Analysis of groundwater drought using a variant of the Standardised Precipitation Index

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General:

The paper deals with a new groundwater drought index, i,e. the Standardized Groundwater Level Index (SGI). The derivation of SGI is inspired by the approach used for the well-known and widely-used Standardised Precipitation Index (SPI). Effects of seasonality were accounted for by determining SGI for each calendar month from monthly groundwater level observations prior to generating a continuous SGI time series for an observation well (at site analysis). The proposed SGI methodology uses a non-parametric normal scores transformation of groundwater data rather than a parametric distribution as done for SPI. The SGI was tested with data from 14 groundwater observation wells, which represent different consolidated aquifer types in the UK.

Time series of SGI were compared with SPI, which shows that maximum cross-correlation is reached when different SPI accumulation periods were used for the selected sites and that in some cases a lag correlation yields better results. Negative SGI values reasonably agree with major droughts in the UK that are reported in the literature. Duration of severe groundwater droughts derived from SGI time series show a close link with the auto-correlation structure. Evidence is given that hydrogeology (aquifer type, depth of water table, transmissivity, storativity) controls to some extent the SGI time series and their auto-correlation structure.

I believe that development of groundwater drought indices is crucial for proper monitoring and management of the resource (e.g. domestic water supply, irrigation), but also for groundwater storage/discharge dependent functions (e.g. inflow to riparian areas/wetlands, capillary rise lowlands). The world of drought indices is dominated by meteorological (in particular SPI) and soil water (PDSI, SMA) indices, whereas there is a clear need for hydrological drought indices to assess impacts, and provide guidance to water resources management and water-related policies. So far development of hydrological drought indices is biased to river flow/runoff (e.g. RDI, low flow characteristics, threshold approaches), whereas science have paid little attention to groundwater indices. This paper contributes to filling this gap and advances our knowledge. The paper deals with relevant scientific questions within the scope of HESS. The work discovered the weaknesses of the SPI methodology to quantify groundwater drought and developed, tested and illustrated a methodology to obtain a new groundwater drought index (SGI). The authors made a first step to link the auto-correlation structure of SGI to hydrogeological control through investigating explanatory variables, like unsaturated zone thickness, aquifer transmissivity.

I found the paper to be well-written and presented. It is understandable and well-documented with tables and graphs. The paper is potentially a very relevant contribution to HESS. However, it needs some additional elaboration (see major and minor items below).

Major items:

1. The study shows too much respect for the Standardised Precipitation Index (SPI). This happens more. It seems that the drought community, when introducing a new index, it always has to "validate" it against the SPI. This paper demonstrates that a straightforward link between a soil water index or hydrological drought index (in this study a groundwater index) and SPI, which is readily transferrable to other regions (this is essential), does not exist. The paper demonstrates through a lag-correlation that a site-specific SPI accumulation period (varying from 6 to 28 (!) months) and in some places a lag (1-2 months) was required to obtain maximum cross-correlation coefficients of 0.7 -0.9. The heat maps (Fig. 8) excellently display the lack of such a straightforward relationship. Why searching for maximum cross-correlations and forget about combinations accumulation period – lag that have a low cross-correlation. We need a breakthrough on this in drought research and associated operational water management; the SPI is a good meteorological drought indicator (with some reported weaknesses), but it is not appropriate because of being too site-specific to identify droughts with SPI in other hydrological domains (soil, groundwater, surface water).
   I suggest to change the focus of the paper from searching a link between SGI and SPI (e.g. Sect. 4.2, Introduction, Discussion, Conclusions), to demonstrating that the SPI does not work (in this case to characterize groundwater drought). Hence, we need other indices than SPI. I believe you still can use all the material (tables and graphs). You only need to rephrase the text at some places to accommodate the revised focus. I also recommend to revise the title to reflect the other focus. The revised title might be: "Analysis of groundwater drought using a new index" or "Analysis of groundwater drought building upon the Standardised Precipitation Index' approach". Your paper earns more credits than just suggesting that you propose a revised SPI applicable to identify groundwater drought.
2. Reconsider the structure of the sections on Results and Discussion. In the manuscript new analysis are reported in the Discussion. The whole link between SGI, i,e, the auto-correlation range, m_{max}, and hydrogeological control is described in the Discussion. The results on the link could be described in Section 4 and the discussion in Section 5. This would reduce the length of Sect 5.
3. Elaborate in the Discussion the pros and cons of the newly proposed SGI versus existing groundwater indices, such as the Standardized Water Level Index (SWI) (Bhuiyan et al., 2006), spring flow as a proxy for groundwater storage (Fiorillo and Guadagno, 2010; 2012), base flow (Fendeková and Fendek, 2012), threshold approaches (Peters et al., 2003; Wanders et al., 2010).

Minor items:

4. "Fewer studies have concentrated on regional characterisation of groundwater droughts, ..." (7539, lines 22-23). This suggests that you will address this in your paper, but you are doing 14 at-site analysis, which you put into a regional perspective (UK). A regional drought analysis involves a spatial analysis (e.g. Tallaksen et al., 2009).
5. "To address this shortcoming, here we present for the first time a systematic assessment of how one of the most commonly used hydrological drought indices, the Standardised Precipitation Index (SPI), can be applied to groundwater level data in order to define a new groundwater level index ..." (7540, lines 5-8). You do not apply the SPI methodology. Please rephrase (see item 1).

6. “The method has recently been extended to include atmospheric water demand...” (7540, lines 26-27). Add: Standardised Precipitation-Evapotranspiration Index, SPEI.
7. “Hence, if an appropriate standardised index can be applied, groundwater levels at observation boreholes are a useful measure of the quantitative status of groundwater resources during a regional drought.” (7541, lines 2-4). There are more societal reasons that people are interested in a groundwater index (see General, pg. 1). I also suggest to delete “regional”. Drought cover a large area by definition.
8. Section 2 (7541-7542): Is there a justification, that you left out unconfined unconsolidated aquifers (e.g. gravel aquifers). They might be not relevant for the UK, but they are elsewhere.
9. “....and are not significantly affected by pumping...” (7541, lines 22-23). What does this mean? Drought is a natural phenomenon caused by climate variability (definition). Changes in SGI should be caused by drought only and not (partly) by human activities.
10. “Since we wish to use a common threshold for all of our SGI series to enable comparison between sites we have selected 0.11 as the SGI autocorrelation threshold, t_{SGI}, ...” (7546, lines 17-19). This choice is subjective. In some cases, we need to make subjective choices, but what is the impact (see also, pg, 7548, lines 1-7)? How will the choice affect the magnitude of the auto-correlation range, m_{max} of the different sites (for example, if the correlogram is a bit flashy, see Fig. 7 (e) and (f).
11. “Note that no pumping test data is available for any of the study sites, so T and S values are estimates based on mean values derived from pumping tests for a given region and aquifer combination as reported by Allen et al. (1997). (7547, lines 1-4). Are there other reports that confirm the *S* values, which you later use in the paper to calculate the diffusivity *D* for the hydrogeological control (Fig. 12(c)). Values are rather low and could be affected by short pumping tests, as mentioned for the Permo-Trias sandstone.
12. Reference to Fig. 7. (7548, lines 17-19). The correlogram gives the autocorrelation as a function of lag. Inform the reader that this lag differs from the lag that you describe in the lines 21-25.
13. “However, investigation of the cross-correlation coefficients for a range of lags between SPI and SGI shows that the maximum correlation may not necessarily occur at a lag of zero months. So for all sites the cross-correlation between SPI and SGI has been estimated for SPI accumulation periods of q = 1, 2, . . .,24 months 25 and for lags of one month increments up to 24 months.” (7548, lines 21-25). Why did you expect a lag of 0 months between the SGI and SPI for different accumulation periods? Early, propagation studies (e.g. Changnon, 1987; Peters et al., 2003; Peters, 2003) and more recently Van Loon and Van Lanen (2012) and Van Loon (2013) clearly distinguish four components in the propagation, namely: pooling, attenuation, lag, and lengthening. The lag is also explicitly mentioned.

    I suggest to add the term “lag-correlation”. Basically, you have performed a cross-correlation to study similarity of two time series with a time-lag applied to one of them.
14. “The maximum cross-correlations between SPI and SGI are generally strong ...” (7549. lines 4-5). I would change the focus and not search for the strongest cross-correlation (see major item 1).
15. “.... and broadly increase in the same order for the study sites.” (7549, lines 12-13). You can only understand this phrase after reading the next sentence that refers to Fig. 10. So, I suggest to move the phrase to after the sentence.

16. Section 4.3. You encountered a classical problem when you would like to "validate" the outcome of a drought index against reported droughts. The latter are mainly based upon impacts. Impacts can have many reasons, e.g. prolonged periods with above-normal temperatures (heat wave), crops suffering from water deficits, too high river temperatures due to release of cooling water of thermal energy plants, low river stages hampering water-born transport. This implies that a particular drought index (only representative for a certain hydrological domain, in this case groundwater) will identify some drought and others not. This also happens in your paper. I suggest to mention this restriction when comparing.
17. You mention Cole and Marsh (2006) and Marsh et al. (2007) for the documented droughts in the UK (Section 4.3). Additional relevant sources might be: Lloyd-Hughes et al. (2010) and Taylor et al. (2009).
18. Order of observations (7550, lines 13-23). I suggest to rank from long ago to recent drought. In your paper you rank from recent to long ago and then you end with droughts in the mid-1960s and the late 1940s.
19. "....(Hannaford et al., 2010)...." (7552, line 5). It should be: "Hydrol. Process. 25, 1146–1162 (2011)".
20. Discussion: You did not address the effect of the location of the groundwater observation well on magnitude of the SGI as a result of recharge and aquifer-stream interaction. For instance, Peters et al. (2005) conclude on the basis of a spatial analysis of groundwater drought in the Pang catchment (UK): "Short droughts (like the 1976 drought) are relatively more severe near the streams, as they are dampened further away, whereas long periods of below average recharge have relatively more effect near the groundwater divide.".
21. "Here drought duration is taken to be a period where monthly SGI is continuously negative at a site." (7552, lines 14-15). Here, you introduce a classification for the newly developed index without justification. I suggest to add "similar to the SPI classification McKee et al. (1993).".
22. "The median drought duration appears to be insensitive to m_{max}, however, as postulated, maximum drought duration is broadly positively correlated with m_{max}, Fig. 12 (left panel)." (7552, lines 19-21). I suggest to add correlation coefficients, certainly for maximum duration.
23. "The first potential source of autocorrelation in SGI...." and "The second possible cause of autocorrelation in SGI" (7553, line 15 and line 21, respectively). You formulate hypotheses. Please add references. There are textbooks on drought that describe the basis for the autocorrelation.
24. "Fig. 12c, shows that for all aquifers log*D* is negatively linearly related to m_{max}." and "...longer SGI autocorrelations are associated with aquifers where the hydraulic diffusivity is relatively low." (7554, lines 16-17 and lines 21-22, respectively). I believe it is the opposite, if log*D* *i*ncreases then m_{max} increases.
25. Conclusions (7555). Needs revision, see major item 1 (other focus).
26. The reference "Van Lanen, H. A. J. and Tallaksen, L. M.: Hydrological drought, climate variability and change, ..." (7559, lines 14-17). I suggest to change this with the more updated and peer-reviewed paper: Van Lanen et al. (2013).
27. Table 1 (7560). Add aquifer type (fractured etc.), "Well depth" add relative to soil surface, "Mean unsaturated zone (m)" change into: "Mean thickness unsaturated zone (m)".

28. Table 2 (7561). Add in the header “Maximum cross-correlation”, although it is already in the caption.
29. Fig. 3 (7565). Low monthly precipitation (drought) is hard to see in such a long record (top panel). It is better to choose a shorter period with a clear drought (e.g. 1980-2005). It would still support the text on pg. 7542 (lines 14-17) and pg. 7543 (lines 17-19).
30 Fig. 6 (7568). “SPI for Dalton Holme for accumulation periods q = 1, 3, 6, 12 and 24 and corresponding SGI.” Add: “SPI for Dalton Holme for accumulation periods q = 1, 3, 6, 12 and 24 (5 top panels) and corresponding SGI (bottom panel).”.
31 Fig. 7 (7570). “The heat maps are for sites listed in Table 1 in alphabetical order from top left to bottom right.”. Add: “The heat maps are for sites listed in Table 1 in alphabetical order row-wise from top left to bottom right.”.
32 Fig. 8 (7571). “The heat maps are for sites listed in Table 1 in alphabetical order from top left to bottom right.”. Add: “The heat maps are for sites listed in Table 1 in alphabetical order row-wise from top left to bottom right.”.
33 Fig. 10 (7572). I miss one of the sites. Only 13 circles, or do two sites coincide? If so, please indicate.
34 Fig. 11 (7573). Insert left y-axis legend, i.e. the numbers from 1 to 14 (numbers of observation wells. Add: “Plots are for sites listed in Table 1 in alphabetical order from top to bottom.”.
35 Fig. 12 (7574). Check the number of sites. For example, I miss one of the sites for the Median drought duration (all aquifers), Fig, 12a. Only 13 triangles, or do two sites coincide? If so, please indicate.

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