 Operational need for greater detail

Each drought is different. When a severe drought arises, it is important to be able to portray the character of the ongoing drought in some detail, to avoid managers inadvertently assuming that the drought will progress in a similar fashion to some previous notable drought. The drought rarity visualisation of Section 5.6 is thought to be an innovation.

4 MODELLING THE DROUGHT DURATIONS LEADING TO FAILURE

4.1 Stock simulation

Reed (2015) presents a method of drought assessment based on stock simulation. Inflow is taken to be rainfall, with no allowance made for catchment "losses". Thus, the annual average inflow is the annual average rainfall (AARF). The AARF values used in this research are centennial averages calculated across 1890-1989.

The monthly rainfalls are fed into a hypothetical storage of given size. Excess rain is spilled when the storage fills. The rate of drawoff from the storage is increased until the storage fails (i.e. just empties) once within the century of analysis. The duration of the drought causing failure is logged. The procedure is repeated for higher rates of drawoff to determine the durations of droughts leading to the 2^{nd}, 3^{rd}, …, 10^{th} independent failure in the century of analysis.

Various storage sizes have been considered in the research, with capacities ranging from 0.05 to 0.50 of the centennial AARF. The current paper focuses on results for small, medium and large storage sizes represented by SS = 0.05, 0.111 and 0.25.

Exploration of larger storages (e.g. 0.50 of AARF) is inhibited by a number of factors, including the inability at some sites to define ten failures within the century of record. This reflects that large storages are sensitive to long and very long droughts. The effect impinged earliest (i.e. for not very large storage sizes) at Armagh, Dublin, Manchester and Stornoway.

4.2 Relative frequency of drought durations leading to resource failure

The red histograms in the left-hand panel of Figure 2 summarise the drought durations leading to failure in stock simulations at the 38 sites, with the drawoff from storage progressively increased to yield one, two, … ten failures per century. There is interesting structure in the profile for the large storage, where – through seasonal effects – 11 to 14-month droughts are responsible for fewer failures than are 15 to 19-month droughts.

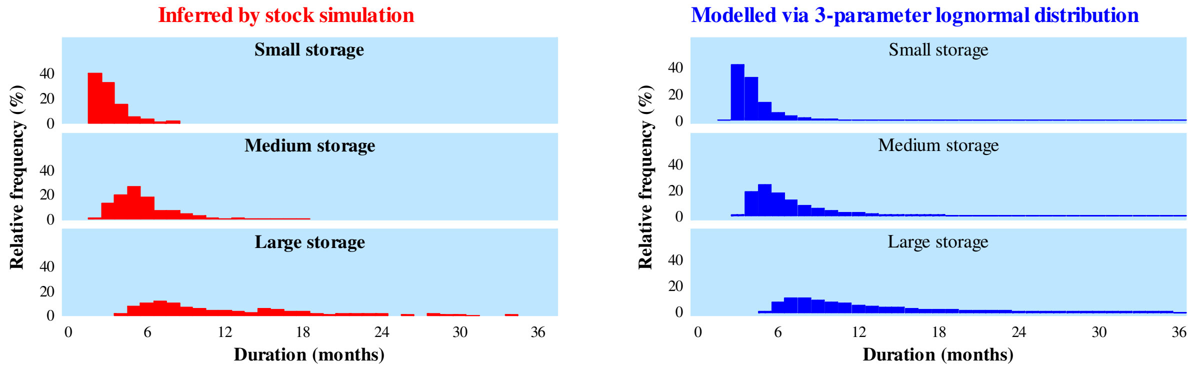

***Figure 2**: Relative frequency (%) of drought durations leading to resource failure at 38 sites*

The blue histograms in the right-hand panel of Figure 2 summarise the outcome of fitting an overarching model to 3040 drought durations leading to failure: ten failures at each of 38 sites for each of eight storage sizes: 0.05, 0.075, 0.10, 0.111, 0.125, 0.15, 0.20 and 0.25. It can be seen that imposition of a unimodal distribution is less convincing for larger storages. The representation for the 0.25 storage is considered just adequate to the task of drought monitoring.

The storage size of 0.111 is included because Reed (2015) found this to be the storage size for which inter-site dependence in resource failure most strongly reflects inter-site distance.

The overarching model is based on the 3-parameter lognormal distribution:

$$\ell n(D - D_0) \sim N(\mu, \sigma^2) \qquad \text{Eqn. 1}$$

where ℓn denotes the natural logarithm, $N(\mu, \sigma^2)$ is the Normal distribution with mean μ and variance σ^2, and D is the drought duration in months. The model parameters D_0, μ and σ (each expressed in months) are determined by storage size SS according to three sub-models:

$$\mu = 3.10 + 0.96\ \ell n SS \qquad \text{Eqn. 2}$$

$$\sigma = 0.72 + 0.80\ SS \qquad \text{Eqn. 3}$$

$$D_0 = 12\ SS\ /\ (1.109 + 0.229\ \ell n SS) \qquad \text{Eqn. 4}$$

D_0 is a threshold parameter representing the shortest drought that poses a threat to the resource. The sub-model structure is motivated by a model for the 98% reliable yield RY derived by Reed (2015):

$$RY = 1.549 + 0.229\ \ell n SS - 0.785\ CV \qquad \text{Eqn. 5}$$

Here, RY is expressed as a fraction of average monthly rainfall and CV is the coefficient of variation of monthly rainfall. The formulation of Eqn. 4 represents the duration in months over which a storage of size SS can sustain delivery of the 98% reliable yield *without inflow*. To allow general use in the UK and Ireland, CV in Eqn. 5 has been set to 0.561, the median value across the 38 sites. Thus, the implemented model has just the one parameter: the storage size SS.

The blue histogram in Figure 2 represents the modelled distribution of the drought duration leading to resource failure. The discrete presentation is derived from the continuous model by evaluating the cumulative distribution function of the 3-parameter lognormal at appropriate intervals (e.g. at 3.5, 4.5, 5.5, 6.5 … months) and differencing to derive the relative frequency of 4-month, 5-month, 6-month ... droughts leading to resource failure. To provide a pragmatic tool for drought monitoring, durations responsible for fewer than 1% of failures are deleted, and the remainder of the relative frequency diagram rescaled to represent 100% of failures. The final products appear in Figure 3.

An explicitly discrete distribution – such as the offset Poisson used by Reed (1995) – might provide a more classical approach to modelling the histogram of durations leading to failure. However, the device of using the continuous 3-parameter lognormal distribution proved successful, and may ease the development of applications allowing 5-daily (rather than monthly) assessments of drought rarity.

4.3 Checking the model

The model defined by Equations 1 to 4 is offered for general use across the British and Irish Isles. A check was made for systematic variation (of the duration leading to failure) with site position, and with the magnitude and variability of monthly rainfalls. A weak tendency was noted for sites to the Northeast to be sensitive to slightly longer droughts than sites in the Southwest.

Checks were made for any trend with the rank of the drought. No significant trend was found. Reed (1995) undertook stock simulation for one site and storage size only. The tendency found at Norwich for droughts causing failure of the 0.25 storage to be shorter for higher-ranking (i.e. less severe) droughts was confirmed. However, it transpired that this was a wholly exceptional result.

5 METHOD FOR DROUGHT RARITY ASSESSMENT

5.1 Masks

The final histograms (see Figure 3) provide standard profiles by which to represent the sensitivity of resources in the British and Irish Isles to droughts of differing duration. They can be thought of as *masks* through which to view the rainfall rarities of the durations most relevant to the resource.

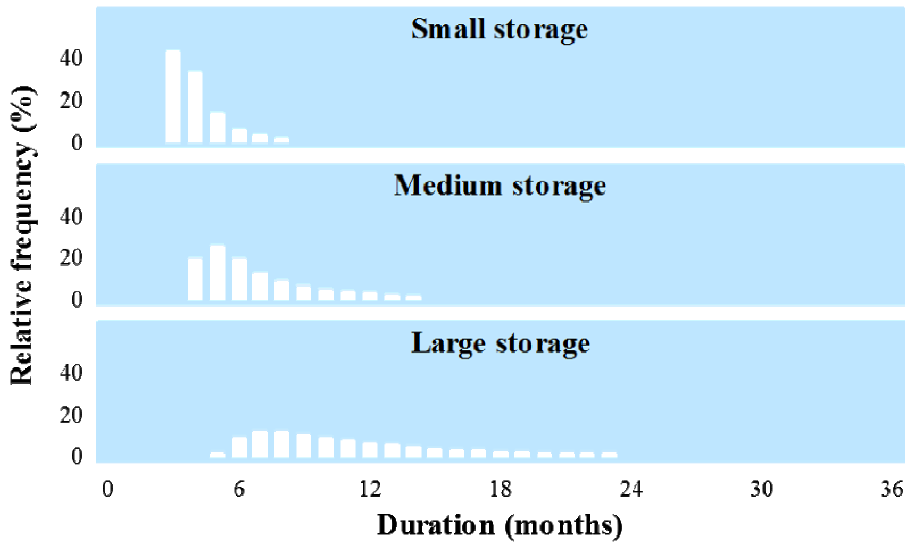

***Figure 3**: Masks for viewing drought durations relevant to resource failure*

Two sets of comparisons of an ongoing drought with history are possible: a comparison with *seasonal extremes* and a comparison with *veritable extremes*. These are briefly introduced.

5.2 Seasonal extremes

The procedure when using seasonal extremes is as follows. The ongoing drought is compared with historical extremes over the same calendar period. The method is typically applied to durations from one to 12 months. Occasionally, the method is applied to longer durations and precautions taken to consider only independent (i.e. non-overlapping) events.

The shortcoming of the approach is readily illustrated for the simple case of a 1-month extreme. A low (e.g.) May rainfall is compared with all previous May rainfalls. It is entirely proper to quote the ranking and to state that only one May rainfall in a record extending back to 1915 is smaller than the May rainfall experienced in the ongoing drought. But, even if a satisfactory frequency analysis can be navigated, one can only estimate a return period in terms of numbers of Mays. This kind of seasonal comparison may have some relevance to understanding impacts on agriculture and horticulture. However, to be of use for drought management of a water resource, the assessment needs to be expressible as a return period in numbers of years. The underlying difficulty is that a given resource is sensitive to a range of droughts of differing duration and of no particular starting month.

It is asserted that the analysis of seasonal extremes has very little to offer drought monitoring for water resources. Space does not permit a demonstration.

5.3 Veritable extremes

What are termed here *veritable extremes* are identified iteratively, and with a separate extraction procedure followed for each drought duration D in turn. In each case, the entire rainfall record is scanned and the D-month period that yields the smallest cumulative rainfall is found. The period and its cumulative rainfall are noted. The rainfall readings in this period are replaced by large default depths and a search made for the next smallest D-month cumulative rainfall. This process ensures that the droughts abstracted are non-overlapping and can be considered independent.

The method applied sought to abstract ten such events from a century of record. The use of buffer years before and after the century of analysis ensured that the relevant cumulative data were available (and selectable, if sufficiently extreme) for all D-month periods centred no earlier than January 1890 and no later than December 1989.

5.4 Long-duration events – an interlude

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. Reed (2011) calls them “wets”.

Figure 4 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 summarised for droughts in Section 5.3 but with the focus on identifying maximum cumulative rainfalls of a given duration. 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.

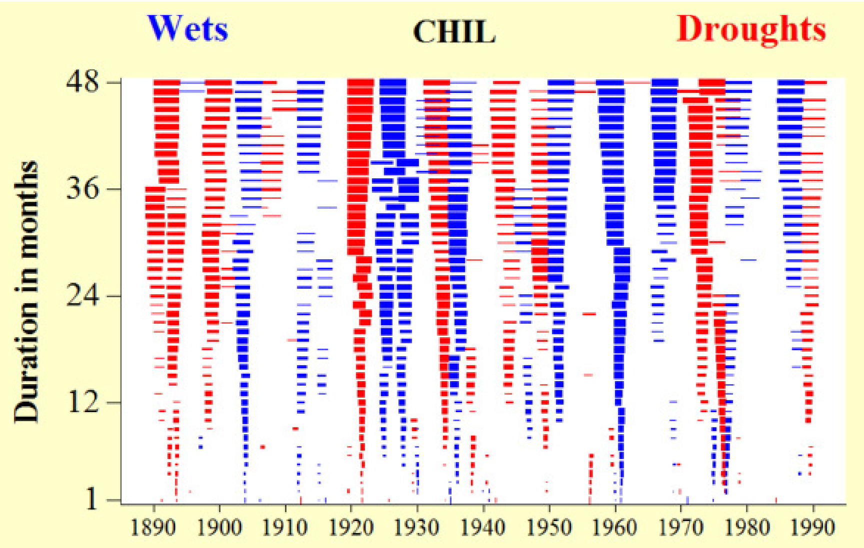

***Figure 4**: Droughts and wets at Chilgrove House, West Sussex*

It would be nonsense to consider a month within such an overlapping period to be both part of an extreme wet and part of an extreme drought. Even where ten droughts can be identified from a century of record, it is wrong to portray them all as *de facto* extreme. Such behaviour highlights that we are not analysing *extreme* long-duration droughts. Rather, we are analysing those few long-duration droughts for which we have the data.

Some analysts fail to notice that only a limited number of long-duration extremes can be derived from a given period of record. Unpublished research by the UK Met Office fitted the generalised extreme value distribution to what they termed *annual maximum* (AM) 90-day summer rainfalls. Studying flood occurrences in the wet summer of 2012, the analysts were seemingly unaware that rainfall accumulations over such long durations do not meet the requirements for an extreme value analysis. In some dry summers, the maximum 90-day rainfall is less than the long-term *mean* 90-day summer rainfall. These are in no sense extreme large values! The mistake contributed to the unsupported classification of many sewer flooding events in Summer 2012 as "rarer than one in 20 years" even though the short-duration rainfalls immediately responsible for the incidents were not of this touchstone rarity. http://wwtonline.co.uk/features/what-is-the-impact-of-rainfall-on-the-sewage-industry-# notes a twofold benefit for the Water Company: "Firstly severe weather events are not included in Ofwat's assessment of our flooding performance and secondly, are not included in our reportable number of properties on the register [i.e. registered as being vulnerable to flooding]." Choosing to start the AM series in the dry summer of 1959 rather than in 1961 – the year from which most UK daily rainfall data have been digitised – further heightened the exaggeration of flood rarity.

5.5 Weighted mean ranking

One application of the Figure 3 masks is to derive a weighted mean ranking of the ongoing drought. In the case of the small storage, the bulk of weight attaches to the rankings of the 3-month (42.1%), 4-month (32.6%), and 5-month (13.4%) rainfall depths to time "now", i.e. the month-end at which the drought is being monitored. The left-hand panel of Figure 5 shows the weighted mean rank (WMR) at Enniscorthy at each month-end from the end of 1889 to the end of 1992.

Four severe droughts (i.e. 2.5 < WMR < 5.5) are identified for the small storage. However, no very severe drought (WMR < 2.5) is found. Given the classification system used (see Table 1), one might expect three severe droughts and two very severe ones in this 103-year period. Although shortfalls at some sites and for some storage sizes are a matter of chance, there is a systematic tendency to under-represent severe and very severe droughts somewhat. This is dealt with in Section 5.8.

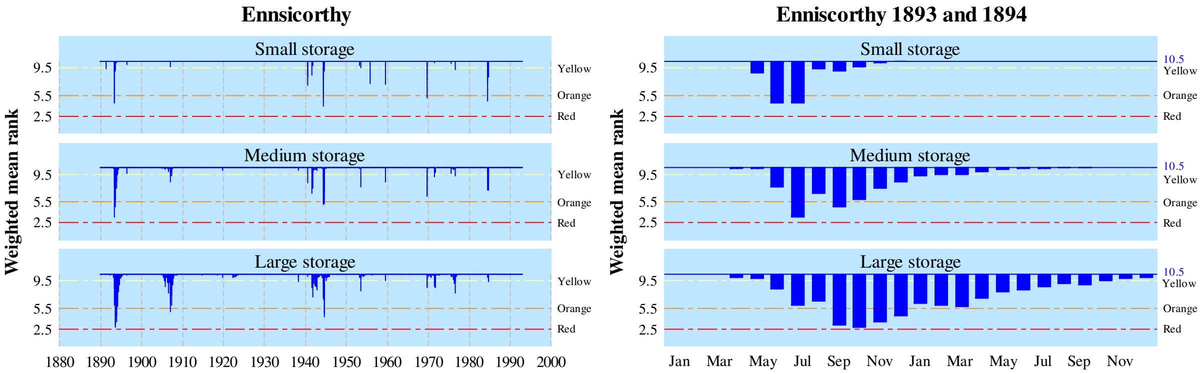

***Figure 5**: Example of time-series of weighted mean rank (with 1893-94 expanded)*

The right-hand panel of Figure 5 shows the prominent 1893-94 drought at Enniscorthy in greater detail. It can be seen that the height of the drought for the small storage is in July 1893. For the medium storage, it transpires that the drought is also at its deepest at the end of July but continues to need watching until the end of 1893. However, one would not know this at the time. The weighted mean rank time-series is revealed only one month at a time, as the drought evolves. An operational tool to assist perception of the structure of an ongoing drought in "real time" is required.

5.6 Drought rarity visualisation

A key innovation in the research is the production of diagrams to aid visualisation of why an ongoing drought is (or is not) challenging a resource. Figure 6 displays the position at Enniscorthy at the ends of June and October 1893. In these visualisations, droughts of a given duration are shown in yellow, severe droughts in orange and very severe droughts in red. The categories are defined in Table 1. The drought rarity classification is viewed through the mask relevant to the storage size.

One glance at the right-hand panel tells us that, at the end of October, the drought is over for small storages but is a deep and continuing concern for large storages.

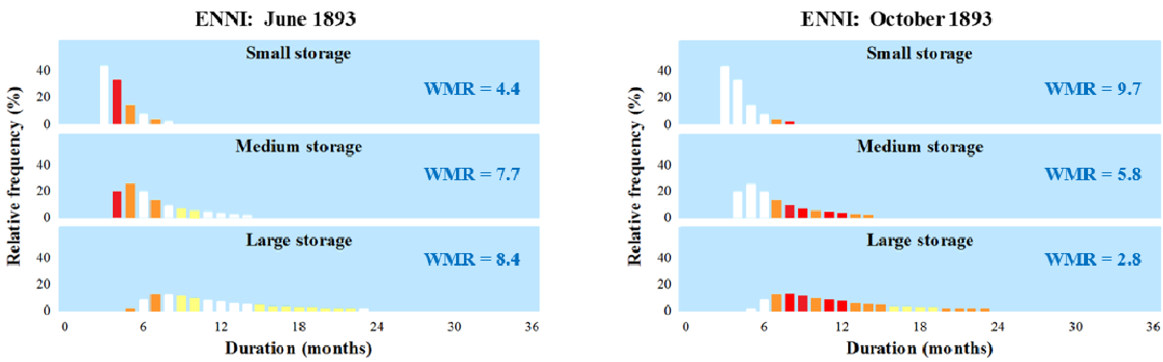

***Figure 6**: Visualisations of Enniscorthy drought rarity at ends of June and October 1893*

5.7 Application beyond the century of analysis

Figure 7 shows weighted mean ranks evaluated across 1850-2010 using the very long record at Armagh Observatory. The 1995 drought is seen to just reach the very severe category for the small storage. The drought of 1870 – very severe at all sizes – is presumably unforgotten in Ulster.

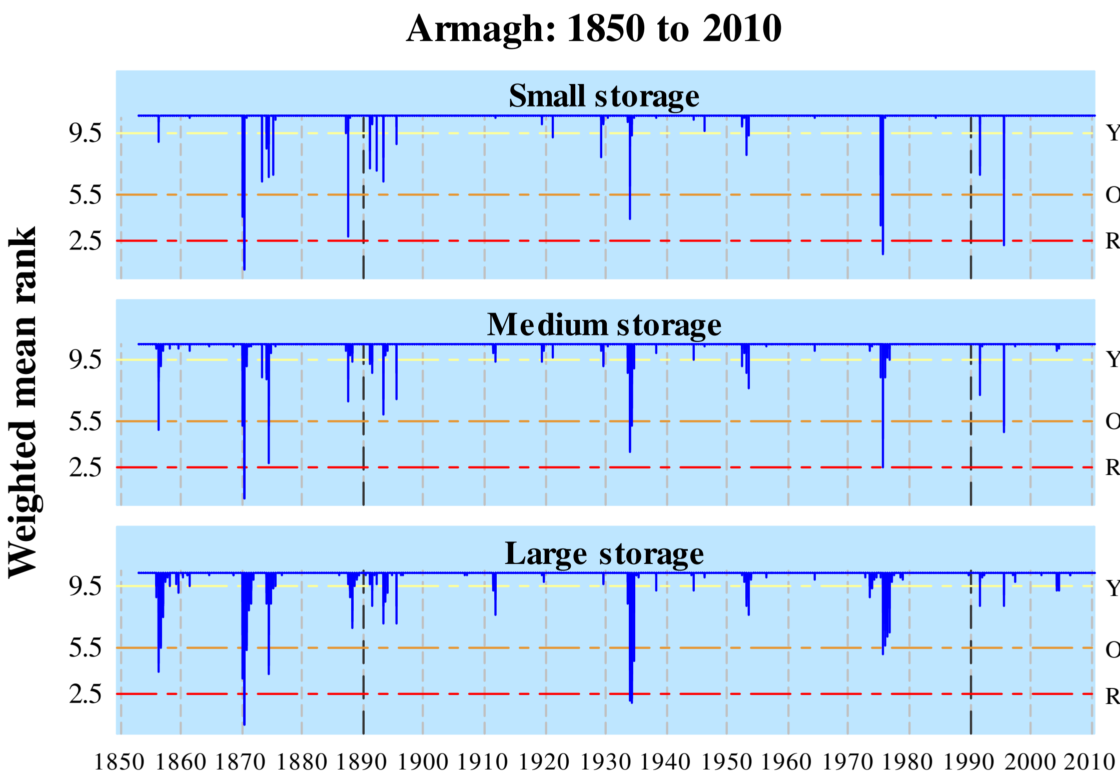

***Figure 7**: Droughts inferred from Armagh monthly rainfall data for 1850 to 2010*

5.8 A final adjustment

A final adjustment is needed to sharpen these new drought-monitoring tools. There is an understandable tendency for the weighted mean rank to under-report severe and very severe droughts somewhat. The final step – undertaken for each storage size in turn – is to distort (by compression and stretching) the weighted mean rank axis so that it generates a total *across the 38 sites and the century of record* of about 38 x 2 = 76 very severe droughts, 38 x 3 = 114 severe (but not very severe) droughts and 38 x 4 = 152 other droughts. This final step is yet to be reported.

6 ADDITIONAL CONSIDERATIONS

The use of monthly data constrains the performance of the drought monitoring system when applied to small storages sensitive to short-duration drought. By studying sites for which long records of daily data are held, it will be possible to explore the extent to which performance can be improved by using 5-day (pentad) analysis.

Applications to very large storage systems might consider 3-monthly analysis. However, performance will be constrained by the inherent difficulty (see Section 5.4) of having too few examples of droughts of very long duration. Stochastic generation of very long rainfall series might assist but is itself problematic.

Some resource systems operated conjunctively are complex in terms of their sensitivity to droughts of different durations. Water Companies might prepare – as part of their drought management planning – a mask tailored to reflect the sensitivity of the overall water resource system to droughts of various durations.

For resources of unknown storage size, or complex structure, one might infer an appropriate mask from knowledge of the droughts known to have been historically most significant. Where a resource system has changed appreciably over the decades, judgement of the historically most important droughts could be based on Water Company models of the current-day resource system.

To support the needs identified in Section 3.1, it may be helpful to forecast drought rarity one month ahead, using projections of one or more of: zero, minimum, lower quartile, median, upper quartile and maximum rainfall. These would be based on rainfall depths for the relevant month.

7 SUMMARY

The paper began by listing some criticisms of assessing drought rarity based on monthly rainfall data alone. These are briefly revisited.

- Why are you dredging up old data no longer representative of the current climate? Response: Because the early data may reveal severe droughts that are important in any climate.
- You must study effective rainfall not total rainfall. Response: There is some validity in this criticism. But the generally strong correspondence between assessed droughts and actual droughts shows that monthly rainfall data tell much of the story for medium and large storages. It may be helpful to transparency that no resource-specific modelling is involved in the assessment.
- Why are you ignoring daily rainfall data? Response: This links to the previous bullet. The detailed pattern of daily rainfall can be influential, especially for small storages. Use of 5-day (pentad) rainfall data would allow more frequent updating of drought rarity assessments.
- You must use hydrological models to link rainfall to the runoff/recharge that feeds your water resource. Response: There is always a role for hydrological modelling to augment and interpret observations, and to update (or backdate) inflow/recharge data to reflect current (or earlier) land-use, resource or climate conditions. The mistake is to allow models to displace inconvenient data, to devalue older data or simply to displace thought.

A general method has been presented for monitoring the rarity of an ongoing water-resource drought based on monthly rainfall data. Some developments have been suggested. Long-term rainfall records are of immense value if adequately curated and validated.

ACKNOWLEDGEMENTS

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