An appraisal of the severity of the 2022 drought and its impacts

Lucy J. Barker[1], Jamie Hannaford[1,2], Eugene Magee[1], Stephen Turner[1], Catherine Sefton[1], Simon Parry[1], Jonathan Evans[1], Magdalena Szczykulska[1] and Tracey Haxton[3]

[1] *UK Centre for Ecology & Hydrology, Wallingford, UK*

[2] *Irish Climate Analysis and Research UnitS (ICARUS), Maynooth University, Ireland*

[3] *Wallingford HydroSolutions, Wallingford, UK*

Introduction

The summer of 2022 was particularly notable for the prolonged and extensive hot and dry conditions experienced across the UK. The resultant 2022 drought had widespread impacts and prompted much discussion about the continuing vulnerability of the UK to drought in the context of anthropogenic warming - particularly given that it occurred only a few years after another major drought episode, in 2018-2019 (Turner *et al.*, 2021).

Drought is widely described as a complex phenomenon. Droughts are usually described as being slow to develop, caused by a prolonged deficit in precipitation (meteorological drought) which propagates through the hydrological cycle and can result in agricultural or soil moisture drought and hydrological drought (affecting both river flows and groundwater levels; Van Loon, 2015). This propagation is dependent on the nature of precipitation deficits in combination with temperature anomalies, and catchment properties (e.g. Barker *et al.*, 2016). Hence, different 'types' of drought can readily be recognised, in terms of timing, duration and intensity, and different regions and systems (whether ecosystems or socio-economic sectors) are vulnerable to different types of event. Commonly, distinctions are drawn between multiannual droughts with multiple dry winters in more groundwater dominated systems such as the south east of England and shorter, more intense events in flashier catchments in the north and west, with less surface or groundwater storage (e.g. Marsh *et al.*, 2007; Barker *et al.*, 2019). In recent years, 'flash droughts' have been defined and characterised as events with rapid intensification, often over summer months when temperatures are higher and drive evaporative demand (Otkin *et al.*, 2018).

Here, we briefly describe the evolution of the drought before focusing on the severity of rainfall, river flow, soil moisture and groundwater level deficits from summer 2022, placing the event into a historical context and addressing the impacts of the drought. We also consider whether the 2022 drought is part of a long-term trend towards increasing drought severity.

The hydrometeorological data underpinning these analyses are from the UK National River Flow Archive (NRFA),[1] National Hydrological Monitoring Programme (NHMP)[2] and COSMOS-UK[3] based at (UKCEH). Standardised Precipitation Index (SPI) data for the UK are available via the UK Water Resources Portal (Barker *et al.*, 2022)[4] and described in Tanguy *et al.* (2017). Location maps showing relevant sites and regions are given at the NHMP website, although specific sites highlighted for detailed analysis in this paper are presented in Figure 1.

Evolution of the summer 2022 drought

The months leading up to the summer 2022 were, overall, mixed. For autumn and winter (September–February; winter half-year), rainfall was near average (95%) for the UK as a whole, but in the Southern and Wessex regions around three quarters of the average were received. Winter half-year mean river flows were generally in the normal range, although some areas such as central and southern England saw below normal flows (Figure 2a). By February, groundwater levels were also below normal, although few were notably low (Figure 3a). While this period was not exceptional, the tendency towards below normal rainfall and river flows intensified coming into spring 2022.

[1]https://nrfa.ceh.ac.uk/

[2]https://nrfa.ceh.ac.uk/nhmp

[3]https://cosmos.ceh.ac.uk/

[4]https://eip.ceh.ac.uk/hydrology/water-resources/

The late spring and early summer was characterised by anomalous anticyclonic conditions over most of western and central Europe (Faranda *et al.*, 2023). For spring, rainfall (March–May) was below 70% of average across most regions, with 59% received in Wales. Seasonal groundwater recessions were sharp, especially in the more responsive aquifers such as the Jurassic limestone of the Cotswolds (Figures 3b and c) and for the spring as a whole, flows were below normal across most of the UK, with widespread notably low flows (Figure 2b). The English Tyne and the Conwy recorded their second and third lowest average flows for spring (in records from 1957 and 1965, respectively).

The summer was notably hot, with maximum temperatures far above average across much of England, and new record highs for both Scotland and Wales. A new UK record temperature of 40.3°C at Coningsby, Lincolnshire, was recorded on 19 July. This combination of dry and hot weather meant that June–August in England joined an exclusive club of exceptionally hot and dry summers (Figure 4, see more below). Summer 2022 (June–August) was the fifth driest for England in a series from 1890 (50% of average). Correspondingly, soils dried out rapidly and river flows declined steeply though the summer. Summer mean river flows across the UK were notably to exceptionally low across much of England, southern Scotland and south Wales (Figure 2c). There were new record summer minima recorded on the Tweed, Yorkshire Derwent, Yscir and Waveney, which all have records of at least 48 years (Figure 2c). By the end of summer, groundwater levels were widely notably or exceptionally low (Figure 3d), and daily river flows were among the lowest ever recorded for some catchments in southern and eastern England, rivalling and sometimes eclipsing those of droughts in 2018, 1995 and 1976 (e.g. Figure 6).

There was a marked change in conditions at the start of autumn 2022. Low pressure systems moved in from the Atlantic bringing, at times, some notable rainfall totals. The unsettled conditions inevitably led to responses in river flows although they were short lived and flows soon dropped once the rain stopped. Autumn as a whole saw above normal rainfall for most of the country, with the exception of the far north of Scotland and in north Norfolk. Rainfall was more than 150% of average in south east England, eastern Scotland and Northern

RMetS Royal Meteorological Society

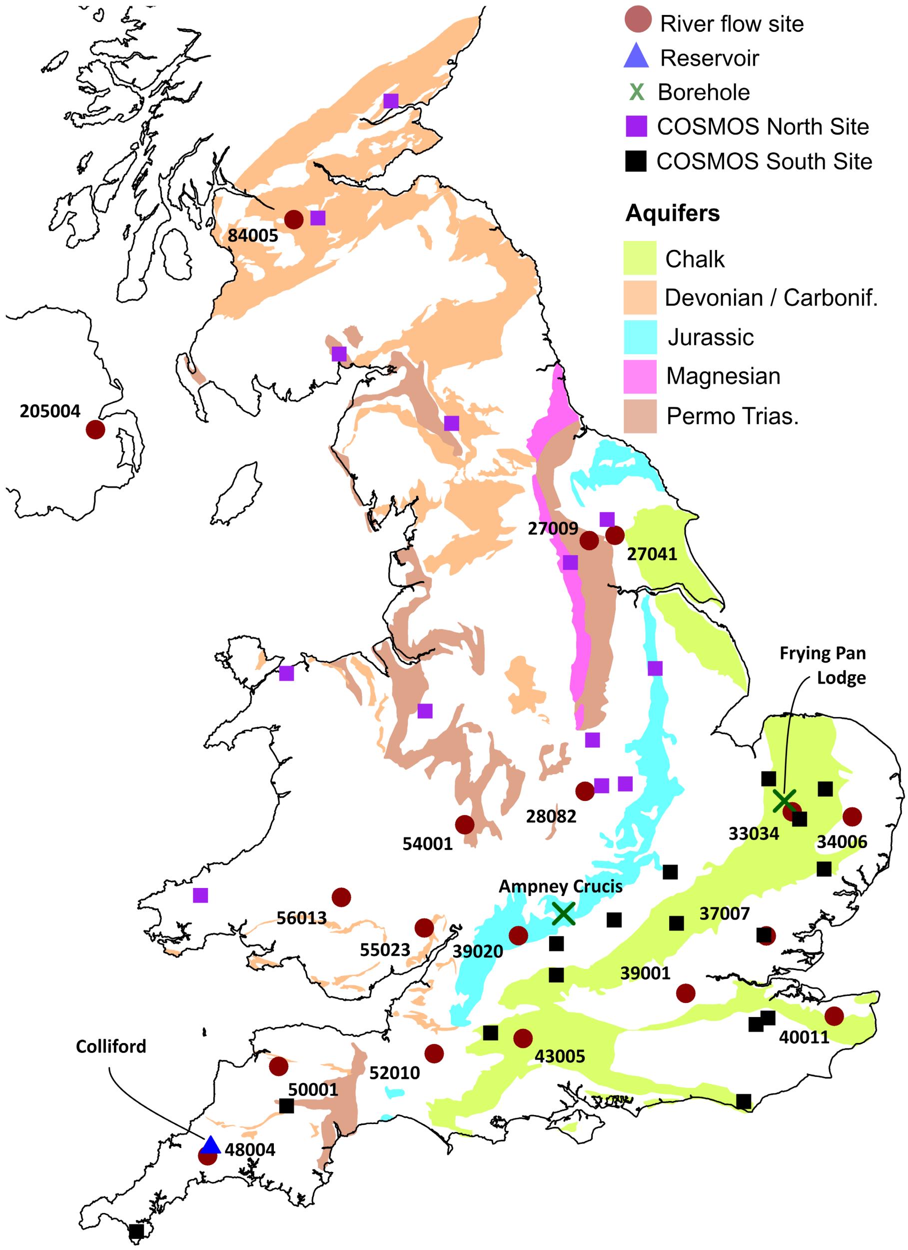

Figure 1. Location map for sites mentioned in the drought severity part of this paper.

Ireland. This led to healthier river flows; they were generally above average across the UK, with below normal flows confined to northern Scotland, east Anglia and flows on the Chalk catchments were often less than half the average for this period (e.g. Lud and Stringside).

Moving into winter 2022/2023, December rainfall totals were slightly below average in many places – in particular in western Scotland, but just above normal in eastern Scotland and southern England, giving an overall UK total of 87% of average. Most of January's rainfall came during the first half of the month, and overall, it was a near-average month with 103% of average UK rainfall in total. February, however, was exceptionally dry, with only 45% of UK average – the driest February since 1993.

These mixed conditions meant that river flows during the winter half-year (September 2022–March 2023) were mainly in the normal to above normal range, with the highest flows being in the south-west, Wales and north-west England and below normal flows again confined to northern Scotland and East Anglia (Figure 2d). By this point with higher river flows and replenished water resources, many areas were lifted out of drought status, except for the south west of England and East Anglia which remained in drought status in 2023 due to depleted reservoir stocks or groundwater resources, respectively (Figure 3e).

Severity of the summer 2022 drought

Although drought impacts were seen in the spring of 2022 and the conditions of the preceding autumn/winter were integral to the development of the event, the event intensified over the summer with the most severe river flow deficits and impacts seen in this period.

At the national scale, the UK received 64% of average summer (June–August) rainfall, and all regions received below average rainfall; however, most English regions received around or less than half the average. Regions in the south east of England received the least, with the Thames region ranking as the fourth driest (46% of average) and Southern and Wessex region the fifth driest (43% and 44% of average, respectively) in series from 1890.

Summer 2022 ranked among the hottest and driest for England – it was the fifth driest summer for England in series from 1890 and joint hottest (with 2018) in a series from 1884 – alongside other notable summer drought years, including 1976, 1995, 2003 and 2018 (Figure 4).

Figure 5 shows the Standardised Precipitation Index (SPI) with a 3-month accumulation period ending in August in 2022 and other historic summer drought years from 1921 to 2018, summarising the rainfall deficits seen over the summer in each year. Extremely dry conditions can be seen across much of England and Wales in 2022, with more of a mix of mild to extreme conditions across Scotland and Northern Ireland. Compared to the previous drought years, the spatial extent of the extremely dry conditions seen in summer 2022 was only exceeded in 1976 and 1995, with more spatially constrained extreme or more mixed conditions seen in summer 1921, 1934, 1984, 2003 and 2018. Note that these patterns will be different when considering different accumulation periods of the SPI and/or different months in each year due to the differing evolution of each event. In addition, the SPI is solely an indicator of precipitation deficits and does not account for evaporation losses, which were an important component of the 2022 drought given the elevated temperatures highlighted previously. Future analyses could incorporate evaporation losses via the use of other drought indicators (e.g. the Standardised Precipitation and Evaporation Index, SPEI).

River flows in many catchments approached or established new summer minima in 2022 (as shown in Figure 2c). Figure 6 shows hydrographs for selected catchments (with locations shown in Figure 1) with data for 2022 alongside the benchmark drought of 1976 and the recent 2018 event. Although these events may not be the most significant in each catchment, they are useful comparators – 1976 is the 'Benchmark' event across much of England and Wales, while 2018 represents the last major drought (Turner *et al.*, 2021). Daily flows in 2022 generally track the flows in 1976 and 2018, receding over the spring, and reaching lowest flows over

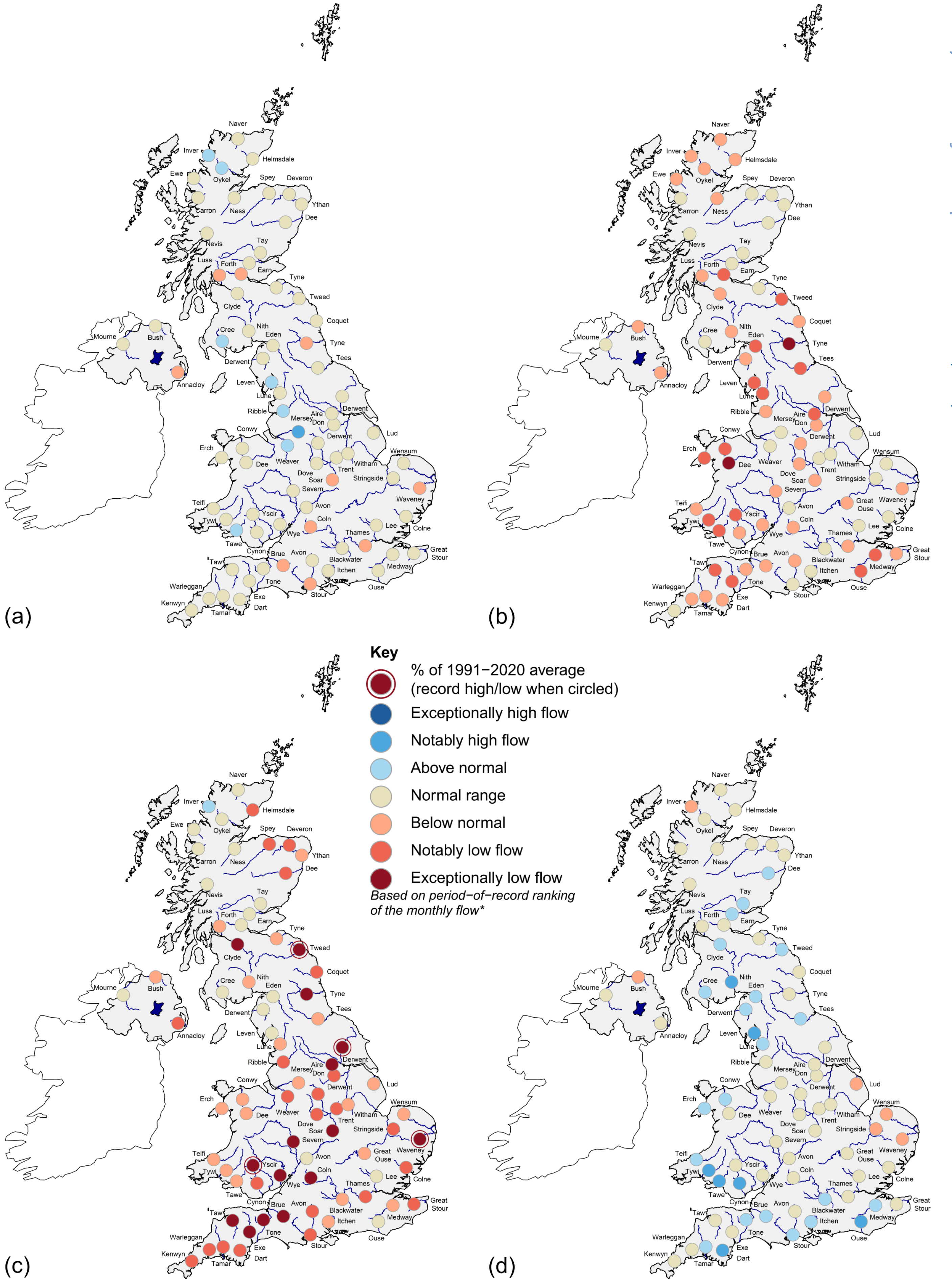

Figure 2. Mean river flows across the UK for (a) September 2021–March 2022: Winter half-year 2021/2022 (b) March 2022–May 2022: spring (c) June 2022–August 2022: summer and (d) September 2022–March 2023: Winter half-year 2022/2023.

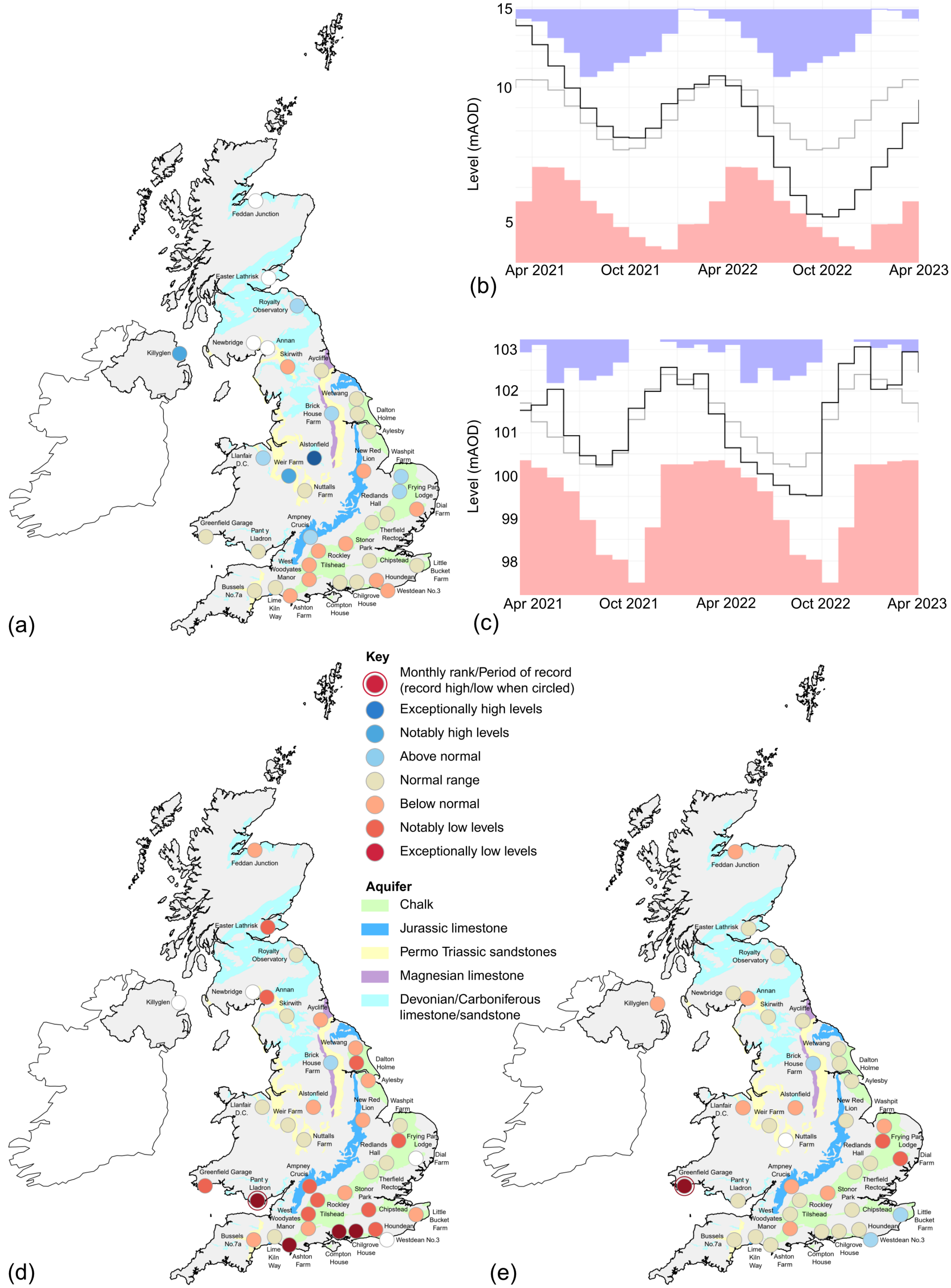

Figure 3. Month-end groundwater levels for (a) February 2022, (d) August 2022, (e) February 2023 across the UK, and from April 2021 to April 2023 for (b) Frying Pan Lodge in the Little Ouse catchment and (c) Ampney Crucis in the Upper Thames.

the summer months, with 2018 generally not reaching flows as low as either 1976 or 2022. However, the event with the lowest daily flow varies between catchments and throughout the year. With the more western catchments (Yscir and Taw), daily flows were lower than those recorded in the two comparator years over the spring, and this continued through summer in the Yscir – whereas for the Taw they were above the previous minima through the summer, but decreased below the 1976 flows at several points in autumn and winter. In the more groundwater dominated catchments of the Little Ouse and the Coln in the south east of England (with relatively nearby boreholes at Frying Pan Lodge and Ampney Crucis, respectively, Figure 3, locations shown in Figure 1) there is a delayed response, and daily flows drop below those of 1976 and 2018 in between June and November and September and November, respectively.

To assess the severity of 2022 flows, a range of *n*-day minima were analysed for a selection of 22 catchments, focusing on the southern half of the UK where low flow minima were more notable (there were relatively few notable minima in northern Britain). The locations are shown in Figure 1, and the analysis results are presented in Table 1. Provisional return periods were also derived for these *n*-day periods using Wallingford HydroSolutions HydroTools package (with default options). It must be noted that these are preliminary analyses conducted using available datasets (for a subset of NRFA gauging stations available to the NHMP, and which have not yet undergone NRFA validation). Moreover, the relative ranking and (especially) return periods could be influenced by data quality or lack of homogeneity – especially changes in artificial influences (e.g. abstractions) over time, which are likely to be an issue in some catchments and could invalidate the assumptions of the frequency analysis (e.g. Zaidman *et al.*, 2002). Further details are given in the Table 1 footnotes. These indicative analyses aim to give a broad-brush national picture of drought severity and do not supplant more detailed local-scale assessments of drought severity.

Flows in 2022 ranked as the lowest on record on the Yscir, Coln and Little Ouse across 7-, 30-, 60- and 90-day periods (all in records of over 40 years). For the Coln, flows were also the lowest on record and return periods were exceptional across the various averaging periods while the 60- and 90-day minimum flows had return periods of 1 in >100 years for the Little Ouse. For these same *n*-day minima, 2022 flows also ranked in the five lowest on record in a number of the catchments shown in Table 1. The Soar, Waveney, Taw, Brue and Lagan all recorded the second or third lowest on record (in records of over 40 years), with 2022 30-, 60- and 90- minimum flows from the Lagan having return periods of 1 in >100 years. Where 2022 flows did not rank as the lowest on record, 1976 had the lowest flows in eight catchments for four *n*-day periods – and was the lowest year for each period for the Soar, Thames, Avon, Taw, Brue and Wye. Where neither 2022 nor 1976 ranked as the lowest *n*-day flows, other notable single-season summer droughts did – for example 1984 and 1995. What is also evident from Table 1 is that the exceptional low flows are widespread but spatially variable in their severity – that is, they were distrib-

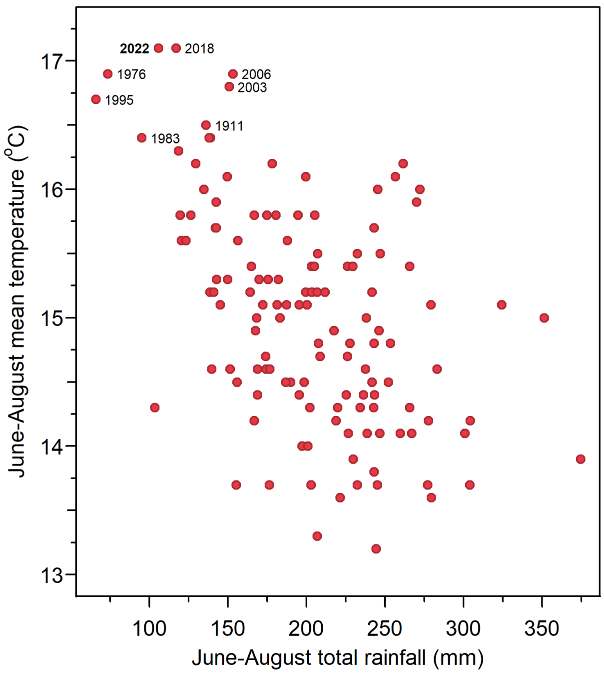

Figure 4. Scatter plot showing summer (June–August) total rainfall and summer mean temperature for England from 1890 to 2022, HadUK-Grid dataset, 1km resolution, v1.2.0.0.

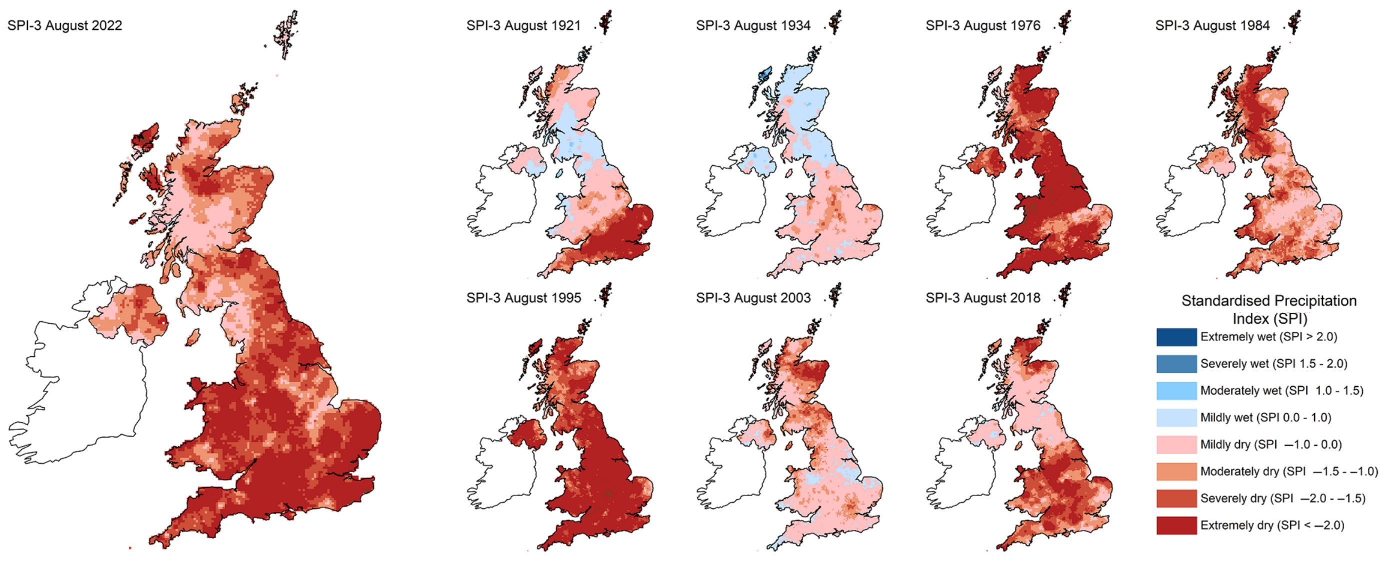

Figure 5. SPI for the 3-month period ending in August (i.e. June–August) for 2022, 1921, 1934, 1976, 1984, 1995, 2003 and 2018.

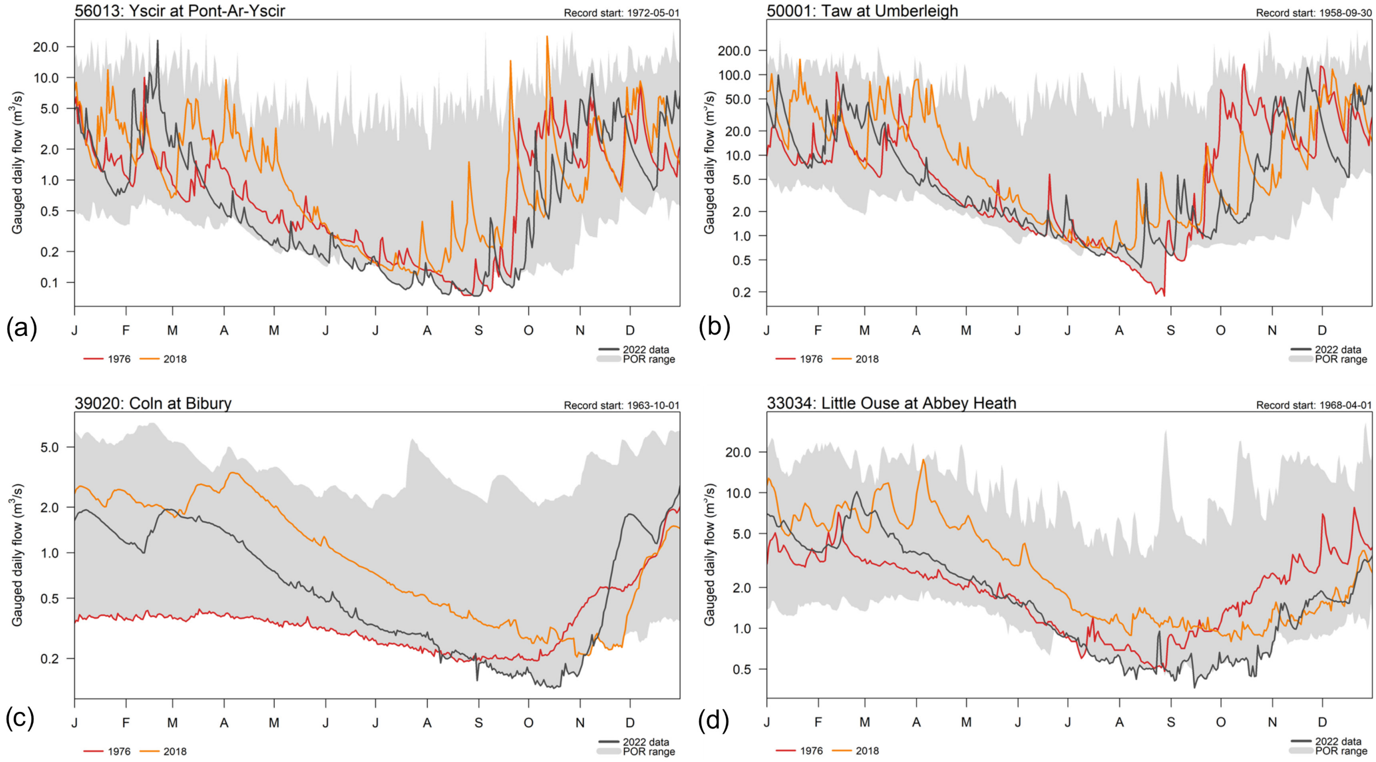

Figure 6. Hydrographs showing 2022 daily mean flows with those from 1976 and 2018 for (a) Yscir, (b) Taw (c) Coln and (d) Little Ouse. The grey area (POR range) represents the full range (minimum to maximum flows) for each day for the period-of-record. Changing artificial influences or other potential data issues could be influential in dictating the relative magnitude of these past events: see text explanation and footnote of Table 2. For locations, see Figure 1.

uted across England and Wales, indicating that there was no one focus point for the drought (although this is based on a small selection of sites – a detailed assessment of spatial coherence would need to consider all catchments, when fully validated NRFA data are available). It is apparent that the small amounts of late rainfall in flashier catchments (such as the Taw, see Figure 6b) were sufficient to reduce the severity of the *n*-day minimum flows in 2022.

Combined outflows from England were below average for much of 2022 (all months except February and November; Figure 7), highlighting the large footprint of the 2022 drought and impact on river flows at the national scale. In ranked periods of outflows for England for 1-, 3-, 6- and 9-month periods (Table 2), July 2022 ranked as the seventh lowest month on record (in a series from 1961) behind other notable summer drought years including 1976, 1995 and 1984. The 3- and 6-month periods ending in September 2022 both ranked as the fourth lowest underlining the exceptional nature of river flow deficits in summer 2022, again behind notable drought years of 1976, 1995, 1996 and 1989/1990.

To provide an understanding of the severity of soil moisture status in 2022, Figure 8 shows a soil moisture index (SMI) averaged across 13 northern and 16 southern sites (for location, see Figure 1) of the COSMOS-UK network for a range of recent years (given the relative brevity of the COSMOS-UK records).

The sites are selected following a criterion that for each year between 2018 and 2022, and for each season, at least 50% of the daily soil moisture data is complete. The SMI is calculated using the definition adopted in (Grillakis, 2019) and takes a range of values between −5 (permanent wilting point or below) and 5 (field capacity or above), with values decreasing from zero indicating increasing plant water stress. The COSMOS-UK observations represent the top soil layer (~20cm depth), and the response to precipitation and evaporation is relatively fast, compared with deeper soil layers.

Both northern and southern sites show a significant plant water stress in the summer months of 2018 and 2022. The overall severity of these events is higher in the southern sites due to both stress intensity and duration. The 2018 event started with a significant dry down in May followed by high stress in late June and July in the northern sites, and with the additional inclusion of August in the southern sites. The subsequent years: 2019, 2020 and 2021 saw minor stress in the northern sites, except for May and early June of 2020 which follow the very dry spring. In the southern sites, soils continued to experience high stress in 2019 and 2020, and relatively less so in 2021.

In 2022, the dry down started in April with water stress in the northern sites lasting through July and most of August. In the southern sites, there is a much more prolonged stress sustained between May and early autumn. Comparing years 2018 and 2022 in the studied southern sites, the 2022 event reaches slightly higher stress intensities and extends for a longer period of time. Based on this case study, we can conclude that the 2018 drought was a more severe soil moisture drought ('agricultural drought') than 2022 in northern areas, but in the south 2022 was the more severe event, although 2018 was comparable in the spring and early summer (a critical time for agriculture).

Impacts of the summer 2022 drought

The low rainfall, exceptional heat, dry soils and low river flows in the summer were responsible for a range of different impacts across the UK including algal blooms, fish kills, wildfires, low crop yields, transport disruption and water restrictions.

Crops and livestock were both impacted by the soil moisture stress and high temperatures, with farmers in England reporting a drop in milk yield from dairy cows (Clarke and Priestley, 2022) as well as a fall in potato and onion crop yields (Stuart Allen, Environment Agency, pers. comm.). Grass in grazing fields began dying, forcing farmers to use winter food stores on livestock in August (BBC News, 2022d). In Scotland, abstraction licences for the River Eden in Fife were suspended, preventing farmers from using water from the river to irrigate fields (Scottish Environment Protection Agency, 2022). Agriculture was also affected by wildfires spreading easily across the dry

Table 1

7-, 30-, 60- and 90-day minima in 2022 and associated return periods for selected catchments across the UK, Cases where 2022 ranks in the top three n-day minima are highlighted light yellow, cases where 2022 is rank 1 are highlighted dark yellow. Rows where 2022 ranks as the lowest flows across all n-day minima are shown in bold. Due to uncertainties, return periods have been assigned to rounded bands.

					7-day minima				*30-day minima*				*60-day minima*				*90-day minima*			
Station number	*River*	*Start year*	*BFI*	*Mean flow*	*2022 Flow*	*2022 RP*	*2022 Rank*	*Yr of min.*	*2022 Flow*	*2022 RP*	*2022 Rank*	*Yr of min.*	*2022 Flow*	*2022 RP*	*2022 Rank*	*Yr of min.*	*2022 Flow*	*2022 RP*	*2022 Rank*	*Yr of min.*
27009	Ouse	Sep-69	0.44	52.08	4.99	15	5	1995	6.16	10	5	1995	7.81	8	6	1995	8.12	15	4	1989
27041	Derwent	Sep-73	0.7	16.94	3.22	10	4	1976	3.35	15	5	1990	3.60	10	6	1990	3.89	10	5	1990
28082	Soar	Aug-71	0.49	1.35	0.13	40	2	1976	0.16	50	2	1976	0.19	50	2	1976	0.21	40	2	1976
33034	**Little Ouse**	**Apr-68**	**0.8**	**3.69**	**0.42**	**50**	**1**	**2022**	**0.49**	**60**	**1**	**2022**	**0.51**	**>100**	**1**	**2022**	**0.53**	**>100**	**1**	**2022**
34006	Waveney**	Dec-63	0.46	1.75	0.17	N/A	1	2022	0.19	N/A	2	2018	0.23	N/A	2	2018	0.24	N/A	2	2018
37005	Colne	Oct-59	0.52	1.07	0.11	15	3	1965	0.12	30	3	1965	0.14	50	3	1976	0.21	8	6	1976
39001	Thames	Jan-1883	0.62	65.37	4.48	10	15	1976	5.35	10	15	1976	6.58	8	16	1976	6.58	10	13	1976
39020	**Coln*** **	**Oct-63**	**0.92**	**1.39**	**0.13**	**>>100**	**1**	**2022**	**0.14**	**>>100**	**1**	**2022**	**0.16**	**>>100**	**1**	**2022**	**0.17**	**>>100***	**1**	**2022**
40011	Great Stour	Oct-64	0.7	3.21	0.78	10	5	1997	0.85	10	4	1997	0.89	15	4	1996	1.00	10	6	1990
43005	Avon	Feb-65	0.91	3.52	0.76	15	3	1976	0.81	15	3	1976	0.87	15	3	1976	0.87	20	2	1976
48004	Warleggan	Sep-69	0.69	0.87	0.14	10	5	1976	0.15	15	4	1976	0.16	20	3	1984	0.17	15	3	1984
50001	Taw****	Sep-58	0.43	18.24	0.48	60	2	1976	0.61	40	2	1976	0.77	20	2	1976	0.96	20	3	1976
52010	Brue	Oct-64	0.47	1.95	0.15	40	2	1976	0.19	30	3	1976	0.21	>>100*	3	1976	0.22	>>100*	3	1976
54001	Severn	Apr-21	0.53	62.05	9.83	3	28	1949	10.54	4	18	1976	10.94	4	18	1976	11.2	10	7	1976
55023	Wye	Oct-36	0.54	73.53	4.93	60	3	1976	5.76	50	4	1976	7.18	40	3	1976	8.06	40	2	1976
56013	**Yscir**	**May-72**	**0.46**	**1.94**	**0.08**	**>>100**	**1**	**2022**	**0.08**	**>>100***	**1**	**2022**	**0.09**	**>>100***	**1**	**2022**	**0.11**	**90**	**1**	**2022**
84005	Clyde	Oct-58	0.44	44.25	5.77	6	9	1984	6.98	5	9	1984	7.79	8	9	1984	8.57	10	8	1984
205004	Lagan	Aug-72	0.42	8.16	0.32	80	2	2021	0.42	>100	2	2021	0.50	>100	1	**2022**	0.60	>100	1	**2022**

*The return period is more than twice as long as the period of record, as such results should be treated with caution.

**Only ranks are shown for the Waveney given operation of augmentation scheme in late 2022 and changing artificial influences over time – ranks should also be treated with caution.

***Recent flows at the Coln at Bibury have been flagged as suspicious and under investigation due to potential changes in artificial influences, but this is as-yet inconclusive.

****Past drought years influenced by augmentation scheme – so flows in past drought years would have had higher flows than the 2022 drought; hence, ranks and return period should be viewed with caution. A separate analysis with naturalised data from the Environment Agency showed lower RPs (40, 30, 15 and 15 years, respectively).

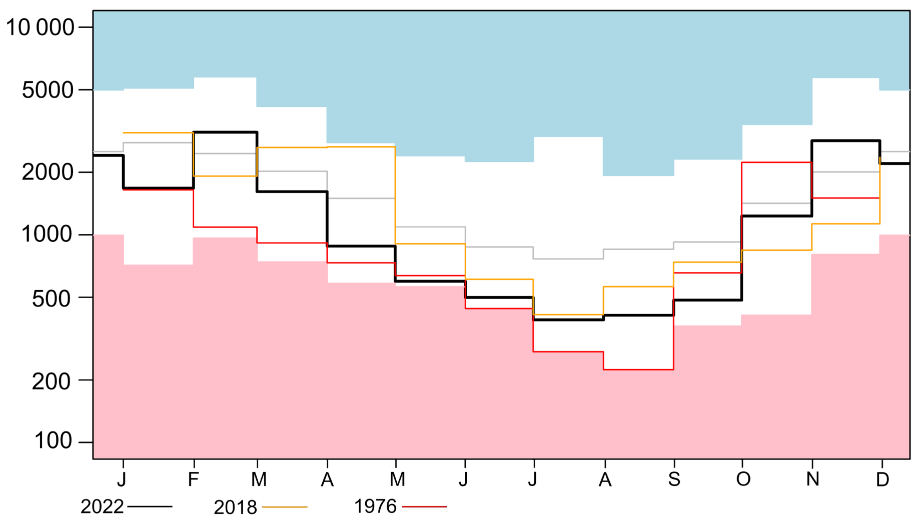

Figure 7. Monthly mean outflows (m³/s) for England (thick black line) for 2022 showing the monthly maximum and minimum outflow (blue and red shading, respectively) and the long-term average (grey line), as well as the 1976 and 2018 droughts.

fields, which also led to property damage in urban settings. On the 19 July alone, 800 wildfires were recorded with 41 properties in London and 20 in Norfolk destroyed or badly damaged and major incidents were declared (e.g. BBC News, 2022a).

A level 4 heat health alert was issued for the first time since its introduction in 2004, and this was accompanied by the first Red National Severe Weather Warning for extreme heat for the 18 and 19 July. There were 2803 estimated excess deaths of over 65s due to heat between June and August (Office for National Statistics, 2022; UK Health Security Agency, 2022).

Wildlife in the UK also felt the effects of the drought as water levels in rivers and fishing lakes dropped leading to birds becoming trapped in exposed mud (BBC News, 2022b). In August 2022, the source of the Thames, which migrates on an annual basis in response to groundwater levels, was recorded at its farthest downstream location since surveys began in 1992 (K. Mullane, 2022, pers. comm., 16 August). The Environment Agency undertook fish rescues across England and used aerators to oxygenate ponds and lakes (Environment Agency, 2022). Algal blooms and fish kills were widespread (e.g. monitored across the Thames; Bowes *et al.*, 2023), causing damage to freshwater ecosystems in many areas.

The drop in water levels also had an impact on navigation of waterways. In April, the use of lock flights on canals was restricted to limit water loss. In summer, sections of the canal network across northern England were closed for navigation including the Peak Forest, Macclesfield, Huddersfield Narrow and Caldon Canals (Canal and River Trust, 2022). Low levels and a build-up of duckweed impacted navigation on rivers in East Anglia and the Thames (Environment Agency, 2022). The intense July heat caused additional issues for transport with major disruption on railways. Grit was spread in Hampshire to absorb melting bitumen on the roads and Luton airport paused operation due to damage to the runway (BBC News, 2022c).

By the end of August in England, 17 out of 18 water companies activated drought plans with five introducing temporary use bans (TUB), covering 19 million people (BBC News, 2022e). Natural Resources Wales also issued a TUB for south west Wales on the 19 August, the first in Wales since 1989 (Natural Resources Wales, 2022). By the end of 2022, most TUBs had been lifted with the exception of South West Water, continuing the TUB for Cornwall and in early 2023 expanding it to cover Devon, highlighting the exceptional stress water resources in this region were under (South West Water, 2022).

The introduction of TUBs was fuelled by low reservoir levels and increased demand due to heat. Reservoir stocks for England & Wales as a whole were below average from April 2022 through to the end of the year and the peak of the anomaly exceeded that of the 2018 drought (Figure 9). Reservoirs in the south west of England were particularly low. Roadford, Wimbleball and Stithians recorded their lowest September stocks and Colliford recorded the lowest October stocks in records from 1988. Levels in Colliford dropped below average in July 2021 and were well below average into the start of 2023, the anomaly peaking in October 2022 at 54% below average (Figure 9).

Table 2

Ranked mean outflows (m³/s) from England for non-overlapping 1-, 3-, 6- and 9-month periods. Months in 2022 are highlighted.

	1 month		3 months		6 months		9 months*	
Rank	End month	Mean flow	End month	Mean flow	End month	Mean flow	End month	Mean flow
1	Aug-76	224.148	Aug-76	313.00	Sep-76	493.75	Dec-95	728.35
2	Jul-76	273.313	Sep-96	399.28	Oct-95	521.14	Sep-76	734.38
3	Aug-95	308.024	Sep-95	402.12	Oct-96	526.63	Nov-96	760.45
4	Sep-96	363.362	Sep-89	428.02	Sep-90	532.64	Nov-03	771.32
5	Aug-90	368.53	Sep-22	430.48	Sep-22	547.26	Nov-90	773.18
6	Jul-84	369.155	Oct-03	433.39	Oct-89	558.30	Nov-97	823.96
7	Jul-22	392.155	Sep-90	437.06	Nov-03	582.92	Nov-73	846.93
8	Sep-89	393.752	Aug-84	483.98	Oct-91	595.12	Nov-11	855.21
9	Jul-95	403.991	Oct-72	497.36	Sep-84	632.38	Dec-75	864.10
10	Jul-96	406.661	Sep-91	505.97	Oct-18	678.90	Dec-91	949.47

*2022 ranked as the 17th lowest 9-month period.

Is the 2022 event part of a trend?

Inevitably, extreme hydrological events like the 2022 drought invite speculation that droughts are becoming more severe due to anthropogenic warming. This is entirely reasonable, as the latest climate change projections suggest future increases in drought severity, and diminishing low flows (e.g. Parry *et al*., 2023, based on the latest eFLaG projections driven by UKCP18).

However, the question of whether or not droughts have already become more severe is a challenging one, and answering it requires analysis of long-term hydrological observations. The evidence base for whether hydrological droughts have changed over time was recently reviewed by Hannaford *et al*. (2023). This review found that there were relatively few compelling trends towards decreasing river flows over the last five decades in a majority of catchments across the UK. It also highlighted how longer-term reconstructions extending back to the 1890s (Barker *et al*., 2019) demonstrate that recent drought events are not necessarily the most severe on record, and eclipsed by many historical droughts before the 1960s.

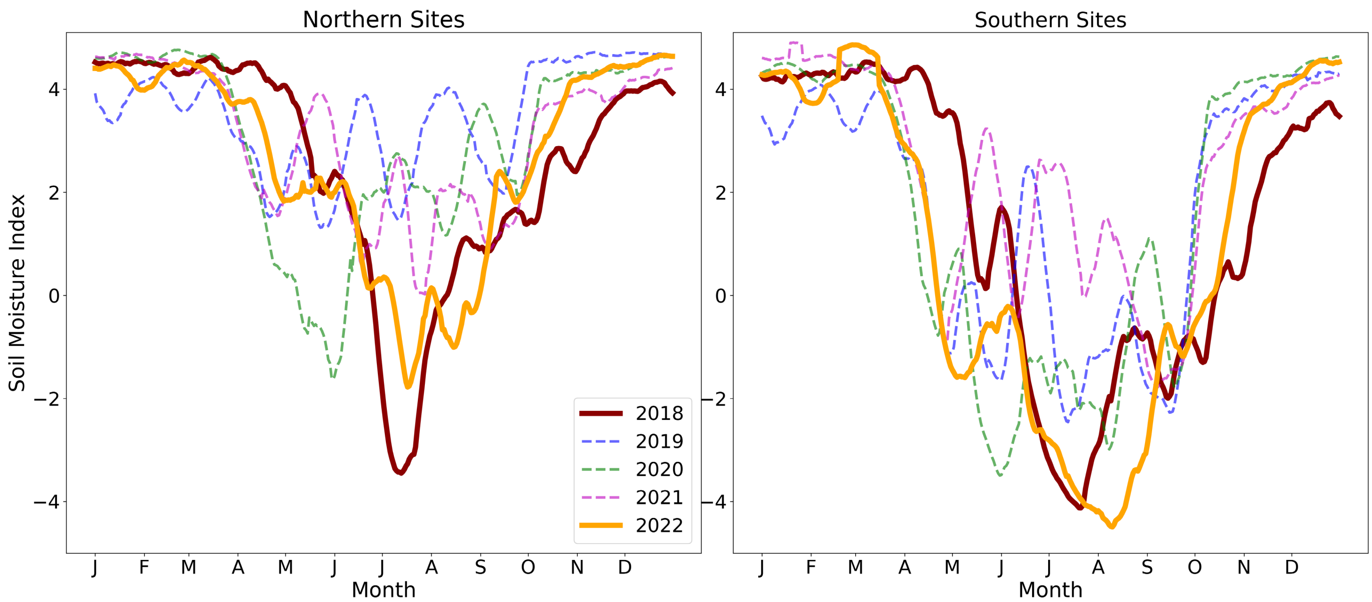

Figure 8. Soil moisture index time series for individual years between 2018 and 2022, averaged across selected 13 Northern (left) and 16 Southern (right) sites of the COSMOS-UK observation network (for locations see Figure 1). The southern sites are sites located in the South East, South West or East of England regions, while the northern sites constitute the remaining UK regions. To obtain the plots, daily soil moistures for each year and each site are first smoothed using a simple moving average with window of 14 days and then averaged across the specified sites.

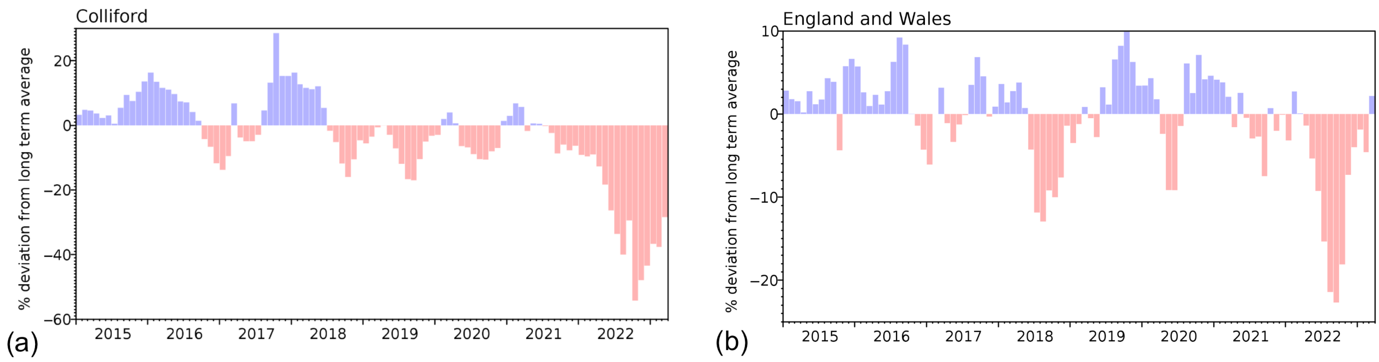

Figure 9. Deviation of reservoir stocks from the long-term average (1988–2012) for (a) Colliford Reservoir, and (b) England and Wales over the 2015 to 2022 period.

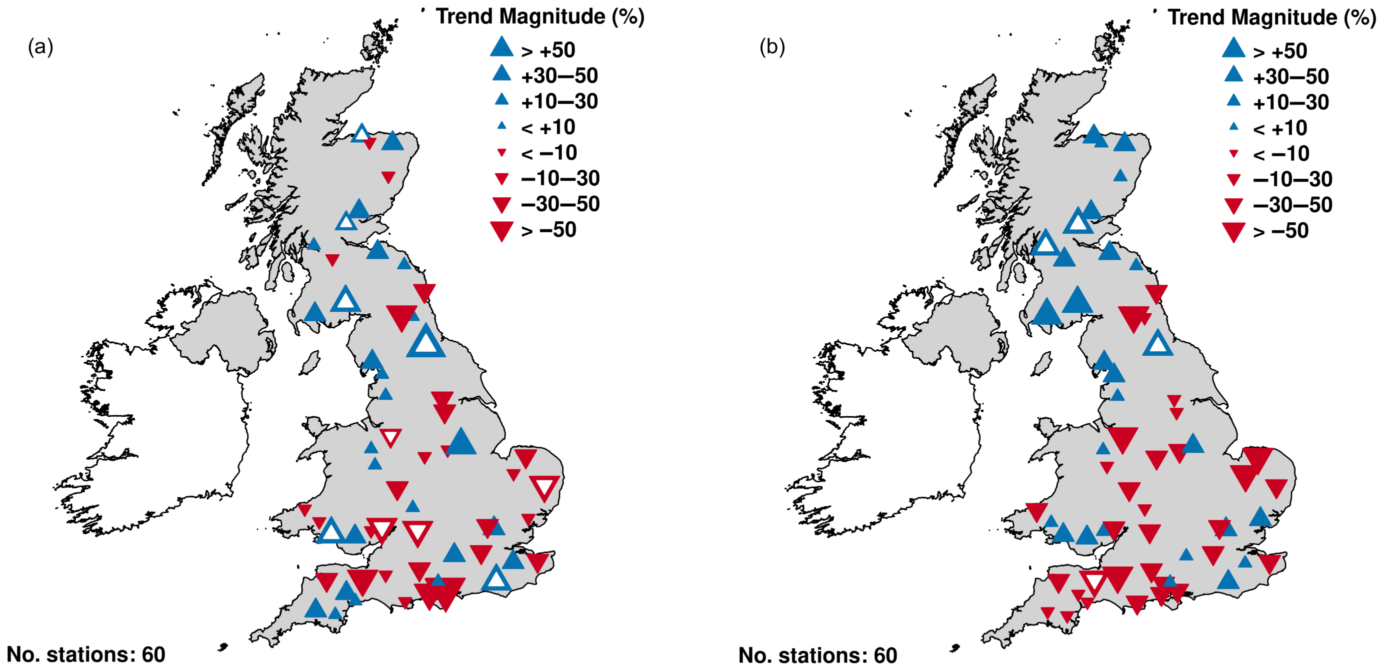

Figure 10. Trend analysis of river flow indicators (a) Q95 and (b) Seasonal Summer flows for the period 1965 to 2022, for all NHMP sites (N.B. naturalised data used for the River Thames). Trend magnitude (using the Thiel-Sen slope estimator) is shown according to the key as a percentage change. White colouration of triangles denotes a significant trend (using the Mann-Kendall trend test, at the 5% level).

To provide an up-to-date assessment including the 2022 drought, we undertook a preliminary trend analysis. We analysed trends using all NHMP catchments using provisional data available up to the end of 2022. The significance of monotonic trends is analysed using the Mann–Kendall trend test, with a block bootstrap test to account for cases with significant serial correlation, and trend magnitude is quantified using the Thiel-Sen estimator. For brevity, we do not describe the methods in detail here: full descriptions can be found in Harrigan *et al*. (2017) and Hannaford *et al*. (2021).

Figure 10 shows a pattern that is largely consistent with previous trend assessments, towards a mixed picture for trends in both low flows and summer flows. There is a tendency towards a greater number of increasing flows in northern and western areas, contrasting with decreases in the south and east, but with significant variations. Significant low flow trends were positive in five catchments in the north/west, and one catchment in the south. Negative low flow trends were seen in four catchments in the English Lowlands. For summer flows, three catchments in the north showed significant increasing trends, whereas one catchments in southern England showed a negative trend.

To explore the 2022 drought in context, Figure 11 shows time series and trends for these same indicators (Q95 and summer flows) for four selected catchments in areas particularly affected in summer 2022 (all are featured in Table 1, for locations see Figure 1). For the two most western catchments (the Yscir and Taw), it can be seen that the extreme 2022 low flows are not part of a significant decreasing trend. For the Coln and Little Ouse in the English Lowlands, which experienced new minima in 2022, there are significant downward trends in both indicators. Further work is needed to investigate these trends in more detail, particularly given the data quality issues raised (Table 1).

In summary, while the 2022 drought follows on from another severe recent drought in 2018, there is little evidence (yet) to suggest it is part of a strong, large-scale pattern of statistically significant trends towards decreasing river flows. Nevertheless, there are coherent patterns of decreasing low flows and summer trends in the south and east of England. These areas are expected to see some of the greatest decreases in low flows, and increasing drought severity in future (e.g. Parry *et al*., 2023).

This preliminary analysis has focused on simple indicators of low flow and summer flow, rather than drought metrics *per se* and has focused on a subset of catchments that include both natural catchments and those with substantial influences. Further work is needed to look at a wider range of catchments and a comprehensive set of indicators, including those that describe

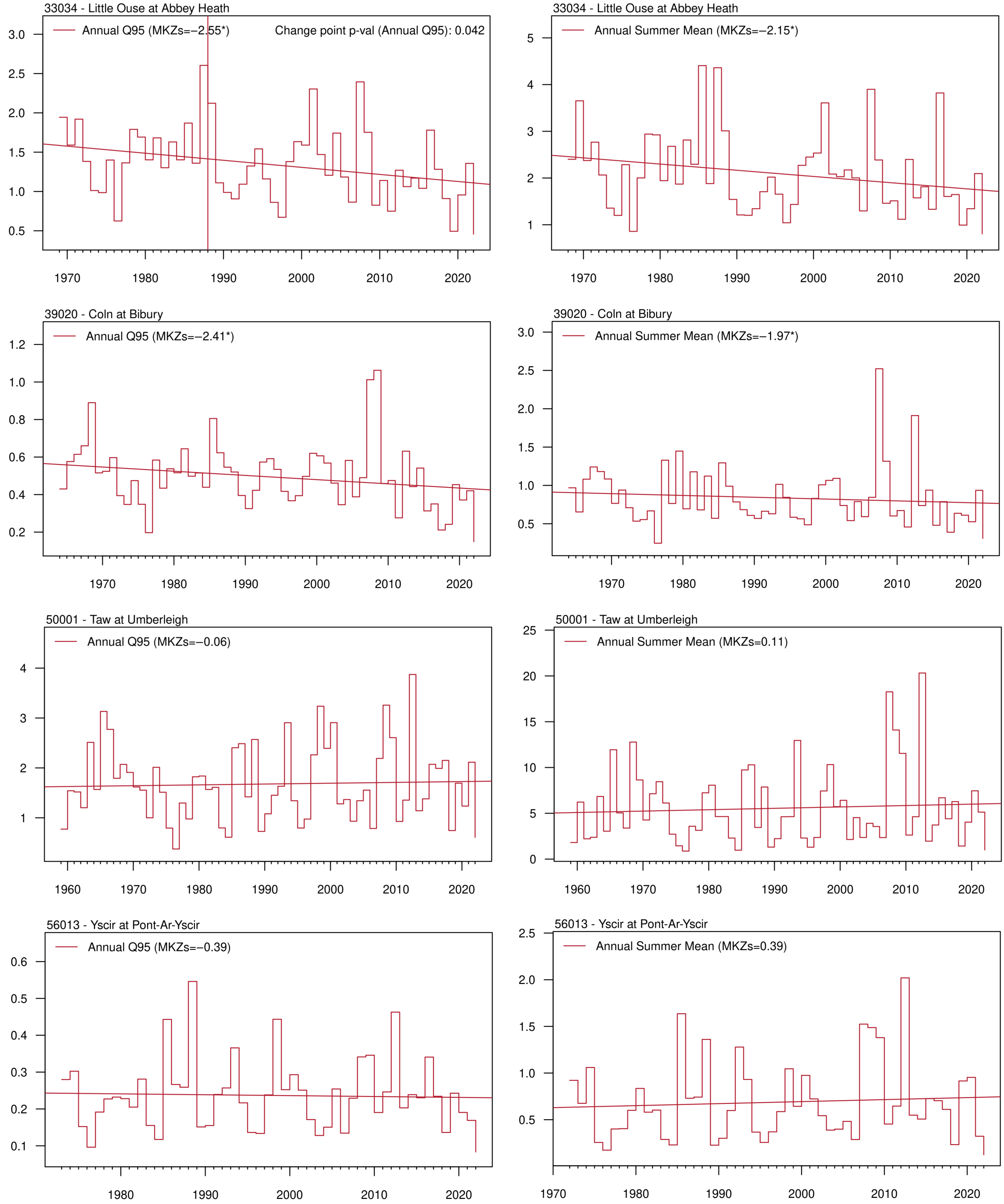

Figure 11. Trends in selected catchments. First column shows low flows (Q95) time series with trend line; second column shows summer flows with trend line. The Mann-Kendall Z Statistic (MKZs) is given for full period of record for both Q95 and summer mean flows. An asterisk next to the MKZ statistic denotes a significant trend.

drought as opposed to low flow. There have been few studies of drought trends, although Peña-Angulo *et al*. (2022) analysed trends in hydrological drought severity up to (1962–2017) for UK catchments, as part of a European wide study, and found little evidence of increasing drought severity, and far more cases of decreasing drought severity over time. Finally, it is worth reaffirming that the absence of compelling trends does not disprove any climate change influence – trends can be obscured by the noise of year-to-year variability (Hannaford *et al*., 2023), and individual drought events are likely to have an anthropogenic warming component, as shown for the wider European drought by Faranda *et al*. (2023).

Concluding remarks

The 2022 drought was a very severe and widespread drought that impacted large parts of the country. In some localities, it was the worst hydrological drought since the 'benchmark' 1976 drought, but more generally it ranks among the most severe droughts witnessed in the last half century. It was, however, largely relatively short lived in most of the country – generally lasting from late spring to mid-autumn. While there were severe impacts on the environment and agriculture, public water supply impacts (and the knock-on social and economic impacts they trigger) were comparatively short-lived. In some areas, however, residual impacts lasted well into 2023 (notably in south west England where temporary use bans were still in place at the time of writing in August 2023). The 2022 drought in the UK was also part of a much wider European drought. During July, the European Commission's Joint Research Centre stated that almost half of the EU and UK territory was under drought warning or alert, and by August, this had increased up to 64%. Preliminary data suggested the drought appeared to be the worst on the continent since at least 500 years (Toreti *et al*., 2022).

Following the broad typology in the introduction, the 2022 drought can be broadly classified as a within year 'summer' drought, as opposed to a multiannual drought driven by successive dry winters. While there is, so far, little compelling evidence of a widespread trend towards increasing hydrological drought severity in the UK, the 2022 drought points to our continuing vulnerability towards these intense droughts associated with low spring/summer rainfall alongside very high temperatures – especially given its occurrence only 4 years after another intense summer drought in 2018, an event which had many parallels. This poses a number of important questions and concerns, particularly because anthropogenic warming increases the risk of droughts like 2018 and 2022, associated with drier summers and higher temperatures (e.g. Parry *et al*., 2023). Following the 2004–2006 and 2010–2012 droughts in southern and eastern England, there has been a greater focus on multiannual droughts associated with two or more dry winters. Yet, while there is significant uncertainty about how multiannual droughts may evolve in future, there is high confidence that we will be increasingly tested by more droughts like 2022, which underscores the importance of preparedness for this type of event.

Intense summer droughts like 2022 are arguably less of a challenge from a water supply perspective, compared to multiannual droughts – although as witnessed in 2022, they can certainly present threats to water supply, especially in northern and western areas with limited storage. Moreover, the impacts seen in 2022 attest to the wider significance of this kind of drought, for agriculture and the environment (with severe impacts on both freshwater and terrestrial ecology) – and especially when considered as a compound hazard alongside the effects of extreme heat, most notably with wildfires. A particular challenge of intense 'flash' droughts is their speed of onset, and the 2022 drought certainly posed significant water management (and drought communication) challenges given the rapidity of onset of drought conditions and associated impacts. Droughts like 2022 underscore the need for improved real-time monitoring and forecasting systems, ideally tools which give an indication of the likelihood of impacts.

Finally, it is worth noting that, with some exceptions, the water supply impacts of 2022 were relatively modest (in terms of duration and extent). As with 2018, this partly reflects some good fortune – mainly, the impacts remained (largely) within-year given relatively favourable antecedent conditions, and wetter periods in winter 2022/2023 that terminated or moderated the drought in most areas. The occurrence of a 'summer 2022' drought following a much drier winter would be an altogether more forbidding prospect (it is worth noting that some major historical droughts, including 1976, followed this pattern, but a similar juxtaposition would be even more challenging with today's temperatures). The summer of 2022 provides water managers with a potential stress test, both on its own (as a harbinger of future summers) and in combination with other pre- and post-event conditions that could be developed into storylines (Chan *et al*., 2021) to test our resilience to such extreme events.

Acknowledgements

The authors would like to thank Stuart Allen, Richard Davis and Lara Williams (Environment Agency) for supplying drought event incident information, naturalised data, and helpful advice on data quality, including reviews of drafts of this paper. We also thank Amit Kumar and Rachael Armitage for helpful comments on earlier drafts. This work is an output of the National Hydrological Monitoring Programme, supported by the Natural Environment Research Council award number NE/R016429/1 as part of the UK-SCAPE programme delivering National Capability, with additional research support from NERC project 'Climate change in the Arctic-North Atlantic Region and Impacts on the UK' (CANARI, Grant Number: NE/W004984/1).

Author contributions

Jamie Hannaford: Conceptualization; formal analysis; funding acquisition; methodology; project administration; supervision; writing – original draft. **Lucy J. Barker:** Conceptualization; formal analysis; funding acquisition; methodology; project administration; supervision; visualization; writing – original draft. **Eugene Magee:** Conceptualization; formal analysis; methodology; visualization; writing – original draft. **Stephen Turner:** Conceptualization; formal analysis; methodology; visualization; writing – original draft. **Catherine Sefton:** Conceptualization; formal analysis; writing – original draft; methodology; visualization. **Simon Parry:** Conceptualization; formal analysis; methodology; writing – review and editing; project administration; funding acquisition. **Jonathan Evans:** Methodology; supervision; writing – review and editing. **Magdalena Szczykulska:** Formal analysis; methodology; visualization; writing – original draft. **Tracey Haxton:** Formal analysis; methodology; writing – review and editing.

Data availability statement

The data that support the findings of this study are all available from the sources highlighted in the introduction and corresponding URLs highlighted in the footnotes. Data can also be requested from the corresponding author upon request.

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Correspondence to: Jamie Hannaford
jaha@ceh.ac.uk

doi: 10.1002/wea.4531