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Hydrology and Earth System Sciences
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Discussions

Interactive comment on "Regionalisation of groundwater droughts using hydrograph classification" *by* J. P. Bloomfield et al.

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We would like to thank Dr Laaha for the helpful and constructive review comments.

Response to the general comments

Laaha makes a number of broad observations including: that the abstract and title do not "optimally reflect the study content", that the structure of the paper could be improved; and that the discussion of the results could be improved, for example by strengthening the links between the findings and existing literature. We acknowledge that these are all valid concerns and will address them in the revised paper. Since these observations are expanded on in the specific comments below from Laaha, we will detail our responses to them there on an item-by-item basis.

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Response to specific comments

Comment 1: The reviewer suggest that the title should be modified to better reflect the content of the paper and specifically notes that the use of "the term regionalisation is misleading as the focus is not to establish a model to predict droughts in space from gauged sites, which is the main purpose of regionalisation". The reviewer also suggests that the sub-section titles in sections 4 and 5 could also be revised.

Response: The term regionalisation was used in a general sense to describe the identification of different regional responses of groundwater to drought, although we agree that there is also a specific use of the term in hydrological modelling literature to predict behaviour away from sites where observations have been made. On reflection we agree that it would be advisable to change the title to avoid confusion and will use the suggested revised title: "Regional analysis of groundwater droughts using hydrograph classification". In addition and where appropriate, all instances of the term "regionalisation" will be changed in the paper to reflect the intended meaning of the work, e.g. regional analysis.

Sections 4 and 5 will be restructured to address the later specific comments about the structure of the discussion in the paper. Consequently, sub-section numbers have been changed and titles simplified (see also response to Comments 5 and 6 below).

Comment 2: Laaha suggests that the abstract could "be sharpened to transport main messages in a concise way". The general review comment from Van Loon made a similar point.

Response: We agree and propose to revise the abstract as follows: "Groundwater drought is a spatially and temporally variable phenomenon. Here we describe the development of a generic method to regionally analyse and quantify groundwater drought. The method uses a cluster analysis technique (non-hierarchical k-means) to classify standardised groundwater level hydrographs (the Standardised Groundwater level Index, SGI) prior to analysis of their groundwater drought characteristics, and has been

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tested using 74 groundwater level time series from Lincolnshire, UK. Using the test data set, six clusters of hydrographs have been identified. For each cluster a correlation can be established between the mean SGI and a mean Standardised Precipitation Index (SPI), where each is associated with a different SPI accumulation period. Based on a comparison of SPI time series for each cluster and for the study area as a whole, it is inferred that the clusters are independent of the diving meteorology and are primarily a function of catchment and hydrogeological factors. This inference is supported by the observation that the majority of sites in each cluster are associated with one of principal aquifers in the study region. The groundwater drought characteristics of the three largest clusters, that constitute ∼80% of the sites, have been analyzed. There are differences in the distributions of drought duration, magnitude and intensity of groundwater drought events between the three clusters as a function of autocorrelation of the mean SGI time series for each cluster. In addition, there are differences between the clusters in their response to three major multi-annual droughts that occurred during the analysis period. For example, sites in the cluster with the longest SGI autocorrelation experience the greatest magnitude droughts and are the slowest to recover from major droughts, with groundwater drought conditions typically persisting at least six months longer than at sites in the other clusters. Membership of the clusters is shown to be related to unsaturated zone thickness at individual boreholes. This last observation emphasises the importance of catchment and aquifer characteristics as (non-trivial) controls on groundwater drought hydrographs. The method, though generic, is flexible and can be adapted to a wide range of hydrogeological settings while enabling a consistent approach to the quantification of regional differences in response of groundwater to drought."

Comment 3: Laaha comments that large citation blocks are not particularly useful tot he reader.

Response: We propose to significantly reduce (more than halve) the references restricting them to those articles most closely related to the specific points being made

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in the text, as follows: “Van Lanen and Peters, 2000;Tallaksen and Van Lanen, 2004; Mishra and Singh, 2010; Van Loon, 2015)” and “Tallaksen et al, 2009; Bloomfield and Marchant, 2013; Van Lanen et al., 2013; Van Loon and Laaha, 2015”.

Comment 4: Section 3.2.2, page 5305. a) what is the ... distance BETWEEN time series. Does this mean that each month is a variable? b) why a different measure is used here as in the hierarchical CA?

Response: a) We have changed the text and now refer to “the squared Euclidean distance between the vectors of time series observations from each site” to more exactly define our measure of similarity/dissimilarity amongst hydrographs. (b) We state in the text that “there is flexibility in the choice of similarity measure” for each clustering method. Our particular choices were largely driven by convention – correlation coefficients have come to be commonly used in dendrograms and Euclidean distances are commonly used in the k-means algorithm. In our initial explorations of the data we found that the clusterings were insensitive to the similarity measure used.

Comment 5: Laaha has provided comments on the results section (section 4) of the paper, including:

i.) the use of the term “regionalisation” in Heading 4.4 and more widely;

ii.) conventions associated with drought definitions and SPI, page 5312, line 17;

iii.) description of correlations in Fig.10, page 5313 line 12;

iv.) 5314 line 20: This is not shown in Figure 11. . .

v.) interpretations of temporal patterns for the three drought events are based on Fig. 5 and 6; and,

vi.) description of lagging of multi-annual groundwater droughts behind meteorological droughts, page 5315 line 18ff

Response: These are all valid observations and we propose to make the following

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changes to the paper:

i.) the term “regionalisation” will be removed from the paper (see our response to Comment 1 above) and in addition sections 4 and 5 will be restructured with appropriate changes in sub-section titles.

ii.) We acknowledge the more recent convention of the WMO although note that it is essentially a question of semantics. We are interested in analysing the full spectrum of below average SGI values as this provides more information than limiting the analysis to values of SGI below, for example, -1. However, we agree that it is useful to highlight the WMO convention so propose to add the following note to the text as follows: “(note, however, that the current convention of the World Meteorological Organisation for SPI refers to drought conditions where SPI is continuously negative and reaches and intensity of -1.0 or less and that negative values between 0 and -1 are classified as near normal and simply indicate less than a median precipitation, World Meteorological Organisation, 2012)”.

iii.) Agreed, text to be revised to read: “there is strong relationship between drought duration and magnitude for all three clusters, Fig. 10” and caption to be revised to read: “... versus drought duration ...”

iv.) Typo, text to be revised to read: ”... before the groundwater drought ended in CL2 (Fig. 9a). ”

v.) Interpretations of the temporal patterns of the three major drought events are based on Fig. 5 and Fig. 9 as stated on page 5309, line 22, page 5310, line 16-17 and page 5313, line 27-28, where Fig. 5 is a plot of the mean cluster SGI and Fig. 9 a heatmap of all the individual SGI time series in each cluster. We propose no make no additional changes to the text related to this comment (though note old Figure 5 will now be new Figure 7 in the revised text).

vi.) We agree that there is ambiguity in this text although note page 5315, line 24 where

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we state that “clearly the nature and degree of the lag is sensitive to the rainfall accumulation method and period used to define the meteorological drought index compared with the groundwater drought index”. To address the concern of the reviewer, we propose to revise the text as follows: “Lagging of the multi-annual groundwater droughts behind meteorological droughts is not so easy to unambiguously quantify. Clearly the nature and degree of the lag is sensitive to the rainfall accumulation period used to define the meteorological drought index most closely correlated with SGI. In the present case, accumulation periods of 4, 16, and 9 months are required for CL1, 2 and 4 respectively to achieve optimal correlation between the SPI and SGI time series”.

Comment 6: Laaha has provided comments on the discussion and conclusions section (section 5) of the paper, including:

i.) suggesting changes to sub-section title 5.1;

ii.) deleting the first two paragraphs in section 5.1 and a paragraph in section 5.2;

iii.) restructuring the Discussion section to include content from Results sections 4.4 and 4.5; and,

iv.) putting the Conclusions in a new final section and writing them in prose rather than in bullet form.

Response: We agree that all the points raised regarding the structure and content of the discussion are valid. To address these queries we propose to make the following changes to the paper:

i.) section 5 will be restructured and there will be no sub-sections

ii.) the first two paragraphs of (old) section 5.1 will be deleted

iii.) The Discussion will be re-structured so that the last half of section 4.4 and all of section 4.5 will be moved into the new discussion.

iv.) Agreed. The conclusions will be placed in a new section 6 and will be re-cast as

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prose rather than bullets.

Comment 7: Laaha suggests that there is an inconsistency between the statement at the start of section 5.2 that “it has been shown that there can be pronounced differences in the characteristics of multi-annual drought episodes between aquifers” and “the message of Fig. 9 ... that time series are coherent within the clusters”.

Response: We think that both statements are correct. However, we chose to emphasise the former in the Discussion since the observation is the starting point for a discussion of implications for groundwater level monitoring that we think is important. Consequently, we do not propose to make any changes to this text.

Comment 8: It is proposed that all symbols used in Tables 1 and 2 should be explained in the heading.

Response: Agreed, the table heading will be amended accordingly.

Comment 9: Laaha suggests that consistent referencing style to figures throughout the text (currently Fig. and Figure are used).

Response: We hope that we have applied the HESS house style appropriately and note that HESS request that: “The abbreviation "Fig." should be used when it appears in running text and should be followed by a number unless it comes at the beginning of a sentence, e.g.: "The results are depicted in Fig. 5. Figure 9 reveals that ...". However, we will check the text again and revise where appropriate.

Comment 10: Laaha suggests revision of the colour coding in Figure 3.

Response: We refer to our response to a similar comment from Van Loon (Van Loon, Comment 12) – “We note that the numbering and colouring of the clusters is arbitrary, but will make the change to enable easier comparison between Figures 3b and 3c”.

Comment 11: Laaha suggests that Figures 5, 6, and 7 are not in logical order and that figures, that Figure 7 could be presented “before current Figures 6, and perhaps

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6 before 5" and that they are introduced in 5308, Line16âĂŘ19 but not discussed "in a logical order".

Response: Agreed. The text will be revised so that old Figure 7 is the new Figure 5 and the old Figure 5 is the new Figure 7. In addition, the text at 5308, Line16âĂŘ19 will be revised to read "Gig. 3c shows the distribution o sites between the six clusters (cluster 1 to cluster6, or CL1 ... CL6)".

Comment 12: Laaha suggests minor change in Figure 6 captioning.

Response: Agreed, we will revise the caption to read "different aggregation periods qmax" as suggested and will add aggregation period used for each cluster.

Comment 13: The reviewer proposes a change in the colour ramp of the heatmap, Figure 9.

Response: We agree that Figure 9 would be improved by altering the colour ramp. As Laaha suggests we will invert the colour ramp used in the left hand panel of the figure.

Comment 14: Laaha suggest a minor change in Figure 10 captioning.

Response: The caption will be changed to read "Drought magnitude versus drought duration for sites in clusters CL1, CL2 and CL4".

Minor Technical comments: Laaha notes three minor technical edits are required as follows:

i.) Eqn. (2) page 5306, g0 needs to be defined.

ii.) 5306 line 18: replace co-efficient with coefficient

iii.) 5307 line5: have instead of has?

Response: We agree with these comments, the following changes will be made:

i.) We have clarified that g(k) reduces to the population variance when k=0 (see Eqn. 1).

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ii.) The text will be changed to read “coefficient”.

iii.) The text will be changed to read “have”.

A copy of the proposed revisions to the text and figures is appended as a Supplement

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/12/C3367/2015/hessd-12-C3367-2015-supplement.pdf

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