A systematic assessment of drought termination in the United Kingdom

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In the study, a concept to quantify and map drought termination, including a number of drought termination metrices, was developed. This concept was applied to 52 catchments across the UK representing different physio-geographic conditions (e.g. rainfall, elevation, catchment storage proxy, urbanisation level) to obtain a number of drought termination metrices (duration, termination rate, onset and end seasons). Drought development and termination chronologies, incl. the spatial distribution across the UK, were presented and discussed. Chronologies of two contrasting multi-year droughts were selected (1995-97 and 2009-12) and drought termination metrices were mapped. Results were put in a horizontal context. Eventually, drought termination characteristics from all 459 events and catchments averages were correlated with catchment characteristics and with drought development characteristics. Results were discussed, research gaps were identified and potential links between drought characteristics and catchment characteristics for practical use were provided.

Studies focussing on drought recovery or termination are still rare. The authors managed to improve knowledge on how to conceptualize drought termination, to develop a dataset with associated drought development and drought termination characteristics, and to comprehensively describe the spatial and temporal distribution across the UK. The authors also started to explore underlying mechanism of drought termination through a statistical analysis and draw the attention to abrupt drought termination. The manuscript is well written and the figures (except Fig. 6) and tables adequately support the text. The study is original and it certainly is worthwhile to be published in HESS, but clarifications and improvements are needed before it can be accepted.

Major comments:

1. The authors are one of the first that conceptualize drought termination. Figure 2 clearly illustrates the procedure and suggests that a comprehensive script has been compiled to identify drought development and drought termination characteristics. It enables application of consistent rules. However, as said by the authors, parameter values have to be set to define drought development and termination, and hence determine outcome. Key parameters are the drought initiation parameters *D* (number of consecutive months that flow has to be below monthly average flow) and *R* (months within the *D*-month duration with above monthly average flow, to account for minor wet phases during drought development). The third key parameter is *T* (number of consecutive months with flow above monthly average flow to end a drought). In this study, these parameters are set on 10, 1 and 2 months, respectively, to maximise detection of multi-season events. Another important assumption is that the drought development phase ends at the end of the month with the maximum negative difference between the observed flow and the monthly average flow (this is called the drought magnitude *DM* in the study). A sensitivity analysis is needed to determine how robust the findings in this study are dependent on the choice of the parameters. The sensitivity analysis can be limited to multi-season droughts (rather high *D*), because characteristics of short-lived are beyond the scope of this study. I am interested in the sensitivity of *R* and particularly *T*. Consequences of the choice of *DM* also have to be elaborated. The revised manuscript needs a separate section on the sensitivity analysis in the Discussion.
2. It is assumed that droughts develop and terminate relative to the average monthly flow (Z_{LTA_m}). Peters et al. (Eq. 3, Hydrol. Process, 2003) also used average flow, but offered the option (drought criterion *c*) to define a threshold related to average flow. In most drought studies using the

threshold approach, a more extreme flow is selected than in the manuscript, i.e. very often the Q_{80} (flow that is equalled or exceeded in 80% of the time) is used as threshold. I wonder if drought durations (both in the development phase and the termination phase) are not overestimated in this study due to using average monthly flow as a threshold.

3. Authors refer to the importance of drought termination for water management. They propose a duration-based procedure. Duration both of drought development and drought termination certainly are important for water managers, but I wonder if they are not more interested how long it will take to replenish the missing water, e.g. for reservoir of aquifer management. This would imply a deficit volume-based procedure, i.e. not using a pre-defined *T*. I suggest to comment on these different approaches in the Discussion section.
4. In the paper there is emphasis on abrupt drought terminations, like the 2009-2012 event. This is an interesting phenomenon, but I believe for drought management the gradual terminations are more relevant (the long time it takes to let hydrological drought recover). In the paper there is reference to abrupt drought terminations derived from the long Thames flow time series. In the period 1883-2013, four of abrupt terminations (similar to 2009-2012 event) occur, but that is about 10% of all identified multi-season droughts.
5. In the Discussion section drought termination in river flow is compared with terminations in other drought types. For instance, Mo (2001) and Dettinger (2013) use drought in precipitation (SPI6) and soil moisture (PDSI, anomalies). We know that there are differences in drought types due to drought propagation, which does not allow a straightforward intercomparison of terminations of different drought types.
6. I support the authors' view that drought termination is a complex interplay of specific hydroclimatic conditions, catchment properties and human influences (abstractions, urbanisation). As said before, I appreciate very much that they share what we know, but also what we still do not know on underlying mechanism (identification of research gaps). Strength of relationships between drought termination characteristics and catchments characteristics that were found, is weak to moderately weak (Spearman's correlation coefficients are lower than 0.5), although some relationships are significant. It would therefore be wise if authors were to show restraint in exploiting these relationships for practical use. Hence, I would delete paragraphs, like the one about possible critical time thresholds within a drought, which may have important implications for the management of water resources (pg. 13, lines 27-29, pg. 14, lines 1-4).
7. The role of groundwater in drought development and termination has been addressed at several places in the manuscript. I would expect long drought terminations in groundwater-dominated catchments. However, this could not convincingly be proven, even not by a subset of catchments. It appeared that the BFI is not a good proxy for groundwater responsiveness. Some of the catchments have long groundwater time series. It is a pity that authors say that a similar analysis for groundwater is beyond the scope of this study. They could have selected some groundwater hydrographs from a few selected catchments to progress on the role of groundwater (could be included in Section 5.1). This does not imply a comprehensive study of chronologies of drought termination in groundwater level records, as has been done for the river flow. Some droughts in river flow might have been incorrectly terminated, because the drought in groundwater still continued. Water following quick flow paths in the catchment could lead to a temporary flow increase, while it will drop again after some time due to lower than normal groundwater inflow in the river. The sensitivity of *T* (point 1) might help to increase understanding.
8. In the Conclusions a number of items are addressed (e.g. influence of parameter selection, monthly time step, abstractions) that should be in treated in the Discussion. Only the main findings about the influence should be described in the Conclusions.

9. This study is one of the first on ending of a drought. It would be good to set the terminology right from the beginning. The authors use the term "termination" for the last phase of a drought (decrease of the deficit to zero), whereas I thought that termination is more associated with an instantaneous point in time. I would the use termination for the latter and "recovery" for the last phase.

Minor comments:

- Pg. 2, lines 1-2: I think this is not the right start of the abstract by referring to dramatic / abrupt terminations (see point 4, major comments);
- Pg. 2, lines 21-24: too speculative, because of weak relationships (see point 6, major comments);
- Pg. 3, lines 1-3: long sentence;
- Pg. 3, lines 1-14: I think this is not the right start of the Introduction by referring to violent weather / abrupt terminations (see point 4, major comments);
- Pg. 3, lines 20-26: I think that also reference has be made to the drought typology studies by Van Loon et al. (HESS, 2012; HESS, 2015), in which ending of the drought is also essential;
- Pg. 4, line 6: "…a period of drought termination." sounds a bit strange (see point 9, major comments);
- Pg. 4, line 20: "…40% of the gauged area)" is not an evidence of representative coverage. Rephrase;
- Pg. 5, lines 26-27 and pg. 6, lines 1-3: flow data from the north / west and south /east seemed to have some bias, near-natural and anthropogenic, respectively. You need to come back to this in Discussion;
- Pg. 5, line 22: you cannot say that the LTA refers to 1971-2000, because some flow gauging started in some in 1982. 13 gauging stations have a record that does not include 1970 (Table A.1);
- Pg. 6, line 6: strange to call *RT* a threshold. Readers will think that a threshold has a specific meaning. Below of above something will happen (e.g. impact). It is usually predefined and derived from other information (e.g. data, unwanted impacts). In the proposed procedure it is the flow (Z_{anom_t}) in the second consecutive month above the average monthly flow (Z_{LTA_m}). It is just a number that is dictated by the time series, rather than it has generic meaning. I suggest not to use the term threshold in this context;
- Pg. 6, line 12: What is the physical / practical meaning of the drought termination rate (DTR)? A low DTR reflects a long termination duration DTD and/or a large difference between the drought magnitude DM and recovery threshold RT; the magnitude of *RT* (Z_{anom_t}) can be small or large, as long as it is > (Z_{LTA_m}). I doubt if it is of any use for water management in the way it is defined now;
- Pg. 7-11, Chapter 4: do not use "central" England (e.g. pg. 9, lines 1 and 9). This region has not been identified Figs. 1 and 3. It is confusing. Stick to regions defined;
- Pg. 7, lines 9-10: I suggest to remove "…., and possibly 2003-2004.". This is not convincing in Northern UK;
- Pg. 7, line 11: you would expect (hard to read details in Fig. 3) ".., 2003-2007 and" ".., 2004-2007 and" because 2003 is a well-known drought year. You also mention it in line 10;
- Pg. 7, line 16: delete "…1943-1945…."; too little gauging stations with flow data to conclude this;
- Pg. 7, lines 22-23: "…followed by a long drought termination phase for catchments in South-west UK, whereas…". I believe this also applies to an equal number of catchments in Anglian;
- Pg. 7, line 25 and pg. 8, line 4: it reads as contradiction. "1995-1998 was relatively coherent at a regional scale" (pg. 7), whereas it is classified as "…the most nationally coherent event …" (pg. 8);
- Pg. 8, line 7: Can you add the catchment in drought in "….but one of the study catchments (Fig. 4; left), offering…". Is it the Tay (ES)?;
- Pg. 8, line 9: you mean that the drought duration is 3 years, but the text suggest that the drought in de south is 3 year longer;

- Pg. 8, lines 14-16: what about the exceptions in these regions (at least 3 catchments);
- Pg. 8, line 18 and pg. 9, line 10: I would not explicitly mention the Thames. The catchment belongs to SE;
- Pg. 8, line 19: add reference(s) "….referred to as the 1995–1997 drought in the literature, it was…";
- Pg. 8, lines 26-27 and pg. 9, lines 1-2: nothing to say about catchments with > 3-seasons drought terminations?;
- Pg. 9, lines 10-11: description of start and end of drought termination implies Win-Spr or Win-Sum. I do not believe this is consistent what is said on pg. 9, lines 26-28 and pg. 10, lines 1-2.
- Pg. 9, lines 24-25: can you say that a "rate" is abrupt? A termination can be abrupt;
- Pg. 10, lines 16-17: revise "…and two drought characteristics (drought magnitude and duration of drought development) were…" into "…and two drought development characteristics (drought magnitude and duration) were…";
- Pg. 10, lines 24-26: is this not obvious because *n=459* (all individual events) instead of *n=52* (catchment-average)?;
- Pg. 11, lines 9-10: I suggest to indicate in Table A.1 which catchments are included in the subset (17 out of 52);
- Pg. 12, line 5: revise "…Two aspects were explored, …" in "…Two aspects were explored in the next section, …";
- Pg. 12-16. Discussion: I would expect here (results from pg. 7, Section 4.1) a comparison with literature dealing with spatial distribution of drought in the UK (e.g. Hannaford et al., 2011; deals in Fig. 4 with spatial extent of catchments in 4 GB regions that experience abnormal low flows; in total over 100 catchments);
- Pg. 13, line 23-24: You have defined drought magnitude DM as the largest negative Z_{anomt} value. DM might have a too instantaneous nature rather than a integrative nature, which could explain the observed weak correlation with drought termination duration;
- Pg. 14, line 10: revise "…than any other event since 1929, …" in "…than any other event since flow gauging started in 1929, …";
- Pg. 14, lines 20-23: I believe that Fig. 6 is not required. You can simply refer to Marsh et al. (2013), if it is just a copy. If not then you need to say what you have changed / derived from the data / results;
- Pg. 16, lines 5-7: I trust that you can refer to Fig. 5, seasonality map (bottom right);
- Pg. 16, lines 27-30 and pg. 17, lines 1-2: does this mean that the drought termination seasonality at the UK national scale is likely to be influenced by one of a combination of the three mentioned large-scale drivers? If so, it should be elaborated, if not, then I suggest to leave out these sentences;
- Pg. 17, lines 12-22: impact of selected parameters on type of droughts (i.e. multi-year droughts) and under representation of short-lived drought, responsive catchments should not be in Conclusions, but in Discussion;
- Pg. 17, lines 23-26, pg. 18, lines 1-2: influence of monthly time step should not be in Conclusions, but in Discussion;
- Pg. 18, lines 3-10: description of influence of abstractions that drought-terminating rainfall must account for this "anthropogenic deficit" in addition to the natural river flow deficiencies, should not be in Conclusions, but in Discussion;
- Pg. 19, lines 2-4: you are right about lack of groundwater chronologies, but do these not exist for other hydrometeorological variables? You refer to number of papers that deal with these (e.g. Dettinger, 2013; Mo, 2011);
- Pg. 24, caption: Duplication with caption Fig. 2 "Drought termination characteristics denoted as follows: DTD = drought termination duration; DTR = drought termination rate. Drought

development characteristics are denoted as follows: DDD = drought development duration; DM = drought magnitude." Only needed in one caption;

- Pg. 25, Table 2: revise headings and order as follows:

Catchment	Number of drought events	Drought termination rate (%.month^{-1})		Year of drought Termination ranking 2nd by drought termination rate
		2009-2012	Rank 2	
Severn	16	90.6	26.5	1997

"Rank (out of total number)" can be replaced with "Number of drought events". Easier to understand.

- Pg. 28, Fig. 1: Add acronyms and description of regions from caption Fig. 3 in caption Fig. 1. Add acronyms also in top left legend. Do not use colours in inset (upper right). These colours are confusing because there is no link with the colours in map with catchments;
- Pg. 29, Fig. 2: you did not define +ve and –ve. It is $Z_{anom\,t}$;
- Pg. 29, caption Fig. 2: revise "…within D; and T is the number of months of above average flows required for the end of the drought termination phase." in "…within D; and T is the number of consecutive months of above average flows required for the end of the drought termination phase.";
- Pg. 30, Fig. 3: How to interpret the width of the red and blue bars? Add temporal resolution of bars. Is a decade (e.g. 1970-1980) subdivided in 120 monthly time steps (x-axis);
- Pg. 31, Fig. 4 and pg. 32, Fig. 5: legend at top "Duration (months)". I believe that a duration of 1 month is impossible when T is set at 2 months;
- Pg. 31 and pg. 32, captions Fig. 4 and 5: acronyms and description of regions from caption Fig. 3 should go to caption of Fig. 1, and can be deleted here (duplication);
- Pg. 33, Fig. 6: not needed (see remark pg. 14, lines 20-23).

Hannaford et al. (2011): Examining the large-scale spatial coherence of European drought using regional indicators of precipitation and streamflow deficit. Hydrol. Process. 25, 1146–1162.