https://doi.org/10.5194/nhess-2023-74
Preprint. Discussion started: 11 May 2023

Natural Hazards and Earth System Sciences
Open Access
Discussions

Added value of seasonal hindcasts for UK hydrological drought outlook

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Abstract.

The UK has experienced recurring periods of hydrological droughts in the past, including the latest drought declared in summer 2022. Seasonal hindcasts, consisting of a large sample of plausible weather sequences, can be used to add value to existing approaches to water resources planning. In this study, the drivers of winter rainfall in the Greater Anglia region are investigated using the ECMWF SEAS5 hindcast dataset, which includes 2850 plausible winters across 25 ensemble members and 3 lead times. Four winter clusters were defined using the hindcast winters based on possible combinations of various atmospheric circulation indices (such as North Atlantic Oscillation, East Atlantic Pattern and the El-Niño Southern Oscillation). Using the 2022 drought as a case study, we demonstrate how storylines of the event could be created in autumn 2022 to provide an outlook of drought conditions and to explore plausible worst cases over winter 2022/23 and beyond. The winter clusters span a range of temperature and rainfall response in the Anglian region and represent circulation storylines that could have happened over winter 2022/23. Although winter 2022/23 has now passed, we aim to demonstrate the added value of this approach to provide outlooks during an ongoing event with a brief retrospective of how winter 2022/23 transpired. Storylines created from the hindcast winters were simulated using the GR6J catchment hydrological model and the groundwater level model Aquimod at selected catchments and boreholes in the Anglian region. Results show that drier than average winters characterised by predominantly NAO-/EA- and NAO+/EA- circulation patterns would result in the continuation of the drought with a high likelihood of below normal to low river flows across all selected catchments and boreholes by spring and summer 2023. Catchments in Norfolk are particularly vulnerable to a dry summer in 2023 as river flows are not estimated to recover to normal levels even with wet La Niña winters characterised predominantly by NAO-/EA+ and NAO+/EA+ circulation patterns due to insufficient rainfall to overcome previous dry conditions and the slow response nature of groundwater-dominated catchments. Storylines constructed in this way provide outlooks of ongoing events and supplement traditional weather forecasts to explore a wider range of plausible outcomes.

1 Introduction

The United Kingdom has experienced recurring periods of hydrological droughts in the past (Marsh et al. 2007; Barker et al. 2019). This includes the latest drought declared in summer 2022 (Parry 2022). Planning against a wide range of plausible outcomes is of interest to water resources planners. Water companies are required to outline demand and supply management actions in their drought plans and to prepare for the application of drought permits and drought orders during an event (Defra 2021). During a drought, demand management measures may include temporary use bans (TUBs) and non-essential use bans (NEUBs). Should a drought worsen and river flows remain low, water companies must demonstrate serious deficiency of supplies due to exceptional shortage of rainfall to apply for drought permits and drought orders to enable continued abstraction as detailed in water company drought plans (e.g. Anglian Water Drought Plan 2022).

The approach taken to plan for ongoing events differs between water companies but existing approaches can be separated into three strands. First, weather forecasts are used for operational drought forecasting. For example, the ECMWF SEAS5 forecasts provide seasonal (up to 6 months) forecasts which can be used as input to hydrological models at a small number of catchments. Other forecasting methods are also applied in practice. This includes persistence forecasts based on flow anomaly in the most recent month and historical analogue forecasts using the most similar historical sequences as employed in the UKCEH Hydrological Outlook (Svensson 2016). Second, plausible trajectories of river flows can be created through catchment hydrological model simulations assuming that rainfall over the next month reaches a specific percentage of long term average (LTA) rainfall (e.g. 60%, 80% or 100% of LTA). This approach is taken by the Environment Agency in their monthly water situation reports (e.g. Environment Agency 2022). Third, outlooks can be provided using information from historical climate, either by assuming the repetition of individual notable historical years (such as benchmark events like 1975-76 or La Niña drought years like 2011) or by repeating all available years in an Ensemble Streamflow Prediction approach such as that taken by the UKCEH Hydrological Outlook (Harrigan et al. 2018).

River flows, groundwater aquifers and reservoirs are often replenished from winter rainfall. Winter rainfall is determined by atmospheric circulation, usually the variability in position and strength of the North Atlantic jet stream. Previous research has found a positive correlation between the North Atlantic Oscillation (NAO) and winter rainfall, particularly for western UK with more storms over northern Europe (e.g. Svensson et al. 2015; Hall and Hanna 2018). For southeast and eastern England, studies have found that variability of winter rainfall arises from the combined influence of various circulation indices, particularly the East Atlantic (EA) pattern which can either enhance or dampen the surface temperature and rainfall response to the NAO (Mellado-Cano et al. 2019; West et al. 2021). Previous research by Emerton et al. (2017) has highlighted the role of ENSO in streamflow variability showing that low flows during winter months across the UK are more likely during La Niña. ENSO can also influence the NAO and other circulation anomalies which can lead to negative winter rainfall anomalies in southern England with past multi-year meteorological droughts featuring dry winters often coinciding with La Niña conditions (Folland et al. 2015). In particular, the Anglian region is particularly vulnerable to prolonged dry weather and droughts as it is the driest region in the UK, receiving only 71% of the average UK annual rainfall (Anglian Water Drought Plan 2022). The specific aims of this study are to:

- Investigate the drivers of winter rainfall for the region of eastern England supplied by Anglian Water using a large sample of plausible winters from the ECMWF seasonal forecasting system SEAS5
- Use knowledge of winter rainfall drivers (e.g. atmospheric circulation patterns) to produce conditional storylines representing plausible winter trajectories based on various combinations of atmospheric circulation patterns
- Create drought outlooks of river flows and groundwater levels for a case study event (the 2022 drought) following each storyline for winter 2022/23 and beyond and calculate drought characteristics (e.g. mean deficit and maximum intensity).

2 Data and methods

2.1 Hindcast data and model fidelity

The SEAS5 hindcast dataset (1982-2021) is used to provide a large sample of plausible winters (Dec, Jan, Feb - DJF). In total, there are 2850 winters in the hindcast dataset across 25 ensemble members and three lead times (Sep, Oct and Nov) (comprising of 38 complete winters between 1983 and 2020 x 25 ensemble members x 4 lead times). Each ensemble member is perturbed with different initial atmospheric and ocean initial conditions (Johnson et al. 2019) This approach follows the UNSEEN framework in Thompson et al. (2017) where a large ensemble of model simulations is used to explore plausible events that could have happened as well as unprecedented events. The credibility of the hindcast winters is tested using the model fidelity test in Thompson et al. (2017) by comparing the statistical moments of observed rainfall with 10,000 subsamples of the SEAS5 modelled rainfall (Figure 1a). After scaling the modelled rainfall to match observed mean winter rainfall, SEAS5 winters over the Anglian Water region are deemed statistically indistinguishable from the observations as the four statistical moments of the observed winter rainfall lie within 95% of the distribution of the respective statistical moments from the subsamples of hindcast winters. Whilst this is guaranteed for the mean due to the scaling, it is not necessarily the case for the three other moments. Additional tests on ensemble member stability and independence were conducted following Kelder et al. (2020, 2022) Stability refers to the potential for ensemble members to drift towards their (biased) climatology from their observation-based initial conditions, and can be assessed by comparing the distribution of simulated variables across lead times (Figure 1b). Independence refers to whether individual ensemble members for each lead time are independent of each other and can be assessed by calculating the Spearman rank correlation of modelled rainfall for every distinct pair of ensemble members

(Figure 1c). The tests show no evidence of model drift and that the ensemble members are independent of each other across the different lead times.

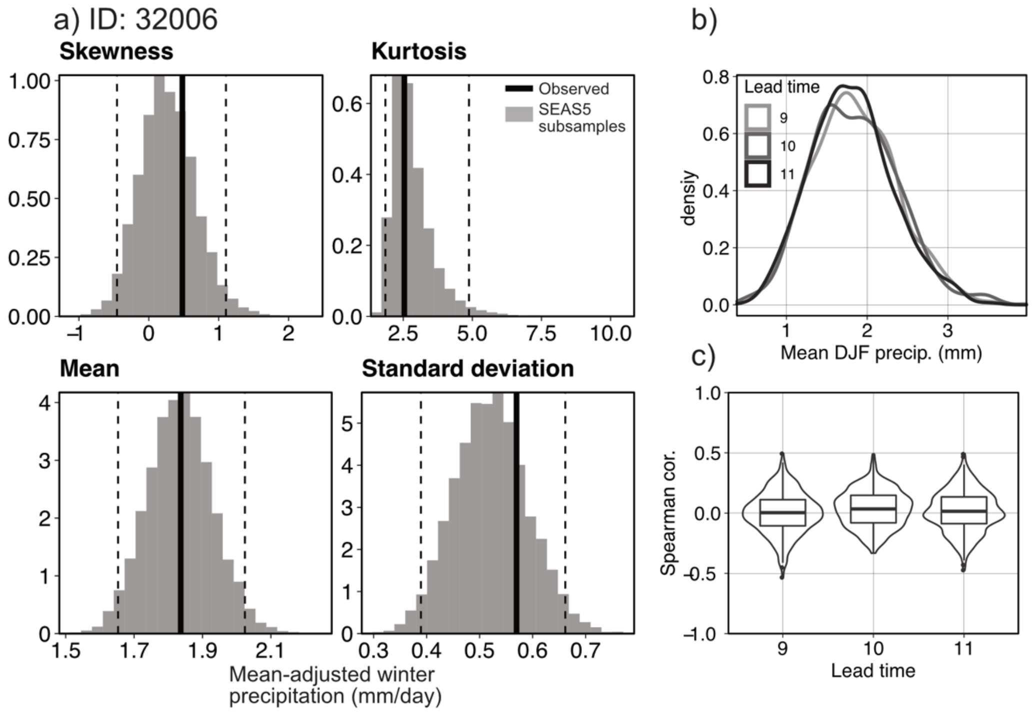

Figure 1: Example of the model fidelity test for one catchment (ID: 32006). a) The statistical moments of observed DJF rainfall and of 10,000 subsamples of the modelled rainfall in SEAS5. Hindcast winters are scaled to match the mean observed rainfall. b) Test for model stability and c) ensemble member independence across three lead times.

2.2 Drivers of dry winters

A series of meteorological indices describing atmospheric circulation patterns are calculated from both observed winters (ERA5 reanalysis - 1960-2015) and for each winter in the hindcast dataset. The North Atlantic Oscillation (NAO) index and the East Atlantic (EA) index are represented by the first two leading modes calculated through empirical orthogonal functions (EOF) analysis using monthly mean sea level pressure anomalies in the European/North Atlantic region. The Niño3.4 index is calculated from average sea surface temperature anomalies in the region (5°S-5°N, 120-170°W) to represent the phase of the El-Niño Southern Oscillation (ENSO). Figures 2(a)-(c) show the relationship between rainfall anomalies over the Anglian Water region for both observed and hindcast winters with the average winter Niño3.4, NAO and EA index. There is no clear relationship between ENSO phase and rainfall anomalies. There is a negative (positive) relationship with the NAO (EA) index. For each winter between 1982 and 2020, there are 75 simulated winters in the hindcasts across ensemble members and lead times. There is considerable variability in the NAO and EA phases across the hindcast winters each year which often spans the four possible combinations of NAO and EA (hence high variability in rainfall anomalies). Conversely, there is little variability in ENSO phase across the hindcast winters for each year as ENSO is comparatively slowly evolving and hence more predictable several months ahead. For example, winters 2015/16, 1997/98 and 1982/83 all exhibited particularly strong El Niño conditions and the hindcasts issued prior to each of those winters all had a similarly high Nino3.4 index value (as shown by the vertical cluster of points in Figure 2a). Figure 2d shows the rainfall anomalies associated with combination of NAO and EA phases. NAO+/EA- are most likely associated with drier than average conditions and NAO-/EA+ winters with wetter than average conditions although there are also outliers with notable dry winters in both the observations and the hindcast. The relationships between rainfall and meteorological indices for the hindcast winters is consistent with past work showing the influence on UK rainfall arising from opposing phases of the NAO and EA in the observations (e.g. West et al. 2021, 2022; Parry et al. 2012).

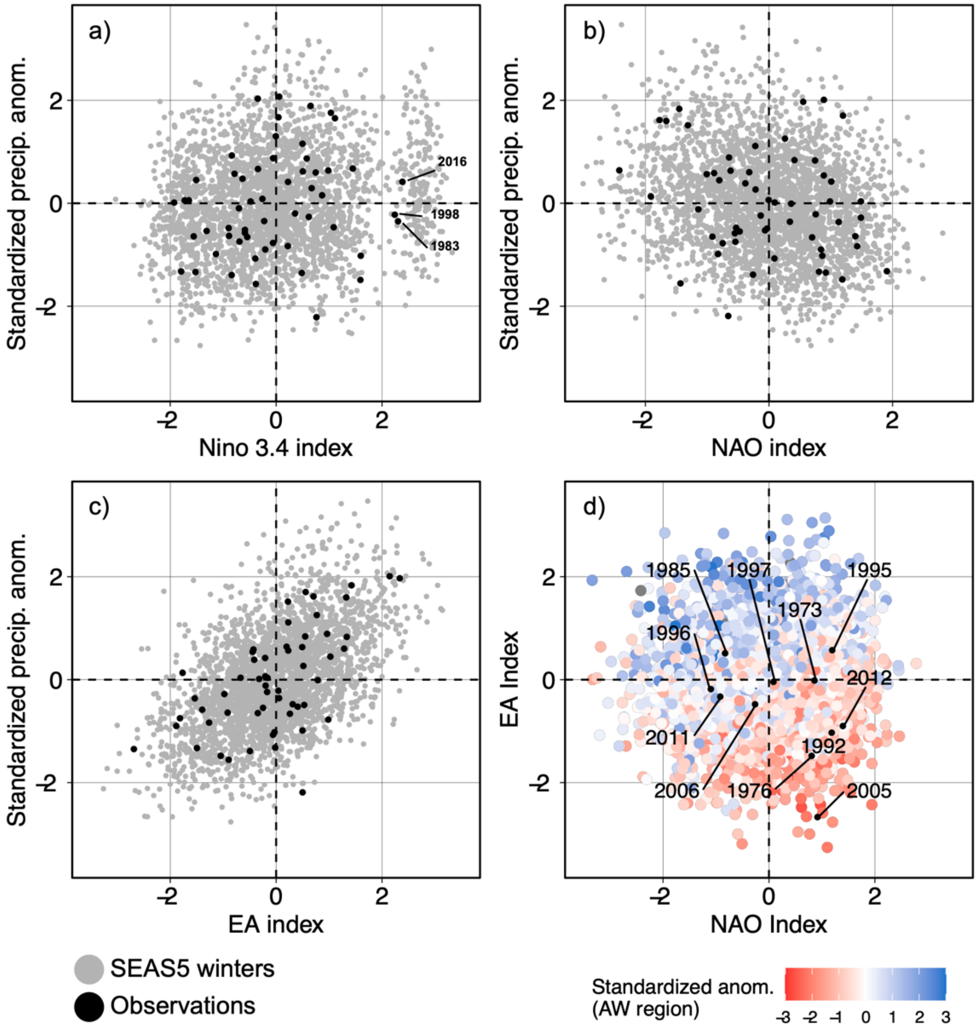

Figure 2: Relationship of a) Niño 3.4, b) NAO, and c) EA index with standardised rainfall anomalies in the Anglian Water region for the SEAS5 winters (grey) and observed winters (black). Panel d) shows the NAO index and EA index for each SEAS5 winter

together with the rainfall anomalies over the Anglian Water (AW) region associated with each winter (colours). The cluster of strong El Niño hindcast winters in panel a) relate to hindcast winters issued prior to winters 2015/16, 1997/98 an 1982/83 (black dots in panel a), which were three of the strongest El Niño winters in the observations. Selected dry winters in the observations are shown in panel d) by the black dots and the year labels.

2.3 Meteorological indices and circulation storylines

In addition to the NAO, EA and ENSO, additional indices were calculated to explore polar vortex strength (defined as average wind speed (U10) at 60°N) and sea surface temperatures (SST tripole index – Fan and Schneider 2012). K-means clustering of all the calculated indices are used to create clusters with similar characteristics. Winter clusters are created separately for La Niña and El Niño winters but subsequent hydrological modelling was only completed for La Niña winters given the La Niña conditions observed over 2022. Figure 3 shows four clusters defined for La Niña winters in the hindcast. The clusters show little difference between El Niño and La Niña for clusters 1 and 3 but La Niña winters are in general drier than El Niño winters for clusters 2 and 4 (Figure S1), which are associated with NAO+ conditions and a strong polar vortex (Figure 3). Temperature anomalies associated with each cluster are shown in Figure S2. Four clusters are chosen as they primarily reflect the four possible combinations of opposing phases of the NAO and EA which have been shown to have distinct signatures for rainfall over southeast England (West et al. 2021), including where opposing phases of the EA pattern may reverse the rainfall signal given a particular NAO phase (Mellado-Cano et al. 2019). The clusters also consider the range of circulation response and climate anomalies such as changes in polar vortex strength. Using the same SEAS5 hindcasts, Kolstad et al. (2022) showed the wide range of winter surface temperature responses that can arise from a given vortex state due to confounding factors such as NAO and ENSO. Clusters 1 and 2 (3 and 4) are generally associated with drier (wetter) than average rainfall over the Anglian Water region although drier than average winters can occur for all clusters. This is exemplified by the fact that notable dry winters in the observations have exhibited characteristics of all four clusters (Figure 4). The observed dry winters of 2011/12 and 1975/76 closely resemble the composite mean sea level pressure anomalies of clusters 1 and 2, respectively. For clusters 3 and 4, the composite mean shows low pressure over the British Isles, resulting in generally wetter winters . Observed winter 1984/85 resembles cluster 3 but with an extension of the high pressure eastwards with the pressure centre over Scandinavia leading to drier than average conditions in eastern England. Similarly, winter 1972/73 resembles the composite mean for cluster 4 but with a northward extension of the high pressure over southern UK.

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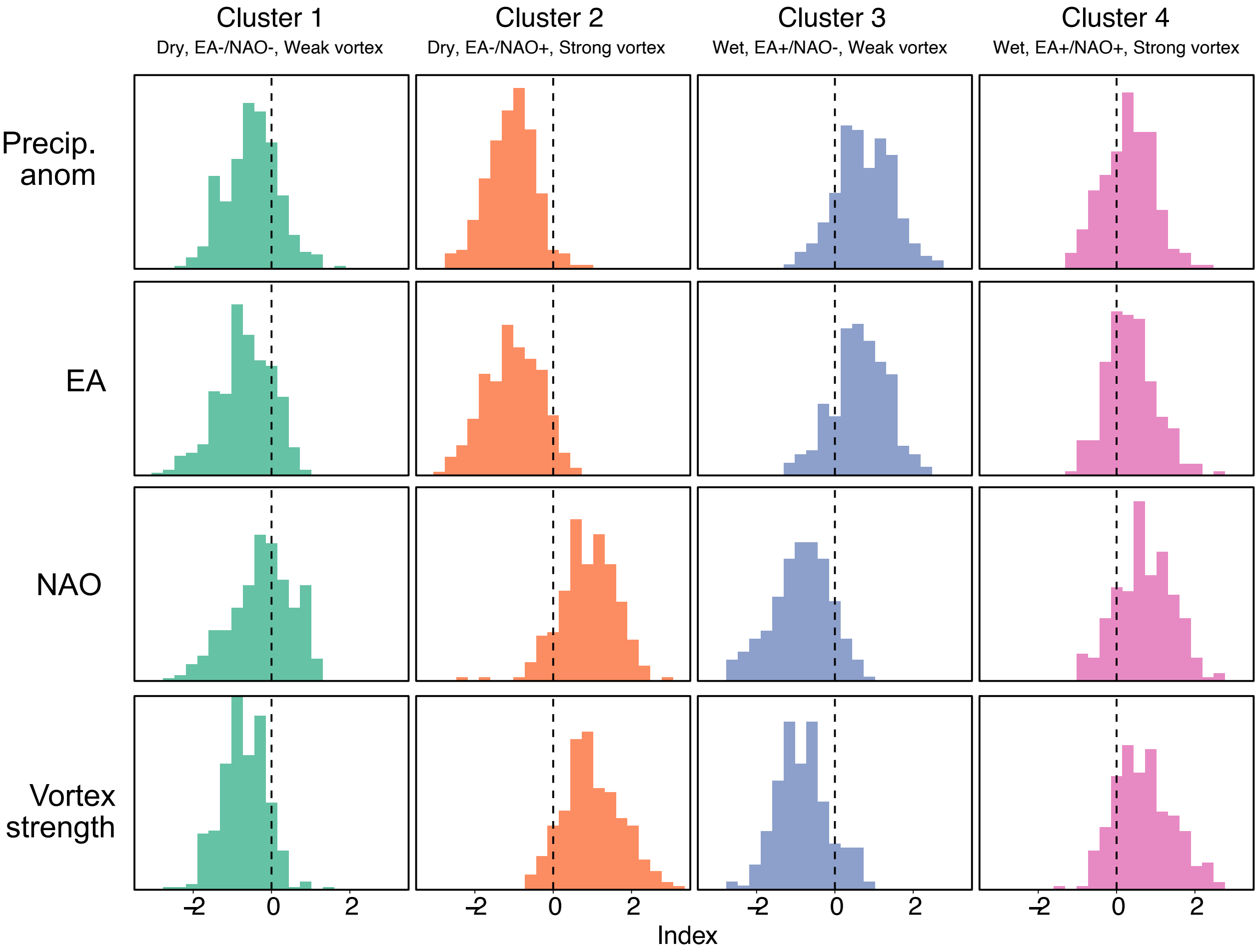

Figure 3: Winter clusters defined from hindcast winters with La Niña conditions using k-means clustering and the rainfall anomalies and meteorological indices associated with each cluster.

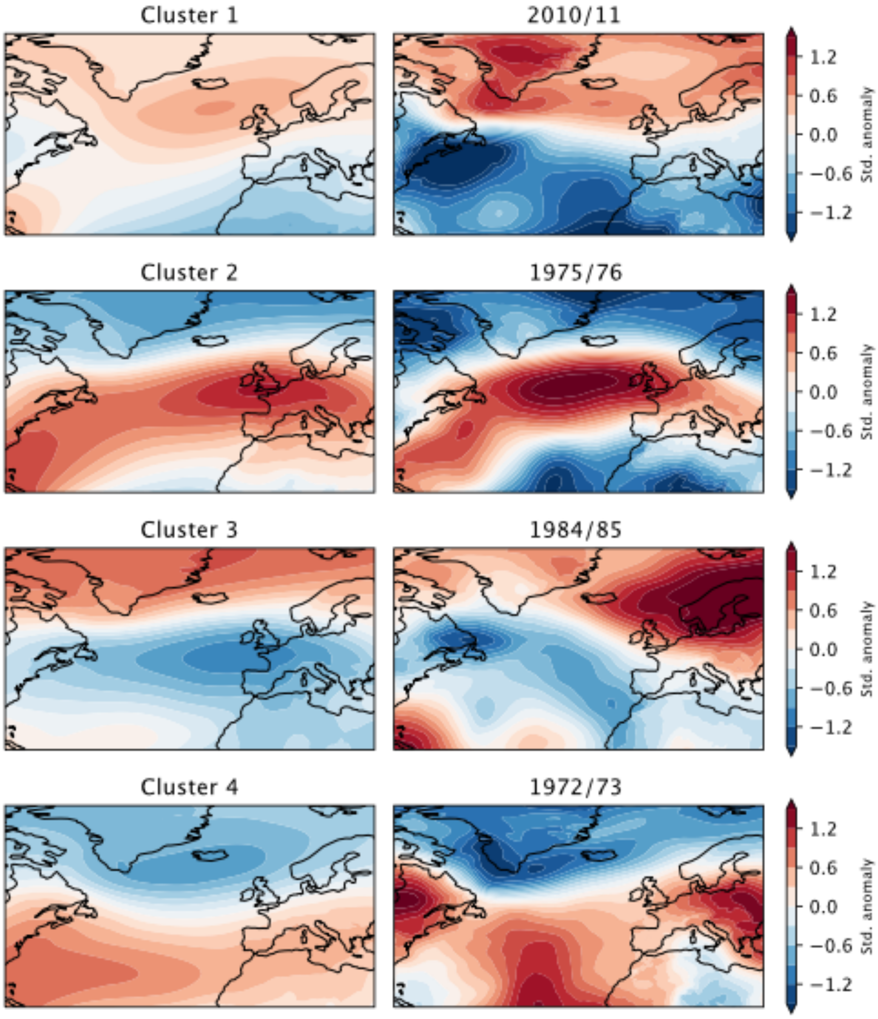

Figure 4: Composite mean sea level pressure (SLP) anomalies (relative to ERA5 1960-2015) for the four circulation storylines and SLP anomalies for selected dry winters from ERA5 associated with similar patterns for each cluster.

2.4 Study catchments and hydrological modelling

The GR6J hydrological model was used to simulate river flows at 16 river catchments within the Anglian Water region (Table 1). The selected catchments include key abstraction catchments and catchments that supply reservoirs operated by Anglian Water. GR6J is a lumped catchment hydrological model with six parameters for calibration and is designed for low flow simulation, particularly over groundwater dominated catchments (Pushpalatha et al. 2011). Aquimod, a lumped groundwater level model developed by the British Geological Survey (Mackay et al. 2014), was used to simulate groundwater levels at 10

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boreholes (Table 2). Both GR6J and Aquimod are increasingly used in research and industry, including by Anglian Water operationally for their drought forecasts and long-term water resources planning (Anglian Water Drought Plan 2022).

Daily observed mean catchment-averaged rainfall (CEH-GEAR dataset – Tanguy et al. 2021) and potential evapotranspiration (PET) calculated from temperature (HadUK-Grid dataset – Hollis et al. 2019) were used to drive the hydrological model over the baseline period (1982-2014) for model calibration. PET was calculated following the method presented in Tanguy et al. (2018) using the McGuinness-Bordne temperature-based equation calibrated for the UK. A temperature-based method to calculate PET was chosen as such methods are relatively simple to apply and are regularly used by water companies for drought forecasting. The standardised streamflow index (SSI) was calculated for each storyline to consider drought intensity. SSI over various accumulation periods was calculated by fitting a tweedie distribution to monthly simulated river flows following Svensson et al. (2017). GR6J was calibrated individually for each catchment across the baseline period via the multi-objective approach set out in Smith et al. (2019). In short, 10,000 parameter sets were generated via Latin Hypercube Sampling and ranked based on model performance metrics that compare simulated and observed river flows. The model performance metrics selected include Nash-Sutcliffe Efficiency (NSE), NSE of logarithmic flows, absolute percentage bias, percentage error in Q95 (low flows) and percentage error in mean annual minimum (30-day averaged) flow. Observed and simulated river flows at six example catchments over the baseline period and observed and simulated standardised streamflow index accumulated over 3-months (SSI-3) are shown in Figures S3 and S4 respectively. Aquimod was driven by rainfall and PET averaged across the closest 40km MORECS grid to the borehole location (Hough and Jones 1997) in the same way as employed operationally by Anglian Water. A Monte Carlo parameter sampling approach was used to generate a random set of parameters and model performance was assessed using NSE (Mackay et al. 2014). The model was previously calibrated for the selected borholes (Bunting et al. 2020) and the top parameter set from that study was used here.

Table 1: Details of the selected catchments within the Anglian Water region. The National River Flow Archive (NRFA) station id, station name, latitude, longitude, baseflow index (BFI) and the Nash-Sutcliffe Efficiency of logarithmic flows (logNSE) for the top performing parameter set are provided.

NRFA station id	Station	Latitude	Longitude	Baseflow Index	logNSE
37024	Colne at Earles Colne	51.94	0.70	0.43	0.69
31007	Welland at Barrowden	52.59	-0.60	0.50	0.76
33026	Bedford Ouse at Offord	52.29	-0.22	0.51	0.75
37005	Colne at Lexden	51.90	0.85	0.52	0.78
31010	Chater at Fosters Bridge	52.62	-0.58	0.53	0.82
33035	Ely Ouse at Denver Complex	52.58	0.34	0.57	0.68

32006	Nene at Upton Total	52.23	-0.95	0.58	0.82
32010	Nene at Wansford	52.58	-0.41	0.60	0.84
34014	Wensum at Swanton Morley Total	52.73	0.99	0.75	0.88
34004	Wensum at Costessey Mill	52.67	1.22	0.76	0.81
33019	Thet at Melford Bridge	52.41	0.76	0.78	0.83
33006	Wissey at Northwold Total	52.54	0.61	0.82	0.84
34011	Wensum at Fakenham	52.83	0.85	0.82	0.84
33029	Stringside at Whitebridge	52.58	0.53	0.84	0.76
33007	Nar at Marham	52.68	0.55	0.90	0.82
29003	Lud at Louth	53.37	0.001	0.90	0.74

Table 2: Details of the selected groundwater boreholes within the Anglian Water region. The Environment Agency code, borehole name, latitude, longitude and the Nash-Sutcliffe Efficiency (NSE) score for the top performing parameter set are provided. NSE is calculated over the period when observational records area available and based on Bunting et al. (2020).

Environment Agency code	Observation borehole	Latitude	Longitude	MORECS grid	NSE
TM04/695	Castle Farm	52.10	1.01	141	0.79
TL65/050	Dullingham	52.21	0.36	140	0.78
1/610	Grange de Lings	53.29	-0.53	108	0.76
5/108	Horkstow Rd Barton	53.67	-0.45	101	0.59
2/544	Leasingham	53.02	-0.43	118	0.71
TG13/765A	Old Hall Thurgarten	52.89	1.23	120	0.51
TL66/094	Springhead Farm	52.25	0.34	140	0.70
2/566	Stow to Oakholt	53.21	-0.43	109	0.80
TL76/110	Tank Hall	52.26	0.54	140	0.77
TF 81/010	Washpit Farm	52.74	0.69	130	0.78

The storyline approach is increasingly used to describe and quantify pathways and unfoldings of past or future events conditioned on plausible changes to the event's drivers (Shepherd et al. 2018). In this study, storylines were created in autumn 2022 without prior knowledge of the winter 2022/23 to represent plausible pathways of the 2022 drought assuming winter 2022/23 resembled each of the four winter clusters. Although winter 2022/23 has now passed, we aim to demonstrate the added

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value of this approach to provide outlooks during an ongoing event. A brief exploration of the observed winter 2022/23 is provided in the discussion (Section 4). Storylines were simulated by running GR6J and Aquimod using the top parameter set for the baseline period up until November 2022 after which hindcast rainfall and PET data for each winter (DJF) in the four winter clusters were appended in place of winter 2022/23. Following the procedure employed by Anglian Water for operational drought forecasting, the hindcast winter rainfall was bias-adjusted for each catchment using quantile mapping (initiated via the *qmap* R package – Gudmudsson 2016) and scaled to match monthly mean observed catchment-averaged rainfall. Spring (MAM), summer (JJA) and autumn (SON) 2023 were assumed to have 100% long term average (LTA) rainfall by selecting the closest years matching 100% LTA rainfall in the observations. To understand the importance of winter rainfall and the effect of a second consecutive dry summer, an additional sensitivity test assumed summer (JJA) 2023 to follow 60% LTA seasonal rainfall.

3 Results

3.1 Storylines of the 2022 drought

3.1.1 River flows

The 2022 drought is characterised by a dry spring-summer sequence (51% of LTA MAMJJA rainfall in East Anglia). The drought also followed an unusual pattern of rainfall in winter 2021/22 with average rainfall in December 2021, settled and dry conditions in January 2022 and wetter than average conditions in February 2022. Total winter rainfall was slightly below normal across East Anglia with drier conditions concentrated in the southeast of the region (e.g. southeast Suffolk). Exceptional soil moisture deficits during the summer 2022 heatwave also exacerbated drought conditions. The Anglian Water region experienced slightly above average rainfall in autumn 2022 (117% of LTA) which saw recovery of river flows at some catchments. Above average rainfall was mostly concentrated in western parts of the region with river flows in the northeast remaining below normal entering winter 2022/23 (Environment Agency 2022). Figure 5 shows simulated river flow response over winter 2022/23 for each circulation storyline. All catchments were estimated to experience below normal river flows when entering spring 2023 given winters in clusters 1 and 2 with particularly severe flow deficits in groundwater-dominated catchments in the northeast of the region. Despite the wetter weather for winters in clusters 3 and 4, the groundwater-dominated catchments in the northeast were still estimated to experience below normal to low flows by spring 2023. This was likely due to the combined effect of insufficient winter rainfall to overcome dry conditions and the slow response nature of groundwater-dominated catchments. The outlook for each storyline is contrasted with the unclustered outlook of flows across all 2850 winters, analogous to the traditional ESP approach (Figure S5). Using all 2850 winters highlight the confidence of below normal flows in the northeast but does not consider the dynamical drivers of winter rainfall that could lead to a different likelihood of possible flow response as shown in the conditional subsets of each storyline.

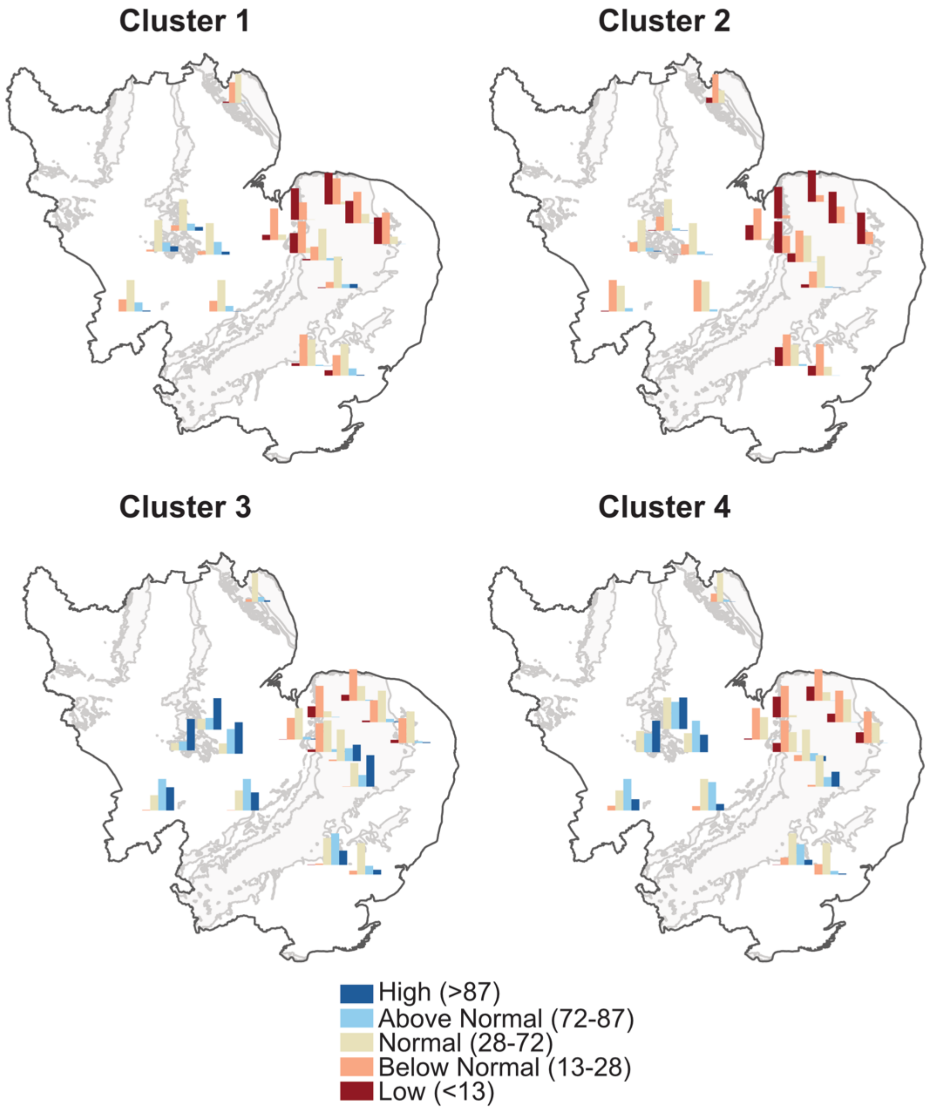

Figure 5: Outlook of river flows for each storyline represented in percentile terms relative to 1965-2015. Each storyline assume winter 2022/23 follows hindcast winters in one of the La Niña winter clusters. Individual plots show the distribution of hindcast winters for each percentile category as indicated by the colour key. Grey shading shows major aquifers in eastern England from the hydrogeology map of the British Geological Survey (https://www.bgs.ac.uk/datasets/hydrogeology-625k/).

Figure 6 compares drought evolution (characterised by the standardised streamflow index accumulated over 3 months – SSI-3) during 1975-76 and 2021-22 with storyline estimates of SSI-3 for 2023 for four example catchments. Similar to 2022, 1976 was characterised by a dry spring-summer sequence (50% LTA rainfall in East Anglia). The decline to drought conditions in 2022 was generally later in the year and less severe with river flows generally recovering later in the autumn compared to 1975-76. Outlooks from the driest (cluster 2) and wettest (cluster 3) storylines show the continued vulnerability of catchments in the Anglian Water region in 2023. For groundwater dominated catchments such as the Nar at Marham (33007) and Ely Ouse at Denver Complex (33035), drought intensity could plausibly match that seen in summer 1976 by summer 2023 given a dry winter in cluster 2 (mostly associated with NAO+/EA-). For these catchments, drought conditions could plausibly decline to similar drought intensity as seen in summer 2022 even with a wet winter in cluster 3 (mostly associated with NAO-/EA+). 245

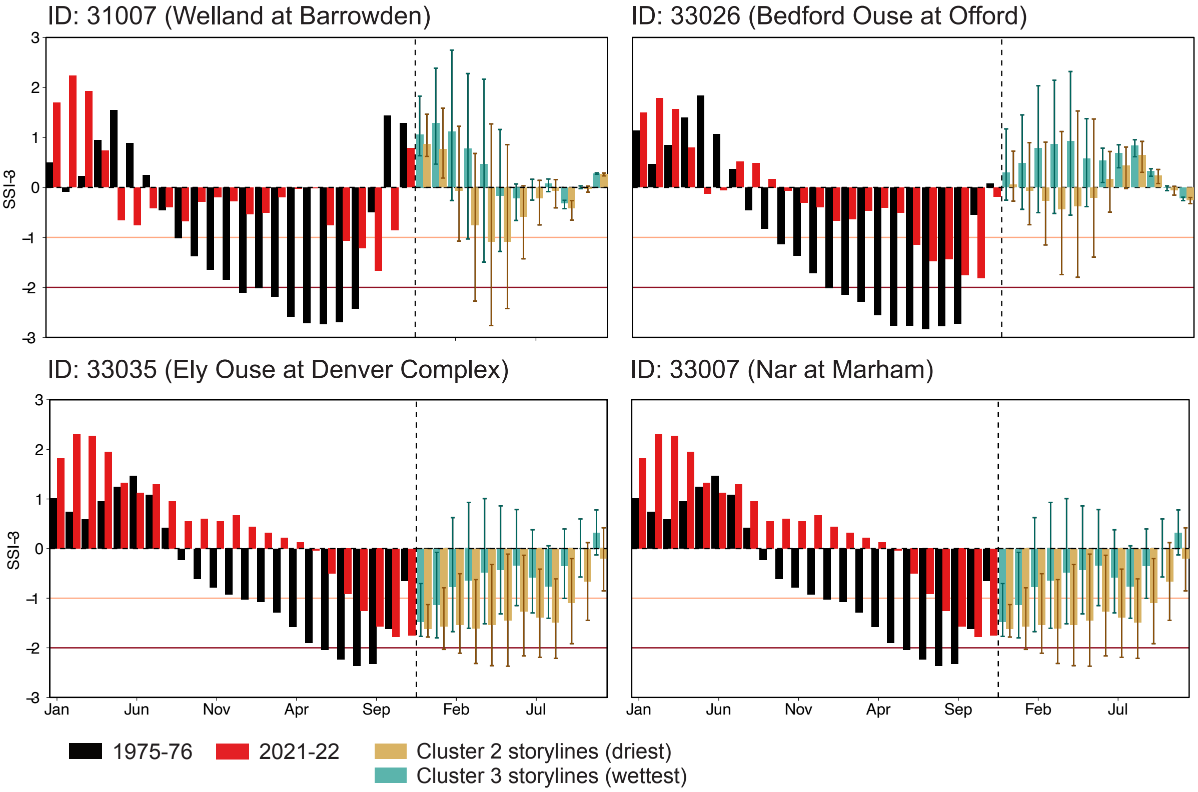

Figure 6: Standardised streamflow index accumulated at 3-months (SSI-3) over 2021-2022 and beyond following the driest and wettest circulation storyline at four example catchments compared with SSI-3 over 1975-1976. Spring to autumn 2023 is assumed to have 100% LTA rainfall.

250 3.1.1 Groundwater

Figure 7 shows an outlook of groundwater levels given each circulation storyline. Given drier winters in clusters 1 and 2, groundwater levels were estimated to be normal to below normal across all boreholes by spring 2023. Wetter conditions over winter associated with circulation patterns in clusters 3 and 4 were estimated to lead to groundwater level recovery to above normal levels, particularly for boreholes in Lincolnshire as groundwater levels at these relatively faster responding boreholes 255 were already recovering after sufficient rainfall in autumn 2022. Similar to the pattern for some slow-responding river catchments in East Anglia, some boreholes in East Anglia (such as Washpit Farm and Old Hall Thurgaton) were still estimated to have a high likelihood of remaining at below normal levels by spring 2023 even with the wetter conditions from winters in clusters 3 and 4.

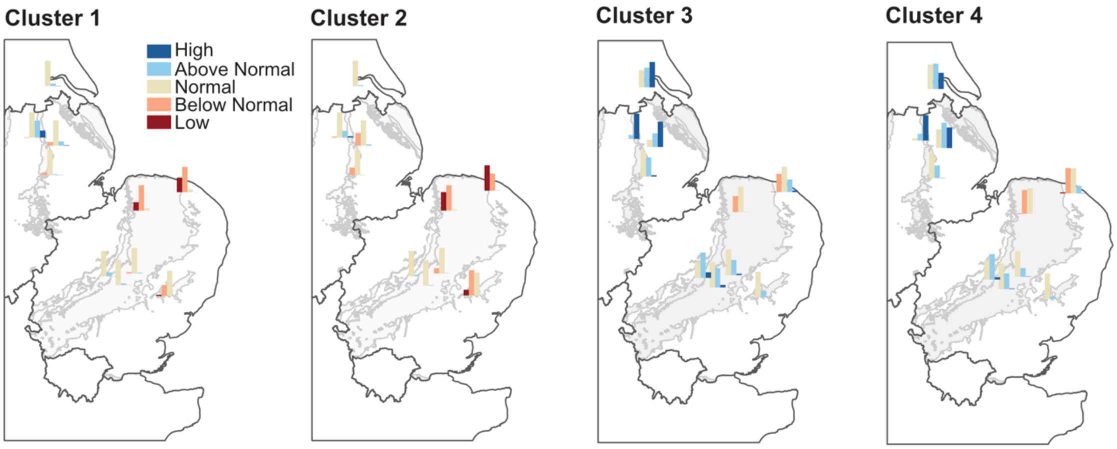

Figure 7: Outlook of groundwater levels for each borehole in different categories (percentiles relative to 1965-2015) by spring 2023 for each storyline. Individual plots show the distribution of hindcast winters for each percentile category as indicated by the colour key in Figure 3. Grey shading shows major aquifers in eastern England from the hydrogeology map of the British Geological Survey (https://www.bgs.ac.uk/datasets/hydrogeology-625k/).

3.2 Influence of spring and summer 2023

Figure 8 shows the influence of a second consecutive dry summer in 2023 on the development of severe drought conditions (SSI-3 < -1.5). An accumulation of three months is used here to provide an indication of the shorter-term seasonal effects. The effect of SSI accumulated over a longer time period at 12-months is shown in Figure S6. Slow responding catchments are more influenced by the effect of a dry winter in clusters 1 and 2 with a comparatively higher likelihood of reaching severe conditions. A dry summer with 60% LTA rainfall (similar to summer 2018) results in a higher likelihood for severe drought conditions to develop, especially following a dry winter characterised by circulation patterns in clusters 1 and 2. Given the higher likelihood of a wetter than average winter in clusters 3 and 4, fewer catchments reach severe drought conditions if summer 2023 receives 100% LTA rainfall. For groundwater-dominated catchments, it is likely that severe drought conditions will be reached even with 100% LTA rainfall in summer 2023 across all four storylines, even for clusters 3 and 4 with wetter than average winters. This is reflected previously in Figure 6, showing that river flows were estimated to be unlikely to recover to normal levels for all four storylines.

https://doi.org/10.5194/nhess-2023-74
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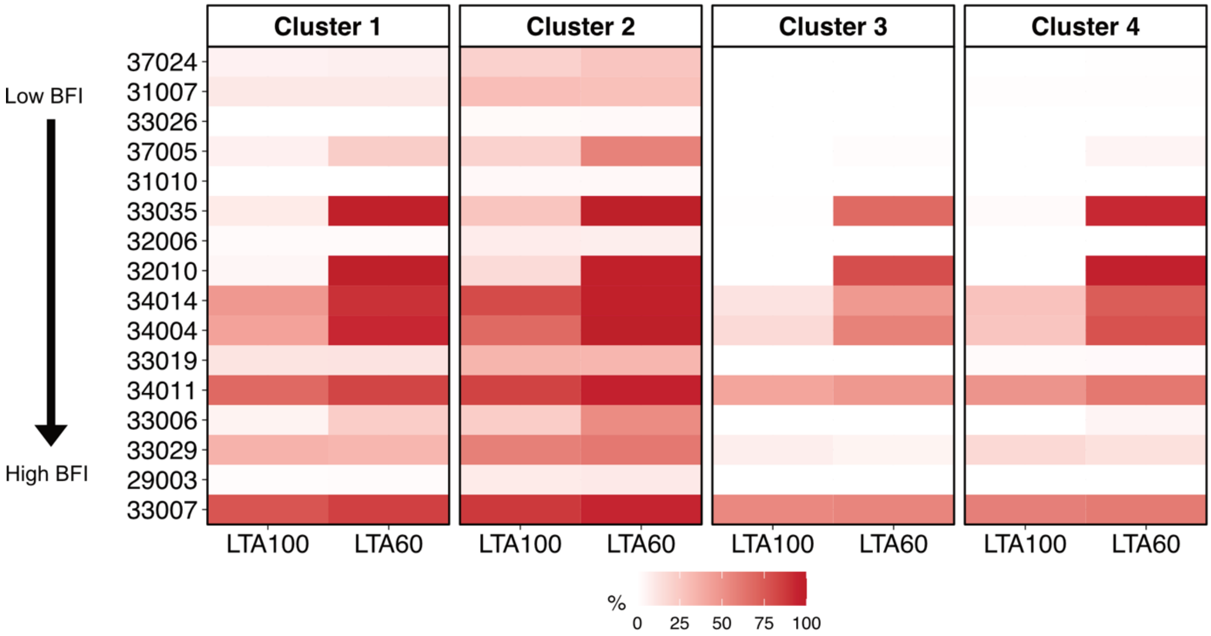

Figure 8: Likelihood of reaching SSI-3 below -1.5 from winter 2022/23 to autumn 2023 for each circulation storyline. In the LTA100 experiment, spring to autumn 2023 are assumed to have rainfall at 100% long term seasonal average whereas the LTA60 experiment assumes summer 2023 to receive 60% LTA rainfall with 100% LTA rainfall for the other seasons. Catchments are ordered by increasing baseflow index (BFI) from the top.

4 Discussion

Conditioning hydrological outlooks based on atmospheric circulation patterns adds a dynamical perspective to existing approaches. The circulation storylines cover a range of possible combinations of the various atmospheric circulation indices and span a wide range of surface rainfall and temperature response. Considering storylines of the 2022 drought can increase risk awareness by allowing water managers to plan for water resources provisions assuming that an upcoming season resembles certain atmospheric circulation patterns, and to explore plausible worst cases that are possibly outside the range of historical years. These results supplement existing products such as the ensemble streamflow prediction (ESP) approach used within the UKCEH Hydrological Outlook (Harrigan et al. 2018). Donegan et al. (2021) recently demonstrated the benefits of a NAO-conditioned ESP approach in planning for dry winters in Ireland by selecting historical years with information from hindcast prediction of the NAO. This is also reflected in the results from this study which shows the advantage of a conditioned approach with a more detailed focus on the drivers of rainfall in eastern England. Although this study did not consider the likelihood of a particular storyline for winter 2022/23, further subsets to the hindcast winters can be made to provide weights for particular storylines that are considered more likely than others over time (e.g. based on prevailing atmospheric circulation patterns). Given the large sample size of the hindcast winters, future work could also condition storylines based on their preconditions. For example, for the 2022 drought, storylines can be created by selecting only winters in the hindcasts with a wetter than average preceding November (as was observed in November 2022). This approach also takes advantage of forecast of winter circulation characteristics (or weather regimes) which may be more reliable than forecasts of winter precipitation and those forecasts can help inform plausible weightings assigned to particular storylines. When employed during an ongoing event, this approach may also shed light on the conditions required for drought termination, such as through calculating the drought termination metrics in Parry et al. (2016) for each storyline.

The results highlighted the continued drought conditions for catchments, particularly in the northeast region of Anglian Water, due to a combination of insufficient winter rainfall and the effects of hydrogeology leading to long persistence of low flows. East Anglia received 69% of LTA rainfall in the observed winter 2022/23. The observed winter exhibited a NAO-/EA- pattern, resembling the atmospheric circulation patterns for winters in cluster 1. Similar to the composite mean SLP anomalies of cluster 1, winter 2022/23 saw high pressure conditions over the UK leading to drier than average conditions with the high pressure centre shifted further westwards (Figure S7). Results from cluster 1 show that it was likely for flows to remain below normal by spring 2023 with the potential to reach severe drought conditions over 2023, particularly for groundwater-dominated catchments, even with spring to autumn 2023 receiving 100% LTA rainfall. The continued vulnerability of catchments in this region in 2023 may result in a return of water use restrictions (Anglian Water 2023). The likelihood of a return to drought conditions nationally was reflected in the statement from the National Drought Group which stated that England is “one hot, dry spell away from drought returning this summer” (National Drought Group 2023). Results from the different storylines can help prioritise and re-direct operational resources such as borehole maintenance in key areas (e.g. Norfolk) where the large sample of hindcast winters show continued drought conditions or areas where plausible worst cases within each circulation storyline could exceed certain thresholds (e.g. relative to past reference droughts).

This study contributes to the growing use of hindcasts to explore a large sample of plausible events to mitigate the challenge of short observational records and better consider internal climate variability (e.g. Kelder et al. 2022; Slater and Brunner 2022). Although this study focused on the winter season given the importance of winter rainfall for the replenishment of river flows and aquifers in the Anglian Water region, a similar approach can be taken for other seasons to provide complementary information. This may be particularly useful when other forecasting approaches may be less informative and when it may be useful to consider a wider range of outcomes to explore plausible worst cases (e.g. during a prolonged dry weather period prior to drought onset). For example, existing practice assumes the repetition of key individual years (such as the La Niña year of 2011) and results from this study highlight the benefits of considering a wider range of outcomes, including the combined effects of NAO and EA patterns during La Niña years. Operational drought forecasting tends to be done within water companies using calibrated hydrological models of key catchments and some companies already make use of seasonal forecasts. The level of resource required to extend existing methodologies to include a wider sample of seasonal hindcasts conditioned on atmospheric circulation patterns is minimal and could provide greater context with more robust evidence to inform the short to medium term hydrological situation.

5 Conclusions

This study demonstrated the use of seasonal hindcasts to create hydrological drought outlooks conditioned on atmospheric circulation patterns. Using the 2022 drought as a case study, storylines of the ongoing 2022/23 drought for river flows and groundwater levels were created in autumn 2022 for the Anglian Water region to represent the plausible progression over winter 2022/23 and spring-summer 2023. Four circulation storylines were defined by clustering a large sample of winters in the SEAS5 hindcasts based on atmospheric circulation patterns responsible for rainfall anomalies in eastern England. Circulation storylines span the possible combinations of various atmospheric circulation indices. Results highlight the importance of winter rainfall, particularly for groundwater-dominated catchments, and the continued vulnerability for catchments and boreholes to drought conditions in 2023. Assuming a second consecutive dry summer in 2023, there is a high likelihood for drought conditions to return and intensify across most selected catchments, especially following the dry winter storyline which actually transpired. This approach can be used in conjunction with existing methods in real time to plan for prolonged dry weather or ongoing droughts and explore plausible worst cases.

Data availability

Observed CEH-GEAR rainfall data is available from the Environmental Information Data Centre (EIDC) (https://doi.org/10.5285/dbf13dd5-90cd-457a-a986-f2f9dd97e93c - Tanguy et al. 2021). Observed HadUK-Grid temperature data is available from the Centre for Environmental Data Analysis (CEDA) archive (http://catalogue.ceda.ac.uk/uuid/4dc8450d889a491ebb20e724debe2dfb – Hollis et al. 2019). Daily SEAS5 hindcasts are available from Climate Data Store (CDS) (https://cds.climate.copernicus.eu/cdsapp - !/dataset/seasonal-original-single-levels). Data before 1993 can be requested using the CDS toolbox. ERA5 reanalysis data is available from CDS (https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels). Observed river flow data is obtained from the National River Flow Archive (https://nrfa.ceh.ac.uk/). Simulated river flows and groundwater level from December 2022 to November 2023 for each storyline is hosted on the Zenodo archive (DOI: https://doi.org/10.5281/zenodo.7756582).

Author contributions

This study was completed during a PhD studentship placement at Anglian Water initiated by WCHC and GD. WCHC conducted the formal analysis and prepared the original paper. TGS, KF, GD, MT and NWA supervised the study. All authors contributed to the writing and interpretation of the results.

Acknowledgements

The authors would like to thank Santiago Rojas Arques (Anglian Water), Anne Bravery (Anglian Water) and Mark Sampson (Anglian Water) for their help in catchment/borehole selection, data access and the use of Aquimod to simulate groundwater levels at the selected boreholes. This research has been supported by the Natural Environment Research Council via the SCENARIO Doctoral Training Partnership (grant no. NE/S007261/1).

Competing interests

The authors declare no competing interests

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