Hydrol. Earth Syst. Sci. Discuss., 10, C4905–C4930, 2013
www.hydrol-earth-syst-sci-discuss.net/10/C4905/2013/

Hydrology and Earth System Sciences Discussions
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Interactive comment on "Analysis of groundwater drought using a variant of the Standardised Precipitation Index" *by* J. P. Bloomfield and B. P. Marchant

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Received and published: 13 September 2013

Response to Interactive comment on "Analysis of groundwater drought using a variant of the Standardised Precipitation Index" by J. P. Bloomfield and B. P. Marchant J. P. Bloomfield & B. P. Marchant Hydrol. Earth Syst. Sci. Discuss., 10, 7537–7574, 2013 Review by H van Lanen

We would like to thank Dr van Lanen for his detailed review comments. We found them to be insightful, and, through our responses to them set out below, we believe that they have resulted in a much improved paper.

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Major Comments.

Comment 1: “The study shows too much respect for the Standardised Precipitation Index (SPI). ... 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).” In addition, van Lanen (2013) recommended that the title be revised to reflect the change in focus.

Response to comment 1: We appreciate the pithy nature of the initial comment from van Lanen (2013) which succinctly captures a major observation related to the paper. Based on a consideration of this and other comments (particularly comments 2 and 3, below and General comment 1 from Anonymous Referee #2), we agree, that a.) we have probably been insufficiently critical of the application of SPI as originally proposed by McKee et al (1993), and Edwards and McKee (1997) to hydrological data such as groundwater level time series, and b.) we have not recognised adequately the work of others who have also identified shortcomings with the SPI approach and subsequently developed revised methods. We agree that an effective way to address these issues is to change the emphasis of some of the text in the Introduction, Discussion and Conclusions sections of the paper and change the title of the paper. Consequently, the text has been revised as follows:

Additional text has been added to the end of the Introduction section to read:

” The new index builds on the SPI methodology, taking into account the nature of groundwater level time series and groundwater droughts. The development of the new groundwater index has reinforced issues previously identified with the application of the SPI approach to other hydrological domains (such as soil water and surface water) beyond the simple characterisation of droughts in precipitation time series (van Lanen 2005; Mishra and Singh, 2010).”

Additional text has been added to the end of Section 1.1 as follows:

“In this paper issues that have previously been identified related to the application of the SPI to hydrometric time series, such as length of record and the approach to standardisation or normalisation (Mishra and Singh, 2010) are explicitly addressed for groundwater level data, and a methodology is presented that enables monthly groundwater level time series to be used as the basis for estimating a new Standardised Groundwater level Index (SGI)”.

The Discussion has been revised to include a.) a critical assessment of the application of the SPI approach to groundwater level time series and b.) a discussion of the pros and cons of SGI compared with existing groundwater and related indices (see also response to comments 2 and 3 below). The text now reads as follows:

“5. Discussion. 5.1 Critical assessment of application of the SPI approach to groundwater level time series. The SPI approach has a couple of features that make it particularly useful as an index of meteorological drought. It can be calculated for a variety of timescales (accumulation periods), and estimated SPI values are comparable in time and space (Lopez-Moreno et al., 2009; Mishra and Singh, 2010). However, it also has two main weaknesses, as explicitly identified by Mishra and Singh (2010). SPI values can be significantly dissimilar for different lengths of observation record due to differences in the shape and scale parameters of the fitted gamma (or other) distribution for different length records (5et al., 2009). In addition, values of SPI are sensitive to the form of the probability distribution that is fitted to the observed data as part of the normalisation process (Mishra and Singh, 2010; Angelidis et al., 2012).”

“The SGI is a normalised drought index for groundwater levels and uses an SPI-like method. Weaknesses inherent in the SPI approach may also affect SGI unless appropriate steps are taken. The issue of distribution fitting has been obviated when developing the SGI by adopting a non-parametric approach to normalization of the groundwater level time series, i.e. the normal scores transform (Everitt, 200). As has been noted, using the normal scores transform results in a distribution of values of SGI that are always normal. The technique is robust when applied to historic time series, although additional measures to check and account for any over-fitting would be necessary should the technique be applied to predict values of SGI. Because the non-parametric normal scores transform is used to normalise the groundwater level time series when estimating SGI, the length of record is not an issue in the same way that it is for SPI estimates (as a gamma or other distribution is not being fitted and the issue of discrepancies between fitted parameter for records of different lengths does not arise). However, since SGI is a normalised drought index, as with any normalised drought index the values of SGI will reflect the period and length of the time series that is being normalised, in this case groundwater levels, for example as shown in Table 2 and Fig. 11, and quantitative comparison of SGI estimates between sites should be undertaken based on similar length records (WMO, 2012)."

"Because groundwater level is a continuous variable, SGI cannot be calculated for a range of timescales in a manner similar to SPI. However, should discrete estimated recharge data (observed or modelled) be available then the SGI methodology could be applied over a range of timescales using accumulated recharge. Alternatively, differencing successive monthly groundwater level observations would produce a change in groundwater level time series that would also enable the SGI methodology to be applied over a range of timescales. Mendicino et al (2008) used monthly 'groundwater detention', an output from a distributed water balance model, as the basis for an SPI-like index of groundwater drought. This could have been accumulated over a range of timescales, but in that particular study it was only considered over a one month accumulation period."

"However, the most significant issue related to the application of an SPI-like approach to groundwater level time series is that SPI is designed to produce a drought index that has values that are comparable in space, i.e. values that are unaffected by geographical differences. As with studies of other hydrological time series, such as soil moisture and stream flow (e.g. Vincente-Serrano and Lopez-Moreno, 2005; Shukla and Wood, 2008; Sheffield et al., 2009; Vidal et al., 2010), groundwater levels and the derived SGI can be strongly influenced by location. Groundwater level and SGI time series reflect not just the meteorological drought driver, but are also influenced by local and site specific recharge processes and by regional to site-specific saturated flow processes that are not simply spatially correlated. It is these recharge and saturated flow processes that result in the autocorrelation structures seen in the SGI time series, Fig.7. As noted by van Lanen (2005) “Drought characteristics derived from groundwater levels ... have spatial effects”. Consequently, any interpretation or analysis of the resulting SGI needs to reflect an appreciation of the hydrogeologial context of the observation boreholes. Notwithstanding these observations, it has been shown that if the autocorrelation structure of the SGI is taken into account, SGI can be shown to scale linearly with SPI (Fig. 9), and a measure of significant SGI autocorrelation, mmax, is a useful parameter that can be related to drought characteristics such as drought duration (Fig.12) and physically meaningful catchment characteristics (Fig. 13).”

“5.2 Comparison of SGI with existing groundwater and related hydrological indices. The SGI uses a normalisation approach to produce a continuous drought index. Such drought indices give relative measures to a mean hydrological baseline, in the case of the SGI the mean monthly groundwater level. In contrast, threshold level approaches produce measures of drought based on absolute values (for groundwater levels mean depth below or height above the threshold) that define drought events.”

“Peters et al. (2003; 2005) introduced the concept of a threshold for groundwater droughts and used it to characterise modelled groundwater level drought return periods. Lopez-Moreno et al. (2009) note that such a threshold approach when applied to river discharge enables the identification of periods of low flow, but typically does not take account of seasonal flows and can lead to the classification of naturally low summer flows as periods of low flow. A similar situation may also pertain to groundwater levels, particularly in flashy, seasonal aquifers where groundwater levels oscillate on an annual basis between high and low groundwater level stands. The threshold approach enables the identification (deficit, duration and intensity) and characterisation (e.g. return period analysis) of discrete drought episodes, and variable threshold approaches have been developed to address the issue of seasonality in hydrometric rime series (Wanders et al., 2010). Fendekova and Fendek (2012) used a threshold approach to characterise drought in baseflow of a groundwater dominated catchment but avoided the issue of seasonality by analysing the average yearly baseflow. However, an important difference between the threshold and normalisation approaches is that the threshold approach does not provide a continuous index of drought, and results from this approach are not so amenable to analysis using techniques that provide insights into temporal structure of the drought records, such as the characterisation of autocorrelation structure (or for example spectral or wavelet analysis). Given the importance of memory, or autocorrelation, in groundwater systems, the SGI provides an important complementary technique to the threshold approach of Peter et al. (2005) to investigate and characterise groundwater droughts."

"A number of previous groundwater related studies have produced drought indices based on a normalisation process. Bhuiyan et al., (2006) applied the SPI methodology to 20 years of twice-yearly (pre- and post-monsoon) groundwater level data from 541 wells across Rajasthan, India. Using a qualitative GIS-based analysis, they investigated the spatio-temporal dynamics of drought in the study region and compared SPI-based on pre- and post-monsoon groundwater levels, SPI, and an index of vegetation health, but were unable to demonstrate any quantitative correlations between the drought indices. Mendicino et al. (2008) applied an SPI-like normalisation to modelled monthly 'groundwater detention' to estimate a Groundwater Resource Index (GRI) for a series of catchments in southern Italy. Using cross-spectral techniques they compared the GRI with SPI and found significant sensitivity in the GRI drought index to the lithological characteristics of the analyzed catchment or region. Based on 80 years of monthly karstic spring discharge for three springs in southern Italy, Fiorillo and Guadagno (2010, 2012) investigated the relationship between meteorological droughts defined by SPI and an index calculated using the SPI methodology as applied to the karstic spring discharge times series. They used cross correlation plots to showed that

SPI for precipitation based on an accumulation period of 12 months was most highly correlated with SPI for the spring discharge time series, and inferred that the karst system only responded to relatively long meteorological droughts due to the large storage of the karst system."

"The present study has formalised the normalisation methodologies developed in these pervious groundwater-related studies, and has extended the joint analysis of hydrogeological drought indices and SPI by building on the correlation analysis of Fiorillo and Guadagno (2012). Unlike Fiorillo and Guadagno (2012) who investigated the cross correlation between an SPI-like drought index for spring flows and SPI for a limited number of SPI accumulation periods (q = 3, 6, 9, 12, 24 and 48) and for a lag of one month between the two drought indices, the present study has introduced a comprehensive cross correlation analysis between SPI and SGI including a wide range of precipitation accumulation periods from one to 48 months and lags between the two drought indices up to ten months (Fig. 8). The benefit of such an approach for analysing groundwater related drought time series is that it acknowledges that there potentially may be strong site specific responses in groundwater levels to meteorological droughts and it enables these site specific responses to be characterised more fully. Extensive cross correlation plots such as in Fig. 8 could be used to investigate the relationship between any hydrological drought index and SPI where it is thought that site or location specific factors may be influencing the hydrological index."

"The Standardised Precipitation-Evapotranspiration Index, SPEI (Vincente-Serrano et al., 2010; McEvoy et al., 2012), has recently been developed to include atmospheric water demand by normalising the monthly (or weekly) difference between precipitation and potential evapotranspiration (PET). The SPEI represents a simple water balance and uses both precipitation and temperature as drivers of drought. A major driver for groundwater drought in the UK is accumulated deficits in autumn and winter recharge (Marsh et al., 2007), however, it isn't clear to what extent recent changes in temperature (Jenkins et al. (2008) may have on groundwater recharge. Consequently, a future

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comparison of SGI with both SPI and SPEI may provide may provide some insight into this question".

The Conclusions have been revised to read as follows:

"Building on the SPI methodology, groundwater level data can be normalised to produce a Standardised Groundwater level Index (SGI) if the SPI methodology is modified to take into account the form and nature of groundwater level time series. Given correlations established between SPI and SGI and good agreement of SGI time series with previously independently documented droughts, SGI provides a robust quantification of groundwater drought. Correlations between SPI and SGI are associated with a range of SPI accumulations periods that are a function of SGI autocorrelation. In addition, groundwater drought durations defined by SGI time series are also a function of SGI autocorrelation. Autocorrelation in SGI appears to be an aquifer dependent function of autocorrelation in groundwater recharge signal and of the effects of intrinsic aquifer properties on saturated groundwater flow and storage. SPI is designed to produce a drought index that has values that are comparable in space, i.e. values that are unaffected by geographical differences. However, SGI can be strongly influenced by location reflecting influences from local and site specific recharge processes and regional to site-specific saturated flow processes that are not simply spatially correlated. Consequently, interpretation or analysis of the resulting SGI needs to reflect an appreciation of the hydrogeologial context of the observation boreholes".

As suggested by van Lanen (2013), the title has been changed to:

"Analysis of drought building on the Standardised Precipitation Index approach".

Finally, the Abstract has been revised to reflect the change in title as follows:

"The SGI builds on the Standardised Precipitation Index (SPI) to account for differences in the form and characteristics of precipitation and groundwater level time series."

Comment 2: van Lanen (2013) suggests that "The whole link between SGI, i.e., the autocorrelation range, mmax, 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."

Response to comment 2: We agree that these changes will make the revised paper more balanced. Sections 5.1 and 5.2 have been moved into the Results section of the paper and now constitute new Sections 4.4 and 4.5. In addition, the Discussion has been revised as described in the response to comment 1 above (see also response to comment 3, below).

Comment 3: van Lanen (2013) suggests that the Discussion should contain an elaboration of 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)."

Response to comment 3: Agreed. This comment has been addressed in our response to Comment 1 above.

Minor Comments.

Comment 4. van Lanen suggests that 7539, lines 22-23 could be read to mean that we are undertaking a regional characterisation of groundwater droughts. He then observes, correctly, that this is not the case, since we have not undertaken a spatial analysis (e.g. Tallaksen et al., 2009).

Response to comment 4. It wasn't our intention to suggest that our study included a regional drought analysis, although re-reading the text we can see how this may be inferred. To avoid misunderstanding, the text has been revised to read:

"Other studies related to groundwater drought have emphasised monitoring, characterisation of longer-term trends and the development of drought warning systems (Chang

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and Teoh, 1995; Bhuiyan et al, 2006; Mendicino et al 2008; Fiorillo and Guadagno, 2010; 2012)".

Comment 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). Van Lanen (2013) observes that we "do not apply the SPI methodology. Please rephrase".

Response to comment 5. Agreed (see also our response i.) to comment 1). Text revised to read:

"To address this shortcoming we present a new groundwater level index for use in groundwater drought monitoring and analysis. The new index builds on the SPI methodology, taking into account the nature of groundwater level time series and groundwater droughts."

Comment 6: "The method has recently been extended to include atmospheric water demand..." (7540, lines 26-27). van Lanen (2013) suggests adding a reference to the Standardised Precipitation-Evapotranspiration Index, SPEI.

Response to comment 6: Agreed. Text revised to read:

"The method has recently been extended to include atmospheric water demand, i.e. the Standardised Precipitation-Evapotranspiration Index, SPEI (Vincente-Serrano et al., 2010; McEvoy et al., 2012)".

Comment 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). van Lanen (2013) notes that there are more societal reasons that people are interested in a groundwater index and suggests that "regional" is deleted.

Response to comment 7: We agree that wider societal reasons for developing a

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groundwater index should be noted. The following text has been added to the Introduction as follows:

"As highlighted in a recent review of drought concepts by Mishra and Singh (2010), groundwater droughts can impact adversely on water resources such as public water supply or water for industry and agricultural irrigation, as well as effecting groundwater discharge to groundwater-dependent surface waters and ecosystems". Specific reference to deployable output from water supply boreholes has been removed from text and "regional" has been deleted.

Comment 8: Section 2 (7541-7542): van Lanen (2013) notes that none of the hydrographs described in the paper are for unconsolidated aquifers (e.g. gravel aquifers). He asks if this is because they are not relevant for the UK, but also points out that they are significant aquifers in many other parts of the world.

Response to comment 8: The text has been revised as follows:

"Note, the UK has no nationally important unconsolidated aquifers. Consequently, there are no long-term high-quality groundwater level monitoring records for such aquifers in the UK. The methodology presented in the following sections, however, is applicable to groundwater level time series from any aquifer type or setting"

Comment 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.

Response to comment 9: The data that has been used is taken from sites in the National Observation Well Network (Marsh and Hannaford, 2008). These sites are intended for long-term monitoring of natural variations in groundwater levels in major aquifers in the UK and do not include sites with known anthropogenic influences. The original text was poorly phrased and has been changed to now read as follows:

"The sites are part of the UKs long-term observation borehole network and consist of a broad range of unconfined consolidated aquifers types (Bloomfield et al., 2009)".

Comment 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, tSGI, ..." (7546, lines 17-19). van Lanen (2013) observes that this choice is subjective as follows "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, mmax of the different sites (for example, if the correlogram is a bit flashy, see Fig. 7 (e) and (f).)"

Response to comment 10: We acknowledge that the choice is subjective. Criteria for selection of a threshold were: a.) it should be a common threshold applicable to all sites, b.) it should be sufficiently large to avoid being influenced by noise in the autocorrelation at low thresholds, and c.) it should capture long, significant correlations. Note that if all the records were of the same length selection of the threshold would not be an issue (see also response to comments from Reviewer #2). We did explore the effect of changing the threshold. Thresholds below 0.11 were found to be unduly influenced by noise in the correlograms and so were excluded. For thresholds above 0.11 we found that that mmax broadly scaled as a function of the threshold, but that qualitatively the relative differences between the sites was the same. So for example, raising the threshold to 0.15 would lead to slightly lower values of mmax. No change has been made to the text.

Comment 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). van Lanen (2013) asks "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."

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Response to comment 11: The aquifer properties data is taken from the most comprehensive, publically available compilation of published pumping test data (Allen et al 1997). Allen et al (1997) summarise pumping test data on an aquifer by aquifer basis and compiled data summaries for regions within each the major aquifers in the England and Wales. For each of the 14 observation boreholes described in the paper, we identified which aquifer and which region they were located in and then used the mean values of all transmissivity (T) and storage (S) data for that aquifer and region to represent the values for each observation borehole. For example, T and S data for Dalton Holme, is taken from Allen et al (1997) for the Yorkshire Chalk, and is based on 87 pumping tests from 68 sites (Allen et al. 1997, page 102) where T is given by the geometric mean and S by the arithmetic mean of the respective data. In the case of S, measurements for this aquifer and region range over an order of magnitude from 0.0015 to 0.018. Allen et al (1997) specifically note problems with pumping test data from the Permo-Trias Sandstones and suggest the use of 0.1 for S as described in the paper. We acknowledge that S values for other formations may also be relatively low due to short tests, but without any additional information, we don't think that it is justifiable to infer or use any other values. No change has been made to the text.

Comment 12: Fig. 7. (7548, lines 17-19). van Lanen (2013) notes that "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."

Response to comment 12: We agree that confusion could arise due to the use of the term 'lag' with two senses. Additional text added as follows:

"Note that the lag in Fig. 7 bottom panels is the temporal shift between the SPI and SGI time series, whereas the lag referred to in discussion of the SPI and SGI correlograms, Fig. 7 upper and middle panels, is the time separating two observations in each series.

and caption to Fig. 7 revised to read:

"Figure 7. a. to c. SPI correlogram for Ashton Farm (left), Dalton Holme (centre) and

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Llanfair (right), d. to f. SGI correlogram for the corresponding sites, where the dashed line is the SGI autocorrelation threshold, tSGI, and g. to i. cross-correlation between SGI and SPI as a function of SPI accumulation period in months for the corresponding sites".

Comment 13: 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). van Lanen (2013) asks "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. ... 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".

Response to comment 13: We did not intend that the text should read as if we expected a lag of 0 months between SGI and SPI. However, we recognise that we could have been clearer and that it would be useful to cite the previous work so we have amended the text to read as follows:

"Previous studies of drought propagation have distinguished four components in the propagation of drought: pooling, attenuation, lag and lengthening (Changnon, 1987; Peters et al., 2003; Peters, 2003; van Loon and van Lanen, 2012; Van Loon 2013). Here we are interested in understanding the full spectrum of behaviour of lag-correlation between SPI and SGI. So for all sites the cross-correlation between SPI and SGI has been estimated for SPI accumulation periods of q = 1,2,. . .,24 months and for lags between SPI and SGI of one month increments up to 24 months."

Comment 14: “The maximum cross-correlations between SPI and SGI are generally strong ...” (7549. lines 4-5). van Lanen (2013) suggests that the paper would benefit from a change in focus away from a search for the strongest cross-correlation and also makes reference to Major comment 1.

Response to comment 14: In responding to Major comment 1, particularly with the redrafting the Discussion section, we believe that we have dealt with van Lanen’s concern that “the study shows too much respect for the Standardised Precipitation Index (SPI)”. Specifically with regard to comment 14, we agree that a more nuanced commentary on Fig. 8 and Fig. 9 would be helpful. However, we think that it is important to quantify the relationship between SGI and SPI as it enables insights into the site specific response of groundwater hydrographs to drought, Fig. 8, and provides a form of validation of the new SGI methodology through the relationships described in Fig. 9 and Fig.10. Consequently, we have revised the text to highlight a.) the site specific nature of relationships between SPI precipitation accumulation period and the lag between SPI and SGI, while at the same time b.) quantifying a relationship between SPI and SGI, Fig. 9 and Fig.10, if qmax is identified. The revised text now reads as follows:

“Fig.8 shows that there are site specific relationships for correlations between SPI precipitation accumulation period, q, and lags between SPI and SGI. Table 2 lists the values of the maximum cross-correlation between SPI and SGI, as well as the associated accumulation period (qmax) and lag between SPI and SGI. The maximum cross-correlation coefficients between SPI and SGI are typically in the range 0.7 to 0.87, Table 2, with the highest coefficient of 0.87 associated with the site at Little Bucket Farm and the lowest coefficients of 0.7 associated with the site at West Dean No.3 - both sites being on the Chalk aquifer. Despite the site specific nature of correlations between SPI precipitation accumulation period and lags between SPI and SGI, plots of SGI as a function of SPI qmax show that for all sites there is a linear relationship between the two drought indices, Fig. 9..”

Comment 15: Van Lanen notes (2013) “.... 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" and suggests moving the phrase to after the sentence.

Response to comment 15: Agreed. The text has been revised.

Comment 16: Section 4.3. van Lanen (2013) notes that "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."

Response to comment 16: We agree with this observation. The text has been revised as follows:

"When a new drought index is developed it is often compared against reported droughts in an attempt to qualitatively 'validate' the new index. However, this is not a trivial task since most reported droughts are described in terms of their impacts, using a particular type or class of drought index, which is representative of only a certain hydrological domain that may or may not be an appropriate comparator. A number previous studies have documented major drought episodes in the UK including studies of hydrological impacts (Cole and Marsh, 2006; Marsh et al, 2007; Lloyd-Hughes et al, 2010) and societal impacts (Taylor et al, 2009). Of these, Marsh et al. (2007) is the most pertinent with respect to the present study in that Marsh et al (2007) identified major drought episodes on the basis of inspection of long river flow, groundwater level, and ranked rainfall deficiency time series and explicitly identified those episodes with a significant groundwater component. Marsh et al (2007) identified ...".

Comment 17: van Lanen (2013) observes ”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).”

Response to comment 17: Agreed. (see the response to comment 16.)

Comment 18: Order of observations (7550, lines 13-23). van Lanen suggest “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.”

Response to comment 18: Agreed. The observations have been re-ordered as suggested.

Comment 19: “...(Hannaford et al., 2010)...” (7552, line 5). It should be: “Hydrol. Process. 25, 1146– 1162 (2011)”.

Response to comment 19: Thank you for pointing this out. The text and reference list have been revised accordingly.

Comment 20: van Lanen (2013) notes “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”.

Response to comment 20: This is an interesting observation, but not one that is easy to deal with based on observational (rather than modelled) data. In Chalk catchments, if surface flow is present at all it is likely to exhibit borne behaviour (stream lengths will vary significantly seasonally and on an inter-annual basis). As a result, defining the location of an observation borehole in relation to the nearest stream is problematic. However, given that unsaturated zone thickness is some positive function of distance to streams (assuming a hydraulic connection between the aquifer and stream), our findings related to fractured aquifers, Fig.12b, i.e. that there is a positive relationship between mmax and unsaturated zone thickness, are consistent with the observations of Peters (2005). Consequently, we have modified the text as follows:

“Given that unsaturated zone thickness is a positive function of distance to streams (assuming a hydraulic connection between the aquifer and stream), the observation is also consistent with the findings of Peters (2005). On the basis of a spatial analysis of modelled groundwater drought in the Pang, UK, a catchment underlain by the Chalk aquifer, Peters (2005) concluded that “short droughts ... are relatively more sever near streams, as they are damped further away, whereas long periods of below average recharge have relatively more effect near the groundwater divide”.

Comment 21: van Lanen (2013) notes “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)”.

Response to comment 21: Agreed. The text has been modified accordingly.

Comment 22: “The median drought duration appears to be insensitive to mmax, however, as postulated, maximum drought duration is broadly positively correlated with mmax, Fig. 12 (left panel).” (7552, lines 19-21). van Lanen (2013) suggests “add correlation coefficients, certainly for maximum duration.”

Response to comment 22: Agreed. The text has been changed to read:

“Based on the common 29 year SGI record, the median drought duration appears to be insensitive to mmax (correlation coefficient 0.12), Fig. 12. However, as postulated, maximum drought duration is positively linearly correlated with mmax with a correlation coefficient 0.81)”.

Comment 23: “The first potential source of autocorrelation in SGI....” and “The second

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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.

Response to comment 23: Agreed. The text has been text modified to read as follows:

"Tallaksen and Van Lanen (2004) describe possible sources of persistence in droughts and emphasise the important role of recharge processes and groundwater storage in generating autocorrelation or memory in drought time series."

Comment 24: "Fig. 12c, shows that for all aquifers logD is negatively linearly related to mmax." and "...longer SGI autocorrelations are associated with aquifers where the hydraulic diffusivity is relatively low." (7554, lines 16-17 and lines 21-22, respectively). Van Lanen (2013) states: "I believe it is the opposite, if logD increases then mmax increases."

Response to comment 24: This confusion appears to have arisen with the use of logD rather than S in the discussion of the association between SGI autocorrelations and aquifers characteristics. Since D=T/S, for larger values of D, because it is inversely correlated with mmax (Fig.12c), mmax decreases. However if we consider S, aquifers with relatively large S will have relatively low values of D and so will be associated with relatively high values of mmax. However, comment 24 has led us to re-examine the use of logD rather than simply use logS to describe the storage properties of the saturated zone of the aquifers. We have calculated correlation coefficients between mmax and logD, logS and logT and found them to be -0.82, 0.76 and -0.57 respectively. We also note that the correlation coefficient between logS and logT is low, -0.37. Given these observations we are content that we have used logD as the preferred descriptor of mmax, but have modified the text as follows:

"We have hypothesised that a second possible cause of autocorrelation in SGI may be associated with saturated storage and drainage processes in aquifers. Correlation coefficients between mmax and logD, logT and logS are -0.82, 0.76 and -0.57 respectively while the correlation coefficient between logS and logT is low at -0.37. A plot of log hydraulic diffusivity, logD against mmax, Fig. 12c, shows that for all aquifers logD is negatively linearly related to mmax“

Comment 25: Conclusions (7555). van Lanen (2013) asks for the Conclusions to be revised in line with Major comment item 1.

Response to comment 25: The conclusions have been revised – see reply to Major comment 1 (above).

Comment 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).

Response to comment 26: Agreed. van Lanen et al (2013) now cited.

Comment 27: Table 1 (7560). van Lanen (2013) request “Add aquifer type (fractured etc.), “Well depth” add relative to soil surface, "Mean unsaturated zone (m)” change into: "Mean thickness unsaturated zone (m)”.

Response to comment 27: Table 1 has been revised as suggested.

Comment 28: Table 2 (7561). Add in the header “Maximum cross-correlation”, although it is already in the caption.

Response to comment 28: Table 2 has been revised as suggested.

Comment 29: Fig. 3 (7565). van Lanen (2013) notes that “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).

Response to comment 29: Agreed. Figure has been revised accordingly.

Comment 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)".

Response to comment 30: The figure has been revised as suggested.

Comment 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.".

Response to comment 31: This appears to be a duplicate of comment 32 below? Fig. 7 are correlograms and plots of cross-correlation coefficients not heat maps. No action has been taken, but see response to comment 32.

Comment 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.".

Response to comment 32: The figure has been revised as suggested.

Comment 33: Fig. 10 (7572). I miss one of the sites. Only 13 circles, or do two sites coincide? If so, please indicate.

Response to comment 33: All sites have been plotted; however, Dalton Holme and Little Bucket Farm both have same qmax and mmax, i.e. a qmax of 10 and an mmax of 8. A note has been added to caption to this effect.

Comment 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".

Response to comment 34: Figure has been revised as suggested.

Comment 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.

Response to comment 35: See response to similar comment 33 above. Dalton Holme and Little Bucket Farm both have the same mmax of 8 and similar median drought durations of 5 and 4 months respectively so they are both plotted but closely overlap on the plot. No change has been made.

References: Allen, D.J., Brewerton, L.J., Coleby, L.M., Gibbs, B.R., Lewis, M.A., MacDonald, A.M., Wagstaff, S.J., and Williams, A.T.: The physical properties of major aquifers in England and Wales, British Geological Survey Research Report WD/97/34, Keyworth, UK, 1997.

Angelidis, P., Maris, F., Kotsovinos, N., and Hrissanthou.: Computation of drought index SPI with alternative distribution functions. Water Resour. Manage., 26, 2453-2473, 2012

Bhuiyan, C., Singh, R. P., and Kogan, F. N.: Monitoring drought dynamics in the Aravalli region (India) using different indices based on ground and remote sensing data, Int. J. Appl. Earth Obs., 8, 289–302, 2006.

Bloomfield, J.P., Allen, D.J., and Griffiths, K.J.: Examining geological controls on baseflow index (BFI) using regression analysis: An illustration from the Thames Basin, UK, Journal of Hydrology, 373, 164-176, 2009.

Changnon Jr, S. A.: Detecting Drought Conditions in Illinois, Illinois State Water Survey Champaign, Circular 169, 1987.

Cole, G. A. and Marsh, T. J.: An historical analysis of drought in England and Wales, in: Climate Variability and Change: Hydrological Impacts, edited by: Demuth, S., Gustard, A., Planos, E., Scatena, F., and Servat, E., International Association of Hydrological Sciences (IAHS) 5th FRIEND World Conference Havana, Cuba, November, 2006, IAHS Publication no. 308, Wallingford, UK, 483–489, 2006.

Edwards, D.C., and McKee, T.B.: Characteristics of 20th century drought in the United states at multiple time scales, Colorado State University, Climatology Report No. 97-2,

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Interactive Discussion

Discussion Paper

Colorado, 1997.

Everitt, B.S.: The Cambridge Dictionary of Statistics, 2nd edition, Cambridge University Press, Cambridge, 2002.

Fendeková, M., and Fendek, M.: Groundwater in the Nitra basin – identification and classification, Hydrol. Hydromech., 60(3), 185–193, DOI: 10.2478/v10098-012-0016-1, 2012.

Fiorillo, F. and Guadagno, F. M.: Karst spring discharge analysis in relation to drought periods, using SPI, Water Resour. Manage., 24, 1864–1884, 2010.

Fiorillo, F. and Guadagno, F. M.: Long karst spring discharge time series and drought occurrence in Southern Italy, Environ. Earth Sci., 65, 2273–2283, 2012.

Hisdal, H., Tallaksen, L. M., Clausen, B., Peters, E., and Gustard, A.: Hydrological Drought Characteristics, edited by: Tallaksen, L. M. and van Lanen, H. A. J.: Hydrological drought. Processes and Estimation Methods for Streamflow and Groundwater, Developments in Water Sciences 48, Elsevier, the Netherlands, 139-198, 2004.

Jenkins, G.J., Perry, M.C., and Prior, M.J.: The climate of the United Kingdom and recent trends. Met Office Hadley Centre, Exeter, 2008.

Lloyd-Hughes, B., Prudhomme, C., Hannaford, J., Parry, S., Keef, C., and Rees, H.G.: 'Drought catalogues for UK and Europe', Environment Agency Science Report SC070079/SR, Environment Agency, Bristol, 2010.

Marsh, T. J., Cole, G., and Wilby, R.: Major droughts in England and Wales, 1800–2006, Weather, 62, 87–93, 2007.

Marsh, T.J., and Hannaford, J.: UK Hydrometric Register. Hydrological data UK series. Centre for Ecology and Hydrology, Wallingford, 2008

McEvoy, D.J., Huntington, J.L., Abatzoglou, J.T., and Edwards, L.M.: An evaluation of multiscalar drought indices in Nevada and eastern California, Earth Interactions, 16,

Full Screen / Esc

Printer-friendly Version

Interactive Discussion

Discussion Paper

1-8, DOI:10.1175/2012EI000447.1, 2012.

McKee, T. B., Doesken, N. J., and Leist, J.: The relationship of drought frequency and duration time scales, 8th Conference on Applied Climatology, 17–22 January 1993, Anaheim, California, 179–184, 1993.

Mendicino, G., Senatore, A., and Versace, P.: A Groundwater Resource Index (GRI) from drought monitoring and forecasting in a Mediterranean climate, Journal of Hydrology, 357, 282-302, 2008.

Mishra, A.K., and Singh, V.P.: A review of drought concepts, Journal of Hydrology, 391, 202-216, 2010.

Peters, E.: Propagation of drought through groundwater systems: illustrated in the Pang (UK) and Upper-Guadiana (ES) catchments, Ph.D. thesis, Wageningen University, Wageningen, the Netherlands, 2003.

Peters, E., Torfs, P. J. J. F., Van Lanen, H. A. J., and Bier, G.: Propagation of drought through groundwater – a new approach using linear reservoir theory, Hydrol. Process., 17, 3023–3040, 2003.

Peters, E., van Lanen, H. A. J., Torfs, P. J. J. F., and Bier, G.: Drought in groundwater – drought 20 distribution and performance indicators, J. Hydrol., 306, 302–317, 2005.

Sheffield, J., Andreadis, K. M., Wood, E. F., and Lettenmaier, D. P.: Global and continental drought in the second half of the 20th century: severity-area-duration analysis and temporal variability of large-scale events. Journal of Climate, 22, 1962–1981, doi: 10.1175/2008JCLI2722.1, 2009

Shulka, S., and Wood, A.W.: Use of a standardized runoff index for characterizing hydrologic drought, Geophysical Research Letters, 35, L02405 doi:10.1029/2007GL032487, 2008.

Tallaksen, L.M., and van Lanen, H.A.J.: Hydrological drought. Processes and estimation methods for streamflow and groundwater, Developments in Water Sciences 48, Elsevier, Netherlands, 2004.

Tallaksen, L. M., Hisdal, H., and van Lanen, H. A. J.: Space-time modelling of catchment scale drought characteristics, J. Hydrol., 375, 363–372, 2009.

Taylor, V., Chappells, H., Medd, W., Trentmann, F.: Drought is normal: the socio-technical evolution of drought and water demand in England and Wales, 1893–2006, Journal of Historical Geography 35, 568–591, 2009.

Wanders, N., van Lanen, H. A. J., and van Loon, A. F.: Indicators for drought characterization on a global scale. WATCH Technical Report No. 24, 2010 [available at: http://www.eu-watch.org/publications/technical-reports/3].

van Lanen, H.A.J.: Interactive comment on "Analysis of groundwater drought using a variant of the Standardised Precipitation Index. " by J. P. Bloomfield and B. P. Marchant. Hydrol. Earth Syst. Sci. Discuss., 10, C3963-C3966, 2013

van Lanen, H. A. J., Wanders, N., Tallaksen, L. M., and Van Loon, A. F.: Hydrological drought across the world: impact of climate and physical catchment structure, Hydrol. Earth Syst. Sci. 17: 1715–1732, doi:10.5194/hess-17-1715-2013, 2013.

van Loon, A. F.: On the propagation of drought : how climate and catchment characteristics influence hydrological drought development and recovery. Ph.D. thesis, Wageningen University, Wageningen, the Netherlands, 2013 [available at: http://www.wageningenur.nl/en/Publication-details.htm?publicationId=publication-way- 343338353130].

van Loon, A. F. and van Lanen, H. A. J.: A process-based typology of hydrological drought, Hydrol. Earth Syst. Sci. 16: 1915-1946, doi:10.5194/hess-16-1915-2012, 2012.

Vidal, J.-P., Martin, E., Franchistéguy, L., Habets, F., Soubeyroux, J.-M., Blanchard, M. and Baillon, M.: Multilevel and multiscale drought reanalysis over France with

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Printer-friendly Version

Interactive Discussion

Discussion Paper

the Safran-Isba-Modcou hydrometeorological suite. Hydrology and Earth System Sciences, 14, 459-478, doi: 10.5194/hess-14-459-2010, 2010

Vincente-Serrano, S.M., and Lopez-Moreno, J.I.: Hydrologic response to different time scales of climatological drought: An evaluation of the standardized precipitation index in a mountainous Mediterranean basin, Hydrogeology and Earth Systems Science, 9, 523-533, 2005.

Vincente-Serrano, S.M., Begueria, S., and Lopez-Moreno, J.I.: A multiscalar drought index sensitive to global warming: The standardized precipitation evapotranspiration index, Journal of Climate, 23, 1696-1718, 2010.

WMO: Standardized Precipitation Index User Guide. Eds. Svoboda M, Hayes M and Wood DA. Published by WMO, Geneva, Switzerland, 2012

Wu, H., Hayes, M.J., Wilhite, D.A., and Svoboda, M.A.: The effect of the length of record on the standardized precipitation index calculation, International Journal of Climatology, 25, 205-520, 2005.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 10, 7537, 2013.