Hydrol. Earth Syst. Sci. Discuss., 12, C3355–C3366, 2015
www.hydrol-earth-syst-sci-discuss.net/12/C3355/2015/

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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Received and published: 27 August 2015

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

Response to the general comments

We acknowledge that the abstract focuses on clusters CL1, 2 and 4 and that it could convey the broader implications of the work more effectively. Consequently, we propose to modify the abstract to emphasise the wider application of the work removing specific references to the individual clusters.

We also agree with the general observation that the manuscript as a whole would be improved by emphasising how the methodology could be applied to other regions and

Full Screen / Esc
Printer-friendly Version
Interactive Discussion
Discussion Paper

could be used for other purposes such as prediction. We note that these general comments are also echoed in some of the specific comments. Consequently, we address these questions in detail in our response to the specific comments below including through proposed changes to the Discussion (section 5).

Response to specific comments

Comment 1: Clustering with expert knowledge. Van Loon notes that the manuscript did "not investigate the effect of clustering without any expert knowledge" and raises the following questions: "What would have happened if no expert knowledge was used?"; "What is the influence of the rules on p. 5308?", and "What if these were not applied? And how appropriate are these rules?"

Response: The two techniques that were used for clustering, the agglomerative hierarchical complete-linkage strategy and the non-hierarchical k-means clustering algorithm, are unsupervised methods. Interestingly, and importantly for their subsequent interpretation, they also both produce very similar classifications (see Fig. 3). However, clustering methods do not produce a unique partitioning of a given data set on their own – they require intervention by some form of "expert judgment". For example, hierarchical algorithms form a hierarchy, e.g. the cluster dendrogram in Figure 3a, from which the user still needs to make a decision regarding how many clusters are significant, or in the case of the non-hierarchical clustering the number of clusters, k, needs to be specified in advance of the analysis – typically through an iterative process. Consequently to obtain clusters, "expert knowledge" is required in the selection of the number of classes to extract from the respective cluster analysis results – hence the development of the study-specific rules on p. 5308. Such rules or decisions have to be subjective to some extent since the number of classes will be dependent upon the eventual use of the clusters and the scale at which a given study is addressing.

To illustrate these points, consider the cluster dendrogram produced by the hierarchical classification (Figure 3a). This shows results for a complete, unsupervised analysis of the cluster structure based on the level of similarity between individual SGI hydrographs. As we note on p. 5307 “the number of clusters is controlled through the threshold on the [Euclidian] distance” – in the present study a threshold distance of 0.62 was chosen to define the six clusters. A smaller distance would have given a larger number of clusters. We chose a threshold to give us the six clusters shown in Figure 3b that met our broad study-specific heuristic rules about classes of interest.

We are unaware of any commonly-used approaches that would select cluster numbers without expert knowledge. If there was such an approach, for example a random process of class selection, it is not clear what criterion could be used to compare that approach with ours beyond the RMSSD we already show in Fig 4. Given that the aim of the study was to develop robust methods to systematically characterise the heterogeneous response of groundwater to droughts at a regional scale, and that it was assumed that the response of groundwater systems to droughts is influenced by spatial variations in intrinsic aquifer characteristics and processes, it seems reasonable that the rule-based approach to cluster identification be based on prior knowledge of the broad hydrogeology of the study area, while also attempting to limit the number of classes due to the limited number of hydrographs being clustered.

We will edit the last paragraph of Section 3.2.2, the methodological description of the cluster analysis, to reflect our comments above and add additional text to the discussion to emphasise the points and help in the generic application of the methodology.

Comment 2: Assumption of spatial coherence of meteorological drought. Van Loon points out that “high spatial coherence of hydrological drought might be due to an attenuation effect of the landscape, smoothing out spatial variability in meteorological drought” and consequently that it is strange that we “support this assumption [of homogeneity of meteorological drought across the study region] by the spatial coherence of hydrological drought [across the same region]”

Response: We agree that the high spatial coherence of hydrological drought can be

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

due in part to the smoothing out of spatial variability in meteorological signals. We also acknowledge that we don't sufficiently point to evidence we present later in the paper to successfully test our original assumption using a correlation between SPI and the regionalised SGI time series. Consequently, we propose to revise the first paragraph of section 2.1 as follows: "As a first-order approximation, it is assumed that the broad meteorological drought history of the study area is spatially homogeneous. This assumption means that any relative differences in drought histories between sites or clusters need to be explained in terms of catchment or hydrogeological factors, rather than differences in the drought climatology. This assumption is tested as part of the analysis of correlations between precipitation and regional groundwater levels (see Sect. 4.2). It is also supported by the observations that the whole study area is governed by the same broad climatic patterns, i.e. rain-bearing low pressure systems from the Atlantic and high pressure systems leading to a lack of rainfall, with only small variation in annual precipitation across the region (600 to 800mm). The assumption is also consistent with the previously documented spatial coherence of major hydrological (surface water) droughts in the UK (Hannaford et al., 2011; Fleig et al., 2011; Folland et al., 2015) where the current study area falls within a homogeneous drought region ("region 4" of Hannaford et al., 2011, "region GB4" of Fleig et al., 2012; Kingston et al., 2013, and the "English Lowlands" of Folland et al., 2015). Although it is noted that the attenuating effects of landscape processes can cause heterogeneous meteorological signals to become attenuated (Van Loon, 2015)."

Comment 3: Groundwater time series vs drought. Van Loon notes that the clustering is done on the complete SGI time series and not just on the "dry end" of the SGI despite subsequent analysis focussing on droughts, that this is mentioned in the discussion and it is conclude that "the resulting clusters have been shown to effectively regionalise groundwater droughts" (p. 5318). The reviewer asks "How is this "effectively" determined?"

Response: Throughout the paper we have been careful to maintain a distinction between the definition of clusters using the full SGI hydrographs, and exploring the distributions and characteristics of groundwater droughts within the clusters once they have been defined in such a way. It is not clear if there would be more information to be gained related to regional drought characteristics if clustering could be done on just the “dry end” of the SGI hydrographs. Since the clustering approaches need a measure of the groundwater level status (SGI) on a common time step (in the present study, every month), if we were just to replace all of the positive SGIs (i.e. the above average groundwater level observations) with zeros then these zeros would still have an effect on the classification. One way to address this issue would be to estimate drought characteristics from each SGI hydrograph first and then attempt some kind of categorisation of the resulting measures or scores for the drought characteristics, though CA may then not be the most appropriate approach. However, just as importantly from a process-based perspective, even though SGI may be positive immediately prior to and after a drought event, the timing and rate of change of positive SGI may include valuable information about the nature of the onset and end of a drought event. If this is the case then this is a compelling reason to use compete SGI hydrographs to undertake the clustering.

We agree that the phrase “yet the resulting clusters have been shown to effectively regionalise groundwater droughts across the study area” has not been qualified sufficiently so we propose to modify it as follows: “Yet the resulting clusters have been shown to effectively regionalise groundwater droughts across the study area. For example, they reflect the major drought history across the study region (Fig. 2 and Fig. 7), and identify spatially coherent hydrographs that are consistent with known hydrogeological differences across the study area (Fig. 3c and Fig. 9a)”.

Comment 4: Aquifer characteristics. Van Loon observes that on p. 5308 a “documented N-S variation in aquifer properties” is mentioned and used in the clustering, but that on page 5316 it is mentioned that Bloomfield and Marchant (2013) found no clear relationship between Mmax and log Diff for fractured aquifers like the ones used in this study and therefore the effect of transmissivity and storativity is not analysed further". Van Loon also noted that information on the characteristics of the aquifers is useful only if used later in the classification or analysis of clusters and points to the need "to make a clearer link between the information of the spatial variability of aquifer characteristics and the clustering and analysis later in the paper".

Response: The descriptions and aquifer characteristics of the three aquifers (the Lincolnshire Limestone, the Chalk and the Spilsby Sandstone) are set out in section 2.2 to emphasise the discrete nature of each of the three aquifers and to inform the heuristic rules used in section 4.2 that guide the selection of the clusters. However, we acknowledge that we don't provide sufficient information about differences in unsaturated zone thickness between the aquifer, over emphasise the importance of differences in T and S, and, as the reviewer notes, do not explicitly link this information to the analysis of the results in the context of the assessment of possible hydrological controls on the clusters (section 4.5). In addition, we note that the rules, including information about aquifer characteristics and heterogeneity, are not discussed generically in section 5.

To address these points we propose to:

i.) Add the following text to the start of section 2.2: "These aquifers are hydrogeologically distinct from each other, and two of them, the Lincolnshire Limestone and the Chalk have previously documented spatially variability. Below we summarise these features as they inform the heuristic rules used in section 4.2 to guide the selection of clusters as part of the CA."

ii.) Modify the text in section 2.2 to include comparative comments about differences in the maximum unsaturated zone thickness over each of the aquifers.

iii.) Move the description of the heuristic rules for cluster selection into the methods section 3.2.2 and add the following text "Here we use a rule-based approach to help identify the number of clusters based on prior knowledge of the general hydrogeology of the study area. Bloomfield and Marchant (2013) have previously shown that groundwater drought characteristics are a function of unsaturated zone thickness in fractured aquifers such as the Lincolnshire Limestone and Chalk aquifers, and that when a broader range of aquifer types are considered groundwater drought characteristics are also a function of the hydraulic diffusivity of aquifers. Here we use these observations and knowledge of the spatial variation in these features across the three aquifers in the study area (section 2.2) to design rules to aid in the selection of clusters".

iv.) Clarify the heuristic rules as follows: "The rules are to identify the smallest number of clusters that: i.) broadly resolve the spatial distribution of the three aquifers across the study region, ii.) given the previously documented N-S variation in aquifer properties and unsaturated zone thickness across the Lincolnshire Limestone aquifer (Allen et al., 1997), that distinguish more than one region of the Lincolnshire Limestone, and iii.) given variations in aquifer properties and unsaturated zone thickness across the Chalk aquifer both N-S and across the buried cliff line (Allen et al., 1997), that distinguish more than one region of the Chalk."

v.) The following text will also be added "For any given study area, the target number of classes, and hence the rules, can be adapted to reflect the regional hydrogeology and in particular any prior knowledge of heterogeneity in the aquifer systems" to the Methodology section following the description of the rules.

Comment 5: CL6. Van Loon asks "How can you select 1 month accumulation period for CL6 from Fig. 7, if there is effectively no correlation at all (p. 5309).“

Response: We agree with the observation that no significant accumulation period for CL6 can be identified in Figure 7. We have modified Table 1 to remove qmax and mmax values and modified the text to read: "Values of qmax for CL1 to CL5 from Fig. 5 are 4, 16, 15, 9, and 17 months respectively". Note that Figure 7 will now be Figure 5 in the revised paper.

Comment 6: CL3, CL5 and CL6. Van Loon notes that clusters 3, 5 and 6 showed unexpected behaviour and questions "could these wells not have been excluded be-

Full Screen / Esc

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Interactive Discussion

Discussion Paper

forehand based on prior knowledge? What does the clustering approach help? What extra information is gained?". The reviewer also suggests that "In the discussion on p. 5319, the authors mention that the clustering method can be used for detection of wells with strong human influence. This might be elaborated a bit more."

Response: All the sites included in the study are part of a regional groundwater level monitoring network and were considered to be free of any significant anthropogenic influences. The following text has been added to clarify this, as follows: "Prior to the study none of the sites were believed to be significantly impacted by abstraction although all three regional aquifers are used for public water supply, and abstractions for agricultural irrigation and industrial use (Allen et al., 1997; Whitehead and Lawrence, 2006)."

If there had been prior knowledge that any particular site was heavily influenced by human activities it could of course have been removed prior to the clustering analysis, and this would have been desirable given that the aim of the work is to demonstrate a method of identifying and characterising regional differences in groundwater response to droughts. However, having made the observation that the method could, by inference, also be used to identify and cluster groups of anthropogenically impacted groundwater hydrographs (section 4.3) we thought that it would be useful to highlight this in the discussion (section 5.1). We agree with the reviewer that this can be elaborated on so we have revised the text in the discussion (section 5.1) as follows:

"Although the CA was not specifically designed to identify anthropogenically impacted groundwater hydrographs the classification scheme could be used to that end since it can differentiate between clusters showing trends superimposed on the regional signals (e.g. CL3 and CL5) and clusters with anomalous phase relationships with the regional signal (e.g. CL6). The presence of a trend in a cluster of hydrographs may be indicative of an anthropogenic impact from unsustainable abstraction (declining trend) or from groundwater rebound (rising trend). For example, where there is limited prior information regarding groundwater withdrawals across a region, a not uncommon situ-

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

ation in areas where abstraction is not highly regulated, cluster analysis could be used, either as it has been in the present study based on a set of heuristic rules to identify a suitable number of clusters, or in an exploratory manner. If it is used in a more exploratory manner, either hierarchical or non-hierarchical clustering could be undertaken and then clusters searched to identify spatially coherent clusters that show significant downward trends in hydrographs (where significance of trends in a cluster could be tested and quantified using standard tests, such as Mann-Kendall and Sen's slope estimates). Any spatial coherence in clusters exhibiting downward trends could be taken as indicating the presence of potentially unsustainable abstraction. Conversely, for the purposes of a study where the stationarity of the data is important, if trends in individual hydrographs are already known then either these hydrographs can be removed from an analysis or the trends could be identified and removed prior standardisation and clustering of the hydrographs."

Comment 7: Novelty. The reviewer suggests that "the authors might stress a bit more the applicability of their method to other regions or its usefulness for prediction in time and space?" and asks "what is the benefit of the clustering method? Can sites that were not used in the cluster analysis, but are located in the same region be allocated to a cluster? Can the clusters be used for prediction?"

Response: We agree that these points should be emphasised in the discussion. The text will be modified to include the following in the new Discussion section: i.) "Although clustering of groundwater hydrographs is not novel in itself (Winter, 2000; Moon et al, 2004; Upton and Jackson, 2011) this is the first time these techniques have been systematically applied to investigate groundwater droughts. The approach described is generic and widely applicable and here we briefly highlight some of the methodological considerations, and implications for monitoring and prediction of groundwater droughts." ii.) "More generally we see a range of possible benefits to clustering groundwater hydrographs. For example, 'sentinel' boreholes within each cluster, those that are closest to the mean behaviour of a group, could be identified and used as indicative

Full Screen / Esc

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Interactive Discussion

Discussion Paper

of the groundwater response of a wider area. Missing data is a common issue with groundwater hydrographs, and clustering techniques could potentially be used to identify suitable boreholes from which groundwater levels could be infilled. However, more importantly, clustering could be used in combination with groundwater models to aid the prediction of groundwater droughts. A range of techniques can be used to model groundwater hydrographs at a site, i.e. non-distributed groundwater models, including statistical models (Ahn 200; Bloomfield et al. 2003), artificial neural network models (Sreekanth et al. 2009) and 'black box' models (Mackay et al, 2014). The hydrograph cluster analysis could be used in combination with any of these techniques for groundwater drought prediction. For example, groundwater level prediction 1 to 12 months out is currently undertaken in the UK for selected sites / hydrographs using a black-box, lumped parameter model (Jackson et al. 2013; Mackay et al. 2014; Hydrological Outlooks, 2015) driven by probabilistic estimates of future rainfall. Regional inferences of future groundwater levels are then based on qualitative interpretations of the individual sites. Applying similar predictive modelling systems to mean cluster hydrographs that representative of spatially coherent regions of groundwater drought instead of individual site specific hydrographs should enable a more rigorous prediction of the spatial distribution of future droughts“

Response to technical comments

Comment 8: p. 5298, l. 18 – p. 5299, l. 3: include section numbers in this paragraph.

Response: Agreed, the appropriate section numbers will be added to the revised text.

Comment 9: p. 5313, l. 20: (Fig. 11) > (Fig. 11a).

Response: Agreed, text revised to read "(Fig. 11a)"

Comment 10: p. 5314: what do you mean with "annual cycles of drought intensification and decline"? Where do we see this in Figure 5 or 9?

Response: The feature is present in both figures, but most clearly seen in Figure 9. Text modified to clarify this as follows: "This is seen in Fig. 9a where between 1988 and 1993 the drought status of CL4 is designated by the red tones in the heatmap, but that these tones show a series of approximately annual variations giving the appearance of vertical stripes during that period and within that cluster."

Comment 11: Figure 2 & 5: include variability around the mean SPI and SGI time series to show the range of individual wells and precipitation gauges.

Response: We agree that it would be possible to plot all SGI time series in Figure 2 and all those time series associated with each cluster in their respective plots in Figure 5, as well as the mean data. We decided not to do this because the focus of the paper is on the definition of the clusters and differences in their mean characteristics, e.g. see the analysis in section 4.4. We thought that to include all data in Figures 2 and 5 would make them overly complicated and may obscure the differences between the mean characteristics of the clusters that we wanted to emphasise and explore. We were, however, aware that it was important to document and consider within cluster variability, hence we plotted all the SGI data separately in the form of the heatmap in Figure 9 which also includes an associated cross-correlation analysis. We think these are still compelling arguments and consequently we have chosen not to amend Figures 2 or 5 in response to this comment.

Comment 12: Figure 3c: switch yellow and light blue points, so that the clusters are similar to those in Figure 3b.

Response: 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 13: Figure 9: include a and b and refer to Figure 9a and 9b in the text. Also reverse the colour scheme, so that drought is red and wet conditions are blue.

Response: Agreed, the figure captioning and text will be revised appropriately.

A copy of the prosed revised text and figures is attached as a Supplement.

Please also note the supplement to this comment:
http://www.hydrol-earth-syst-sci-discuss.net/12/C3355/2015/hessd-12-C3355-2015-supplement.pdf

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