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Storylines of UK drought based on the 2010-2012 event

Wilson C.H. Chan[1], Theodore G. Shepherd[1], Katie A. Smith[2], Geoff Darch[3], Nigel W. Arnell[1]

[1]Department of Meteorology, University of Reading, Reading, UK
[2]UK Centre for Ecology and Hydrology, Wallingford, UK
[3]Anglian Water, Peterborough, UK

Correspondence to: Wilson Chan (wilson.chan@pgr.reading.ac.uk)

Abstract. Spatially extensive multi-year hydrological droughts cause significant environmental stress. Given the impacts of climate change, the UK is expected to remain vulnerable to future multi-year droughts. Existing approaches to quantify hydrological impacts of climate change are often scenario-driven and may miss out plausible outcomes with significant impacts. Event-based storyline approaches aim to quantify "storylines" of how observed events could hypothetically have unfolded in alternative ways. This study uses the 2010-2012 drought, the most recent period of severe hydrological drought in the UK, as a basis, and analyses counterfactual storylines based on changes to 1) precondition severity, 2) temporal drought sequence, and 3) climate change. Evidence from multiple storylines shows that maximum intensity, mean deficit and duration of the 2010-2012 drought were highly conditioned by its meteorological preconditions, particularly for northern catchments at shorter time scales. Recovery time from progressively drier preconditions reflect both spatial variation in drought conditions and the role of physical catchment characteristics, particularly hydrogeology in the propagation of multi-year droughts. Two plausible storylines of an additional dry year with dry winter conditions repeated either before the observed drought or replacing the observed dramatic drought termination confirm the vulnerability of UK catchments to a "three dry winter" scenario. Applying the UKCP18 climate projections, we find that drought conditions worsen with global warming with a mitigation of drought conditions by wetter winters in northern catchments at high warming levels. Comparison of the storylines with a benchmark drought (1975-76) and a protracted multi-year drought (1989-93) shows that for each storyline, drought conditions could have matched and exceeded those experienced during the past droughts at catchments across the UK, particularly for southern catchments. The construction of storylines based on observed events can complement existing methods to stress test UK catchments against plausible unrealized droughts.

1 Introduction

Droughts incur significant impacts on the natural environment and across multiple sectors. Meteorological droughts — continuous periods of below-normal precipitation — propagate through the hydrological cycle and translate into hydrological and soil moisture droughts (Van Loon 2015). Drought propagation, conditioned by catchment properties, can result in hydrological droughts — extended periods of below-normal river flow or groundwater levels — that are significantly longer in duration, more intense and affect a larger area (Barker et al. 2016). Hydrological droughts threaten

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water resources availability and incur additional environmental and socio-economic consequences. The UK has experienced several periods of severe hydrological droughts since the 1950s, including the "benchmark" 1975-76 drought (Marsh et al. 2007). However, although intense, this drought was relatively short-lived and other events are more significant in locations where hydrological systems are sensitive to longer droughts. The 1989-93 and 2004-06 droughts and the more recent 2010-12 drought further raised awareness of the vulnerability of the UK to future multi-year droughts under climate change. Previous research has shown that past UK multi-year droughts were characterized by at least one winter with significant precipitation deficit, although significant uncertainties remain over the role of remote climate drivers and changes to atmospheric circulation under climate change (Parry et al. 2012; Folland et al. 2015). A deeper understanding of the causal factors of multi-year droughts is a significant challenge for current and future water management.

Climate change is expected to impact global water resources through changes to the quantity, quality and timing of river flow and other hydrological processes (Arnell and Gosling 2013). National-scale climate change assessment for the UK point to a general reduction in annual river flow except for western Scotland, with higher certainty over a decrease in summer flows for southern England and lower agreement over changes in winter flows (Arnell 2011; Prudhomme et al. 2012; Christierson et al. 2012). A recent synthesis identified that significant uncertainty remains over the magnitude of seasonal flow changes, with lower agreement on changes in the autumn and spring (Garner et al. 2017). Comparing two generations of UKCP probabilistic projections at 10 UK catchments, Kay et al. (2020) found that low and average flows at the selected catchments are projected to decrease in most cases for the 2050s, although the magnitude of change for UKCP18 is smaller compared to the UKCP09 projections. Specific studies focusing on droughts point to increased drought intensity and frequency with more significant changes beyond the 2050s (Burke et al. 2010; Rahiz and New 2012). Studies diverge on changes to the frequency and impacts of long duration droughts with some suggesting more intermittent, shorter-duration droughts (e.g. Blenkinsop and Fowler 2007; Chun et al. 2013) and others highlighting large parts of the UK, particularly southern England, as hotspots for future multi-year droughts (e.g. Prudhomme et al. 2014; Brunner and Tallaksen 2019). Using the UKCP09 climate projections and a gridded hydrological model, Rudd et al. (2019) further found that there is a high likelihood of coincident hydrological droughts occurring in the Thames and Severn basins and that both peak drought intensity and duration is projected to increase in southeastern England particularly in the far future (2070s).

A common characteristic of existing studies is that they have predominantly been GCM-driven. This approach is scenario-driven and top-down in nature as its outcomes are constrained by projections from the selected GCMs, often presented and employed in decision-making via the ensemble mean (Smith et al. 2018; Shepherd 2019). The traditional impact modelling chain also incurs a "cascade of uncertainty" whereby multiple sources of uncertainties cascade and total uncertainty increases through each step of the modelling chain (Wilby and Dessai 2010). GCM-related uncertainty — i.e. uncertainty among projected impacts from different climate models — is regularly cited as the largest source of uncertainty. This relates to uncertainty in projections of circulation-related aspects (e.g. precipitation) over land (Shepherd 2014). Although studies

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often attempt to analyse as much of the cascade of uncertainty as possible, even the most comprehensive ones are unable to fully analyse all sources of uncertainty along the entire modelling chain (Smith et al. 2018). Recent studies have thus tended to consist of increasingly computationally demanding data processing workflows and its outcomes often involve large amounts of data presented with wide uncertainty ranges not conducive for decision-making (Løhre et al. 2019).

This drive to disseminate probabilistic information from GCM projections (e.g starting from the UKCP09 projections) may fail to adequately consider the full range of possible futures and in particular, the risks associated with low likelihood, high-impact events (Sutton 2019). Bottom-up approaches have emerged to consider a wider range of plausible futures and reverse the top-down, scenario-driven approach by using GCM projections as complementary information rather than as the only line of evidence. Scenario-neutral approaches explore system sensitivity by combining GCM output with exploratory simulations on a two-dimensional response surface (e.g. changes in temperature and precipitation seasonality) encompassing a wide range of plausible outcomes (Prudhomme et al. 2010). Similarly, decision scaling seeks to link response surfaces with specific decisions to identify thresholds where the system becomes unreliable (Brown et al. 2012). However, these approaches are designed as an initial screening tool and more detailed analysis of selected futures identified on the response surface are still needed (Prudhomme et al. 2015). A known limitation is that it is difficult to consider more than two dimensions at a time and may require multiple response surfaces to consider additional variables. These approaches can also be resource intensive as they cover sensitivity over large ranges regardless of plausibility or empirical experience. Recent research also highlighted additional uncertainty in the methods selected to populate the response surfaces (e.g. RCM-scaling, weather generator or seasonal scaling: Keller et al. 2018).

New approaches are needed to take specific concerns raised by the water resources industry and conduct exploratory experiments to identify ways in which high impact events may develop. Recent studies have advocated for the creation of "tales" (Hazeleger et al. 2015) or "storylines" (Shepherd et al. 2018) of extreme events. Storylines are defined as physically self-consistent unfoldings of past events and the plausible evolution of these events in a future climate (Shepherd et al. 2018). Event-based storylines can be constructed to characterize how high impact events could hypothetically unfold given different changes to their physical drivers in both present and future climate. The drivers and impacts of every drought event vary significantly. Analyzing the spatial coherence of European hydrological droughts since the 1960s, Hannaford et al. (2011) concluded that every drought event had distinctive drought signatures. There is therefore merit in looking at individual droughts following an event-based storyline approach (as opposed to aggregation over many dissimilar events). An event-based storyline approach operates on the basis of the observed event and enables a "forensic investigation" describing the impacts from a wide range of plausible changes to causal factors of the event (Lloyd and Shepherd 2020). This approach is specifically designed to consider plausible high impact events and strengthen risk awareness to avoid type II errors (i.e. missed warnings) (Shepherd 2019). Storylines thus need not have probabilities attached and place emphasis on specific drivers of extreme events and how the associated impacts of the event may change given changes in those drivers.

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Recent examples of event-based studies include case study analyses of six past droughts in East Anglia (Lister et al. 2018), analysis of anomalous European temperatures during winter 2010 (Cattiaux et al. 2010), retrospective comparison of the 2003 and 2015 European summer droughts (Laaha et al. 2016), and an in-depth investigation of the seasonal drivers of the 2018 European heatwave (Bastos et al. 2020).

In this study, we select the 2010-12 UK drought as a case study from which counterfactual storylines are constructed. The aims of this research are to:

- Analyse the drivers and development of the 2010-12 UK drought and the geographic variation in hydrological response across UK catchments
- Create a number of storylines representing alternative unfoldings of the 2010-12 drought event with changes to 1) precondition severity, 2) temporal drought sequence, and 3) climate change at different warming levels
- Quantify and compare characteristics of the observed event, its counterfactual storylines and that of a number of selected severe droughts in the past

2 Methods

2.1 Streamflow data and hierarchical clustering

In this study, we make use of the Low Flow Benchmark Network (LFBN) designated by the National River Flow Archive (NRFA). The LFBN comprises of UK catchments that are deemed suitable for the low flow analysis given their near-natural conditions (Harrigan et al. 2018). We select the 100 catchments within the LFBN that are located in England, Scotland and Wales and which overlap with the catchments selected in previous studies of droughts by Smith et al. (2019) and Barker et al. (2019). Daily observed river flow (m^3/s) and catchment properties were extracted for each catchment from the NRFA via the *rnrfa* R package (Vitolo et al. 2016).

The Standardized Streamflow Index (SSI) is used in this study to characterize drought events (Vincente-Serrano et al. 2012). The SSI is calculated by accumulating streamflow over a baseline period across a user-defined *n* number of months. Daily observed and simulated river flow for each catchment is aggregated into mean monthly river flow. A probability distribution function is fitted to the *n*-month(s) accumulated monthly river flow for each calendar month and standardized by transformation to a standard normal distribution. In this study, the tweedie distribution is selected to fit the accumulated streamflow. Comparing a number of probability distribution functions, Svensson et al. (2017) concluded that the tweedie distribution is most suitable for calculating drought indicators in UK catchments. The use of SSI fitted using the tweedie distribution has previously been employed to characterize hydrological drought risk in the UK in Barker et al. (2015; 2019) and Arnell et al. (2021). Agglomerative hierarchical clustering, a dendrogram-based clustering approach, was used to group catchments with similar drought response during the 2010/12 drought using the *TSclust* R package (Montero and Vilar

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2014). Similar hydrographs of SSI accumulated over 6 months (SSI-6) are grouped using the Ward's minimum variance method, which aims to minimize total within-cluster variance (Ward 1963).

2.2 Storylines considered in this study

The storyline approach provides a flexible means to investigate counterfactuals (i.e. events that did not happen in reality). In this study, we create counterfactual storylines by statistical adjustments to meteorological drivers, historical climate analogues and climate change impact assessment using the UKCP18 climate projections. Table 1 shows the various storylines considered in this study and example research questions that each storyline aims to address.

Table 1: Storylines considered in this study and description of example research questions

Storyline	Explanation	Example research questions
Precondition severity		
Drier preconditions (DP)	3- and 6-months prior to 2010-12 drought altered by estimated return periods (10, 20, 50 and 100-years)	How sensitive is the drought to progressively drier preconditions?
Temporal sequence		
Seasonal contributions (SC)	Winter and autumn within event replaced with daily climatological precipitation and temperature (1965-2015)	What were the seasonal contributions to the development and termination of the drought?
Dry year before (DB)	Replace 2009 with a dry year (2010) before the 2010-2012 drought	What if the 2010-12 drought was preceded or succeeded by another dry year with dry winter conditions (i.e. a third dry winter situation)?
Dry year after (DA)	Replace 2012 with a dry year (2010) after the 2010-2012 drought	
Climate change		
UKCP18 regional projections (GW)	UKCP18 projections applied to all months at 4 warming levels	What would happen if the 2010-12 drought occurred in a warmer world?

2.2.1 Precondition severity

Precondition storylines of varying severity are generated for 3- and 6-months preceding the 2010-12 drought to investigate catchment response time and the sensitivity of the event to progressively drier preconditions. The formulation of these storylines follows similar methodologies employed in previous studies to create scenarios for the understanding of catchment drought sensitivity in German (e.g. Stoelze et al. 2014; 2020) and Swiss catchments (e.g. Staudinger et al. 2015). The preconditions are altered based on estimating return periods in precipitation over the particular months. Specified return periods (10, 20, 50 and 100-year) are estimated from annual average 3-month (October-December) and 6-month (July-December) precipitation for each of the 100 catchments for the time period 1965-2015, and fitted with the generalized extreme value (GEV) distribution. Observed precipitation for the 3- and 6-months prior to the 2010-12 drought is then reduced to match the estimated average precipitation at each return period. The temporal variability of the reduced

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preconditions precipitation is therefore unchanged from the observed precipitation of the specified 3- or 6-months period. The number of days needed for river flow at each catchment to return to values close to the baseline simulation (<1%) from each precondition perturbation is taken as the catchment recovery time.

2.2.2 Temporal sequence

Two sets of storylines are created by altering the temporal sequence of precipitation and temperature of the 2010-12 drought by retaining certain periods and altering others based on historical observations. Firstly, to investigate the relative importance of individual seasons in the development of the drought, we create storylines of seasonal contributions by prescribing daily climatological average precipitation and temperature for winter 2010/11 and 2011/12 and for autumn 2010 and 2011 while retaining observed values for the rest of the time series. The difference between the storylines and the baseline is indicative of the individual contribution of winter/autumn.

Secondly, we create storylines with changes to the temporal drought sequence using historical climate analogues. Climate model projections indicate changes to average temperature and precipitation in a future period — for example, drier summers and wetter winters. However, these changes do not necessarily occur concurrently and may not be true for all years. Consecutive years with dry winters and summers are possible and the hydrological response to long dry sequences merits further investigation. We create storylines exploring the hydrological impacts of the "third dry winter" scenario — three consecutive dry years that includes consecutive drier than average winters (Spraggs et al. 2015). The "Dry year before" storyline replaces the year preceding (i.e. 2009) the drought with a dry year. The "Dry year after" storyline replaces the year succeeding the drought with a dry year (i.e. from March 2012 onwards) to explore the plausible consequences if drought conditions were not terminated by anomalously wet conditions in spring 2012. We select 2010 as the dry year to be repeated as it was notable for its anomalously cold and dry conditions dominated by an anticyclonic weather pattern centered over the UK. These storylines are inspired by the "historical climate" approach employed by Hydrological Outlook UK (HOUK) where 3-month probabilistic projections of river flow trajectories are simulated using hydrological models driven by ensemble sequences of precipitation and temperature sampled from the historical record combined with up-to-date observations (Prudhomme et al. 2017).

2.2.3 Climate change

The UKCP18 12-member HadRM3 Perturbed Parameter Ensemble (PPE) regional climate projections at 12km resolution are used. The 12-member PPE is based on the HadGEM3 GCM and represents a plausible range of the climate model parameter space (Rostron et al. 2020). The regional projections are selected as they provide spatially and temporally coherent projections, important given the spatial characteristics of droughts. A time-sampling approach (James et al. 2017) was used to select the 10-year time period starting from the year each ensemble member reaches conditions equivalent to four global warming levels (1.5, 2, 3 and 4°C) relative to 1981-2010. The delta change method is used to apply the

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projections (Anandhi et al. 2011). Monthly change factors for precipitation (%) and temperature (°C) are generated from comparing projections for a baseline period (1981-2010) to projections of the designated 10-year future periods. Change factors are generated for each river basin region designated by UKCP18. Change factors are applied either additively (for temperature) or multiplicatively (for precipitation) to the baseline temperature and precipitation for each selected catchment according to the river basin region the catchment is located in. The delta method is widely employed in studies projecting the impacts of climate change across UK catchments (e.g. Arnell et al. 2003; Wilby and Harris 2006; Kay et al. 2020). The change factor method is valuable given the cascade of uncertainty as it is based on perturbing the observed time series and does not incur the uncertainties involved with bias correction and downscaling. However, in its standard form, the change factor method retains the historical variability of the observations and changes in dry/wet spell lengths are not considered.

2.3 Drought characteristics

Maximum drought intensity, mean drought deficit and drought duration (months) are extracted using the SSI (Table 2). Simulated river flow accumulated over 6, 12 and 24 months are translated into the SSI for the calculation of drought characteristics. The parameter values for fitting the tweedie distribution are retained from the baseline and used to fit the distribution for each storyline. The same drought characteristics were used in Barker et al. (2019) to characterize historic droughts for the same set of UK catchments.

Table 2: Drought characteristics considered in this study and their derivation method

Drought characteristic	Method
Drought event	Periods of negative SSI with at least one month reaching severe drought (SSI < -1.5). Catchments without a single month of severe drought are regarded as not under drought conditions.
Drought duration	Total number of months across all periods of identified drought conditions within event time frame
Mean deficit	Sum of all SSI/SPI values within periods of drought conditions (accumulated deficit) divided by drought duration
Max. intensity	Minimum SSI/SPI value across all identified periods of drought conditions within the event time frame

2.4 Hydrological modelling and parameter uncertainty

The GR4J hydrological model is used to simulate the river flow for the baseline and counterfactual storylines. GR4J is a daily lumped, bucket-type hydrological model with four model parameters available for calibration (Perrin et al. 2003). GR4J is driven by catchment-averaged daily precipitation (CEH-GEAR dataset; Robinson et al. 2020) and potential evapotranspiration (PET). PET is estimated using the temperature-based McGuinness-Bordne equation calculated from daily mean temperature (CEH CHESS dataset) with parameters tuned specifically for the UK (Tanguy et al. 2018).

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Parameter uncertainty for GR4J for the selected catchments has previously been assessed by Smith et al. (2019). In Smith et al. (2019), GR4J was calibrated at the selected catchments using a multi-objective Latin hypercube sampling (LHS) strategy. 500,000 parameter sets for each catchment were produced and ranked at each catchment based on model performance assessed using multiple evaluation metrics. The top 500 parameter sets (LHS500) were subsequently used to reconstruct historic river flows. To ensure adequate simulation of severe drought and consider non-stationarity, we conduct a differential split-sample experiment to re-rank LHS500. For each catchment, the 10 driest years were selected based on mean annual precipitation (1965-2015). Model performance for each of the driest years was calculated using daily observed and simulated river flow for four metrics: Nash-Sutcliffe efficiency (NSE), NSE on logarithmic flows (logNSE), mean absolute percent error (MAPE) and absolute percent bias (PBIAS). For each catchment, the parameter sets are then ranked from best to worst for each metric and given a score (1 to 500, where a higher score implies worse performance). Finally, we re-rank LHS500 based on the total score — the sum of the scores for each parameter set for each metric. Retaining the new parameter set ranking, the performance metrics are re-calculated for each catchment, first for the ten wettest years and again for all years. By doing so, we investigate the extent to which model performance changes under different conditions.

Model performance is comparable between the new ranking (Dry rank) and the original rank (LHS500) (Fig.1). During the driest years, the top parameter set in Dry rank generally performed better than LHS500 in all four metrics, particularly NSE and logNSE. This indicates that the top parameter set in the Dry rank is, in general, better able to capture high (measured by NSE) and low flows (measured by logNSE) during dry years. Notable outliers with poor model performance in both rankings were fast-responding catchments in northern Scotland. These catchments, also identified in Smith et al. (2019), have “flashy” river regimes that are difficult to capture with possible influences from snowmelt that are not incorporated in GR4J. The split-sample experiment indicates that optimizing the parameter ranking from LHS500 based on dry conditions does not result in significant differences although the top parameter set in the Dry rank results in marginally better performance when only the driest years are considered. For the simulation of the baseline 2010-12 drought and its counterfactual storylines, we therefore make use the top-ranked parameter set from the Dry rank.

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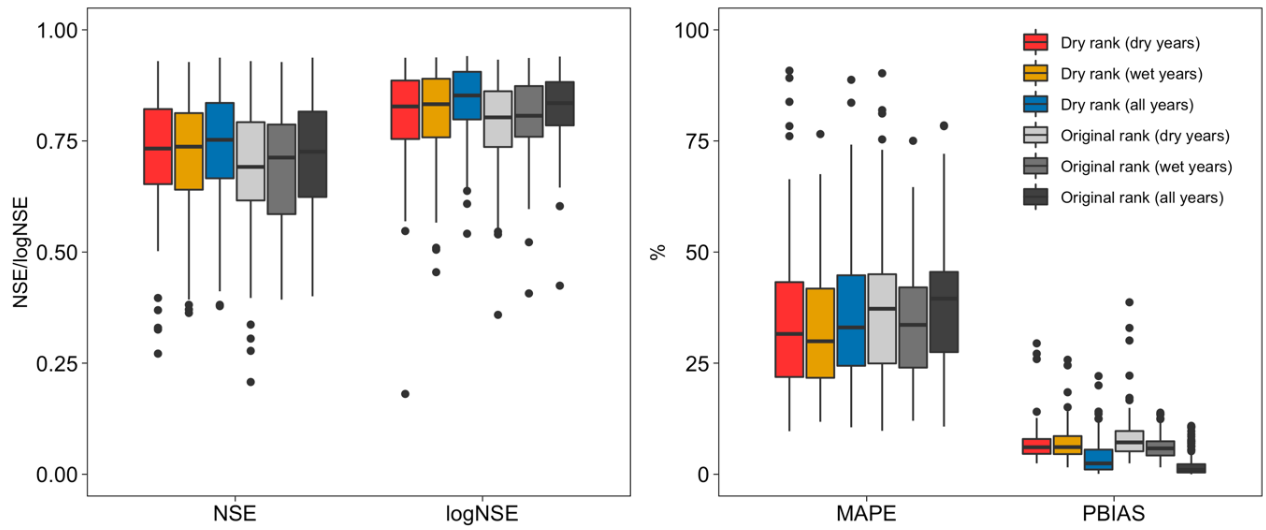

Figure 1: Model performance of the top ranked parameter set across the selected catchments between parameter sets ranked based on the 10 driest years (Dry rank) and the original LHS500 rank (Original rank). Comparison is made for the top ranked parameter set in either the Dry rank or the Original rank when model performance metrics are calculated for the 10 driest years, 10 wettest years, and all years.

3 Results

3.1 Anatomy of the 2010-12 drought

The 2010-12 drought was the most recent period of spatially extensive drought in the UK. The event was characterized by persistent blocked weather patterns over the UK from a northward shift of the jet stream over 2010 and 2011. Precipitation deficits were concentrated in winter, an important period when aquifer replenishment and reservoir re-fills normally occur (Kendon et al. 2013). The drought was notable for its dramatic termination when anomalously wet conditions occurred over spring and summer 2012, leading to a drought termination rate that was almost four times quicker than other droughts in the observed record (Parry et al. 2013; 2016). The event ranks within the top ten most significant multi-year droughts in the English Lowlands for the past 100 years (Kendon et al. 2013). Drought orders were used by multiple water companies to supplement reservoir stocks, and temporary hosepipe and water use bans affecting over 20 million customers were ordered in early 2012, in anticipation of continued drought stress, prior to its abrupt termination (Environment Agency 2012; Kendon et al. 2013). The 2010-12 drought also incurred over £400 million in agricultural losses from reduced yields and significant impacts to business and industrial activities from water use restrictions (Rey et al. 2017).

Figure 2 shows mean SSI accumulated over six months (SSI-6) across the event at the selected catchments. The most severe conditions were experienced in southern England although the majority of catchments also experienced mild to severe drought conditions for a number of months between 2010 and 2012. Yearly autumn and winter precipitation and temperature

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anomalies (relative to 1965-2015) showed that precipitation during winters 2009/10, 2010/11 and 2011/12 were all below average, confirming the importance of consecutive dry winter conditions in the development of the 2010-12 drought (Fig 2b). Autumn and winter are presented here as they represent crucial seasons when water resources are usually recharged. The exceptionally cold and dry conditions during winter 2009/10 were the precursor to the beginning of the drought where precipitation was significantly below average with blocked weather patterns across the western UK. The further northward shift of the jet stream in 2010 and across 2011 led to the development of a significant NW/SE precipitation gradient with normal to above normal precipitation in the north and continued drier than average conditions in the south (Kendon et al. 2013).

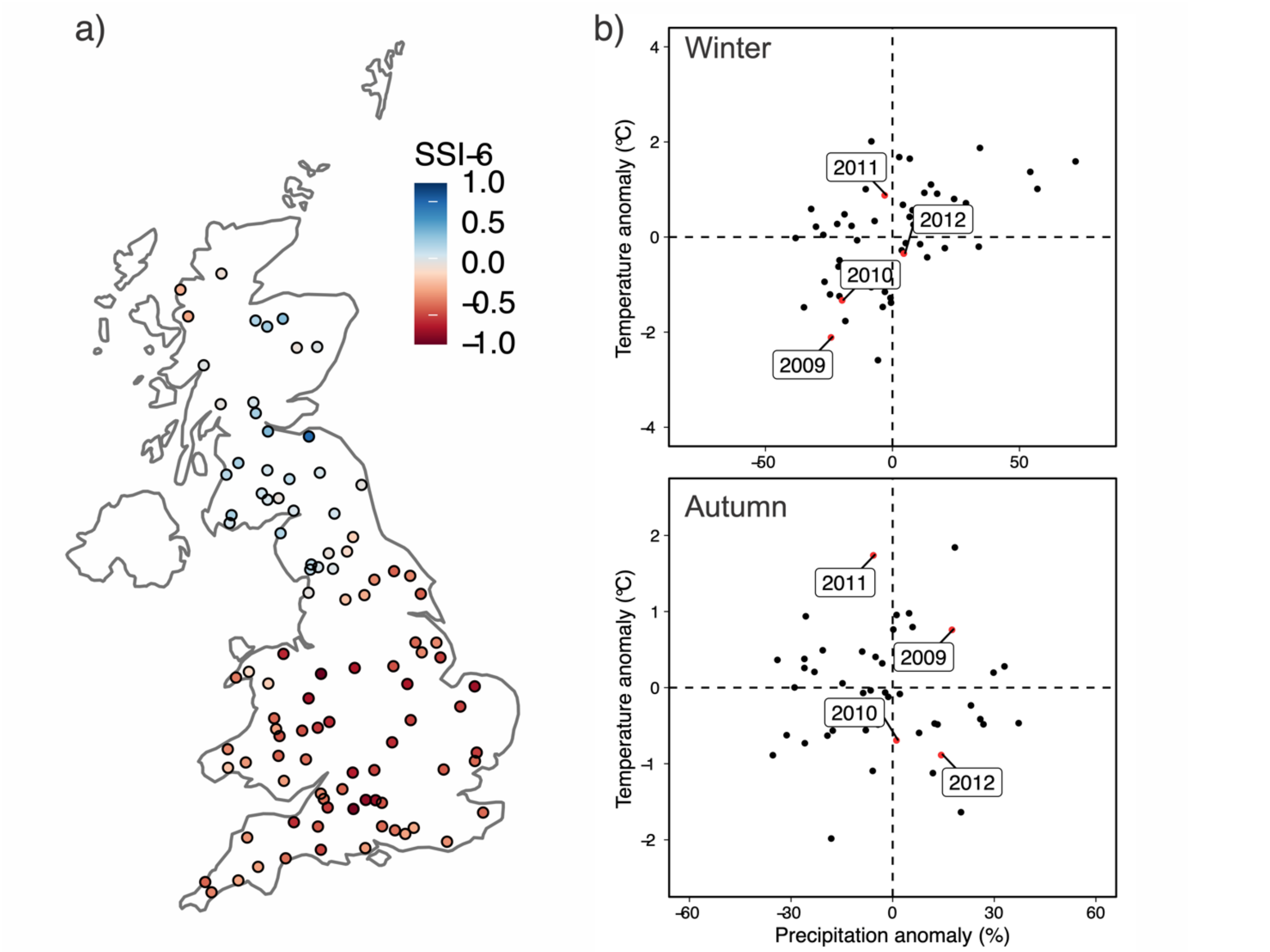

Figure 2: a) Mean SSI-6 values between Jan 2010 and Mar 2012 b) Yearly winter and autumn precipitation and temperature anomalies (relative to 1965-2015) averaged over the 100 selected catchments. 2009, 2010, 2011 and 2012 are shown by the red dots and the rest of the years are shown by the black dots.

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We use hierarchical clustering based on SSI-6 time series between January 2010 and March 2012 to identify groups of catchments with similar drought response (Fig.3). Cluster numbers between 2-10 were tested; five clusters are chosen as an appropriate number as this provides a clear distinction between hydrogeological units across southern England. The diversity of hydrological response to droughts in groundwater-dominated catchments in southern England has previously been shown in Merchant and Bloomfield (2018), and differences in hydrological drought response among catchments in this region should be considered. Five clusters also divides the northern catchments into east and west Scotland and distinguishes catchments in eastern Scotland where the influence of snowmelt processes may be more prevalent (also catchments with relatively poorer model performance). We select SSI-6 to delineate clusters instead of longer accumulated periods as it allows for a greater separation of catchments based on a larger variation in short-term drought response. SSI calculated with longer accumulation periods leads to a grouping of the hydrological response where only two clusters can be qualitatively identified. Subsequent storyline analyses will employ SSI-6, 12 and 24 in order to consider the role of catchment memory.

Initial streamflow response was relatively uniform in response to precipitation deficit in early 2010 for all clusters with moderate to severe drought conditions (SSI < -1.5). Catchments in Clusters 4 and 5 (southern and southeast England) were the most significantly affected, with severe drought conditions developing as a result of the influence of a second consecutive dry winter. The majority of catchments in Cluster 4 are underlain by chalk aquifers and are slow-responding catchments with significant groundwater storage. Catchments in Cluster 3 (southwest England) saw severe drought conditions develop over late 2010 and 2011 but the impacts did not persist as long and were not as severe as catchments in Clusters 4 and 5. Conversely, catchments in Clusters 1 and 2 (west and east Scotland) were the less affected. Although mean SSI-6 over the drought in these clusters was not particularly severe, the SSI-6 time series show mild to severe drought conditions in initial response to precipitation deficit over winter 2009/10, after which streamflow recovered and did not descend to significant drought conditions across the rest of 2011 and 2012. Catchments in Cluster 2 were the least affected, with streamflow not reaching significant drought conditions at any point between 2010 and 2012.

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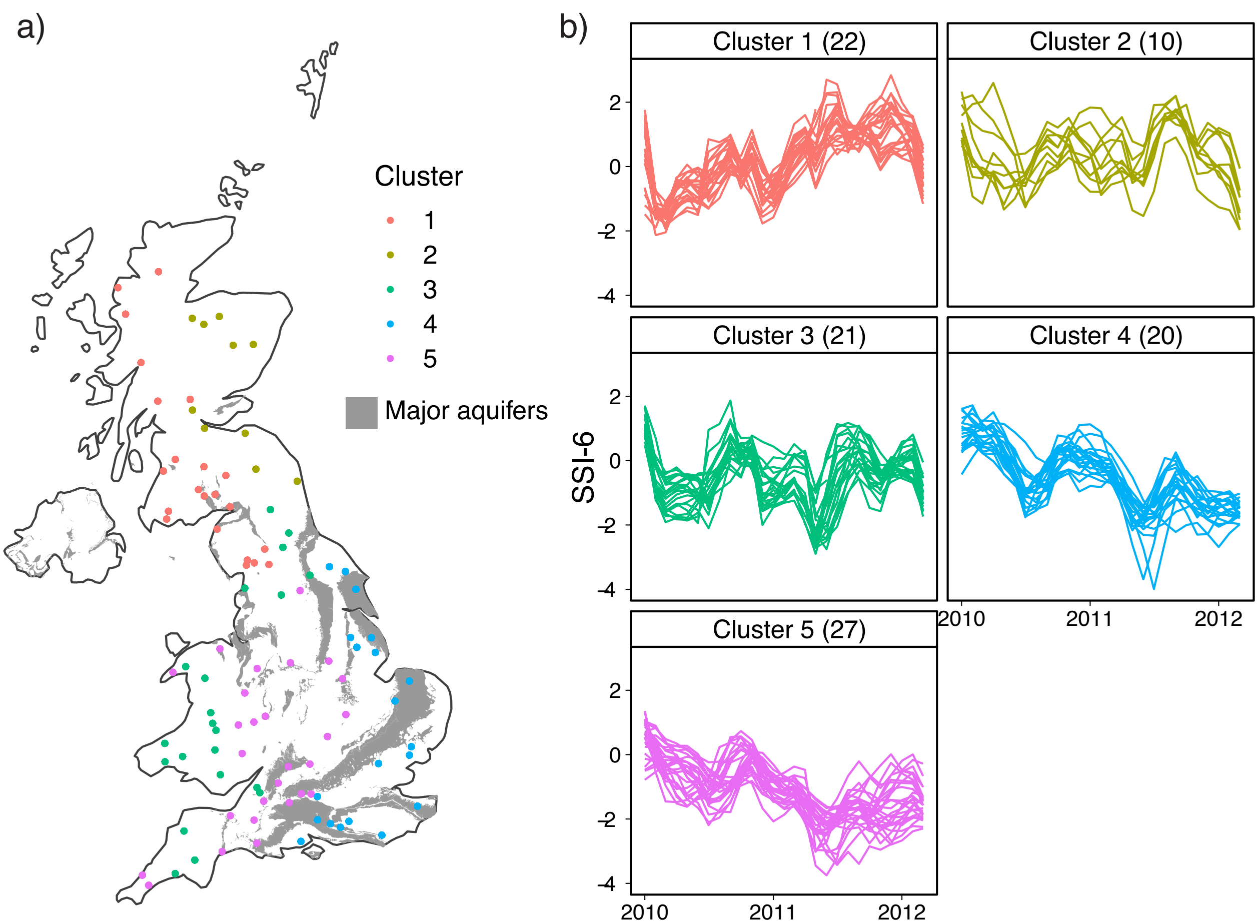

Figure 3: Hierarchical clustering of SSI-6 during the 2010-2012 drought event. a) Spatial variation in the five identified clusters. b) SSI-6 between Jan 2010 and Dec 2012 for the catchments in each cluster.

3.2 Storylines of seasonal contributions

Storylines of seasonal contributions reveal the relative importance of individual seasons in the development of the 2010-12 drought. Figure 4 shows cluster mean SSI-6 for the baseline and the two storylines of seasonal contributions (Figs S2 and S3 for SSI-12 and 24). The storylines confirm the importance of dry winters in the development of multi-year droughts. Drier than average winters in 2010/11 and 2011/12 were a major determinant of the severe drought conditions observed across all clusters apart from Cluster 1 for winter 2011/12. Baseline drought conditions across 2011, particularly for catchments in southern England (Clusters 4 and 5), can be attributed to both an abnormally cold start to winter 2010/11 and low precipitation across the latter parts of the season. Drier than average winter 2011/12 prolonged the dramatic drought

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termination in the baseline event for all clusters apart from Cluster 1. For Cluster 1, winter 2011/12 were wetter than average and the replacement of winter 2011/12 with climatology meant that catchments could have experienced short-term minor drought conditions before recovery from wet conditions in 2012.

In addition to dry winter conditions, wetter than average autumn 2010 prevented catchments in all clusters from an earlier drought inception and more intense drought conditions apart from Cluster 5. For Clusters 5, autumn 2010 was drier than average which accelerated drought inception for SSI-6 but the effects are less noticeable at longer accumulation periods. Conversely, autumn 2011 was drier than average which exacerbated drought conditions across all clusters when combined with drier than average winter conditions apart from Cluster 1 and 2. The most affected catchments in Cluster 4 and 5 would have begun drought recovery earlier and dry winter conditions alone would have been enough to cause continued descent into drought conditions seen in the baseline. For Cluster 1 and 2, wetter than average autumn 2011 prevented recovered catchments from returning to mild drought conditions, particularly when considering longer accumulation periods

In summary, the wetter (drier) than average autumn 2010 (2011) resulted in diverging effects for catchments in Cluster 1 and 2 compared to Cluster 3-5. Drier than average winter 2010/11 and 2011/12 worsened drought conditions. At the most affected catchments, the effects of dry winters is most notable for SSI-24, highlighting the role of catchment storage in attenuating the effects of dry winter conditions in drought development. Autumn conditions was a determinant of the timing of drought inception while winter conditions were important in determining the drought's eventual length.

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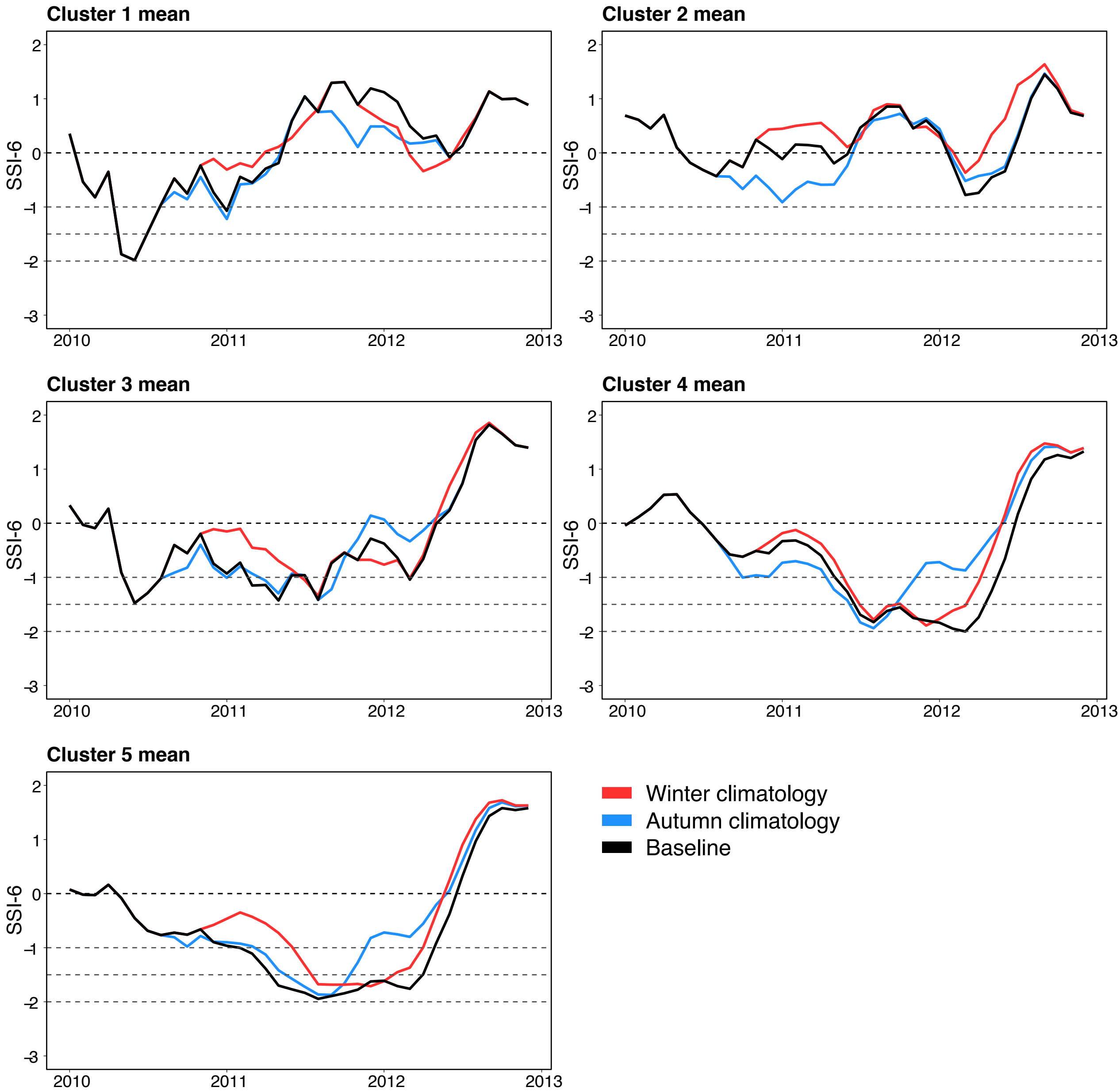

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Figure 4: Cluster mean SSI-6 for the storylines of seasonal contributions with winter 2010/2011 (red) and with autumn 2010 and 2011 (blue) replaced by daily climatological values. See supplementary figures S2 and S3 for the equivalent figure for SSI-12 and SSI-24.

3.3 Storylines of precondition severity

Prescribing drier preconditions at varying severity for the 3- and 6-months prior to the 2010-12 drought reveals the influence of preconditions on the baseline event (Fig.5). As the aims of altering precondition severity are to investigate short-term sensitivity to drier preconditions and the time taken for catchments to recover from them, only SSI-6 is used here. The alteration of drought preconditions based on four return periods leads to 12-month precipitation prior to the drought varying between 66-113% (61-89%) relative to the long-term average for the 3-months (6-months) perturbation, with significantly greater deficit for catchments in Clusters 4 and 5 (Fig.S1). Unsurprisingly, both max. drought intensity and mean drought deficit increase for all clusters with an increase in precondition severity. Max. intensity and mean deficit are more sensitive for catchments in Clusters 1-4 compared with those in Cluster 5. The difference between the two precondition lengths is most notable for catchments in Clusters 1 and 2, where a 6-month precondition length results in much greater change in drought characteristics. Precondition length is less important for catchments in Clusters 5, indicating that the conditions that developed over the 3-months prior to 2010 (i.e. winter 2009/10) were already dry enough for the development of severe drought conditions, and only preconditions with longer return periods would result in significant differences to the eventual drought characteristics.

Recovery time from the most severe preconditions (i.e. 6-months, 100-yr return period) separates clusters into relatively fast-responding (Clusters 1-3) and slow-responding (Clusters 4 and 5). Drought conditions at fast-responding catchments are sensitive to the least severe preconditions with only a 10-yr return period. Conversely, change in max. intensity is relatively minimal for slow-responding catchments and is only notable with preconditions beyond a 20-year return period.

Spatial variation in recovery time from the storyline with the driest preconditions (i.e. 6-months, 100-yr return period) differentiates catchments based on latitude with those in southern England showing the longest recovery time, coinciding with regions of major aquifers (Fig.6). Recovery time also differentiates latitudinal differences in catchment properties shown in Table 3 (Fig.6). There is a positive relationship between recovery time and both the baseflow index (BFI) and the proportion of arable/horticultural land. Higher values of the BFI are associated with more permeable catchments in the English lowlands. These catchments have high groundwater storage which contributes to surface streamflow during drought and are more associated with agricultural/horticultural activities compared to impermeable catchments. Catchments with longer recovery times also tend to be larger in size and less steep. Additionally, climate properties show that catchments with longer recovery times receive lower annual average precipitation and exhibit dry soil moisture for a larger proportion of time. This confirms that permeable lowland catchments are more vulnerable to long drought propagation with a lag (and lengthening) between meteorological and hydrological droughts. Drought response from drier preconditions shows that

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catchment sensitivity reflects a combination of spatial characteristics of the drought and catchment properties, particularly the influence of hydrogeology.

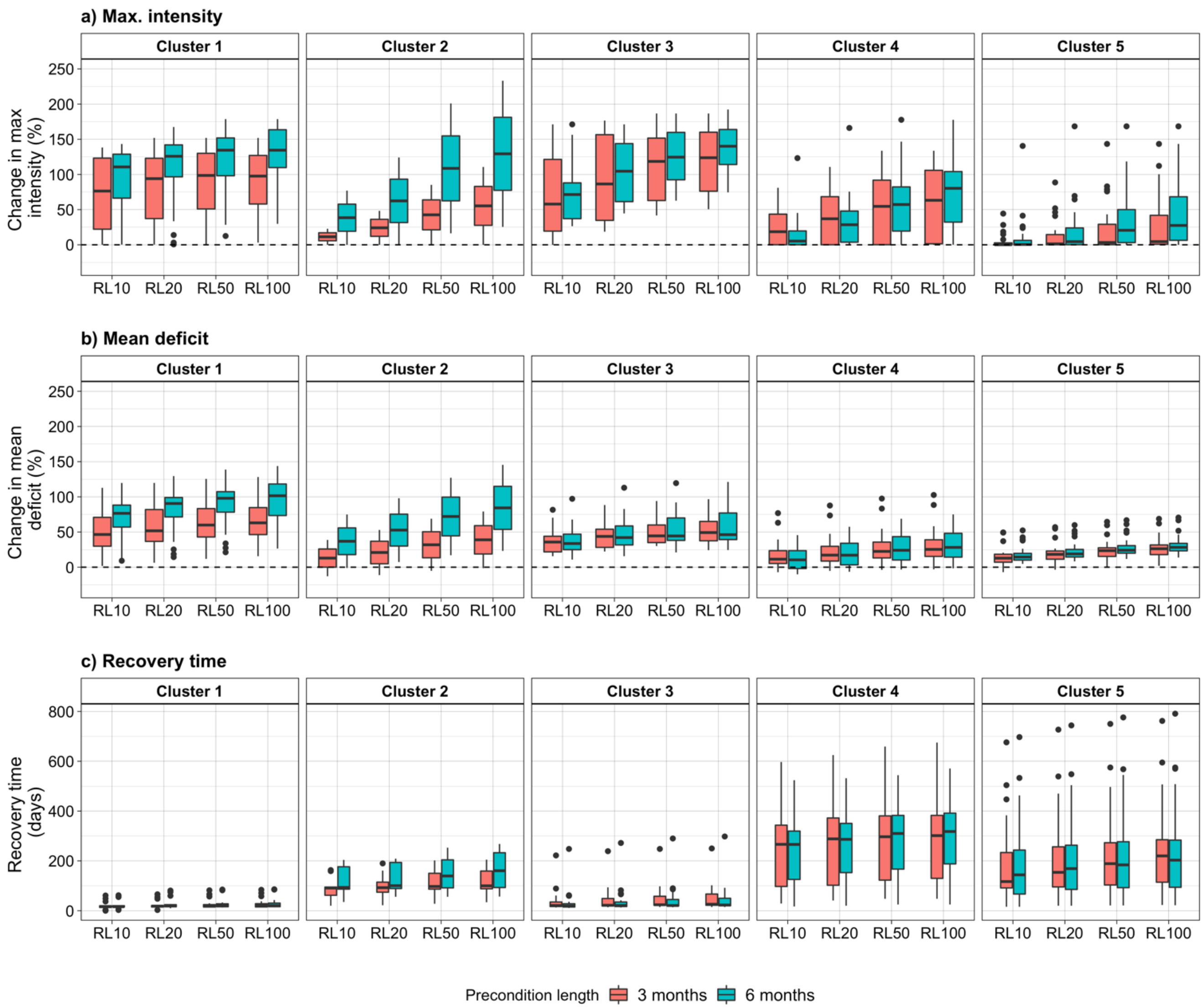

Figure 5: Change in mean drought deficit (%), max. drought intensity (%) and recovery time (days) from the storylines of precondition severity at different return levels calculated from SSI-6.

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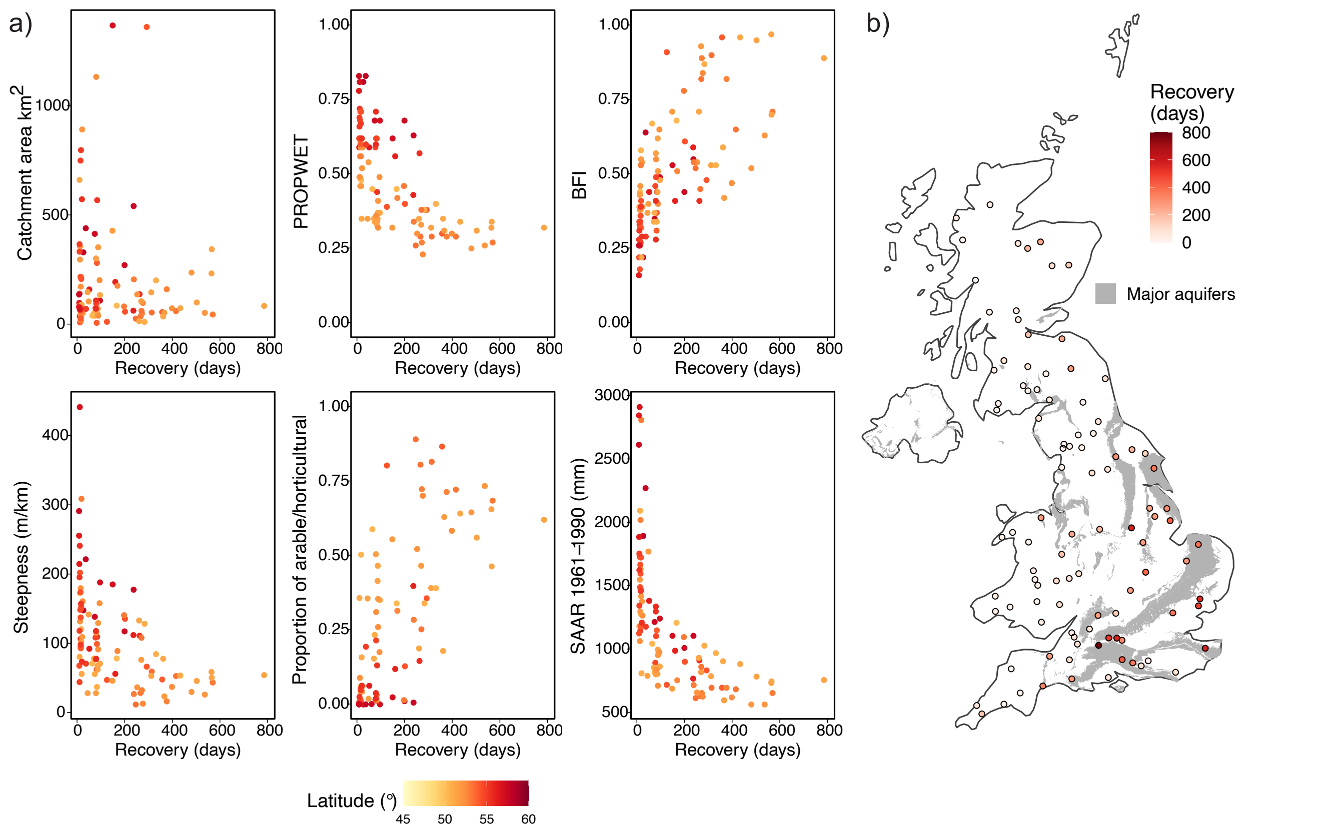
Table 3: Description of selected catchment properties

Catchment properties	Description
Catchment area (km^2)	Total area of the catchment (km^2)
DPSBAR (m/km) – catchment steepness	Mean drainage path slope (DPSBAR) is an index for catchment steepness calculated as the mean inter-nodal slopes within a catchment. Higher values indicate steeper terrain and lower values flatter terrain.
PROPWET (%)	Proportion of time soils within a catchment are designated as being wet (i.e. higher values indicate wetter). PROPWET varies from <20% to >80% across the UK.
Proportion of horticultural/arable land (%)	Land use information derived from the Land Cover Map 2000 and the NRFA Land Cover Classes 2000
BFI	Baseflow Index (BFI) is a measure of the proportion of river flow that derives from groundwater storage. Higher values indicate more permeable catchments with high groundwater contribution to river flow during dry periods.
SAAR 1961-1990 (mm)	Standardized Annual Average Rainfall (SAAR) over 1961-1990 30-year period



370 **Figure 6: a) Relationship between recovery time (days) of the 6-month precondition storyline (100-year return period) with selected catchment characteristics and b) Spatial variation of recovery time for the selected catchments.**

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3.4 Storylines of temporal sequence

Altering the temporal drought sequence illustrates how much worse the 2010-12 drought could have been, given another dry year (Fig.7). The drought is estimated to worsen for the "Dry year before" storyline for all clusters except for mean drought deficit for Cluster 4 for SSI-6. The anomalous reduction in mean drought deficit for Cluster 4 at SSI-6 relates to an increase in drought duration that is greater than the increase in accumulated deficit and maximum intensity. For this storyline, change in drought characteristics is greatest for Clusters 1 and 3, with a larger increase with longer accumulation periods. This indicates that the addition of a dry year prior to the observed event increases the risk of abrupt and intense drought conditions in these catchments. Changes in drought conditions are significant enough and is noticeable at longer accumulation periods, despite the relatively fast catchment recovery time for catchments in these clusters. Conversely, change in max. intensity and mean deficit for catchments in Clusters 4 and 5 is notable only at longer accumulation periods. The larger change in drought characteristics for SSI-24 is particularly important long accumulation periods are often used to assess drought at catchments in Clusters 4 and 5, with long catchment recovery times and significant catchment storage.

Compared to the "Dry year before" storyline, the "Dry year after" storyline has a greater effect in the worst affected catchments in southern England. Without the dramatic drought termination in 2012, drought duration would have increased significantly for catchments in all clusters. Max. intensity and mean deficit are estimated to increase for all clusters, with the largest increase for Cluster 4 followed by Cluster 5 at all accumulation periods. This suggests that there is still considerable scope for even worse drought conditions to develop if dry conditions had persisted across 2012. The change in max. intensity is greatest for SSI-12 for all clusters except Cluster 5 while the magnitude of change in mean deficit increases with accumulation period and is greatest (smallest) for SSI-24 for Cluster 3-5 (Clusters 1-2). This indicates the importance of assessing drought conditions at multiple accumulation periods and highlights the importance of catchment and water resource memory. At Clusters 1-2, SSI-6 and 12 are useful to capture changes in drought conditions from the storylines but for Clusters 3-5, SSI-12 or longer are needed to fully assess the drought response.

Individual catchment examples again reflect the role of catchment response time in determining the catchment sensitivity to an additional dry winter. Figure 8 shows SSI-6 of nine catchments spanning the five clusters for the two storylines (Figs S4 and S5 for SSI-12 and 24). We can identify three categories of response. First are fast-responding catchments (e.g. 81002 – Cluster 1, 7001 – Cluster 2) that recover from both the "Dry year before" and "Dry year after" storylines quickly, with changes observable only for the perturbed year. Second are slow-responding catchments (e.g. 38026 and 42008 – Cluster 4) where streamflow response from the "Dry year before" storyline persists across 2010 but not significantly beyond 2011. Third are slow-responding catchments (e.g. 43014 and 39019 – Cluster 5) where streamflow response to the "Dry year before" storyline persists across 2010 and beyond into 2011. The "Dry year after" storyline also shows that even with

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continued dry conditions, the meteorological conditions over 2013 would still have been wet enough to allow the most affected catchments to exit drought conditions.

In summary, the impacts of the "Dry year before" and "Dry year after" storylines vary spatially. The impacts of the "Dry year before" storyline is particularly severe for catchments in Clusters 1 and 3 although impacts remain apparent when considering catchment memory for Cluster 5. The impacts of the "Dry year after" storyline is particularly severe for Clusters 4 and 5, highlighting the role of catchment storage in slow drought propagation.

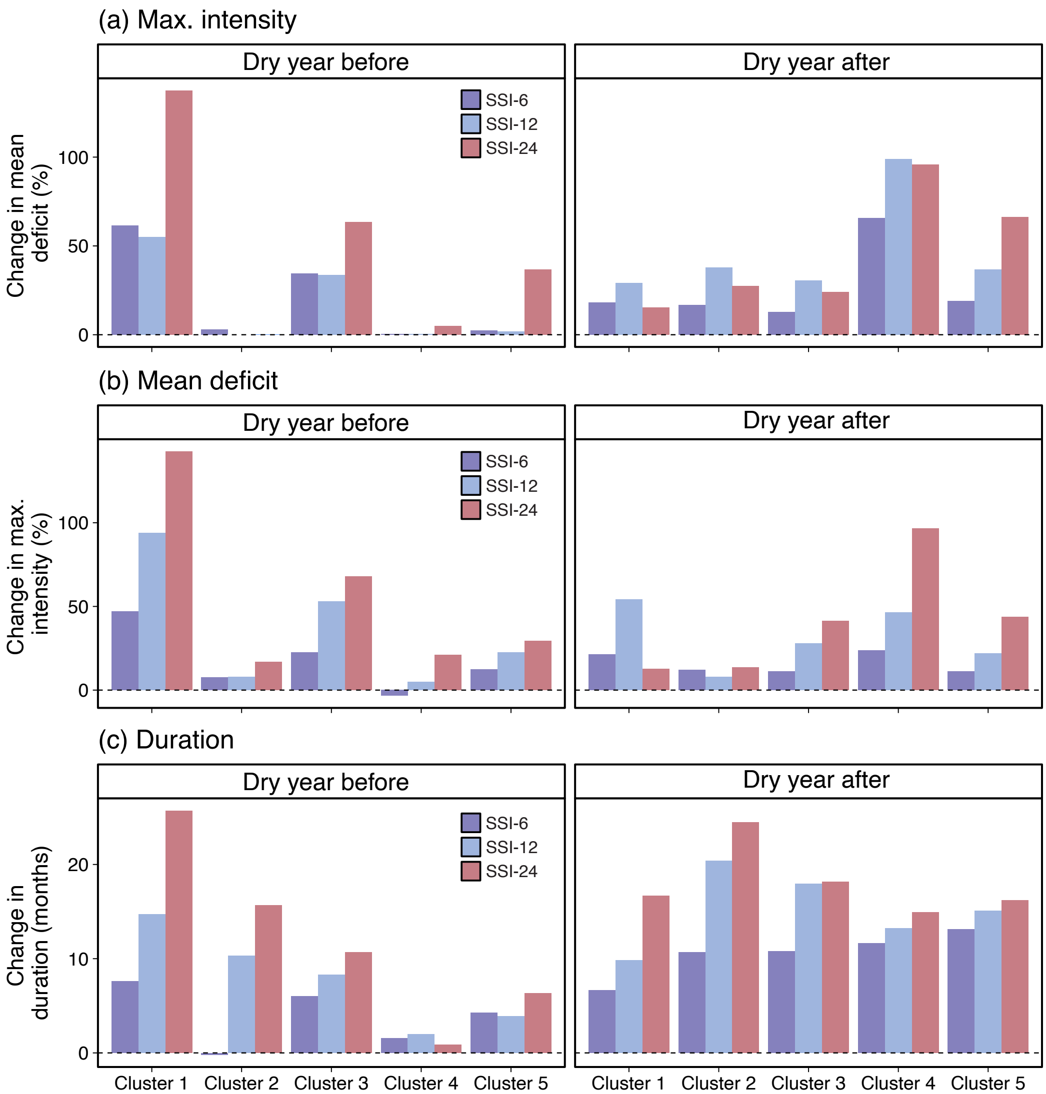

Figure 7: Mean change in max. drought intensity (%), mean drought deficit (%) and duration (months) relative to the baseline for each cluster for either repetition of a dry year (2010) before (left) and after (right) the 2010-2012 drought.

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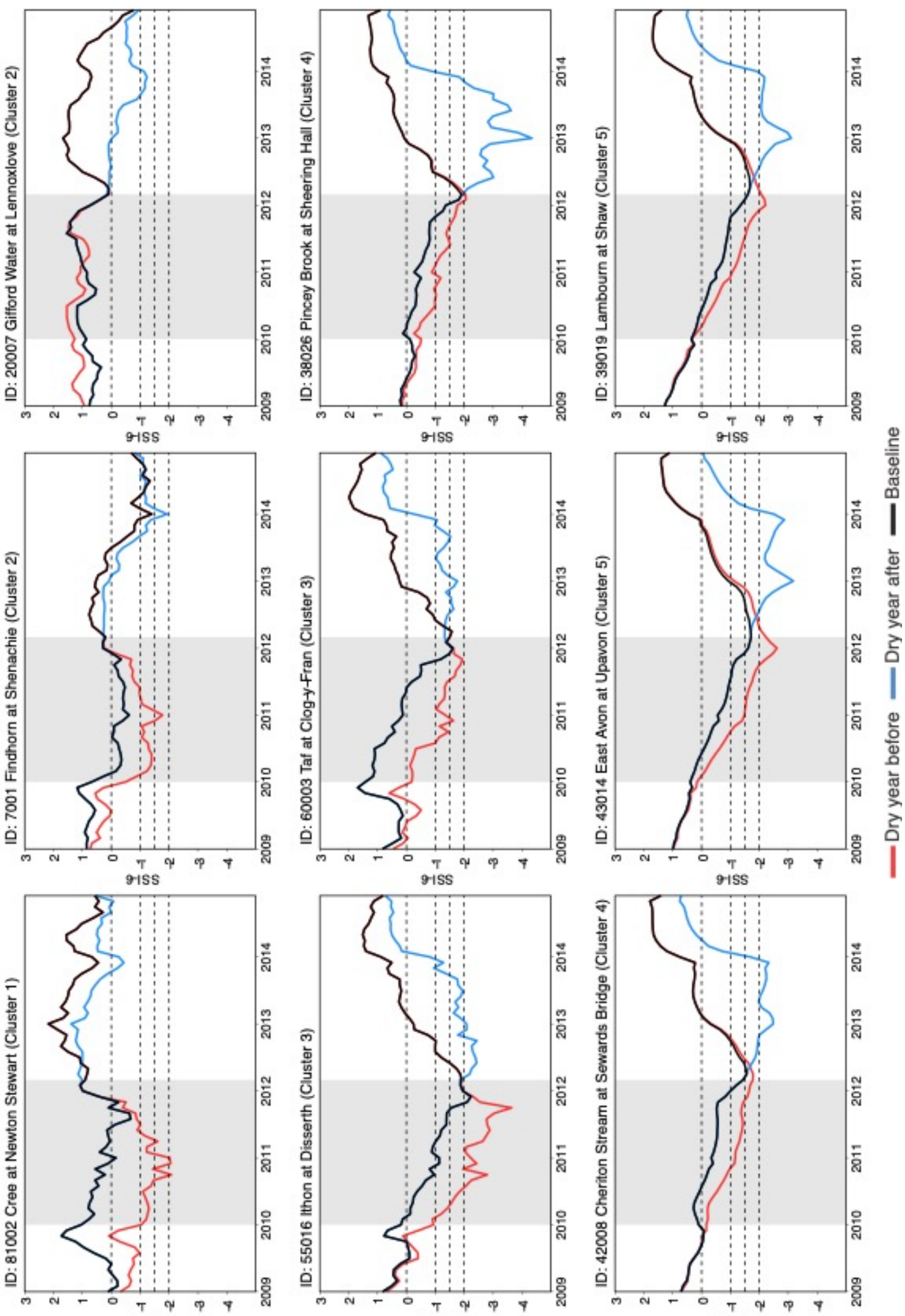

Figure 8: Baseline (black) and simulated SSI-6 for a repetition of a dry year before (red) or after (blue) the 2010-2012 drought for nine example catchments spanning the five hydrograph clusters. The shaded region indicates the duration of the baseline 2010-2012 drought event (January 2010 to March 2012). See Figure 10 for the locations of the nine example catchments. See Figures S4 and S5 for SSI-12 and SSI-24

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3.5 Storylines of climate change

The hydrological impacts of climate change are assessed using the UKCP18 regional projections. The projections point towards, in general, wetter winters and drier summers with increasing temperature rise (Fig. 9). This climate change-induced change in seasonality of precipitation is particularly noticeable at 3°C and 4°C rise in temperature, with general agreement among the 12 regional projections over the sign of change. Projections also point to increased seasonality in temperature changes with greatest change in temperature in the summer, reaching 6°C higher relative to 1981-2010 in the summer of a 4°C world.

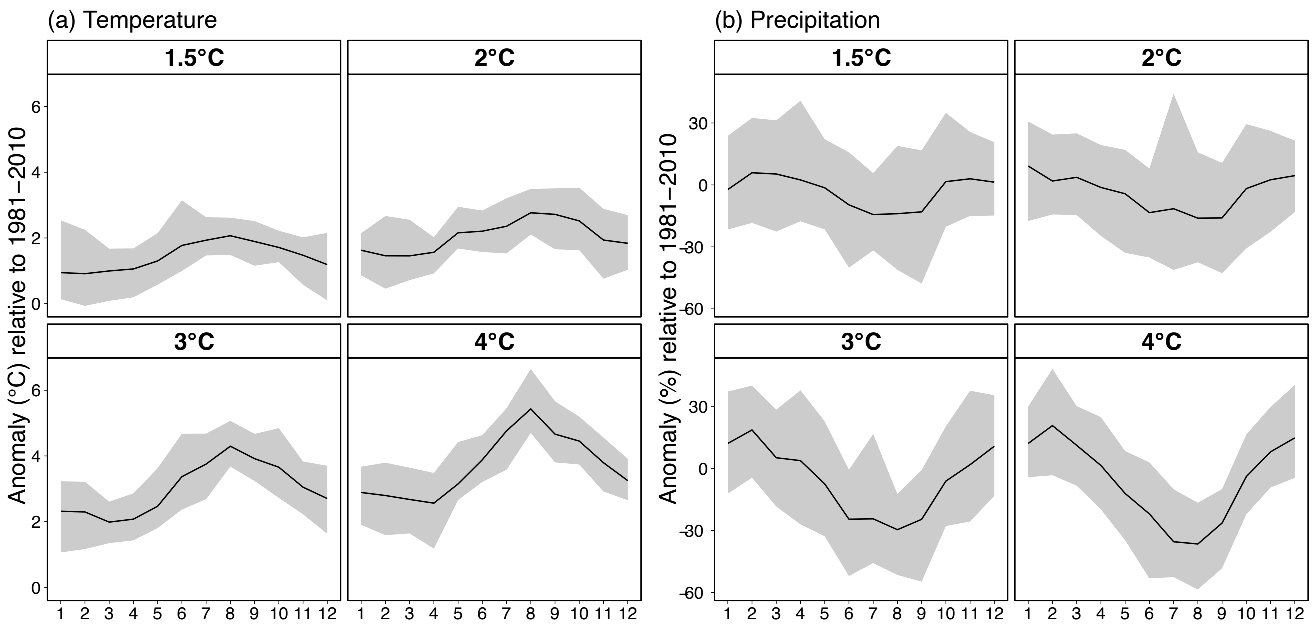

Figure 9: Projected percentage change in monthly average a) temperature and b) precipitation relative to 1981-2010 from the UKCP18 regional projections at four warming levels averaged across the 100 selected catchments. The shaded region represents the maximum and minimum range of projected change amongst the 12 regional projections. The solid black line represents the ensemble mean.

Under climate change, river flow across the 2010-12 drought is projected to decrease for the majority of catchments (Fig.10). In fast responding catchments (Clusters 1 and 2), winter river flows increase due to the projected increase in winter precipitation. In these catchments, the buffer effects of wetter winters compensate for increased evaporative demand from increased temperature. Mean discharge across the drought event for catchments in southern England and Wales is projected to decline substantially, with progressively larger declines for higher warming levels. River flow is projected to decrease in all seasons for even a 1.5°C rise in temperature with increasingly drier conditions for high warming levels, particularly for slow-responding catchments in the south (Clusters 4 and 5). In these catchments, river flow is also projected to decrease progressively over the event timescale.

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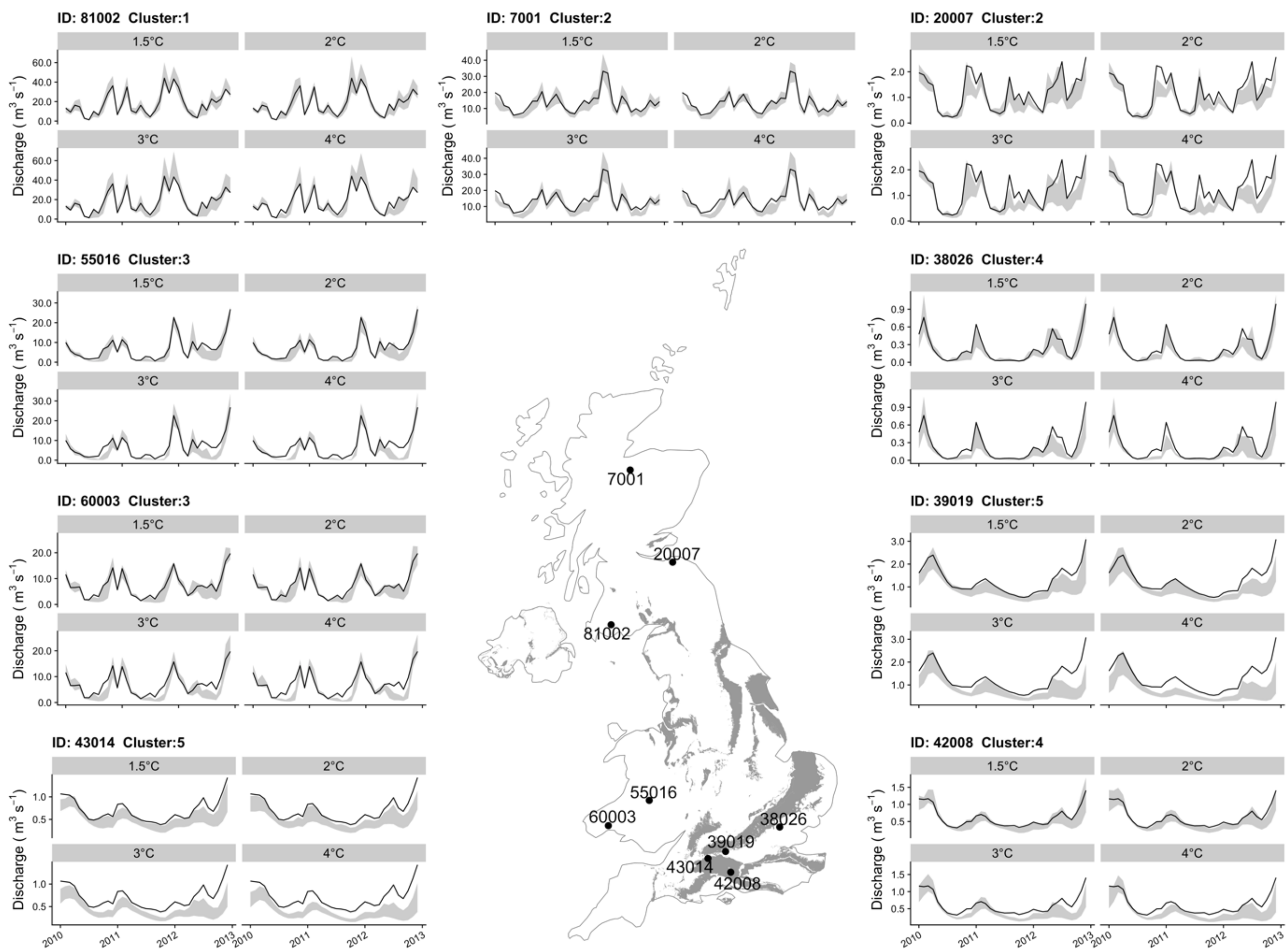

Figure 10: Projected change in river discharge across 2010-2012 at four warming levels. Nine example catchments spanning the five hydrograph clusters are presented here. The solid line represents the baseline simulation and the shaded region represents the uncertainty range of the 12 UKCP18 regional projections. Shaded regions on the map indicate the location of major aquifers.

Conditions of the 2010-12 drought are all projected to worsen with global warming across all clusters for all accumulation periods (Fig.11). Percentage change in drought characteristics relative to baseline for initial temperature rise (1.5°C and 2°C) is greater for Clusters 3-5 compared to Clusters 1 and 2. Beyond 2°C, drought characteristics are projected to worsen by a similar magnitude for all clusters except Cluster 1. The magnitude of change is larger at longer accumulation periods for Clusters 2-5, particularly notable for drought duration. Although max. intensity and mean deficit are projected to increase with temperature rise for Cluster 1, the increase in drought duration at 4°C is smaller compared to lower warming levels, indicating more intense drought conditions with greater deficit despite a smaller increase in drought duration. For SSI-12 and 24, the magnitude of change in drought characteristics is comparable between the warming levels without the clear

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progressive increase in drought characteristics seen using SSI-6. This reflects the fast response times and limited catchment memory for catchments in Cluster 1 where drought conditions may be better captured using short accumulation periods. Nonetheless, for SSI-12 and 24, mean drought deficit at 3°C and 4°C and in max. intensity at 4°C is estimated to be smaller than the change projected for lower warming levels. This anomalous behaviour is attributed to progressively wetter winters for northern Scotland, especially at high warming levels, which provide interludes to periods of drought and mitigate drought conditions of the event.

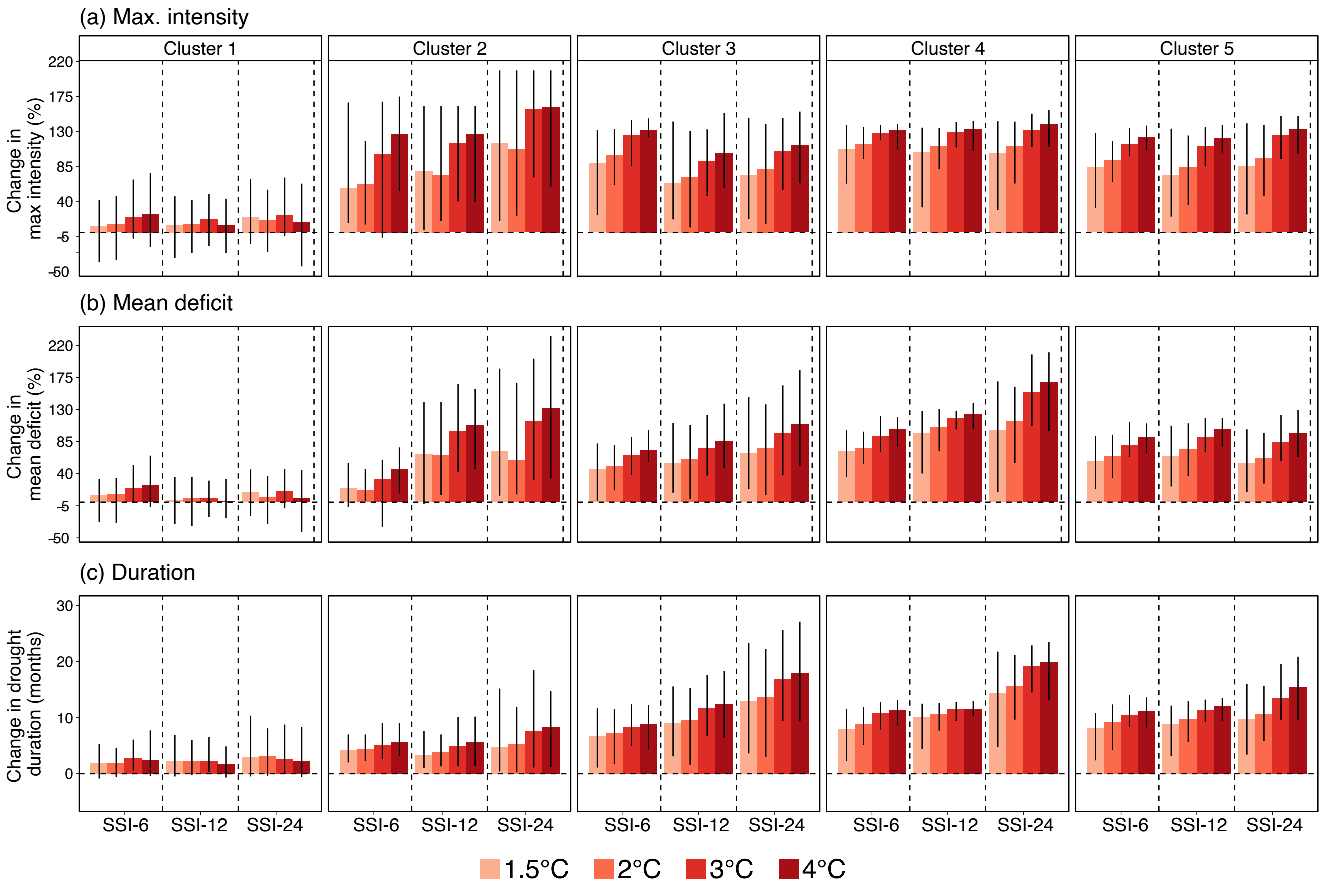

Figure 11: Mean change across the 12 UKCP18 regional projections in a) max. drought intensity (%), b) mean drought deficit (%) and c) drought duration (months) for the 2010-2012 drought across four warming levels for each cluster and SSI accumulation period. Error bar indicates spread across the 12 regional projections.

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3.6 Comparison between storylines

To place the counterfactual storylines in historical context, drought characteristics from selected storylines are compared with two past droughts. We select the benchmark 1975-76 drought and the more protracted multi-year 1989-93 drought as comparators. Both droughts rank among the most severe national-scale droughts since the 1970s (Marsh et al. 2007). Based on the characterization of severe droughts in the same set of catchments by Barker et al. (2019), the 1975-76 drought was the most severe in terms of maximum intensity and mean deficit across northeast Scotland and southern England (corresponding to Clusters 2 and 5), while the 1989-93 drought was most severe for catchments in eastern England (corresponding to Cluster 4). Four storylines are selected to compare with past droughts – 1) "Driest preconditions", 2) "Dry year before", 3) "Dry year after" and 4) 2°C warming.

Figure 12 shows percentage change in max. intensity and mean deficit of the four selected storylines relative to the same characteristics calculated for the two past droughts. First, for the 1975-76 drought, drought conditions calculated using SSI-6 are in general less severe across all four selected storylines. Cluster 1 is the exception where drought conditions match the 1975-76 drought for the "Dry year before" and "Driest precondition" storylines. When considering drought conditions at longer time scales using SSI-24, drought conditions of the four selected storylines exceed that of the 1975-76 drought for Clusters 3-5. The 2°C warming storyline (and warming levels beyond that) result in the largest increase out of the four selected storylines. For Clusters 1 and 2, drought conditions calculated using SSI-12 and 24 are less severe than the 1975-76 drought and less severe than SSI-6. The "Dry year before" storyline for Cluster 1 is the exception where drought conditions exceed that of the 1975-76 drought for SSI-24 even though catchments in this cluster are fast responding.

Second, for the 1989-93 drought, conditions across the four selected storylines are estimated to be more severe apart from Cluster 4. Catchments in Cluster 4 were the most affected during the observed 1989-93 drought and only storylines with the more extreme changes to the baseline drought could have led to similar or worse conditions than observed (i.e. "Driest preconditions" and 2°C and beyond warming). Out of the four storylines, a 2°C warming is estimated to result in the largest deviation from the 1989-93 drought for Clusters 3-5. The 2°C warming storyline is less severe for Clusters 1 and 2 where, respectively, the "Dry year before" and the "Driest preconditions" instead result in greater deviations from the 1989-93 drought. For all four selected storylines, the magnitude of change relative to the 1989-93 drought increases with accumulation period and is greatest for SSI-24 for Clusters 3 and 5, indicating the importance of catchment memory.

In summary, the four selected storylines are all capable of causing more severe drought conditions for all clusters compared with the two past droughts at different accumulation periods. Conditions across the four selected storylines are estimated to match the 1975-76 drought with comparatively more severe conditions for southern catchments at long accumulation periods. Conditions are estimated to exceed the 1989-93 drought for all clusters apart from Cluster 4 which were the most

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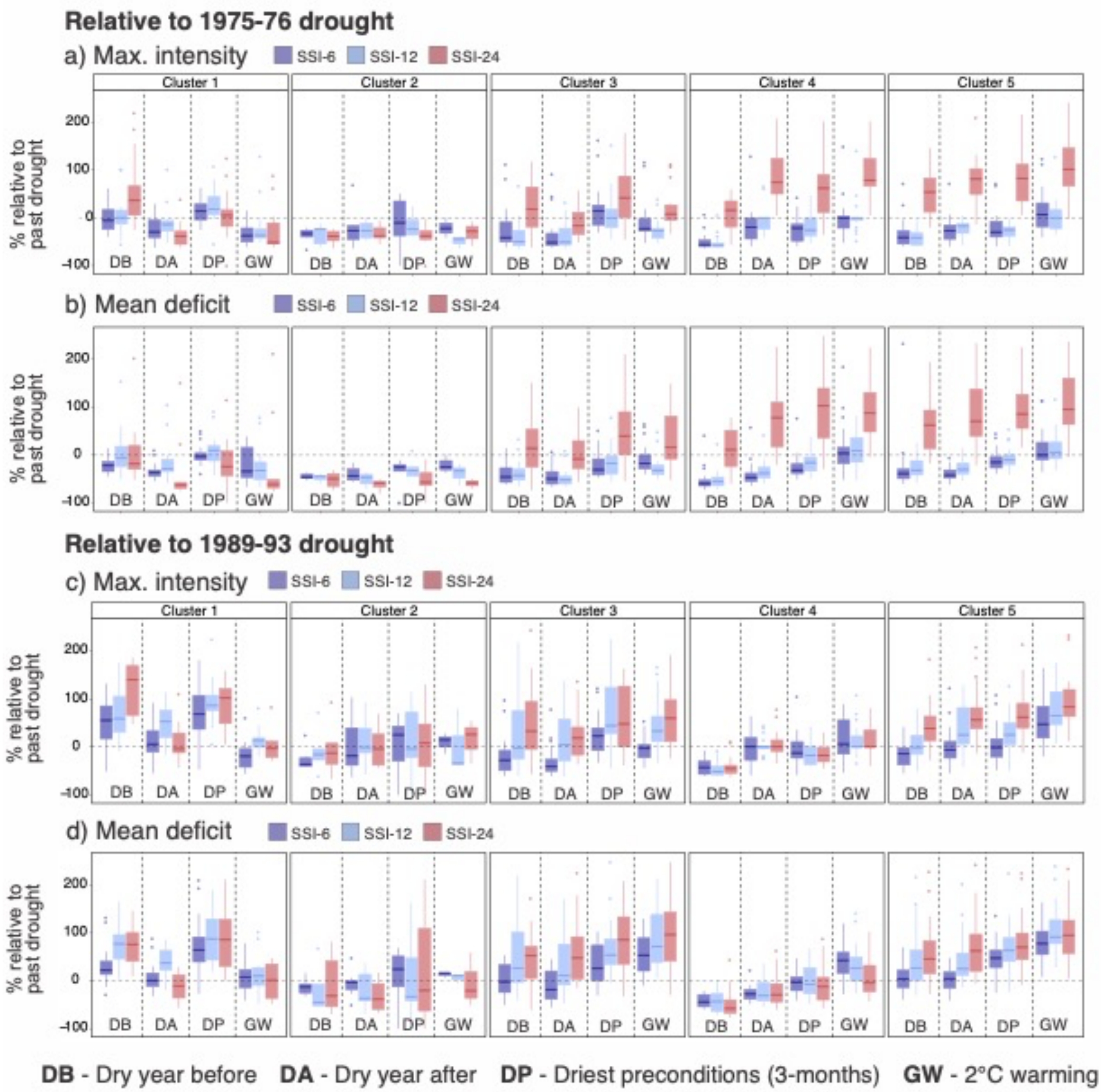
affected in the observed event. Drought conditions decrease (increase) in severity with longer SSI accumulation periods for Clusters 1-2 (Clusters 3-5).



505 **Figure 12: Percentage difference in max. intensity (a and c) and mean deficit (b and d) calculated from SSI-6, 12 and 24 of selected storylines relative to the 1976-76 drought (top) and the 1989-93 drought (bottom). Drought characteristics of the past droughts are calculated from simulated river flow using the same input data for the baseline simulation as detailed in the methods section.**

4 Discussion

4.1 Hydrological drought risk

Drought characteristics of the 2010-12 drought support the northwest/southeast gradient for drought susceptibility identified for multi-year droughts in Folland et al. (2015) and Barker et al. (2016). The five clusters correspond well with clusters identified in Barker et al. (2016), with upland catchments that were less permeable and southeastern catchments with higher storage, although the current study distinguishes an additional cluster distinguishing between catchments in southeastern and central England. Barker et al. (2016) also shown that these clusters showed significant spatial variation in meteorological and hydrological drought characteristics for severe droughts since 1891.

The storylines of precondition severity show that the sensitivity of the 2010-12 drought to progressively drier preconditions varied spatially across the selected catchments. A consideration during the creation of these storylines via the reduction of precipitation by return periods is whether they are plausible. Comparing the 12-month precipitation deficit for each precondition storyline (Fig. S1) with previous studies shows that they are within the range considered in the H++ climate change scenarios for low rainfall and droughts (Wade et al. 2015). Additionally, the resulting 12-month rainfall deficit from each return period is also comparable to the rainfall deficit increments of the drought vulnerability framework. The drought vulnerability framework forms part of the guidance for water resources planning. Statistically plausible droughts are produced using weather generator and other stochastic methods and visualized using response surfaces of incremental variation in long term average rainfall (%) and drought duration (months) (Environmental Agency 2020).

The response to drier preconditions shows that catchment recovery times vary across the clusters and can be differentiated by spatial variation in hydrogeology. The relationship between catchment recovery time and hydrogeology was also found in German catchments by Stoelze et al. (2014) and Staudinger et al. (2015), where long recovery times from worst-case recharge scenarios were found to be located at lower elevations, which are also generally flatter with the presence of porous aquifers. The spatial variation in recovery time (and hence catchment properties) confirms the importance of preconditions in determining the eventual timing and severity of the 2010-12 drought, with variation to the eventual drought characteristics between fast-responding northern and slow-responding southern catchments. Laaha et al. (2017) similarly concluded that preconditions of the preceding seasons in the 2003 and 2015 summer droughts played a crucial role in controlling the temporal and spatial dynamics, and that eventual event characteristics were modulated by both preconditions and catchment properties. Results of the storylines of seasonal contributions, in particular, highlight the often-neglected role of autumn conditions in the development of multi-year droughts. Autumn conditions over the 2010-12 drought were significant in controlling the timing of drought inception and termination, and considerably worsened drought conditions when coupled with consecutive years of dry winters.

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Table 4 summarizes hydrological drought response for the storylines of temporal sequence and climate change. Placing the various storylines in context with a relatively short-term severe drought (1975-76) and a protracted multi-year drought (1989-93) suggests that some or all of the selected storylines are estimated to result in are more severe drought conditions than the two past droughts. Conditions for all storylines could have exceeded that of both the 1975-76 and 1989-93 droughts even in catchments that were most severely affected in the observed droughts, particularly when considering long SSI accumulation periods. Comparison with the 1975-76 drought is consistent with findings in Burke et al. (2010) which placed future ensemble projections in the context of the 1975-76 drought and concluded that the likelihood of future droughts with similar characteristics to the 1975-76 drought can reach once every 10 years depending on the ensemble member considered.

Table 4: Summary of drought response for fast and slow-responding catchments in the storylines of temporal sequence and climate change

Cluster	Location	Response	Hydrological drought response
1 and 2	E and W Scotland	Fast	- **Temporal sequence:** "Dry year before" highlights risk of intense drought in immediate response under progressively drier preconditions. - **Climate change:** Drought projected to worsen with temperature rise. Change in intensity and deficit more pronounced for western Scotland. Conditions projected to be less severe at high warming levels due to wetter winters.
3	Midlands and SW England	Fast	- **Temporal sequence:** 2010-12 drought could have been more intense given an additional year with a third dry winter. "Dry year before" has a greater effect on drought characteristics although the "Dry year after" results in a greater increase in duration. - **Climate change:** drought conditions projected to worsen with temperature rise, with particularly large increase in drought duration for the longer accumulation periods.
4 and 5	SE and Central England	Slow	- **Temporal sequence:** Conditions which were already the most affected in the 2010-12 drought would have been significantly worse without the dramatic termination in 2012. Observed preconditions were already dry that the repetition of a dry year prior to the event would have made little difference. - **Climate change:** drought conditions projected to worsen with temperature rise with max. intensity and mean deficit both exceeding that of the 1975-76 drought beyond 2°C warming.

It is interesting to consider the difference between UKCP18 and other projections such as the previous UKCP09 or CMIP5. Compared to UKCP09 and CMIP5 GCMs, UKCP18 projects a slightly larger reduction/smaller increase in precipitation during summer and autumn and greater warming during summer under the RCP8.5 scenario (Lowe et al. 2018). Precipitation is also projected to increase by a smaller magnitude in the winter compared to UKCP09. Recent analysis shows that the UKCP18 projections are better able to represent the observed spatial patterns of UK heatwaves than the CMIP5 models

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(Kennedy-Asser et al. 2021). The regional projections used in the study are thus representative of worst case scenarios that track the warmer end of the full range of outcomes for the RCP8.5 scenario in CMIP5. The storylines of seasonal contribution point towards an important role of autumn in the propagation of multi-year droughts. Compared to other projections, the smaller increase in autumn precipitation projected by UKCP18 may point to increased impacts of multi-year droughts developing as a result of autumn rainfall deficit, and drier conditions entering winter which take longer to recover and are thus more susceptible to the development of multi-year droughts during dry winters.

4.2 Value of the storyline approach

The storyline approach represents a new research avenue to understand the impacts of unrealized droughts. Following the Water Act 2014, water companies are required to consider water supply reliability under plausible unobserved worst-case droughts (Environmental Agency 2015a). One method is to use hydrological models to reconstruct historic river flows. Barker et al. (2019) recently identified the spatial coverage and hydrological characteristics of key pre-1961 droughts on a national and catchment-scale. A main drawback relates to hydrological model uncertainty and non-stationarity when faced with changes in climate and land use (Spraggs et al. 2015; Barker et al. 2019). An alternative method is to resample the observed record (e.g. Environmental Agency 2015b) or generate synthetic meteorological sequences using stochastic weather generators in a response surface framework describing drought response from meteorological sequences that resemble incremental changes in certain statistical characteristics (e.g. Environmental Agency 2013). However, challenges remain to verify the plausibility of synthetically generated droughts as they do not stem from actual drought events. Additionally, weather generators have predominantly been used as tools to statistically downscale coarse GCM projections for use in catchment hydrological models. Consequently, their use is associated with challenges such as uncertainty related to multi-site generation, the choice of statistical model and selection of evaluation/verification methods (Maraun et al. 2010).

Storylines present an alternative way to consider specific scenarios reflecting stakeholder concerns on how catchments may respond in a given situation. Stoelze et al. (2020) recently advocated for a catchment-scale recharge stress test framework, similar to the storylines of precondition severity in this study, to complement climate change scenarios. When running water resources models to test management measures against long droughts by stacking multiple observed/reconstructed long duration droughts, Watts et al. (2012) emphasized that basing their analyses on actual events helped increase realism amongst decision-makers compared to stochastic or weather generator approaches. The storyline approach demonstrated here also adds towards recent proposals to increase focus on event-based case study analyses that can better consider type II errors and combine multiple lines of evidence in the construction of plausible counterfactuals to inform risk management (Lloyd and Shepherd 2020; Sillmann et al. 2021). The in-depth comparative analysis by Laaha et al. (2017) of the 2003 and 2015 summer droughts demonstrated the potential for new insights to inform water management based on event-based studies. Results from the various storylines in this study also confirm the potential of this approach to better consider and quantify worst case scenarios. For example, there were widespread concerns over water supply reliability during late 2011

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and early 2012 when multiple water companies issued drought orders and further water use restrictions in anticipation of further depletion in water resources over summer 2012 (Bell et al. 2013; Marsh et al. 2013). The "Dry year after" storyline is thus able to consider this hypothetical but plausible scenario and show that such a situation could have significantly increased maximum drought intensity with a lengthening of drought conditions, leading to potential record-breaking drought conditions compared to past severe droughts.

4.3 Limitations and future work

An event-based storyline approach can be used to assess counterfactuals of additional drought events. Additional insights may be obtained from contrasting drought events where minimum river flow occurs in different seasons (e.g. summer vs winter) or compound events associated with hydrological droughts (e.g. heatwave-driven). Storylines in this study are based on resampling and perturbing the meteorological time series of the 2010-12 drought. Future storylines could be created via weather type analysis (e.g. Richardson et al. 2018) or the use of meteorological analogues (e.g. Cattiaux et al. 2010) to provide a basis for additional plausible changes. Future work could also relate each storyline with management decisions through the use of water resource system models. This would require consideration of socio-economic factors such as agricultural activities and water abstractions in relation to changes in reservoir yields. This was not included here as the majority of the selected catchments are not major catchments contributing to public water supply. Additionally, as an extension to Smith et al. (2019) and Barker et al. (2019), this study employed the same hydrological model and parameter set to simulate hydrological response to each counterfactual storyline. To account for hydrological model structural and more explicitly consider parameter uncertainty, the use of an ensemble of hydrological models and the entire suite of LHS500 parameter sets in Smith et al. (2019) would increase robustness of the results.

5 Conclusions

This study employs an event-based storyline approach to quantify "storylines" of how the 2010-12 UK drought could hypothetically have unfolded in alternative ways. We extend previous work on historic droughts by applying the same set of hydrological models at catchments within the NRFA Low Flow Benchmark Network. Counterfactual storylines show the influence of preconditions and seasonal contributions on spatial and temporal drought development. Significant changes in drought characteristics from progressively drier preconditions highlight the importance of preconditions in controlling drought propagation and characteristics. Recovery time from dry preconditions shows that catchment recovery time reflects both the spatial variation in drought characteristics and the role of catchment properties, especially hydrogeology, in drought propagation. Catchments across the UK remain vulnerable to a "third dry winter" situation as simulated by the "Dry year before" and "Dry year after" storylines. The "Dry year before" storyline shows that northern catchments are especially vulnerable to flash droughts in immediate response to dry winter conditions. The "Dry year after" storyline shows that drought conditions in southern catchments, which were already the most affected, could still have intensified significantly

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given continued dry conditions instead of abrupt drought termination. UKCP18 climate change projections applied to the 2010-12 event point towards a decrease in mean streamflow across the majority of catchments at four global warming levels. Drought conditions are projected to intensify with temperature rise, with wetter winters for northern catchments mitigating drought conditions at high warming levels. Comparing drought characteristics of the multiple storylines shows how close the 2010-12 drought could have been to conditions observed in past severe droughts. Perturbations for all four sets of storylines could have resulted in drought conditions matching and exceeding that of both the benchmark 1975-76 and the 1989-93 droughts, particularly for catchments across southern England.

Although no probability is attached to each storyline, understanding outcomes from different storylines helps to navigate the cascade of uncertainty and reveals insights into pathways of plausible drought events that may have significant implications for water resources. Return periods for each counterfactual storyline can also be estimated in combination with historical events (e.g. through extreme value analysis) to obtain further information on the severity of the counterfactual storylines.

Author contributions

WC conducted the formal analysis and prepared the original paper. TGS, KAS, GD and NWA supervised the study and all authors contributed to the writing and interpretation of the results.

Competing interests

The authors declare no competing interests

Data availability

Precipitation data (CEH-GEAR) is freely on the Environmental Information Data Centre (Tanguy et al. 2019). Daily mean temperature (Had-UK Grid) is available from the CEDA Archive (https://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb). Daily observed river flow data is available from the National River Flow Archive (https://nrfa.ceh.ac.uk/). Calibration parameters for the GR4J hydrological model at 303 UK catchments is available from the Environmental Information Data Centre (Smith et al. 2018).

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