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Demonstrating the utility of a drought termination framework: prospects for groundwater level recovery in England and Wales in 2018 or beyond

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Abstract

During prolonged droughts, information is needed about when and how the extreme event is likely to terminate. A drought termination framework based on historical data comprising current rate and historical ensemble approaches is presented here for assessing the prospects of groundwater level recovery. The current rate approach is evaluated across all initialisation months in the historical record and provides reasonable estimates for the duration of recovery from relatively severe groundwater level deficiencies in some slowly responding boreholes. The utility of the framework is demonstrated through a near-real-time application to 30 groundwater boreholes in England and Wales from October 2017 onwards. Recovery during winter 2017/18 was considered unlikely, as some aquifers required increases in groundwater levels that have occurred seldom, if ever before, in long historical records. Data to February 2018 confirmed the success of these pre-winter outlooks. Recovery by mid- to late-2018 or beyond was more likely; slow rates of recovery by October 2017 and increasing return periods of effective rainfall required for recovery over timeframes in the summer half-year underlined the importance of winter rainfall and suggested that the historical ensemble may underestimate the duration of recovery. There was moderate confidence for a delay in recovery beyond the end of 2018 in some slowly responding Chalk boreholes in south-central and eastern England. There is considerable potential for the transferability of the drought termination framework beyond the UK wherever there are sufficient historical data. The two approaches provide limited information in distinctly different circumstances and their relevance and value may differ in space and time, suggesting their complimentary use as the most robust way to incorporate information on the prospects for groundwater level recovery into existing seasonal forecasting services, supporting decision-making by water managers during prolonged droughts.

1. Introduction

Interest in drought termination has grown in recent years following notable events in California in 2016/17 (Wang *et al* 2017) and the UK in 2012 (Parry *et al* 2013). As droughts become more severe and extend over multiple years, stakeholders want to know how long the current situation might continue, how much rainfall would be required for recovery and the likelihood of this occurring (Byun and Wilhite 1999).

Such questions are particularly relevant for regions where groundwater is a significant proportion of water supply (Gleeson *et al* 2016). The post-drought recovery of groundwater levels typically lags behind other components of the hydrological cycle (Wang *et al* 2016). Whilst drought termination is often characterised as rapid (e.g. Dettinger 2013), it may also proceed over

monthly to seasonal timescales (e.g. Mo 2011, Schwalm *et al* 2017), particularly so in aquifers because groundwater droughts are slow-cessation phenomena (Correia *et al* 1987).

Drought termination is less predictable than drought onset (Mo 2011) and the absence of suitable approaches hinders progress (Panu and Sharma 2002). As a result, drought termination cannot yet be predicted (Watts *et al* 2012) but recent advances have assessed the likelihood of recovery. During a multi-year drought in California, assessments were undertaken of the likelihood for replenishing rainfall deficits (Wahl *et al* 2017) and snowpack (Margulis *et al* 2016). In the UK, a similar evaluation assessed recovery of subsurface storage deficits from drought (Bell *et al* 2013). Studies on post-drought recovery of groundwater levels have focused on monitoring by remote sensing (Chaussard *et al* 2017), propagation through the hydrological cycle (Yang *et al* 2017), or management through water policy (Singh *et al* 2017). There is an opportunity to capitalise upon these advances by developing a framework for assessing the prospects of recovery in near-real-time during groundwater droughts.

The remarkably low groundwater levels in the UK in October 2017 (NHMP 2017) provided an opportunity to test such an approach. Water resources in the southeast of the UK are vulnerable to successive dry winters (Wilby *et al* 2015), and a second dry winter (the critically important season for groundwater replenishment; Watts *et al* 2012) in 2017/18 would have significant water resource implications.

Operational forecasting services, such as the Hydrological Outlook UK (HOUK; Prudhomme *et al* 2017), offer a view on the likely water situation up to one season ahead. However, the skill of seasonal hydroclimatic forecasting is relative low in the UK (Wedgbrow *et al* 2002), so there is greater reliance upon historical records (e.g. Svensson 2015, Harrigan *et al* 2018). These techniques are part of a wider initiative to better assess UK drought using historical data (e.g. Watts *et al* 2012, Spraggs *et al* 2015, Wilby *et al* 2015). The use of ensembles of historical data for forecasting is commonplace within applied hydrology (e.g. Wood and Lettenmaier 2008, Harrigan *et al* 2018), and the value of probabilistic forecasting in reservoir management has also been demonstrated (e.g. Golembesky *et al* 2009, Zhao *et al* 2011). Although probabilistic forecasting of groundwater levels is conducted within the HOUK (Prudhomme *et al* 2017), in general such approaches have been less frequently applied to groundwater.

This study presents an empirical framework for assessing groundwater level recovery. The utility of this framework is demonstrated through a case study application to UK groundwater level deficits in late 2017. The data and underpinning drought termination framework are outlined first. The results include an evaluation based on historical borehole data in the UK before an assessment of the prospects for groundwater

level recovery from October 2017 onwards. Finally, the wider applicability of the framework is discussed, as well as the caveats and robustness of the outlooks.

2. Data and methods

2.1. Groundwater level and 'effective rainfall' data

Groundwater level data were obtained from the UK National Groundwater Level Archive. The selected 30 study boreholes have at least 30 years of data to October 2017 and the full period of record was used. These records are a compromise between data completeness and quality across a representative sample of UK hydrogeology (figure S1) available at stacks.iop.org/ERL/13/064040/mmedia. They are also relatively free of significant artificial influences and are routinely used for assessments of the status of groundwater in the UK (e.g. NHMP 2017, Prudhomme *et al* 2017). The 30 study boreholes were categorised into nine aquifer regions (figure S1). To account for variations in the sampling frequency, observations were aggregated into daily mean levels then linearly interpolated over durations of up to 60 d before aggregation to monthly mean levels. This follows the method used in existing water situation monitoring activity in the UK (e.g. NHMP 2017).

Monthly potential evapotranspiration (Tanguy *et al* 2017, 2018) and rainfall data (Tanguy *et al* 2016) were extracted for a 5 × 5 km grid cell around each borehole (following Jackson *et al* 2016) for the period 1891–2015. Potential evapotranspiration was subtracted from rainfall totals to derive monthly series of the climatic water deficit for 1891–2015 (henceforth referred to as 'effective rainfall', equivalent to the rainfall unaccounted for by evapotranspiration).

2.2. Drought termination framework

A drought termination framework (Parry *et al* 2016a, figure S2) is applied to monthly mean level data that have been converted into percentage anomalies relative to a baseline period. For application to groundwater levels an additional step was required because they are recorded with reference to an arbitrary datum which differs between boreholes. Otherwise, drought termination metrics calculated from the same groundwater level hydrograph but for two different boreholes could differ simply because of the datum. To rectify this, monthly mean levels at each borehole were first expressed in metres above the lowest monthly mean level in the historical record. Levels were then converted into percentage anomalies from the 1987–2016 baseline period using equation (1):

$$Z_{\mathrm{anom}\,t} = 100\left(\left(Z_{\mathrm{obs}\,t}/Z_{\mathrm{LTA}\,m}\right) - 1\right) \qquad (1)$$

where $Z_{\mathrm{anom}\,t}$ is the percentage anomaly at time t, $Z_{\mathrm{obs}\,t}$ is the monthly mean level at time t, and $Z_{\mathrm{LTA}\,m}$ is the 1987–2016 mean level in the given month m. Percentage anomalies were preferred to the use of standardised

indicators such as the Standardised Groundwater Index (Bloomfield and Marchant 2013) because of issues around distribution fitting (e.g. Vicente-Serrano *et al* 2012, Tijdeman *et al* 2018) and the sensitivity of the framework metrics to ill-fitted extreme values.

The drought termination framework was applied here using the parameters established by Parry *et al* (2016b). The framework sub-divides identified droughts into development and termination phases either side of the maximum negative anomaly (drought minimum; DM). The drought termination duration (DTD) is the number of months between the DM and the end of the termination phase, and the drought termination rate (DTR; the gradient of the recovery) is the change in percentage anomalies between these two points divided by the DTD. The DTR and DTD metrics underpin two approaches to assess prospects for recovery.

2.3. Approaches for assessing prospects for recovery

2.3.1. Current rate

The 'current rate' approach calculates the rate of change in percentage anomalies from the DM to the most recent observation then linearly extrapolates this rate until the recovery is achieved. Whilst the gradient of the recovery may change each month depending on the latest precipitation, groundwater levels in some aquifer systems are not so responsive and the current rate may be a reasonable approximation. The month of recovery, $S_{current}$, based on the current rate is calculated by equation (2):

$$S_{current} = S_{DM} + n,$$

$$\text{where} \quad DM + (n-1) \; DTR_{current} > 0 \tag{2}$$

where S_{DM} is the month of DM, $DTR_{current}$ is the rate of change in percentage anomalies between DM and the latest observation, and n is the smallest integer such that $DM + (n-1) \; DTR_{current} > 0$. The $(n-1)$ term satisfies the requirement for two months with above average groundwater levels (i.e. positive percentage anomalies) for recovery, one of the criteria established by Parry *et al* (2016b).

Figure 1 illustrates $S_{current}$ in October 2017 for Redlands Hall (Chalk eastern England; figure 1(*a*)) and Rockley (Chalk south-central England; figure 1(*b*)). At Redlands Hall (figure 1(*a*)), DM in February 2017 was ~−63% and by October 2017 percentage anomalies had recovered only marginally to ~−50%, equating to a $DTR_{current}$ of ~1.6% month⁻¹. The smallest value of n such that $DM + (n-1) \; DTR_{current} > 0$ is 40 (i.e. positive anomalies occurring 39 and 40 months following S_{DM}), giving $S_{current}$ as June 2020 (i.e. February 2017 + 40 months).

To evaluate the current rate approach, the absolute error between $S_{current}$ and the actual month of recovery was calculated for all $S_{current}$ forecasts initialised in all months of every drought termination phase in the historical record (blue bars in figure S3). The mean

absolute error (MAE) was calculated for ranges of percentage anomalies of the initialisation month and for each borehole (figure 1(*c*)). The MAE, the average error in $S_{current}$ in months, pertaining to the percentage anomaly in October 2017 was rounded to the nearest integer and formed a range for $S_{current}$ to provide an indication of the relative uncertainty in forecasts based on the current rate (e.g. figures 1(*a*) and (*b*)).

2.3.2. Historical ensemble

The 'historical ensemble' approach capitalises on extensive historical records of groundwater levels to provide an adequate representation of the variability in recovery profiles, applying the characteristics of all historical drought termination events (blue bars in figure S3).

Figure 2 demonstrates the historical ensemble approach for Washpit Farm (Chalk eastern England). This approach appends both the DTR and DTD from all historical events in turn, thereby giving two sets of months for the completion of recovery (S_{allDTR} and S_{allDTD}). Individual months corresponding to each historical event i (S_{DTR} and S_{DTD}) are calculated using equations (3) and (4):

$$S_{DTR} = S_{DM} + n,$$

$$\text{where} \quad DM + (n-1) \; DTR_{HEi} > 0 \tag{3}$$

$$S_{DTD} = S_{DM} + DTD_{HEi} \tag{4}$$

where S_{DM} is the month of the DM, DTR_{HEi} is the DTR of historical event i, DTD_{HEi} is the DTD of historical event i, and n is the smallest integer such that $DM + (n-1) \; DTR_{HEi} > 0$. The distribution of S_{allDTR} and S_{allDTD} are illustrated by the boxplots in figure 2(*a*).

As a recovery progresses, historical scenarios will be surpassed ($S_{surpDTR}$ and $S_{surpDTD}$; hatched in grey across the boxplots in figure 2(*a*)) leaving a smaller number of plausible scenarios ($S_{plausDTR}$ and $S_{plausDTD}$). Only $S_{plausDTR}$ and $S_{plausDTD}$ for the month of assessment are relevant for further consideration.

For each borehole, cumulative effective rainfall totals (mm) for every drought termination event (blue bars in figure S3) were expressed as average rates (mm month⁻¹) by dividing by the DTD. The relationships between these effective rainfall rates and DTR (figure 2(*b*)) and DTD (figure 2(*c*)) were established for S_{allDTR} and S_{allDTD}, with $S_{surpDTR}$ and $S_{surpDTD}$ again removed from consideration (grey dots in figures 2(*b*) and (*c*)).

Return periods (RPs) of the median effective rainfall rate of $S_{plausDTR}$ and $S_{plausDTD}$ were calculated using the L-moments procedure with a generalised logistic distribution following Vicente-Serrano *et al* (2010) and Tanguy *et al* (2015). For Washpit Farm (figure 2), $S_{plausDTD}$ is 11–20 months (orange boxplot; figure 2(*a*)), the median effective rainfall rate of $S_{plausDTD}$ is 23 mm month⁻¹ (figure 2(*c*)), and the RP for an average of 23 mm month⁻¹ over $S_{plausDTD}$ is 5–20 years (figure 2(*d*)). The same procedure
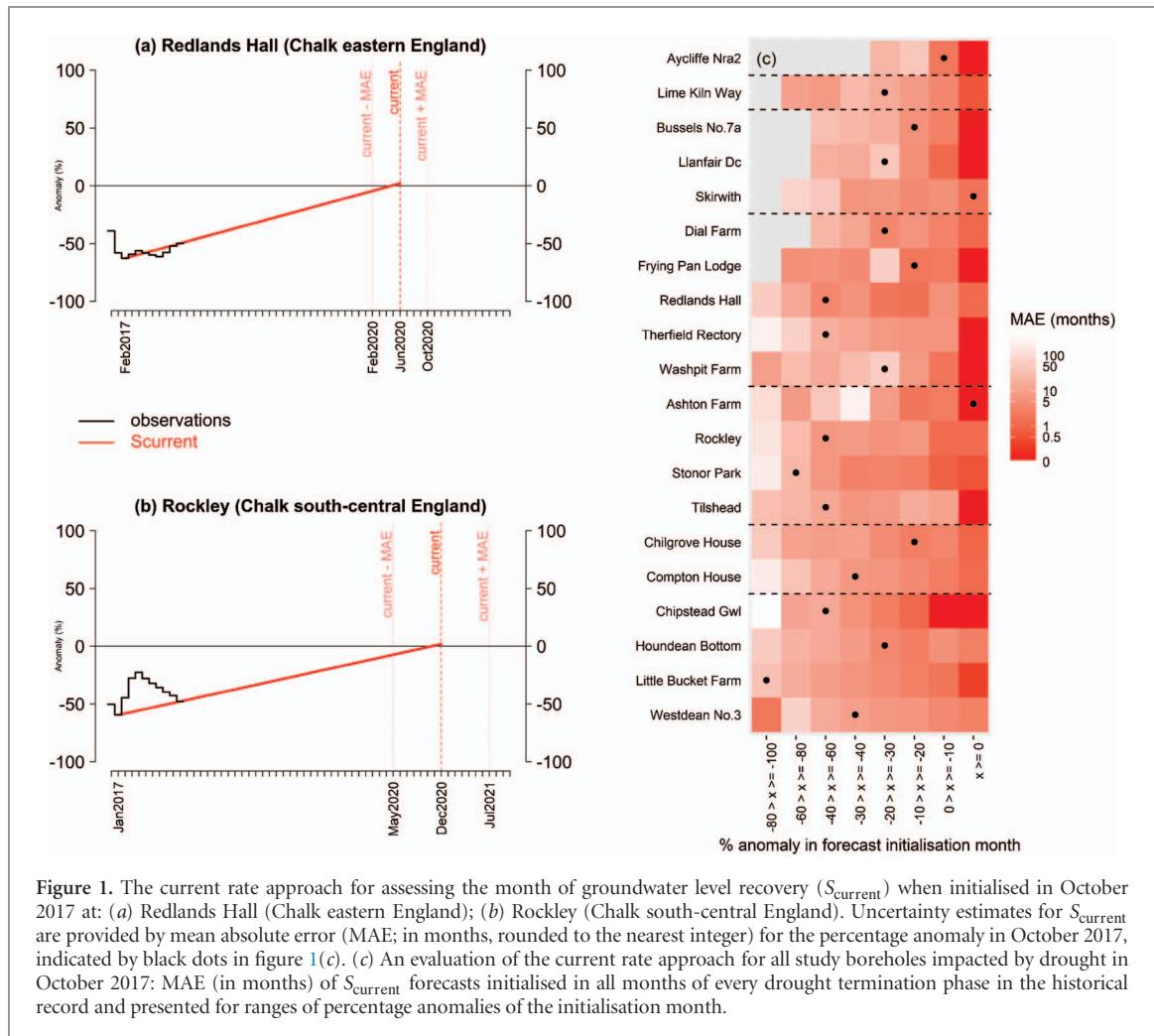
Figure 1. The current rate approach for assessing the month of groundwater level recovery ($S_{current}$) when initialised in October 2017 at: (*a*) Redlands Hall (Chalk eastern England); (*b*) Rockley (Chalk south-central England). Uncertainty estimates for $S_{current}$ are provided by mean absolute error (MAE; in months, rounded to the nearest integer) for the percentage anomaly in October 2017, indicated by black dots in figure 1(*c*). (*c*) An evaluation of the current rate approach for all study boreholes impacted by drought in October 2017: MAE (in months) of $S_{current}$ forecasts initialised in all months of every drought termination phase in the historical record and presented for ranges of percentage anomalies of the initialisation month.

is adopted for $S_{plausDTR}$. RPs of effective rainfall are only calculated up to the maximum $S_{plausDTR}$ and $S_{plausDTD}$ in the historical record (i.e. 20 months in figure 2).

3. Results

3.1. Evaluation of the current rate approach

The accuracy of the current rate approach was evaluated by assessing differences between $S_{current}$ and the actual month of recovery, for $S_{current}$ initialised in all months of every drought termination phase in the historical record. This analysis was undertaken for the 20 study boreholes that were still exhibiting drought conditions in late October 2017. For most boreholes, the MAE decreases as the percentage anomaly at initialisation approaches zero (figure 1(*c*)). These percentage anomalies are closer to the completion of recovery and therefore have more certainty in the timeframe over which this could take place. Conversely, more severe percentage anomalies are further from the end of the recovery so a wider range of scenarios is still feasible. Some boreholes produce more reliable $S_{current}$ than others for given initial percentage anomalies. For instance, Redlands Hall, Stonor Park and Chip-

stead Gwl all exhibit relatively low MAE for percentage anomalies of as much as -60%. Conversely, Tilshead has low predictability (high MAE) until percentage anomalies are positive, only requiring levels to remain static for a second consecutive month in order for complete recovery.

Where MAE does not increase from left to right in figure 1(*c*), this is likely to be influenced by sample size with fewer months of more severe percentage anomalies. This is apparent in the generally more responsive aquifers (top five rows of figure 1(*c*)) where negative anomalies less than −60% are rare.

3.2. Prospects for groundwater level recovery: the current rate and historical ensemble approaches

For current rate forecasts at each borehole, the MAE corresponding to the percentage anomaly in October 2017 (black dots in figure 1(*c*)) is subtracted and added to $S_{current}$ (e.g. figures 1(*a*) and (*b*)), indicating the uncertainty of the current rate forecast initialised in October 2017. The size of the symbols in figure 3(*a*) indicates this uncertainty, with larger symbols representing lower MAE and less uncertainty. Current rate forecasts were not available for five of the 20 boreholes because recoveries had yet to begin (i.e. October 2017 was the DM).
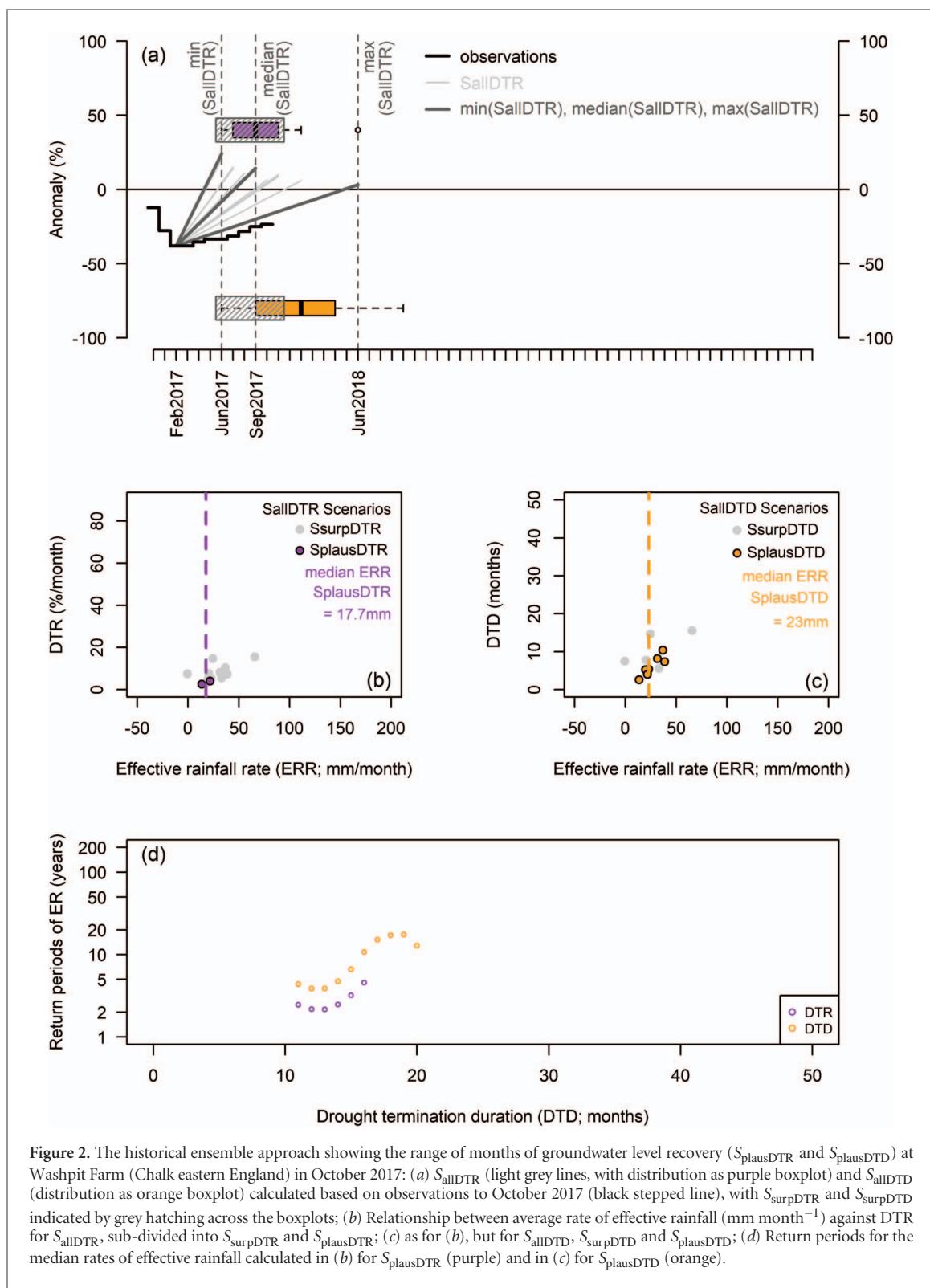
Figure 2. The historical ensemble approach showing the range of months of groundwater level recovery ($S_{plausDTR}$ and $S_{plausDTD}$) at Washpit Farm (Chalk eastern England) in October 2017: (*a*) S_{allDTR} (light grey lines, with distribution as purple boxplot) and S_{allDTD} (distribution as orange boxplot) calculated based on observations to October 2017 (black stepped line), with $S_{surpDTR}$ and $S_{surpDTD}$ indicated by grey hatching across the boxplots; (*b*) Relationship between average rate of effective rainfall (mm month^{-1}) against DTR for S_{allDTR}, sub-divided into $S_{surpDTR}$ and $S_{plausDTR}$; (*c*) as for (*b*), but for S_{allDTD}, $S_{surpDTD}$ and $S_{plausDTD}$; (*d*) Return periods for the median rates of effective rainfall calculated in (*b*) for $S_{plausDTR}$ (purple) and in (*c*) for $S_{plausDTD}$ (orange).

The most confident forecasts (largest symbols) by the current rate approach suggested recovery would occur in November 2017 or winter 2017/18 for only four of the remaining 15 boreholes (figure 3(*a*)). These were close to recovery in October 2017, consistent with forecast accuracy generally increasing when nearing completion (figure 1(*c*)). There is moderate confidence in recoveries by summer 2018 or autumn 2018 for a cluster of boreholes in southern and south-west England. Most notably, the current rate approach suggests that recoveries at Redlands Hall (figure 1(*a*)) may not occur until 2020 or beyond for Rockley (figure 1(*b*)). Both outlooks have moderate confidence, with an average accuracy of ±4 months and ±7 months, respectively.

The historical ensemble approach suggested that groundwater level recoveries in winter 2017/18 were likely in northern England (figure 3(*b*)). The

completion of recoveries in either winter 2017/18 or spring 2018 was also expected for a number of boreholes across England and Wales. Median $S_{plausDTR}$ and $S_{plausDTD}$ indicated that recoveries were not likely until summer 2018 for parts of south-west England and most of southern and eastern England. One borehole in the far south-east of England may not recover until autumn 2018 but none of the median $S_{plausDTR}$ or $S_{plausDTD}$ scenarios indicated that recoveries would continue into 2019.

For many boreholes, RPs for the effective rainfall needed for recoveries from conditions in October 2017 over $S_{plausDTR}$ and $S_{plausDTD}$ were more than five years (figure 3(c)), or an 80% chance of not receiving drought-terminating effective rainfall in a given year. RPs of 10–20 years were estimated for the Chalk of eastern England, and were longest for Dial Farm and Llanfair Dc (10–100 years or more). Even in this unlikely event, DTRs at Llanfair Dc are very low with effective rainfall rates of 30–120 mm month^{-1} only yielding DTRs of 2%–9% month^{-1} as the limited permeability of the aquifer constrains the rate of response to effective rainfall. It should be noted that the *x*-axis in figure 3(c) has been truncated; at high RPs, the exact values are less important than the recognition that recovery is very unlikely according to historical precedents.

4. Discussion

4.1. Comparing the current rate and historical ensemble approaches

In general, the median $S_{plausDTR}$ and $S_{plausDTD}$ from the historical ensemble approach suggested that completion of groundwater level recoveries is expected to occur over much shorter timescales than those indicated by the current rate approach. In part, this is because $S_{current}$ from the current rate approach were proceeding more closely to or beyond the *maximum* $S_{plausDTR}$ and $S_{plausDTD}$ in October 2017 which suggested protracted recoveries into 2019, 2020 or beyond.

For many boreholes, DTDs in October 2017 were already amongst the most prolonged on record (illustrated by the proportion of S_{allDTR} and S_{allDTD} that had become $S_{surpDTR}$ and $S_{surpDTD}$ in figures 2(a) and (b)). Despite registering some of the slowest recoveries on record, percentage anomalies remained well below average in late October 2017, either near-constant (e.g. figure 1(a)) or becoming yet more negative (e.g. figure 1(b)). Some reduction of anomalies would need to have already been underway by October 2017 to enable recovery by winter 2017/18 and, in general, the prospects for recovery in early 2018 were limited by a lack of recharge during the drought termination phase through 2017.

Given such negative percentage anomalies in October 2017, the transitions required for recovery by February 2018 had occurred only once before

at five boreholes including Compton House (record from 1894), and never before at two others. This suggested forecasts from the current rate approach are more likely to be realised for boreholes across southern and eastern England, and is consistent with the characterisation of groundwater drought as a slowly-terminating phenomenon (Correia *et al* 1987).

Near-real-time data to the end of February 2018 enabled an assessment of the accuracy of the outlooks. All but three of the 20 boreholes remained in drought at the end of winter; these three that recovered were amongst the four predicted to do so from information available in October 2017. Two of those three had already registered a first month of above average groundwater levels in October 2017 and the current rate approach highlighted the high confidence of an early winter 2017/18 recovery in these boreholes. Of the seven boreholes with limited historical precedent for a recovery by February 2018, none achieved this outcome. Percentage anomalies generally remained closer to those of October 2017 than those required for recovery.

Looking forward into 2018, the prospects for recoveries given by the historical ensemble approach do not reflect seasonal variations in RPs for effective rainfall. As $S_{plausDTR}$ and $S_{plausDTD}$ increase from October 2017 to include subsequent winter and summer seasons, RPs decrease then increase (respectively) as high amounts of effective rainfall are more then less likely (e.g. figure S4). This underlines the importance of winter as the season with greatest potential for the quantities of effective rainfall required for recovery.

4.2. Limitations of the approach

This study applied a framework originally developed for river flows in the UK, using parameters based on sensitivity analysis (Parry *et al* 2016b). The lower responsiveness of groundwater levels to rainfall and the frequency with which levels persist above or below average for long durations means that nine of ten consecutive months below average was easier to satisfy, potentially overestimating the frequency of drought occurrence. In addition, using accumulated totals of effective rainfall throughout the DTD may be less important in determining recovery than two months of very high effective rainfall.

The application of a historical ensemble drawn from records with non-stationary influence of groundwater abstractions may affect the outlooks in this study. Whilst this factor has been limited by excluding highly impacted borehole records, abstractions from groundwater in England and Wales were 80% higher in the early 1990s than in 1948 (Downing 1993). As such, historical scenarios which pre-date this increase in groundwater use may underestimate the observed length of recoveries from contemporary drought events.

Although short-term prospects for recovery were limited when appraised in October 2017, the links
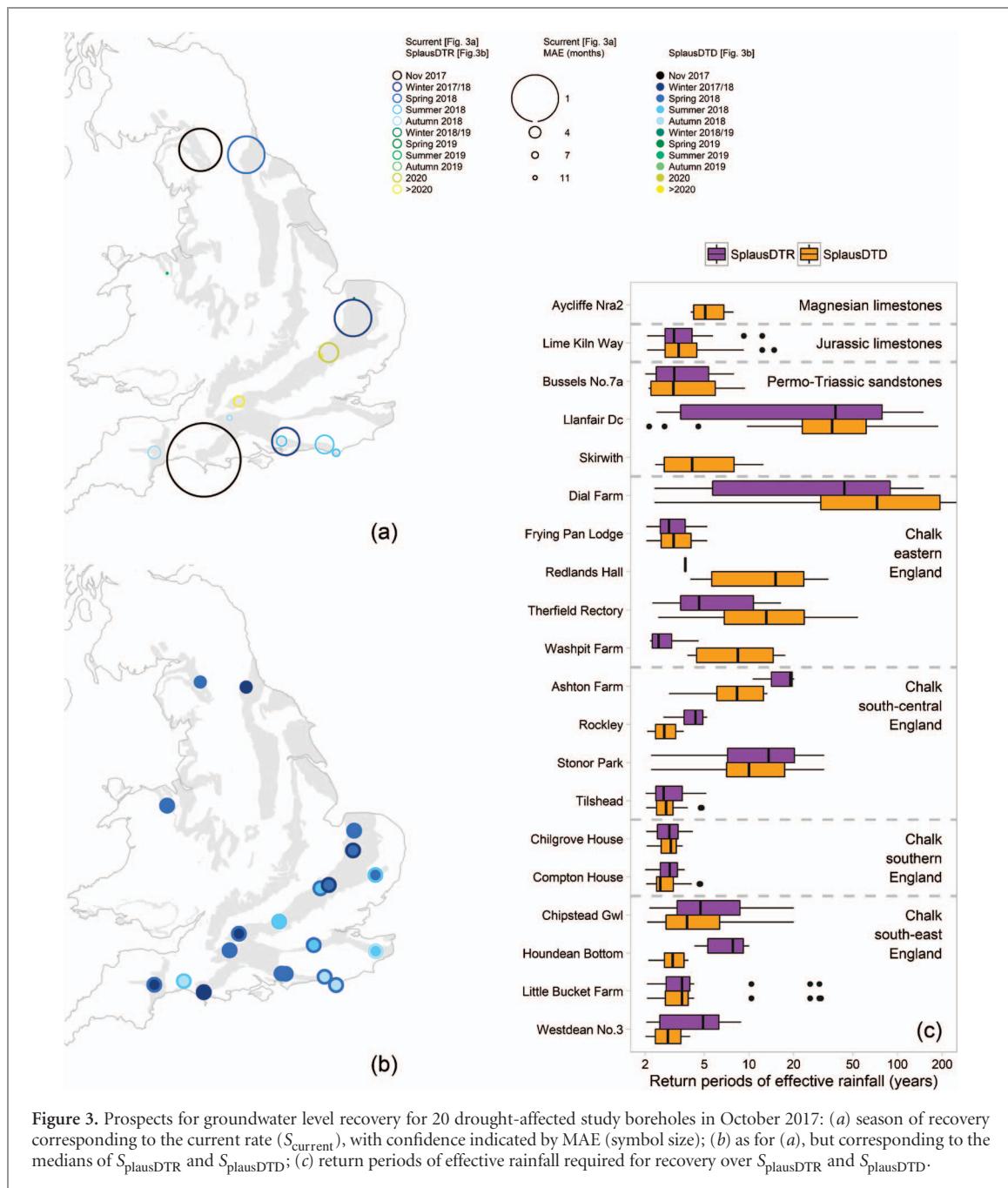
Figure 3. Prospects for groundwater level recovery for 20 drought-affected study boreholes in October 2017: (*a*) season of recovery corresponding to the current rate ($S_{current}$), with confidence indicated by MAE (symbol size); (*b*) as for (*a*), but corresponding to the medians of $S_{plausDTR}$ and $S_{plausDTD}$; (*c*) return periods of effective rainfall required for recovery over $S_{plausDTR}$ and $S_{plausDTD}$.

between persistently low groundwater levels and water supply restrictions are complex. The likelihood of water restrictions depends on the status of a number of elements of the water supply system, including river flows and reservoir stocks (Marsh *et al* 2007). There are also relevant questions about what constitutes a long duration event (Watts *et al* 2012) and the period over which these are of practical significance to water supplies. Long duration low groundwater levels can cause substantial contraction of the streamflow network (e.g. Wood and Petts 1999) and localised water shortages for agricultural irrigation (Bloomfield and Marchant 2013) in the south-east of England but are less relevant elsewhere in these contexts and for water supplies.

4.3. Recommendations and transferability

The two approaches presented herein have merit both in the UK and elsewhere. In certain circumstances for a given borehole, only one or other of the approaches provide forecasts (figure S5). First, if the surpassed subset of events encompasses all historical events, the historical ensemble approach cannot provide any information (e.g. the absence of boxplots relating to $S_{plausDTR}$ for both Aycliffe Nra2 and Skirwith in figure 3(*c*)). This also underlines the importance of considering historical ensembles of both the DTR and DTD metrics since only one might provide information. Second, if an ongoing drought has yet to enter the drought termination phase (i.e. the month of assessment corresponds to the DM; DTD = 0), the

current rate approach cannot provide any information. This situation applied to five of the 20 boreholes in October 2017 in the UK.

When the DTD of an ongoing event is greater than zero but less than the maximum historical DTD, both approaches can be applied simultaneously. Crucially, the two approaches are mutually exclusive such that there is never a situation for DTD when neither approach is available (figure S5). Hence, there is a clear rationale for considering both within a near-real-time operationalisation of this framework.

It is envisaged that the framework could be transferable to other regions, although the relative utility of the two approaches may vary by location. The two approaches are most likely to be useful in slowly responding groundwater systems, such as sandstone aquifers, where more constrained estimates of recovery could be made as levels in the past are a better guide to those in the future. Nevertheless, methodological parameters appropriate to the hydrogeological system of interest for defining drought events should be selected. Regions in which groundwater systems are artificially influenced are less well suited to the historical ensembles approach since the characteristics of past events may not be relevant under changing groundwater use patterns. Where groundwater use has a well-defined seasonal cycle it may be possible to sub-sample the historical ensemble to select only events that are relevant to the season. In addition, the application of the current rate approach would still produce valid assessments of the prospects of recovery, though confidence may be much lower owing to artificial factors.

5. Conclusions

The drought termination framework introduced herein has demonstrated the utility of information on past and present drought events for providing insights about the prospects for groundwater level recovery. A case study application in the UK in October 2017 yielded a number of important conclusions with regard to the prospects for recovery. Groundwater level recoveries within winter 2017/18 would be have been historically exceptional in records of up to 100 years; these were considered unlikely and data to February 2018 validated these forecasts. Return periods for monthly effective rainfall rates typically required to achieve recovery were longest for recoveries that extend into the summer half-year. These findings highlight the critical role played by rainfall in winter 2017/18 in determining the prospects for recovery of groundwater levels (and hence the water resources outlook for south-east England) in 2018 and beyond. The diagnostics applied in this study have demonstrable value because they capitalise upon a wealth of historical information within a seasonal outlook framework. The framework has strong potential for application in other regions, pending the availability of sufficient ground-

water level data, the customisation of methodological parameters and the evaluation of performance. Moreover, there is potential for this approach to contribute to existing operational services which provide monthly updates on the water situation outlook for the UK.

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