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Discussions

Interactive comment on "Asymmetric impact of groundwater use on groundwater droughts" *by* Doris E. Wendt et al.

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General response to Reviewer 1

We would like to thank Reviewer 1 for their careful reading of the manuscript and their constructive comments. In this general reply, we would like to respond to comments 1-3 to allow further discussion. The other comments (4 - 9) will be addressed later in the new version of the manuscript, because some comments (4, 5, and 9) involve gathering additional material.

Comment 1

The first comment of Reviewer 1 deals with our use of correlation analysis to determine the human influence on groundwater level time series. We understand the concern raised in comment 1 and recognize that much of this can and will be addressed by changes to the framing and phrasing of the statements at Lines 171-172. We also agree with the reviewer that we need to include additional discussion of uncertainties associated from the method for recognizing the presence or absence of human-influence on groundwater. This discussion will be included in revisions to the text in Section 3.2.2 and will draw on our comments below.

Reviewer 1 questions the use of correlation analysis to determine the presence or absence of human influence on groundwater drought and observes that, for example, anthropogenic influences on groundwater drought status might increase SPI$_Q$-SGI correlations at longer accumulation periods. If this is the case such relatively high correlations between SPI$_Q$-SGI in the current scheme might not represent sites unaffected by anthropogenic activities (e.g. abstraction) during droughts. Finally, they suggest that analysing temporal variations in groundwater may better help recognize human influences.

However, we would observe that there are four main reasons why we believe that our approach is appropriate, as follows: 1) the definition and nature of SGI and SPI and the long-term average nature of SPI$_Q$-SGI correlations, 2) the high SPI$_Q$-SGI correlation of near-natural reference clusters, 3) the irregular and dynamic nature of groundwater abstraction in the water management units, and 4) consistency with the results of previous studies.

We would like to emphasize that correlations between standardized precipitation and groundwater time series are generally high in unconfined systems and for near-natural conditions (Bloomfield & Marchant, 2013; Bloomfield et al., 2015).. SGI and SPI are estimated for a continuous period that includes all seasons and both anomalously dry and wet periods. So relatively high SPI$_Q$-SGI correlations are associated with near-natural conditions and represent a long-term average relationship. Under these near-natural conditions, anomalies in precipitation propagate with a relatively constant delay in recharge to the groundwater. This is due to, subsurface controls on recharge, the antecedent condition of the land surface, and non-linear response of groundwater systems (Peters et al., 2006; Tallaksen et al., 2009; Eltahir and Yeh, 1999). This constant delay is included in the correlation analysis, as the optimal precipitation accumulation period is selected when calculating the SPI$_Q$-SGI correlation.

There are two main reasons why the long term average, high SPI$_Q$-SGI correlations may be reduced. The first reason for reduced long-term SPI$_Q$-SGI correlation is when groundwater level response becomes disconnected from driving precipitation under confined conditions (Bloomfield, et al. 2015; Lee, et al. 2018). This is not considered to be a significant issue with the sites that we have investigated, as only a few sites are semi-confined (see notes in Table 1). We will modify the section 3.2.2 to make this point. The second reason for reduced long-term SPI$_Q$-SGI correlation is the effects of abstraction. In this study, groundwater abstraction is conceptualised as exerting change in groundwater storage and hence groundwater levels, independent of natural changes in groundwater storage associated with changes in precipitation. We don't have quantitative information about either the detailed operational practices during individual episodes of drought or the long-term changes in abstraction and management practices in the study areas. However, we have sufficient evidence that both are likely to have changed in an *ad hoc* and potentially irregular manner. Consequently, our working hypothesis is that where either or both occur this will contribute to a reduction in the long-term average SPI$_Q$-SGI correlation.

Groundwater abstractions in water management units (i.e. a well field) are likely to vary in space and time, as multiple abstraction wells are used to meet the water demand. The amount of abstracted groundwater depends on variable groundwater demand, management policies in place, and practical local constrains for groundwater abstraction. For example, water demand is often seasonal with higher abstraction in spring and summer. This seasonal change in water use was previously found to reduce correlations (Lorenzo-Lacruz, et al. 2017). At the national scale and over the longer-term, we know that groundwater abstraction in England increased up until the late 1980s since when legislation has resulted in a general reduction in groundwater abstraction, but with a redistribution of where water is taken from to minimise the impacts of surface flows (Ohdedar, 2017; Whitehead and Lawrence, 2006; Environment Agency, 2010; Shepley and Streetly, 2007; Shepley et al., 2008).

Our conceptual model is that this highly dynamic pattern of groundwater abstraction, variable in space and time, will result into reduced SPI$_Q$-SGI correlations between precipitation and groundwater time series that are ordinarily seen in unconfined natural systems. This was also concluded by Bloomfield et al. (2015), who found lower SPI$_Q$-SGI correlations for wells that are influenced by groundwater abstractions (clusters 3 and 6). Another example of disturbance of this relationship is given by Haas et al. (2017), who showed that correlations between precipitation, streamflow, and groundwater observations are reduced due to the interference of power plants.

Reviewer 1 has suggested that anthropogenic influences on groundwater drought status might increase SPI$_Q$-SGI correlations at longer accumulation periods. However, given the long-term average nature of the correlation statistic this would only occur if sustained abstraction effects were felt for the majority of the period, not just for the periods of drought. However, we have no evidence that this has occurred at any of the sites in any of the study regions. The complexity and irregularity of management practices across the study sites combined with the lack of quantitative information on abstractions have also mitigated against our use of an analysis of temporal variations in groundwater response to abstraction.

Comment 2

In comment 2, Reviewer 1 questions our use of the ‘Z’ statistic of the Mann-Kendall test and suggests to apply linear regression instead. We agree with the reviewer that the description of the trend Z indicator [R 191-194] could be improved. The ‘Z’ statistic of the non-parametric Mann-Kendall trend test indicates indeed the significance level of a mono-tonic trend and the significance level does not directly indicate the impact of groundwater use. We will improve the manuscript by clarifying the interpretation of the Mann-Kendall trend test. We intended to show that the ‘Z’ statistic of the modified Mann-Kendall trend test indicated how much the trends deviate from the null hypothesis (no trend). Given the absence of trends in the precipitation and evapotranspiration time series, we assumed that trends in groundwater time series are related to the change in groundwater abstraction.

The significant auto- and serial correlation in the groundwater time series limits the application of parametric trend tests, such as linear regression, which is only applicable to normally distributed, independent data. We tested the groundwater time series and only 5 out of 170 time series are normally distributed (Shapiro-Wilk Normality Test). All others (165 time series) deviate from a normal distribution, which was also found by Bloomfield & Marchant (2013), for their groundwater time series. Therefore it seems unsuitable to apply linear regression to the majority of the groundwater dataset.

Comment 3

In comment 3, Reviewer 1 refers to the spatial heterogeneity shown in Figure 1. In this Figure, 8 near-natural groundwater clusters are shown and their droughts are highlighted in the SGI time series. Reviewer 1 is concerned that the difference in spatial heterogeneity would result in a higher SPI$_Q$-SGI correlation in case of longer accumulation periods, or longer periods in between drought events, compared to shorter accumulation periods and shorter periods between drought events.

In the current manuscript, we show that the standardised groundwater time series in Figure 1 correlate well with standardised precipitation time series at different precipitation accumulation periods [R212]. These different optimal accumulation periods (the accumulation period for precipitation with highest correlation with groundwater levels at a given site) were selected for each of the groundwater time series [R212-217]. The optimal accumulation period is indeed different for the two highlighted examples (cluster C2 and C4), respectively 18 and 8 months. This difference is to account for the different autocorrelation within the groundwater time series and the natural (short/long) delay in recharge. The identified optimal accumulation periods are similar to the published results in Bloomfield & Marchant (2013), who also analysed the relation between optimal accumulation period and autocorrelation of groundwater time series. When applying these different, optimal precipitation accumulation periods, high SPI_Q-SGI correlations were found for the Chalk clusters (Table 1). The high correlations are not surprising, as these Chalk groundwater wells are considered near-natural [R121-126] and the high correlations confirm that differences in periods between drought events and drought occurrence in these clusters are related to driving precipitation and the hydrogeological setting [R301-311]. The slight variation in SPI_Q-SGI correlation within these Chalk clusters is included in the analysis when distinguishing between influenced and uninfluenced groundwater time series. The lowest SPI_Q-SGI correlation of each cluster (3rd column) was used as threshold to determine which groundwater time series are influenced and uninfluenced for the paired water management units [R176-178].

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Chalk clusters	Average SPIQ-SGI	Lowest SPIQ-SGI in cluster	Average optimal accumulation period (in months)
1	0.78	0.75	12.6
2	0.82	0.69	18.2
3	0.81	0.71	24.0
4	0.73	0.66	8.0
5	0.75	0.70	7.5

Table 1. SPI$_Q$-SGI correlation for Chalk clusters presented in Figure 1 in manuscript of Wendt, et al. (2020)

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