Hydrol. Earth Syst. Sci. Discuss.,
doi:10.5194/hess-2015-476-AC2, 2016

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

Interactive comment on "A systematic assessment of drought termination in the United Kingdom" *by* S. Parry et al.

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Received and published: 8 April 2016

General Comments

We thank the reviewer for their very comprehensive review and positive conclusion. The comments provided by the reviewer are constructive in their nature and have helped to considerably improve the manuscript. We have responded below to each of the points in turn, providing the clarifications requested and making the changes necessary. We hope that the reviewer finds our responses acceptable so that we can revise and improve the manuscript accordingly.

Major Comments

1) We thank the reviewer for their thoughts on the methodological approach applied

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in this study. Using the drought magnitude (DM) to subdivide a drought into drought development and drought termination is a core element of our approach. The decision that the DM should be the maximum negative anomaly (rather than the absolute lowest flow) was taken to objectively compare droughts and drought terminations that occur in different seasons. We agree wholeheartedly that the decisions on the parameter values are probably the most important factor in the number and characteristics of the identified drought termination events. This was demonstrated by a very preliminary sensitivity analysis as part of a previous application (not published). Following this test case, we realised that this is a complex topic and worthy of a more comprehensive analysis that we believe is beyond the scope of this already relatively long paper. For this application, we tested a number of different combinations of parameter values (informed by that previous sensitivity analysis) and decided upon 10, 1 and 2 for D, R and T (respectively) because they identify droughts (and terminations) that are well known and which appear in the literature (e.g. Marsh et al. 2007 and Parry et al. 2013, both cited in the manuscript). As we suggest in the manuscript, these parameters identify multi-year to multi-season droughts well and capture the spatial variability in drought risk (lower in the north and west, higher in the south and east of the UK). Our study is one of many in the literature that must make subjective decisions on parameter values related to threshold-based drought indices, such as the threshold quantile and any n-month accumulation period. One of the main aims of this paper is a proof of concept to demonstrate the utility of the approach in systematically identifying and characterising drought termination in the historical record. The next stage will be to undertake a robust assessment of the sensitivity of the results to parameter values to provide advice to users. This is now included in the discussion.

2) We recognise that many drought studies apply a lower threshold than the average monthly flow such as Q70, Q80, Q90 or Q95. We have not applied any of these lower thresholds but it can be assumed that the durations of drought overall (and therefore both drought development and drought termination phases) would decrease. A lower threshold is likely to sub-divide long duration events into a number of shorter more ex-

treme episodes each of which would have a drought termination phase. It is difficult to envisage a well constrained drought (e.g. 2010-12) containing n Q80-derived droughts, for example, each with their own termination. In order to focus on the multi-season to multi-year events (pg. 6, line 20) which cause water supply problems, a duration-based approach using a higher threshold is required. The question of the most appropriate threshold will also be subject to a sensitivity analysis, but is outside the scope of this paper as a proof of concept. We acknowledge that the suitability of a given threshold differs depending on individual perceptions or applications and have added text in the discussion to provide this caveat.

3) We agree with the reviewer that deficit volume based approaches are certainly important for some studies on the recovery from drought, such as to replenish stores within the catchment (e.g. reservoirs or aquifers). However, river flows are naturally integrative and the focus of this study is on river flow dynamics rather than recovering a volume of water in a river that was 'lost' during drought development. We have included text in the discussion section to reflect these different approaches.

4) One of the main overall aims of the study is "assessing the full range of drought termination types and characteristics" (pg.3, lines 14-15). The two brief case study events (1995-98 and 2009-12; sections 4.2 and 4.3) were chosen to provide a contrast between a more gradual event (1995-98) and a more abrupt event (2009-12). We recognise that the focus on 2009-12 in sections 5.2 and 5.3 may shift the focus towards abrupt events, but this was only to put the most recent event in its historical context (we could have performed the same analysis of historical context on the more gradual 1995-98, for example). We identified three comparably abrupt events to 2009-12 for the Thames catchment, but we do not say that these are the only abrupt events (4/35) for this catchment. The 2009-12 event was an extreme drought termination event; it is likely that smaller values of DTR also caused substantial problems for water managers.

5) We agree with the reviewer and have decided to remove this sentence from the manuscript.

6) We accept that the correlations presented in the manuscript are relatively weak and cannot yet be the basis of water management decisions. We have removed the suggested sentence and caveated a corresponding part of the conclusion (pg. 18, lines 20-23).

7) Whilst the approach used in the manuscript could be applied to groundwater level data, we stand by our view that this would be beyond the scope of the study which was to demonstrate that the concept can be used to systematically analyse hydrological drought termination. Future work will provide a similar systematic assessment of drought termination in long groundwater level records and show comparisons with those derived from river flows to better understand the complex concept of the propagation of drought termination. The reviewer is correct that drought termination in river flows may not correspond to drought termination in the associated groundwater level records, but this does not necessarily imply that river flow terminations have been incorrectly identified. There are also important differences between drought terminations identified in river flow and groundwater level records even within the same catchment; boreholes provide an understanding of a very localised part of a heterogeneous aquifer whereas river flow records integrate over a larger area. This question of the propagation of drought termination through the hydrological cycle is a key question that our approach could address but we feel is a large enough topic for a study in its own right.

8) We have moved the paragraphs mentioned in the reviewer comments into the discussion section.

9) It is true that the termination is traditionally an instantaneous point in time. However, we feel that 'recovery' is also a loaded term that may create confusion amongst readers. Recovery is frequently used in ecological studies to refer to the resilience of ecosystems and can relate to a period of up to five years or more over which plants and animals return following a drought disturbance. In hydrology, recovery might imply the longer-term cumulative water deficit method which our approach does not use (see response to point 3 above).

Minor comments

Pg. 2, lines 1-2: By removing the specific reference to recent events in the UK and combining the first two sentences of the abstract, we have reduced the emphasis on abrupt terminations and strengthened the recognition that there are a wide range of possible scenarios for drought termination.

Pg. 2, lines 21-24: We have removed the element of the sentence that implies potential use for water resources management (given the lack of strong relationships) and we have been more specific about the direction of correlations.

Pg. 3, lines 1-3: We have reduced the length of this sentence.

Pg. 3, lines 1-14: We have removed references to violent weather and flooding, and re-structured the first paragraph to better reflect the range of possible scenarios of drought termination.

Pg. 3, lines 20-26: We have made reference to these two papers in terms of their consideration of the end of a drought.

Pg. 4, line 6: Following our response to point 9 above, we hope to maintain the terminology that is used consistently throughout the manuscript: drought termination as a phase of drought. We have modified the sentence explaining Bonsal et al. (2011) and Nkemdirim & Weber (1999) to better explain that these two studies also apply the concept of drought termination as a phase.

Pg. 4, line 20: We have rephrased this sentence so that representativeness is not concluded from having coverage of ∼40% of the gauged area.

Pg. 5, lines 26-27 and pg. 6, lines 1-3: We have added text into the anthropogenic influences paragraph of the discussion to recognise the north-west / south-east bias.

Pg. 5, line 22: We have now included text that recognises the shorter records and explains the calculation when this applies. We have included statistics on data availability

for those shorter records that intends to reassure the reader that the LTA values are derived from large enough sample sizes of data.

Pg. 6, line 6: We agree with the reviewer that the use of the term 'threshold' is confusing to readers. We have renamed this as the 'termination magnitude' (or TM) and have revised Fig. 2 accordingly.

Pg. 6, line 12: The DTR provides an indication of the slope of a line from the DM to the RT (now TM). We agree that the RT (TM) is an arbitrary point and we could use instead the average over the two months of >ZLTAm, for example. We believe that the DTR is potentially useful to water managers. For two events of the same duration, a higher DTR indicates a more rapid transition from drought to potential flooding. The research presented in this manuscript focuses on the identification of events and their characterisation (including their DTR). Water managers may use the information provided by the historical chronologies to better understand how different types of catchments respond to different scenarios, and could tailor decisions or actions accordingly.

Pg. 7-11, Chapter 4: We have updated references to "central" England to now read "the Midlands" because these terms essentially refer to the same geographic region.

Pg. 7, lines 9-10: On reflection we agree with the comments of the reviewer so we have removed this event.

Pg. 7, line 11: The use of both "2003-04" and "2004-07" is deliberate in order to differentiate between two different events. For many catchments in south-eastern England, the events are identified separately. The 2003 event was not as severe in the UK as in Europe, and the 2004-07 event was much more problematic than the 2003 event in south-eastern England. Hopefully now that "2003-04" has been removed (see response above) any confusion can be avoided.

Pg. 7, line 16: On reflection we agree with the comments of the reviewer so we have removed this event.

Pg. 7, lines 22-23: We agree with the comments of the reviewer and have added Anglian into this statement.

Pg. 7, line 25 and pg. 8, line 4: We agree that this reads as a contradiction so we have removed the first statement and clarified the second statement.

Pg. 8, line 7: We propose to retain the current text because we prefer the reader to consider the widespread nature of drought rather than being pre-occupied with why a specific catchment was the exception.

Pg. 8, line 9: The reviewer is correct that we mean a three-year overall drought duration in the south and east, so we have clarified the text accordingly.

Pg. 8, lines 14-16: We have specified the exceptions to this statement.

Pg. 8, line 18 and pg. 9, line 10: We have removed the two references to Thames region.

Pg. 8, line 19: We have added two example references from the literature.

Pg. 8, lines 26-27 and pg. 9, lines 1-2: We have added text to acknowledge the prevalence of >3-season drought terminations.

Pg. 9, lines 10-11: We agree with the reviewer that there is inconsistency and we have modified both paragraphs for clarity.

Pg. 9, lines 24-25: We agree with the comments of the reviewer and have made this modification.

Pg. 10, lines 16-17: We have made this modification.

Pg. 10, lines 24-26: We have removed this sentence.

Pg. 11, lines 9-10: We have indicated in Table A1 the catchments which are included in the subset, and have referred to Table A1 on pg.11, lines 9-10.

Pg. 12, line 5: We have made this modification.

Pg. 12-16. Discussion: We have added a new section into the discussion which evaluates the chronologies of drought termination relative to the wider literature on the spatio-temporal distribution of drought (and drought termination) in the UK.

Pg. 13, line 23-24: Even though the DM is an instantaneous value, one would think a larger DM is more likely to lead to longer drought termination duration (DTD), as found by Nkemdirim & Weber (1999), rather than shorter. For responsive catchments, it may be that DTD is insensitive to DM because the rainfall input dominates the trajectory of drought termination.

Pg. 14, line 10: We have made this modification.

Pg. 14, lines 20-23: We have removed Fig. 6 and now refer to Marsh et al. (2013).

Pg. 16, lines 5-7: We have added a reference to Fig. 5 bottom right.

Pg. 16, lines 27-30 and pg. 17, lines 1-2: We have modified the text in order to retain some of the different synoptic drivers that have been shown to be influential on drought termination, but to clarify that further work is required to assess whether these factors are important in the historical chronology of drought termination for the UK.

Pg. 17, lines 12-22: We have moved this section into the discussion.

Pg. 17, lines 23-26, pg. 18, lines 1-2: We have moved this section into the discussion.

Pg. 18, lines 3-10: We have moved this section into the discussion.

Pg. 19, lines 2-4: We have removed the reference to hydrometeorological variables but maintained groundwater and merged it with the following sentence on water quality and ecology.

Pg. 24, caption: There is no duplication in explaining the definition of DTD, DTR, DDD and DM between the captions of Table 1 and Fig. 2. The terms DTD, DTR, DDD and DM are not used in the caption of Fig. 2.

Pg. 25, Table 2: We have revised the table headings in Table 2 as suggested by the reviewer.

Pg. 28, Fig. 1: We have added acronyms and description of regions from the caption of Fig. 3 to the caption of Fig. 1 (and removed them from the caption of Fig. 3 to avoid duplication). We have added acronyms to the legend in the top left. We have removed the colours from the inset map and now use lines to label constituent countries.

Pg. 29, Fig. 2: We have removed the '+ve' and '-ve' directions for Zanom.

Pg. 29, caption Fig. 2: We have added the word "consecutive" into the caption of Fig. 2.

Pg. 30, Fig. 3: We have modified the caption of Fig. 3 to indicate that a decade can be subdivided into 120 monthly time steps as well as information on the total number of time steps along the x-axis. We have deleted the acronyms denoting the regions from the caption of Fig. 3, moving them instead to the caption (and legend) of Fig. 1.

Pg. 31, Fig. 4 and pg. 32, Fig. 5: We have modified the duration legend accordingly.

Pg. 31 and pg. 32, captions Fig. 4 and 5: We have deleted the acronyms and descriptions of regions from the captions of Fig. 4 and Fig. 5 and added them into the caption of Fig. 1.

Pg. 33, Fig. 6: We have removed Fig. 6.

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