The 2018/2019 drought in the UK: a hydrological appraisal

Weather – August 2021, Vol. 76, No. 8

S. Turner[1], L. J. Barker[1], J. Hannaford[1,2], K. Muchan[1], S. Parry[1] and C. Sefton[1]

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

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

Introduction

While the intense drought of summer 2018 is etched into many people's memories, there is perhaps less widespread recognition of a longer period of dry conditions leading up to this heatwave, and a similarly protracted dry spell extending into late 2019 in some parts of the United Kingdom.

Droughts are widely regarded as complex phenomena that elude precise definition, and identifying their onset and termination can be challenging by virtue of their slow evolution and large spatial extents (e.g. Bachmair *et al*., 2016; Parry *et al*., 2016). In general, droughts are caused by a prolonged deviation from normal precipitation. These precipitation deficits then propagate through the hydrological cycle – the speed of which is dependent on the nature of the precipitation deficits (i.e. the meteorological drought), climate and catchment properties (e.g. Barker *et al*., 2016a). Different types of drought can be identified according to the compartment of the hydrological cycle in which impacts occur, for example hydrological droughts are typically characterised by below-normal river flows (Van Loon, 2015). In this regard, it is unsurprising that it is difficult to pinpoint a precise start and end to drought conditions, and such definitions are necessarily somewhat arbitrary. We describe the 2018/2019 drought as a compound drought event incorporating several distinct drought periods, with varying regional foci, within a wider period of prolonged dry conditions across the UK. The summer (June–August) of 2018 was particularly notable in this event. It was the joint-hottest on record[1], outflows from Great Britain were the second lowest (after 1984; record since 1961) and there were restrictions on water use and widespread environmental impacts such as fish kills and wildfires.

Following the summer of 2018, the drought focus shifted to southeast England with a prolonged, but not especially severe hydrological drought that primarily affected groundwater-dominated catchments, leading to water supply and environmental impact concerns that extended into late 2019. Elsewhere however, summer 2019 saw a decisive termination of the drought and a rapid transition to very wet conditions (e.g. flooding in Wainfleet and the south Pennines; Sefton *et al*., 2021).

This paper focuses on rainfall, river flows and drought impacts from the heatwave of 2018, and the following year, placing the events into historical context. The hydrometeorological data underpinning these analyses are from the UK National River Flow Archive (NRFA) and National Hydrological Monitoring Programme (NHMP) based at the UK Centre for Ecology and Hydrology (UKCEH). Standardised Precipitation Index (SPI) data for the UK are available via the UK Water Resources Portal[2] and described in Tanguy *et al*. (2017). Using incident data for 2018 from the Environment Agency (EA) and Scottish Environment Protection Agency (SEPA) we also explore drought impacts for this period.

Preceding conditions 2016–2018

The prelude to drought conditions can be traced back to 2016 in some parts of the UK. The winter half-year (October 2016–March 2017) was particularly dry in southern England. The Thames, Southern, South West and Wessex regions all recorded around three quarters of average rainfall, whilst Northern Ireland recorded 69% of average, its fourth driest winter half-year on record (all since 1910).

Fears of an impending drought were, to some extent, calmed during summer 2017. Persistent and heavy rainfall, associated with the passage of Atlantic frontal systems, traversed the UK as the jet stream followed a more southerly track compared to its typical position (Kendon *et al*., 2018). Despite this, the lingering effects of the dry spring and winter were still evident in parts of central and southern England where river flows and groundwater levels were below normal, sometimes notably so, and reservoir levels remained below average.

By autumn 2017, dry weather had returned to southern and eastern England. October was notably dry in the southeast, and whilst November rainfall was near average for the UK, many areas of southern England received less than half the average. Correspondingly, river flows were generally below normal, and exceptionally low in places, including the Great Stour in Kent, where a new November minimum flow was registered (in a series from 1964). Groundwater levels in parts of the Chalk of southern and eastern England continued to fall and remained notably low in many boreholes; for example, Little Bucket Farm recorded its lowest end-of-November level in a series from 1971. Recharge was delayed at several sites in the southern Chalk leading to low flows in many groundwater-fed rivers, such as those in the Chilterns. In addition, in some parts of the southeast, reservoir levels were also substantially below average (e.g. levels at Bewl in Sussex were 31% below average, the lowest November stocks on record). In contrast, areas in northwest England received over 150% of average November rainfall, and there were several localised flooding episodes over the autumn (e.g. in Lancashire in late November). This unsettled weather persisted through the winter and for the UK overall, near-average winter rainfall was recorded.

During spring 2018, the more usual northwest/southeast rainfall gradient reversed with exceptionally wet weather in the southeast, whilst the northwest was very dry

[1]The mean summer temperature for the UK in 2018 was 15.8°C, for 2006 it was 15.78°C, for 2003 it was 15.77°C, and 1976 it was 15.77°C all of which are within 0.03°C of each other. In line with the Met Office who report temperatures to 0.1°C accuracy, 2018 is reported as joint hottest with 2003, 2006 and 1976 (Met Office, 2018).

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

RMetS Royal Meteorological Society

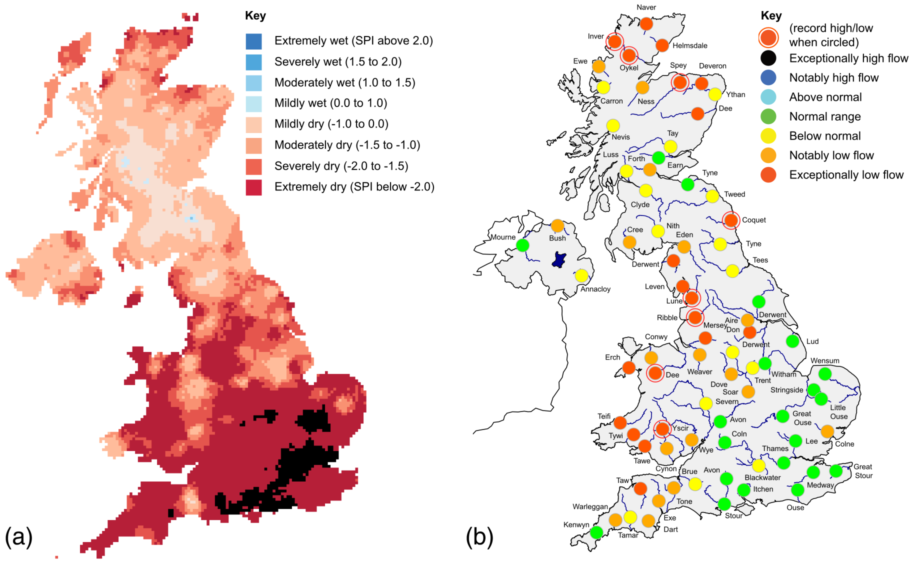

Figure 1. (a) Standardised Precipitation Index (SPI-1) for June 2018. Black areas indicate SPI less than -4.0. (b) Mean river flows June–July 2018.

(similar to patterns seen in 2010). This wet spring in the southeast went some way to replenish groundwater reserves and temporarily eased fears of water resource stress in an area which relies on groundwater resources for many public water supplies. There was above average spring rainfall in England, and the Thames, Southern and Wessex regions all recorded in excess of 140% of average. This meant some catchments registered new record mean spring flows (e.g. on the Teme, Tone and Kenwyn). The wet spring also extended the groundwater recharge season across England and levels were notably high in the southern Chalk. Meanwhile, with a dry spring following a dry winter in northern and western Britain, significant rainfall deficits were evident. It was the driest April–June period since the 1984 drought for the North East Scotland region. For the same period, river flows in northern Scotland and northwest England were notably and exceptionally low, including on the Inver and Oykel which registered their lowest flows on record (both since 1977).

2018 Heatwave

The period of unusually hot weather between June and August 2018 saw temperatures well above average across the country, which led to the joint-warmest summer on record for the UK (alongside 1976, 2003 and 2006) and the warmest on record for England in series since 1884. These conditions were a result of continental drivers that had a similar effect across northern and central Europe (Peters *et al.*, 2020).

Under the influence of persistent high-pressure systems due to a positive phase of the summer North Atlantic Oscillation (SNAO) and a northward-shifted jet stream (McCarthy *et al.*, 2019), June ranked as the fourth driest in the Climate Research Unit England and Wales Precipitation series (starting in 1766; Alexander & Jones, 2001). Many parts of southern and eastern England received minimal appreciable rainfall in June. The Southern region received just 3mm of rainfall (6% of average) making it the driest June on record, whilst the Thames and Wessex regions registered their second driest on record, both after 1925 (all in records from 1910). The one-month Standardised Precipitation Index (SPI-1; data from Tanguy *et al.* (2017); description of SPI in McKee *et al.* (1993)) for June registered exceptionally dry conditions (Figure 1a) and in many cases the driest by some margin. Following the persistent dry weather, the MORECS[3] soil moisture product showed UK soils at the end of June were the driest for that month and the driest for any month since August 1995 (in a series from 1961). These dry conditions continued into July with large parts of England receiving little rainfall for the first three weeks. One example was at the meteorological station in Wallingford (Oxfordshire), which recorded no rain days (i.e., days with ≥1mm of rainfall) between 1 June and 20 July – a spell of 48 days which equalled the record of consecutive dry days at the site set in spring 1997 (in a series from 1962). It was also very dry in much of northern and western Britain which, exacerbated by the dry spring in these regions, resulted in significant rainfall deficits. At the end of July, soil moisture deficits (SMDs) remained high across the country and were the fifth highest (of any month) after the notable drought years of 1976, 1984 and 1995. The North West England region had the highest SMDs on record for this time of year and the dry soils were linked to an increase in insurance claims for damage resulting from subsidence (BBC, 2018a). The dry soils also provided a feedback loop by increasing the maximum temperatures experienced in southeast England during July (Petch *et al.*, 2020).

In July, many responsive rivers receded towards record low flows at month-end. Average flows for the month were notably or exceptionally low across northern and western Britain, and the lowest on record in several catchments (e.g. the Scottish Dee and the Tywi in Wales, in series from 1929 and 1959, respectively). When averaging the river flows for June and July (Figure 1b), record low flows for this period were seen in many catchments (e.g. the Spey and Whiteadder in Scotland, the Lune and Ribble in northwest England and Tywi and Yscir in south Wales). Despite the exceptional dryness and warmth, groundwater levels generally remained in the normal range in southeast England, as did flows in groundwater-fed rivers (particularly those in southeast England), which was a residual effect of the very wet spring.

By late-July, reservoir stocks were below average across the north and west, with stocks in many reservoirs more than 10% below average and some more than 20%. The Derwent Valley reservoir group saw its third lowest late-July stocks (after 1990 and 1996) in a record from 1988. For reservoir storage in England and Wales as a whole, the stocks at the end of July were only 1% above those in July 1995, an exceptional drought year (Marsh, 1996).

2018 Impacts

The low rainfall and high evaporation associated with the hot summer caused a wide range of impacts across the country. Environmental stress caused by the drought manifested itself in many ways – fish kills, water pollution, algal blooms, navigation incidents and wildfires were all reported by UK regulatory staff during their site visits.

In England, the EA recorded over 200 dry weather-related incident reports between July and August alone, more than four times the number of incidents reported over the same months in 2017 (Environment Agency, 2018). The incidents were flagged as 'exacerbated or caused by dry weather'. This is likely to be an under-estimation of the true number of events due to the inexact nature of the descriptor. The incidents recorded as being exacerbated or caused by dry weather were classified on a four-point scale ranging from 'no impact' (which included items such as low water levels which caused no environmental degradation) to 'major impact' such as severe fish kills, serious degradation of water quality and wildfires. These were mainly reported in late spring and summer, but in places (northwest England and

[3]Meteorological Office Rainfall and Evaporation Calculation System (MORECS). MORECS provides estimates of monthly soil moisture deficit in the form of averages over 40×40km grid squares over Great Britain and Northern Ireland.

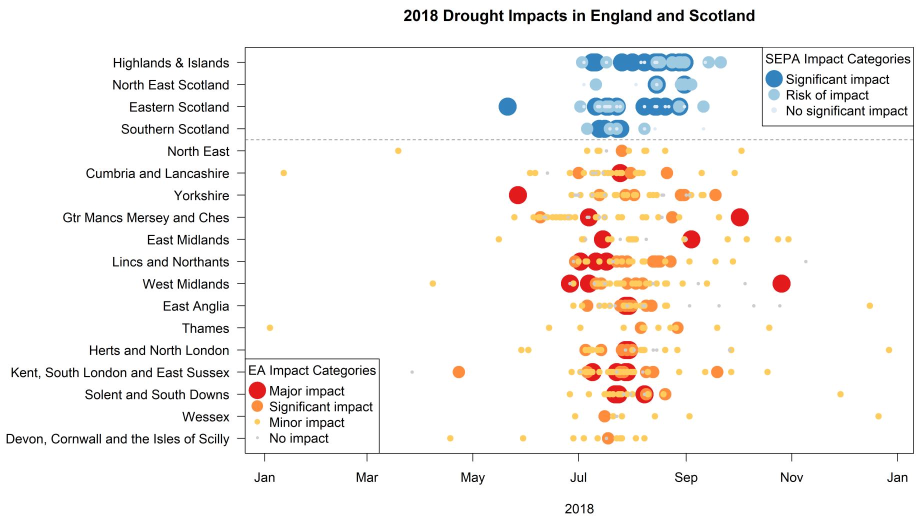

Figure 2. Timeline of drought impacts in England (EA) and Scotland (SEPA) split by EA region in England and NUTS2 regions in Scotland. The classification scheme for Scotland (SEPA) is different to that of England (EA). Data supplied by EA and SEPA.

Table 1

EDII classification of drought related incidents logged in 2018 in England by the EA and Scotland by SEPA.

Impact category	*Count*
Freshwater ecosystems	397
Water quality	76
Wildfires	38
Public water supply	10
Terrestrial ecosystems	10
Waterborne transportation	2
Soil	2
Agriculture & livestock farming	1
Human health & public safety	1
Total	537

the Midlands) impacts continued into the winter (Figure 2). Between May and August 2018, 10 fish kill incidents were classified as major incidents in central, southern and eastern England (including on the Teme on the Welsh borders) which were directly attributed to the dry weather. Numerous wildfires occurred during this period, including the fire on Saddleworth Moor (Greater Manchester) which was extinguished after 24 days. United Utilities, the water company serving north-west England, announced a temporary use ban (TUB or 'hosepipe ban') which was to start on 5 August, though this was not activated largely due to wetter conditions in August.

In Scotland, drought impacts were measured on a three-point scale by SEPA staff, from 'no impact' to 'significant impact'. Significant impacts from drought were recorded in southern and eastern Scotland through late July to September, slightly later in the year compared to England (Figure 2). Thirty-one of these incidents recorded dry riverbeds or isolated pooling of water, whilst nine of these recorded evidence of dead, diseased or distressed animals.

Natural Resources Wales (NRW) entered prolonged dry weather status in early July and investigated and responded to dry weather-related incidents, such as fish kills, algal blooms (blue-green algae), pollution and wildfires across Wales. Other environmental issues included drying of riverbeds with detrimental effects on fish migration and spawning (Natural Resources Wales/Tracey Dunford, 2019). The dry weather also had some positive impacts, including uncovering the locations of Roman fortifications across Wales (BBC, 2020).

In Northern Ireland, a TUB was introduced at the end of June and other areas introduced water efficiency campaigns. However, this was a response to infrastructural challenges of meeting high consumer demand resulting from the heatwave conditions, rather than major resource shortfalls.

The drought incidents recorded by the EA and SEPA in 2018 were grouped according to the European Drought Impact Report Inventory (EDII) classification scheme, a description of which can be found in Stahl *et al.* (2016). The classification scheme has the advantage of allowing stratification by impact type and assessment of the gathered drought impacts across the UK, and allows for comparison with other drought events (if applied retrospectively, and/or used for future events). Of a total of 537 incidents logged relating to drought in 2018 in England and Scotland, the majority fell into the impact category of freshwater ecosystems (74%), followed by water quality (14%) and wildfires (7%) as shown in Table 1.

Of course, the results presented here in Figure 2 and Table 1 are heavily influenced by the remit of regulatory bodies in the UK and thus do not reflect the full range of impacts experienced over the summer. We know from other sources that the agriculture sector was severely hit by the hot and dry weather. During 2018, crops, grass, and feed and livestock were the most impacted areas of farming (Holman *et al.*, 2021). Almost all the reported agricultural impacts were negative: poor crop growth and development led to reduced yields (for both food crops and grassland), and reduced livestock feed availability. Shortages of grass and feed occurred in 2018 as farmers used their winter feed earlier than usual due to vegetation dieback, and shortages extended into the following year. The lower yield of crops also led to increased prices (Salmoral *et al.*, 2020). In Scotland, the brewing and distilling sectors recorded impacts on the quality and yield of malt barley and the sector faced increased raw material costs going forwards (Ecosulis, 2019).

Likewise, with regards to waterborne transportation (another area less well-represented in the incident reports), several sections of canals (managed by the Canal & River Trust) in northern England were closed in late July and early August due to low levels in feeder canals. These included the Leeds and Liverpool, Huddersfield Narrow, Rochdale, Peak Forest and Macclesfield canals, whilst there were reduced opening times and closures on impounds further south, including on the Grand Union and Oxford canals (Canal and River Trust, 2018).

How does summer 2018 compare historically?

During the summer, the hot and dry conditions inevitably led to comparisons with 1976 (as seen in the media: BBC, 2018b), which was a benchmark drought across much of the UK (Rodda and Marsh, 2011; Barker *et al.*, 2019). Meteorologically, there is some basis for the comparison of these exceptional heatwave summers, and for the May–July 2018 period the rainfall recorded in the UK was, in fact, lower than in 1976. River flows in some catchments showed similar trajectories to those in 1976, particularly during the late May to July 2018 period; however, 1976 was more severe over longer timeframes.

In 1976, the arid summer followed a very dry spring and winter in the southeast, whereas in 2018, the wet spring in southeast England sustained flows in groundwater-fed rivers. Reduced winter half-year (October–March) groundwater recharge is a key driver of droughts in southeast England, and most severe past droughts have arisen from multiple dry winters (e.g. 2010–2012, 2004–2006, 1990–1992), sometimes also in combination with intervening hot and dry summers (e.g. in 2006, 1990 and 1976).

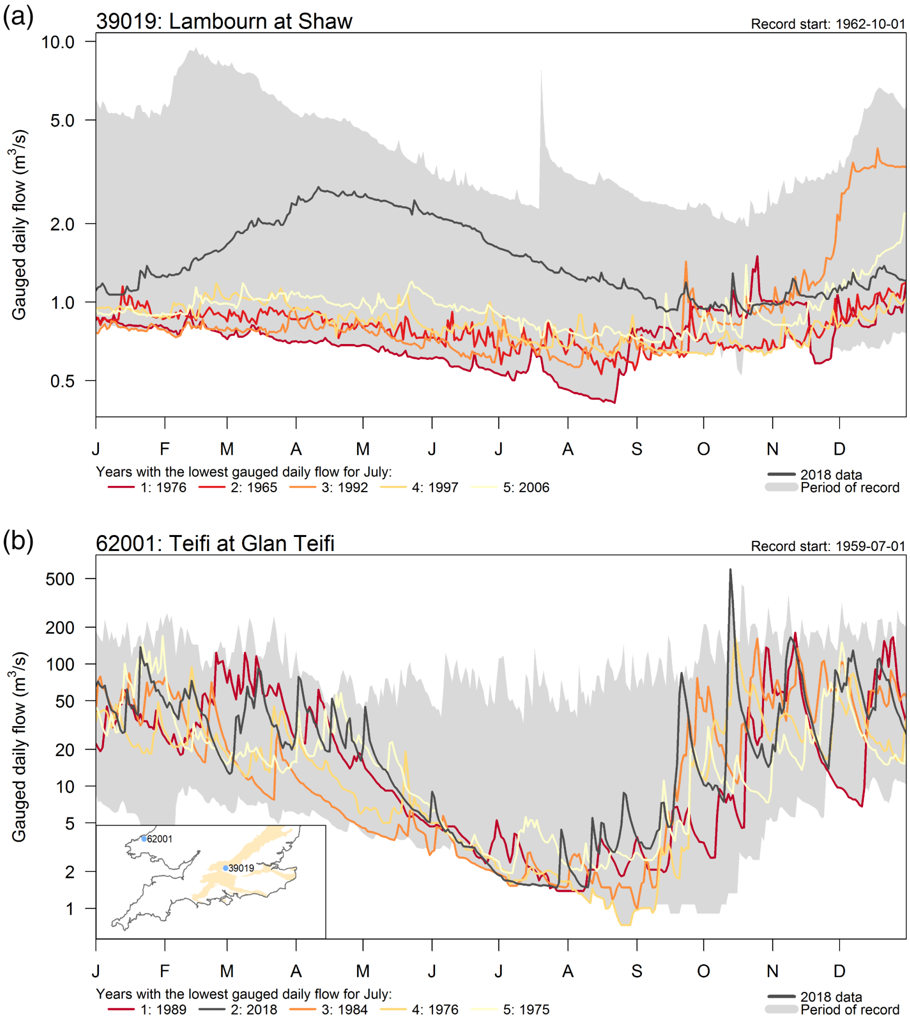

Figure 3. River flows in 2018 against the five years with lowest July flows at (a) 39019: Lambourn at Shaw and (b) 62001: Teifi at Glanteifi.

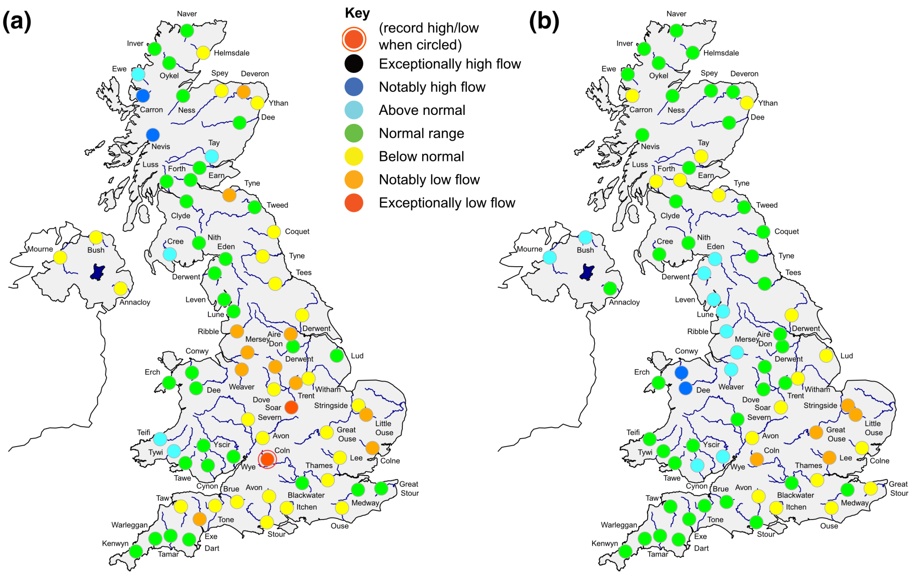

Figure 4. Monthly mean river flows for (a) autumn 2018 (September–November) and (b) spring 2019 (March–May).

Taking a groundwater-fed catchment in southeast England (Lambourn – Figure 3a) and a responsive catchment in south Wales (Teifi – Figure 3b) the 1976 drought features as one of the most severe low flow years in both, but the position of 2018 in the rankings is very different. For the Lambourn, 2018 had higher flows as a result of the winter recharge which was not seen in 1976, highlighting how the antecedent conditions can result in disparate river flow responses.

Post-summer 2018

Following declining river flows during the record-breaking summer, autumn 2018 started with below-normal flows in southern and eastern areas, notably or exceptionally so in some catchments. Groundwater levels were also low, particularly in the Chalk aquifer in southeast England. While the wet spring had provided a pulse of recharge, it was not enough for levels to fully recover as recharge commenced late following an exceptionally dry winter.

The autumn (September–November) of 2018 was characterised by more typical unsettled weather, and included three named storms: *Bronagh*, *Callum* and *Diane*. Although rainfall for the UK was average, this masked some areas where conditions were drier. Northern Ireland, England, Wales and parts of eastern Scotland received below-average rainfall for autumn, particularly in central England where many areas received less than 70% of the long-term average. There were some exceptionally low flows, e.g. on the Coln and Soar (Figure 4a) and groundwater levels at Chilgrove House (West Sussex) in November were the ninth lowest recorded in a series of nearly 200 years.

The winter (October 2018–March 2019) was drier than average at the national scale (93% for the UK). Correspondingly, several catchments recorded river flows less than half the average over the same time period (e.g. the Warwickshire Avon, Great Ouse and Colne in southern England, but also the Tweed and Tyne in northeast England). In fact, the situation in early December 2018 was similar to December 2017, with below-normal river flows across large areas of the English Lowlands. Concern naturally arose for the water situation in summer 2019, particularly in southern Britain, where the effect of long-term rainfall deficits remained apparent.

Following the dry winter, spring 2019 also saw lower than average rainfall, particularly in the south and east of England (the Anglian, Thames and Southern regions all received around three quarters of the average for March–May) which again saw river flows recede to below average (Figure 4b).

The situation in the southeast continued to worsen into the summer and autumn and on 1 October 2019 the Hertfordshire and North London area of the EA declared an environmental drought (Environment Agency, 2019) and cautioned on the need to reduce water use. The sustained lack of rainfall over the three previous years led to contractions in the stream network on many Chalk streams in the southeast, with drought conditions worse in this area in late-summer 2019 than in the previous sum-

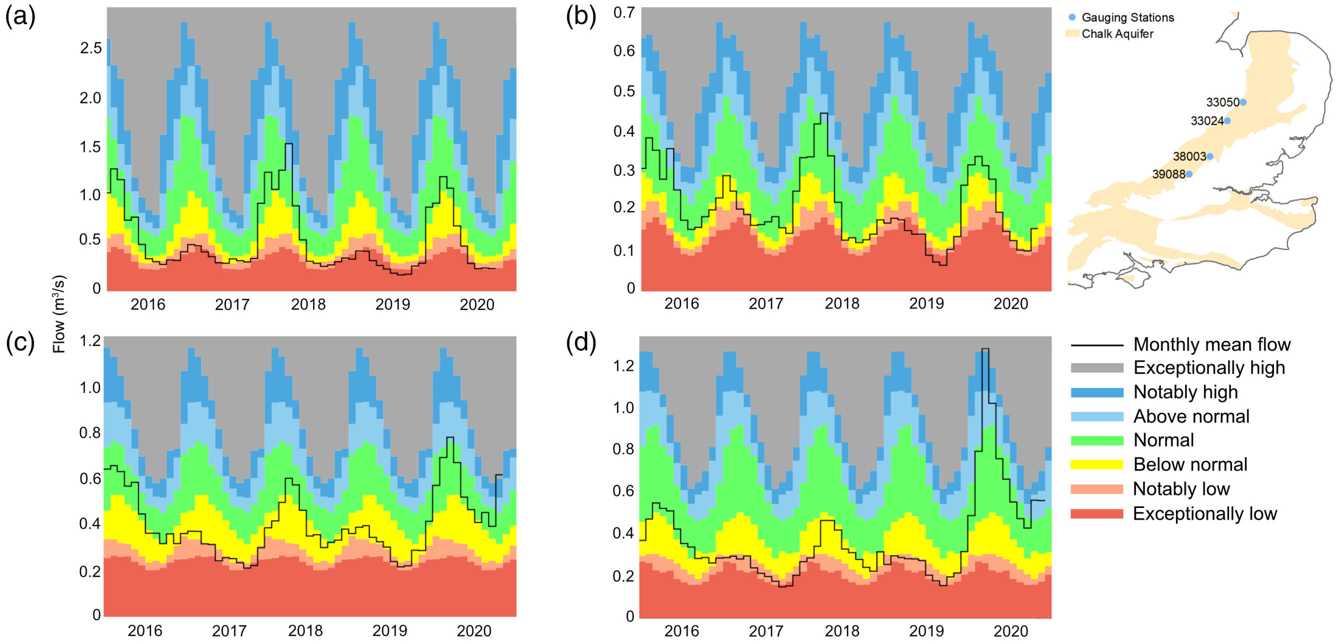

Figure 5. Monthly mean flows between 2016 and 2020 with flow regime bandings at: (a) 33024: Cam at Dernford, (b) 33050: Snail at Fordham, (c) 39088: Chess at Rickmansworth and (d) 38003: Mimram at Panshanger Park.

mer. Many gauging stations in southeast England and East Anglia were exceptionally low by September 2019. For example, on the Cam at Dernford, mean summer flows (June–August) in 2019 were the lowest in a record since 1949. Elsewhere over the summer and autumn, unsettled conditions prevailed, with isolated intense rainfall events impacting central England in June and July. The autumn/winter of 2019/2020 was exceptionally wet for the UK as a whole and was associated with record-breaking flooding in parts of central Britain (Davies *et al*., 2021; Sefton *et al*., 2021).

While the wet winter effectively marked the end of the prolonged drought in much of the southeast, in parts of East Anglia below-normal flows persisted through another winter. Moreover, this was followed by an exceptionally dry spring in 2020: for the UK overall, spring rainfall (March–May) was just 61% of the average, which also resulted in a rapid (albeit temporary) decline in river flows across the country. The residual effect of long duration rainfall deficiencies could still be seen in September 2020 in parts of East Anglia where some catchments entered the 2020/2021 recharge season with notably low flows. The effect of multiple consecutive dry winters is highlighted in the southeastern catchments which had little chance to recover outside of the recharge season due to their groundwater-dominated regimes (Figure 5).

Conclusion

The drought conditions of the late 2010s, together with the previous major event of 2010–2012, have underscored the continuing vulnerability of the UK to drought. Like the 2010–2012 drought, the period discussed in this paper was bookended by, and overlapped with, major flood events (Barker *et al*., 2016b; Sefton *et al*., 2021) which further illustrates the hydrological volatility of recent decades (e.g. Hannaford, 2015).

It is widely known that different areas of the UK are vulnerable to different 'types' of drought, with a broad distinction often drawn between short duration heatwave-driven 'summer' droughts in the northwest compared with multi-year groundwater droughts in the southeast (e.g. Marsh *et al*., 2007; Barker *et al*., 2019). The 2016–2019 period demonstrated elements of both these broad drought types: a long duration drought in southeast England punctuated with several arid summer heatwave episodes mostly affecting responsive western catchments. It has parallels with other compound drought episodes with a multi-year groundwater component with intense arid episodes and wetter interludes (e.g. 2004–2006, Marsh *et al*., 2007; 1988–1992; Marsh *et al*., 1994).

The period described here also highlights the seasonal variability seen in recent years and underscores the importance of the sequencing of wet and dry periods in dictating the impact of droughts. The heatwave of summer 2018 would have had far more hydrological impact in the southeast were it not for a wet spring. While heatwaves in summer 2018 and early summer 2019 had serious impacts on the environment and some sectors (notably agriculture), water supply impacts were moderated by wetter Augusts (another developing drought in spring 2020 was also arrested by a wetter summer). In effect there were several near misses, when drought concerns heightened to levels triggering mitigation actions, only to see abrupt changes in weather conditions. It is important to reflect on 'what might have been' for future planning – for example, if the summer 2018 heatwave had followed an exceptionally dry winter/spring (e.g. 1975–1976). In these instances, greater understanding of historic drought events can provide important context to underpin drought risk assessments and to develop drought management plans (Barker *et al*., 2019).

The 2018/2019 period exemplifies the challenges of defining drought onset as well as drought termination (e.g. Parry *et al*., 2016). While drought conditions terminated abruptly in parts of the north in summer 2019, they intensified in the southeast, leading to simultaneous drought concerns and flood alerts across the UK. The 2018/2019 drought also highlights the challenges of drought communication, and of water resources management in general, against a backdrop of seemingly increasing climate variability. Based on demographic, economic and predicted climate changes (e.g. Water UK, 2016; National Infrastructure Commission, 2018) the need for increased drought resilience is clear and the period described in this paper highlights the complexity and intricacies of this task over the coming decades.

Acknowledgements

The authors would like to thank Mike Dunbar, Katharine McChesney and Dilek Saunders (EA), Stephen McGuire (SEPA) and Tracey Dunford (NRW) for supplying drought event incident information. Further context of the hydrological conditions presented

may be found in NHMP Hydrological Summaries and blogs (https://nrfa.ceh.ac.uk/nhmp) and on the UKCEH UK Water Resources Portal (https://eip.ceh.ac.uk/hydrology/water-resources/index.html).

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. Support was also received from the NERC Drought and Water Scarcity Programme, via the 'Historic Droughts' project (NE/L01061X/1).

Author contributions

Stephen Turner: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; supervision; validation; visualization; writing-original draft; writing-review & editing. **Lucy Barker:** Data curation; formal analysis; methodology; visualization; writing-review & editing. **Jamie Hannaford:** Conceptualization; supervision; writing-review & editing. **Katie Muchan:** Writing-review & editing. **Simon Parry:** Writing-review & editing. **Catherine Sefton:** Writing-review & editing.

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Correspondence to: S. Turner

stetur@ceh.ac.uk

doi: 10.1002/wea.4003