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Putting the English Flooding of 2019–2021 in the Context of Antecedent Conditions

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ABSTRACT

England experienced a sequence of extreme flood events between June 2019 and April 2021. To understand the severity and likelihood of the events, a set of over 300 flow and river level stations was investigated for key events (identified by Environment Agency Area Teams), focusing on frequency analysis of peak flow, peak level and cumulative flow volume. In addition, groundwater, soil moisture and seasonal total rainfall were analysed to understand the antecedent conditions affecting the impacts of the rainfall experienced. While the period contained some of the wettest months on record, there were few extreme short-duration rainfall events. Record-breaking flows and river levels were seen across the country, in part due to the extreme antecedent conditions where many parts of England had record groundwater levels and soil moisture content preceding the events. A kernel density approach was used to identify statistically significant clusters of events over the study period (compared with a Poisson process) and found that most stations in northern and western England experienced a cluster during the study period. Urbanisation was investigated as a possible driver of these trends, but urban increase was not seen to be a significant driver.

1 | Introduction

Flooding is currently considered one of the highest risks facing many countries across the world, with millions of properties in the UK at risk of fluvial or coastal flooding (HM Government 2023). Between June 2019 and April 2021, a sequence of intense storm events impacted the UK, alongside periods of long-duration rainfall that left the ground saturated in many areas. Intense rainfall is typically thought of as the key driver for fluvial flooding, but antecedent soil moisture conditions and groundwater levels are just as pivotal (Ledingham et al. 2019; Merz and Blöschl 2003). Flood response is a complex problem dependent on geology, soils, topography and anthropogenic changes (Berghuijs et al. 2019), as well as climate.

Widespread flooding in particular is of note due to the increased pressures that multiple simultaneous flooding events can put on a response network and its resources (sand bags, emergency services etc.). Griffin, Kay, Sayers, et al. (2022) discussed how the mechanics of widespread flooding vary in time and space across the UK, and how they might change in the future, using UKCP18 climate data. Brunner and Slater (2022) used the European Flood Awareness System's data to explore this through using pooling reforecast ensemble members to increase event set sizes and get a wider picture of possible extreme events across Europe.

This paper discusses the 2019–21 flooding in England, putting it into the context of the antecedent conditions that preceded each flooding event, and assessing whether extreme soil wetness led to increased flood magnitudes. The events in the 2019–21 study period are a key example of how antecedent conditions and prolonged wet weather can lead to extreme flooding despite few extreme short-duration rainfall events (Davies et al. 2021; Sefton et al. 2021).

A series of analyses into flow, level and volume of floods were undertaken, alongside analysis of antecedent conditions such as long-duration rainfall, soil moisture and groundwater levels. The data used are described in Section 2; the methods in Section 3; the results in Section 4; and discussions and conclusions follow in Sections 5 and 6. This work was undertaken as part of an English Environment Agency project, where specific stations, dates and analysis types were determined based on local experience.

2 | Data

2.1 | Flow, Level and Volume Data

River discharge data, both level and flow, were collated for 196 flow stations and 134 level-only stations (Figure 1a). From these stations, 15-min, annual maxima (AMAX) and peak-over-threshold (POT, see https://nrfa.ceh.ac.uk/peaks-over-threshold for further details) series were obtained. Where available, peak flow data were taken from the National River Flow Archive (NRFA 2022). Where not available, data were either acquired from the EA WISKI hydrometric archive, or from the EA Hydrology Data Explorer (HDE, Environment Agency 2023) API.

Where AMAX series were not available, they were extracted from 15-min level and flow series from WISKI or the HDE. Annual maxima were taken according to hydrological year (October 1—September 30). Peaks over threshold were identified using a percentile of flow corresponding to an average of five events per year. To ensure independent peaks, a minimum separation between peaks based on mean time-to-peak was used, and peaks must have had a minimum between-peak flow value of 2/3 the smaller peak. Records range between 4 and 102 years, but AMAX and POT were only taken from complete years.

Where 15-min flow data were available, the maximum volume of flow accumulated over a 2-week period was calculated for each hydrological year and used to assemble an AMAX series for each station.

In addition to these AMAX series, peak flow and peak level values were calculated for key events during the study period. Total volume of flow (in m^3) was also calculated for a 2-week period from the start of each event.

2.2 | Groundwater Data

Groundwater data were collected at 76 stations across England (Figure 1b). These stations either measured groundwater level above ordnance datum (mAOD, by pressure transducer) or by manual depth dipping. To describe antecedent conditions at flow/level stations, groundwater stations were matched with appropriate nearby flow/level stations by expert knowledge. In cases where a flow/level station did not have an expert-identified groundwater station, the nearest groundwater station within 50 km was used. Groundwater extremes (maximum level above ordnance datum or minimum dip depth) were calculated at each station for each hydrological year, along with values corresponding to key events. While the annual minimum dip depth series is referred to by AMIN, it is equivalent to a groundwater level AMAX series. Records range between 6 and 72 years, stations were chosen with near-complete records, and extrema only taken from complete years.

2.3 | Soil Moisture Data

Soil moisture data from the COSMOS-UK network of soil moisture sensors (using cosmic ray neutron detectors) (Cooper et al. 2021) were used as another source of understanding the antecedent conditions before flooding events. This network of 51 sites, 38 in England (Figure 1c), has approximately 10 years of data describing average field-scale volumetric water content (VWC, as a percentage) of the soil near the surface. Due to the small size of the soil moisture network, flow/level stations were simply linked to the nearest COSMOS-UK station to understand the pre-event soil moisture. For specific events, maximum VWC was compared with the equivalent quarter-month average (e.g., first quarter of June) in each year of the record. Records all range between 3 and 10 years, and are complete.

2.4 | Rainfall Data

Rainfall data came from two sources: point data, directly from raingauges, and catchment-average estimates, derived from gridded data. The closest telemetered raingauge (263 raingauges selected) to each station that was available on the EA Hydrology Data Explorer was analysed (Environment Agency 2023). Alongside this, two gridded datasets were used: (1) daily gridded data from the Met Office HadUK gridded data (Met Office et al. 2022), a 1 km × 1 km gridded dataset with daily rainfall from the year 1891, and (2) UKCEH 15-min gridded rainfall data, H24, which merges raingauge and radar data using topographic information. Using catchment boundaries, catchment-average total rainfall was determined for specified events, which, alongside rain gauge data, were used to calculate 1- to 96-h rainfall accumulations for each event. HadUK-Grid data were used to calculate 30- to 180-day rainfall accumulations for each event, and to create 30- to 180-day AMAX series for annual exceedance probability (AEP) analysis (Tables 1 and 2).

For the rainfall data, the H24 gridded data is complete for the 2019–2021 period, the HadUK gridded data are complete for the full period of analysis (though heavily interpolated in the early part of the record), and the direct raingauge data records are between 4 and 61 years and were chosen for completeness of their time series. In Figure 1, and all subsequent figures,

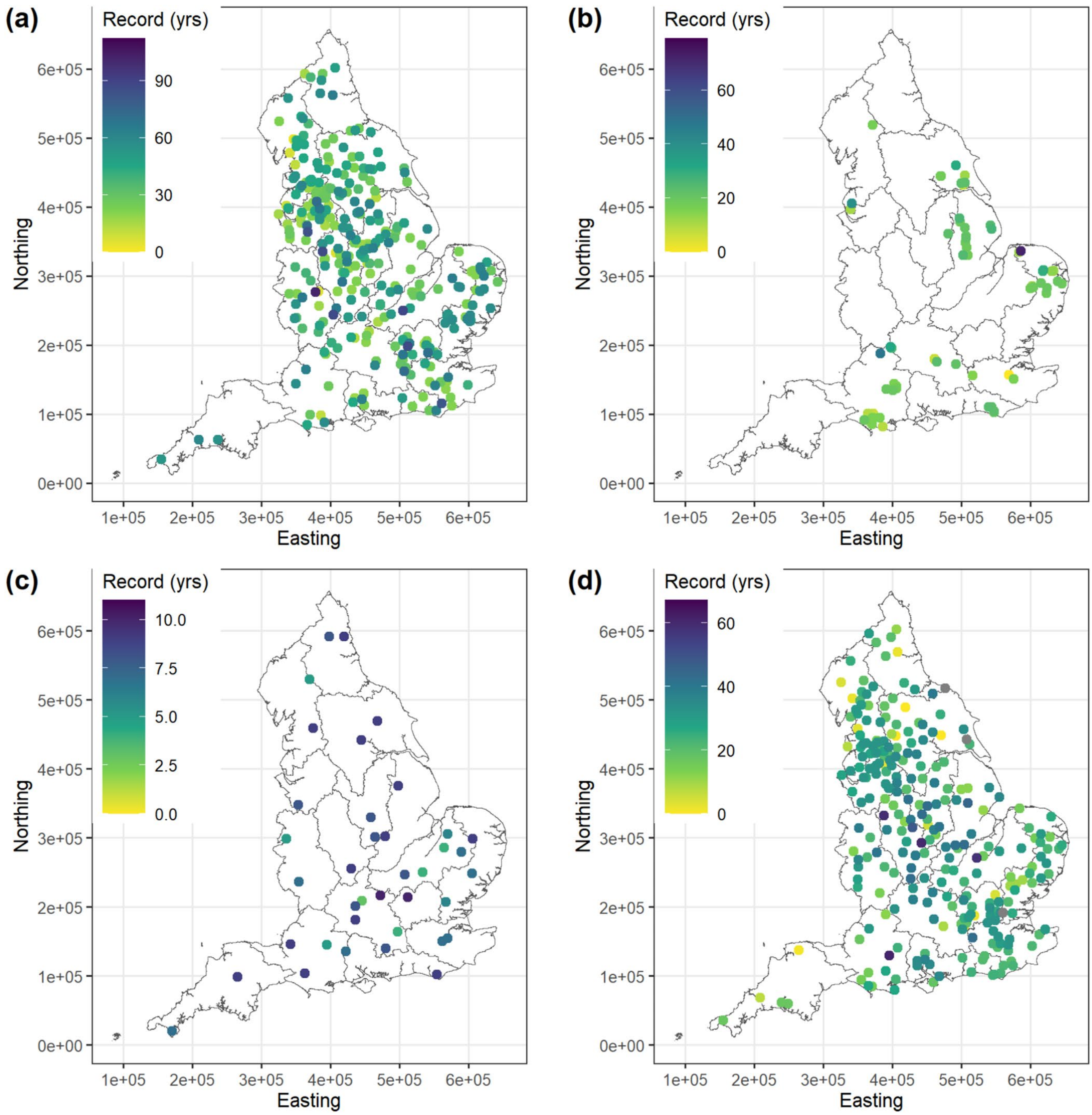

FIGURE 1 | Locations of (a) level and flow gauging stations, (b) groundwater stations, (c) COSMOS-UK sensors, (d) raingauges used in this study. Regions indicate Environment Agency operational areas. Record indicates time between earliest and latest reading.

locations are given on the British National Grid in terms of 'Eastings' and 'Northings', metres east and north of a point at approximately 49° N, 2° W, and gridlines on figures are at 100 km intervals.

3 | Methods

In the following, AMAXn will denote the nth largest value in an AMAX series, and POTn will denote the nth largest value in a POT series.

3.1 | Station, Event and Analysis Selection

During the inception phase of this project, Environment Agency area hydrology and hydrometry teams were asked to identify any stations that were notably affected by flooding between June 2019 and June 2021, and the dates on which the stations were affected (up to six events per station). Dates were often found to be approximate or inaccurate, and so extreme events were identified as long as they were within 2 days of the stated date. This led to 102 unique dates being identified over the study period.

TABLE 1 | Sources of hydrological point data used in this study.

Data type	Units	Number of stations	Range of data	Mean record (years)	Reference
Flow	m^3/s	196	1959–2022	39.1	Environment Agency (2023), NRFA (2022)
Level	m (AOD)	134	1958–2022	32.1	Environment Agency (2023), NRFA (2022)
Groundwater	m (AOD or dip depth)	76	1951–2022	20.6	British Geological Survey/EA
Soil moisture (volumetric water content)	%	38	2013–2022	7.6	Stanley et al. (2023)
Precipitation	mm	263	1961–2022	25.5	Environment Agency (2023)

TABLE 2 | Sources of gridded data used in the present work.

Data type	Units	Grid resolution	Range of data	Reference
Gridded daily rainfall depth	mm	1 km × 1 km × 1 day	1891–2022	Met Office et al. (2022)
Gridded 15-min rainfall depth	mm	1 km × 1 km × 15 min	1891–2022	
Land cover map	Ordinal (21 classes)	25 m × 25 m	1990–2021	Marston et al. (2022)

Depending on the station and the requirements of the local teams, different types of analysis were requested from those outlined in the rest of this section. As a result, some spatial and temporal patterns are strongly influenced by the choice of locations where different types of analysis were considered useful or relevant.

3.2 | Flood Frequency Analysis

Peak flow analysis was undertaken using the UK Flood Estimation Handbook (Kjeldsen et al. 2008; Robson and Reed 1999) statistical method. This is an index-flood method using a region-of-influence flood frequency approach where a Generalised Logistic (GLO) distribution is parameterised according to the *L*-moments (Hosking and Wallis 1997) of the AMAX series at both the station of interest and a group of hydrologically similar catchments.

Peak-over-threshold data were examined using a Generalised Pareto distribution (GPa) fitted to the POT series at a given station. A Poisson approximation was used to convert between per-event and per-year probabilities of exceedance (PoE): $PoE_{\text{ANNUAL}} = 1 - \exp\left(-N \times PoE_{\text{EVENT}}\right)$, where N is the mean number of POT events per year at a given station. This Poisson approximation assumes independent exponentially-distributed arrival times of POT events. This aligns with how the POT were derived, using a static threshold and the independence criterion outlined in Section 2.1.

Through the rest of this study (except for non-stationary analysis in Sections 3.3 and 4.8), the AMAX and POT series of all data types were assumed to follow a stationary distribution, and so likelihood of occurrence is described in terms of annual exceedance probability (AEP): AEP = 1/PoE, measured in chance-per-year.

Throughout, measures of rarity are given as single values, but are often subject to considerable uncertainty, and the true value should be considered to be within a range around the stated estimate.

3.3 | Non-Stationary Flood Frequency Analysis

Mann–Kendall tests of trend (Kendall 1975) were performed on all flow series with at least 20 years of record to assess for trends in peak flow. An estimate of the magnitude of this trend was calculated using a Theil–Sen slope (Sen 1968).

3.4 | Volume and Groundwater Frequency Analysis

To compute AEP for volume and groundwater level/depth, stationary Generalised Extreme Value distributions (GEV) were fitted to AMAX/AMIN series.

3.5 | FEH Rainfall Frequency Analysis

To estimate at-site and catchment-average rainfall AEP, the FEH22 rainfall depth-duration-frequency model (Vesuviano 2022; Vesuviano et al. 2021) was applied. This model uses a Gamma mixture distribution to derive growth curves for different durations, using the FORGEX regional approach (Stewart et al. 2010) to generate weighted network annual maxima series.

In this study, the FEH22 AEPs for each event were calculated for durations of 1–96 h, based on 15-min raingauge data and 15-min catchment-average data derived from gridded H24 data. Note that the FEH22 model used to estimate return periods is based upon rain gauge data and does not include radar data. Applying radar data to the FEH22 DDF model is likely to generate overestimated return periods as radar data is more likely to capture isolated, extreme rainfall that may be missed by rain gauges.

To examine the long-duration rainfall, which contributed to antecedent conditions, 30–180-day rainfall accumulations were calculated and ranked for both the full period of record and for the periods immediately preceding identified events. AMAX series were derived, to which a stationary GEV distributions were fitted. These distributions were used to assess event long-duration rainfall rarity.

3.6 | Rate-of-Rise Analysis

For selected flow and level stations, rate-of-rise analyses were performed. Rate-of-rise was calculated as change in level/flow, measured in m/h (level) or m^3/s/h (flow), over a given period of time, ranging from 15 min to 6 h. A POT series was derived for each station, with a percentage exceedance chosen to give, on average, five peaks per year. Independence of peaks was determined by forcing at least a 7-day gap between peaks. Maximum rates-of-rise within 2 days of the peak flow or level were recorded for each key event.

3.7 | Kernel Density Clustering of POT Flow Events

In order to understand whether the events of this period were part of a significant cluster of events, a kernel density approach was applied to compare the distribution of events to the naïve assumption of close to five events per year for each year in the full period of record. This used a Poisson process assumption (and in the POT probabilities of exceedance above) of independent, exponentially distributed inter-arrival times. Following the approach of Merz et al. (2016), POT series of flow were used to derive a kernel density over time using a bandwidth of 2 years. A bootstrapping approach (500 Poisson process time-series based on the observed mean arrival rate) was used to derive 95% confidence intervals, where a cluster of events is significant if, roughly, more than 12 POT events occur in a 2-year period (in a POT series with five events per year on average). The exact number depends on the exact frequency of events per year, which varies between stations.

3.8 | Event **Ranking**

For all measurement types, values were ranked within their respective AMAX series. The exception to this is the COSMOS-UK data, where maximum VWC was compared between quarter-months (e.g., first quarter of June, third quarter of September) across the period of record. Quarter-months were chosen in preference to weeks, as quarter-months always correspond to the same dates in different years and can more easily incorporate the 29th–31st days of each month.

3.9 | Context Analysis

To put the events into historical and hydrological context, the conditions antecedent to the key events were compiled, and a simple rank comparison was applied. Antecedent conditions (preceding groundwater, COSMOS VWC, or antecedent long-period rainfall) were determined to be 'high' if they were above a certain threshold (Table 3).

Co-occurrences of high antecedent conditions and flood hazard were counted for each combination for each season and region.

3.10 | Land Cover Analysis

An investigation was also undertaken into the impact of urbanisation on flooding, using Land Cover Maps (LCM, Marston et al. 2022) to compare changes in urban extents over time with the existence of trends in the flow AMAX data. Three metrics were calculated for the catchments gauged by the flow stations in the dataset:

TABLE 3 | Threshold for 'extreme conditions' for antecedent impact.

Flood metric	Threshold for 'extreme'
Groundwater level	AMAX5
Soil moisture (VWC)	Greater than 3rd highest value for the corresponding quarter-month
90-day antecedent rainfall	AMAX5
Peak flow	AMAX5
Peak level	AMAX5
2-week volume	AMAX5
6-h rainfall	AEP < 1 in 20
1-h rate-of-rise	POT20

- Percentage change of gridcells from urban to non-urban between 1990 and 2015.
- Percentage change of gridcells from non-urban to Urban between 1990 and 2015.
- Percentage of urban cells in the LCM2021 product (2021 edition of current land cover in the UK, (Marston et al. 2022)).

For the changes between 1990 and 2015, 'Urban' was a single class taken from a reduced set of six simplified classes: woodland, arable, grassland, freshwater, built-up (or urban) and other. In LCM2021, two classes 'urban' and 'suburban' were selected to cover the 'urbanisation' of an area. These were compared to the results of Mann–Kendall tests of trend (Kendall 1975).

4 | Results

In order to discuss the June 2019–June 2021 period, it is sensible to group the key events into a number of seasons (Table 4), some of which are associated with named storms (as co-named by the UK Met Office, Met Éireann and KNMI). Some key storm seasons from other notable periods in UK flood hydrology in the 21st century are also mentioned. Note that not all flooding events were triggered by named storms.

4.1 | Summer 2019

The 2 years leading up to summer 2019 were exceptionally dry (Turner, Barker, et al. 2021), due to heatwaves in 2018, record low rainfall in the south of England in June 2018 (6% of long-term average), and below-average national rainfall from October 2018 to March 2019 (93% of UK long-term average), leading to below-average river flow across much of central and southern England. This came to an abrupt end in many parts of the country with a large amount of rain between June and August 2019. Between the 10th and 13th June 2019, seven stations across central England in the study dataset experienced 4-day rainfall with AEP less than 1 in 30 (Figure 2). This was also seen at other stations in the East Midlands (Met Office 2019). However, few stations saw extreme river levels at this time.

TABLE 4 | Seasons referred to in this work.

Season	Date range	Key named storms
Winter 2014–15[a]	December 2015–January 2016	Desmond, Frank
Summer 2019	June–August 2019	
Autumn 2019	September–November 2019	
Winter 2019–20	December 2019–January 2020	Atiyah, Brendan
Spring 2020	February–May 2020	Ciara, Dennis, Jorge
Summer 2020	June–August 2020	
Autumn 2020	September–December 2020	Alex (named by Meteo-France), Aiden, Bella
Winter 2021	January–February 2021	Christoph, Darcy

[a]Winter 2014–15 is included for context but was not part of the study.

At the end of July, a number of stations around the Pennines experienced very high intensity rainfall including a 6-h point rainfall AEP less than 1 in 90 at Arkle Town in Yorkshire (Figure 2d). This led to five flow stations experiencing record flow values, with the Dean at Stanneylands experiencing an AEP less than 1 in 300, and a further three stations exceeding AMAX3.

4.2 | Autumn 2019

Rainfalls in this season were extreme in terms of overall volume, but not hour-to-hour intensity (few extreme 15-min observations). This led to ground saturation, especially in the northern half of England (Davies et al. 2021). High rainfall occurred on 28th September, which led to two rainfall stations in Cumbria/Lancashire having two-week total rainfalls above AMAX5, despite not having any large short-duration rainfalls.

Between the 25th–29th October, 23 flow or level stations in the study dataset experienced key events. Four stations experienced a flow above AMAX5, eight experienced a level above AMAX5, and seven experienced a two-week volume above AMAX5. Once again, no rainfall station recorded an extreme 6-h rainfall. However, the extreme river response can be explained by the antecedent soil moisture. During this period, the four nearest COSMOS-UK sensors all experienced record or AMAX2 soil moisture for the 24th–31st October quarter-month relative to other years (Figure 3a).

During the period of 6th–17th November, 25 of the 44 stations, which selected that event as notable had a peak level above AMAX5, and 9 of the 19 flow stations showed a peak level above AMAX5. Again, these events were not triggered by extreme short-duration rainfall but were exacerbated by wet antecedent conditions observed in the COSMOS-UK soil moisture and the 90-day rainfall accumulation (Figure 3b). This led to overall extreme outcomes in flow and level (Figure 4).

4.3 | Winter 2019–20

In winter 2019–20, storms Atiyah and Brendan hit the south of England with force, but few stations outside this region noted these events. For the 26 stations with level measurements that identified these events, 11 experienced levels above AMAX5 and two experienced new AMAX1 level events, each with AEPs less than 1 in 50: 1 in 52.6 AEP at Medway at Colliers Land Bridge, and 1 in 58.8 AEP at Medway at Teston & East Farleigh Combined. All 11 of these stations experienced a 90-day accumulated rainfall above AMAX5, which will have included the

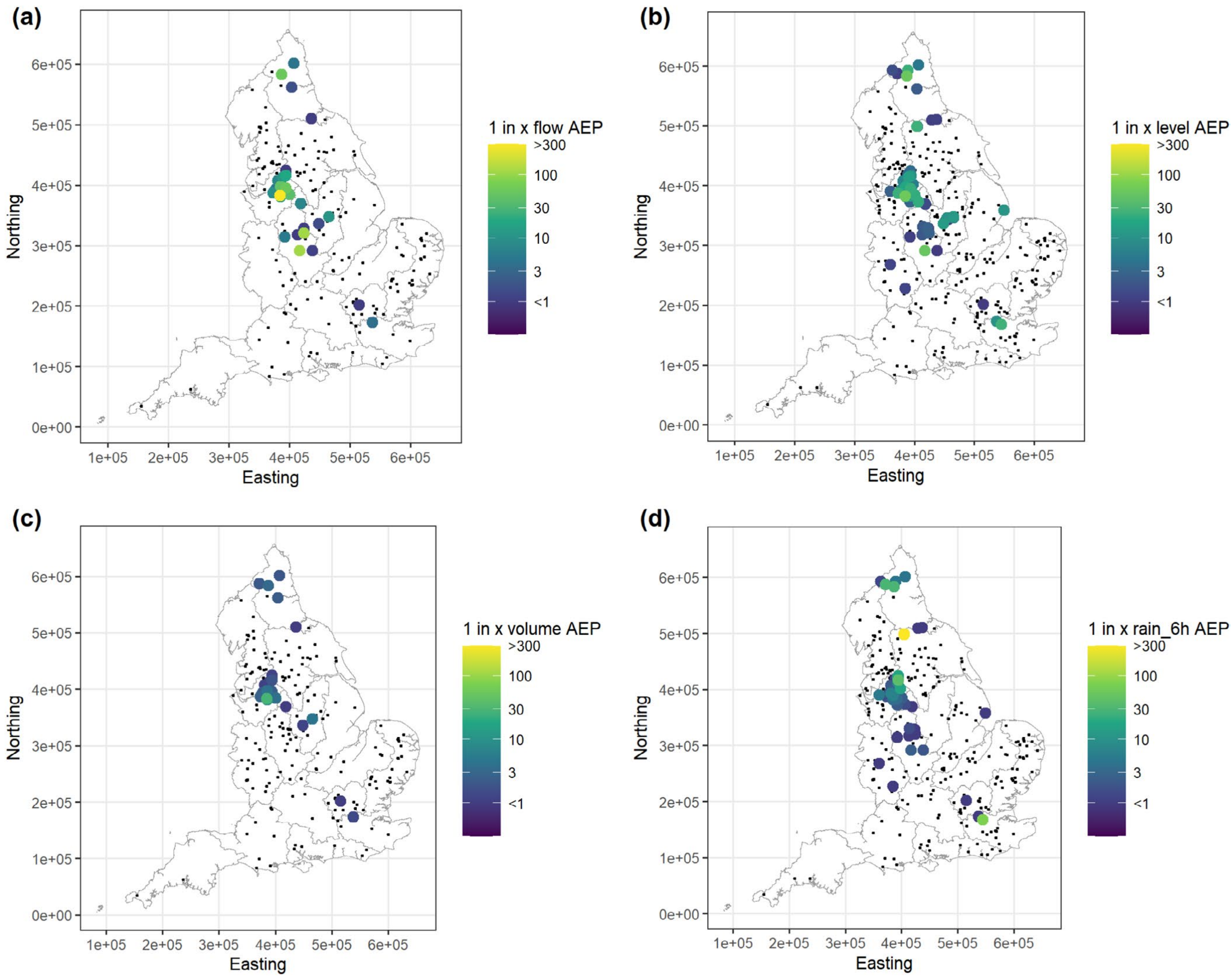

FIGURE 2 | Maximum AEPs of (a) flow, (b) level, (c) 2-week volume and (d) 6-h point rainfall during Summer 2019. Black dots indicate other gauges (flow/level/rainfall) that were included in this study but were not selected for events during this period.

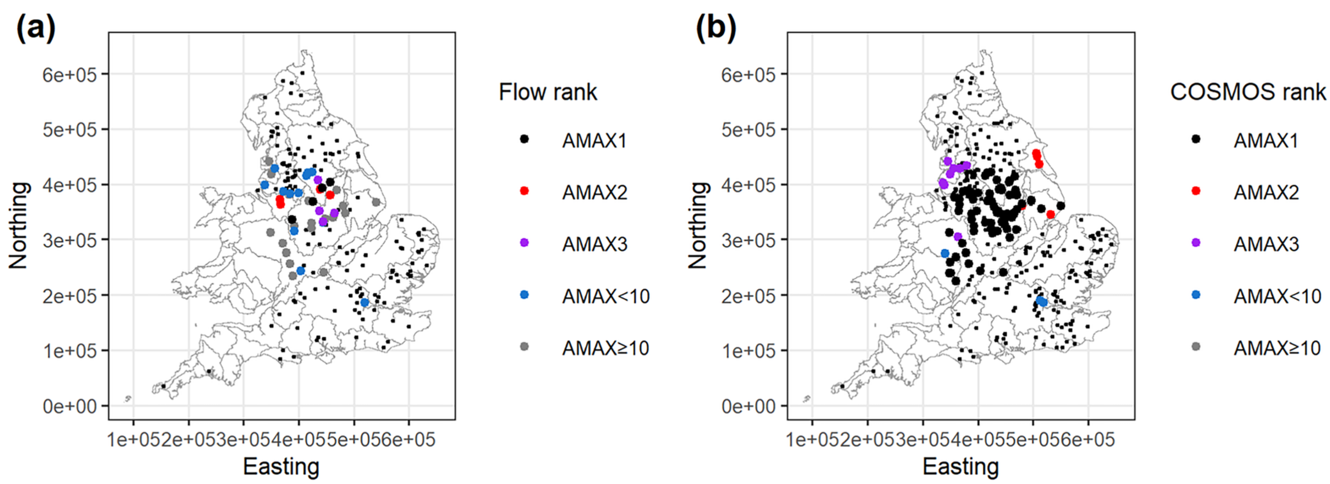

FIGURE 3 | (a) Flow ranks for flow stations which identified 6th–17th November as a key event. (b) Volumetric water content ranking from nearest COSMOS stations compared with the 4th quarter of October. Boundaries show UK hydrometric areas (NRFA 2014).

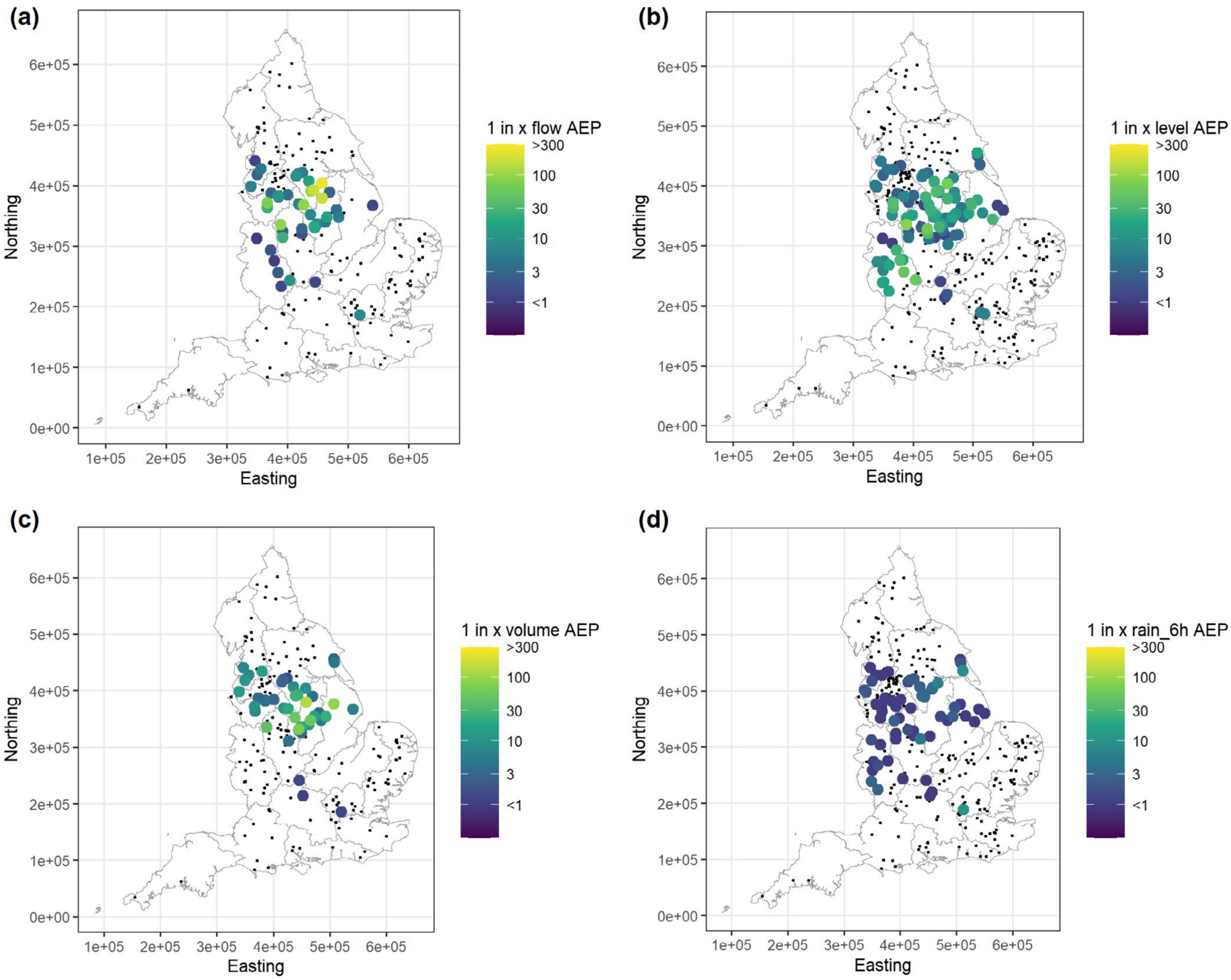

FIGURE 4 | Maximum AEPs of (a) flow, (b) level, (c) 2-week volume and (d) 6-h point rainfall during Autumn 2019. Black dots indicate other gauges (flow/level/rainfall) that were included in this study but were not selected for events during this period.

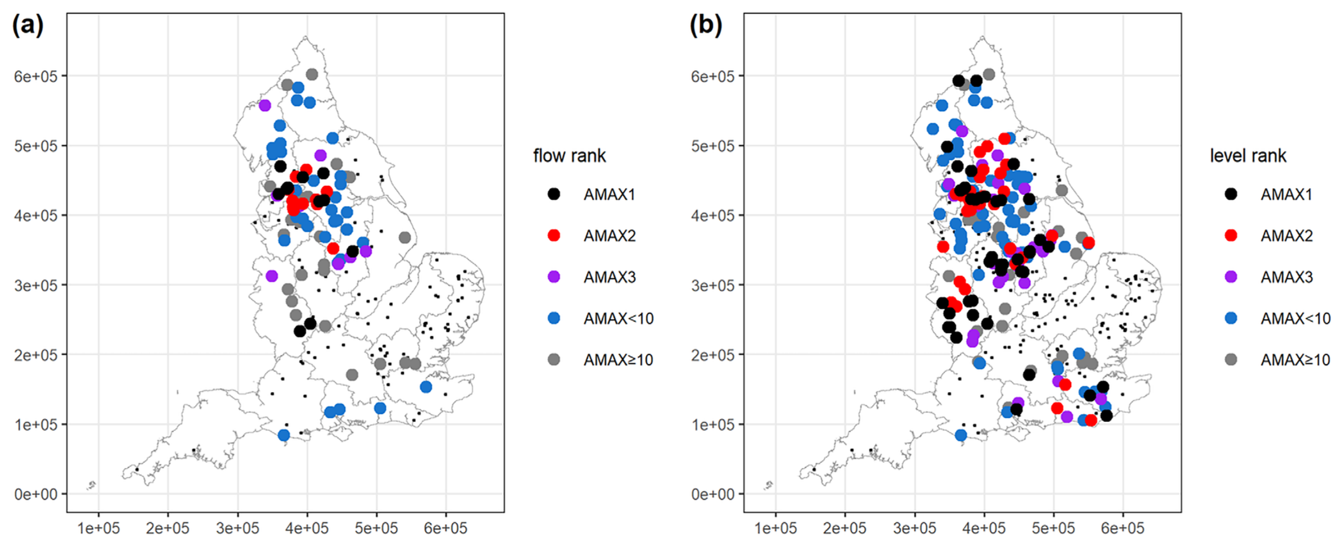

FIGURE 5 | Maximum ranks of (a) flow and (b) level during Spring 2020. Small black dots indicate other gauges (flow/level) that were included in this study but were not selected for events during this period.

prolonged rainfall from the autumn 2019 period noted in the rest of this section.

4.4 | Spring 2020

In contrast to the preceding winter, spring 2020 saw England experience three major named storms: Ciara, Dennis and Jorge, with long-duration but low-intensity rainfall occurring for much of this period. Storm Ciara was selected for analysis at 53 flow and level stations across the country, with flow AEPs between 1 in 2 and 1 in 100, and 5 AMAX1 flow events. This is corroborated by Sefton et al. (2021) for seven additional stations in the NRFA Peak Flow dataset.

In terms of flow, 17 stations experienced flow above AMAX5 due to Storm Dennis and the rain on 21st–24th February (Figure 5 shows how this extends to the whole season). Three stations in the West and East Midlands regions experienced AMAX1 flows with AEP less than 1 in 90. Hydrological impacts were magnified by antecedent conditions: 22 of 79 level stations in the study dataset that identified the storm had a VWC rank above 3 at the corresponding COSMOS-UK station (compared with the respective quarter-month in other years), 19 level stations had above AMAX5 level and above AMAX10 (or below AMIN10) at the corresponding groundwater station, and five stations had a 90-day accumulated volume above AMAX5, likely due to the continued rainfall from Ciara and Dennis (Figure 6).

Storm Jorge added to this extreme prolonged period of rainfall, with five stations in the study dataset highlighting events with 90-day accumulated rainfall above AMAX5, five with record (AMAX1) 2-week flow volume, and six of the ten nearby COSMOS stations with record soil moisture in the 4th quarter of February (22nd–29th). However, there were fewer stations with extreme instantaneous peak flow; no AEPs below 1 in 15 were observed at stations that identified the event (Figure 7).

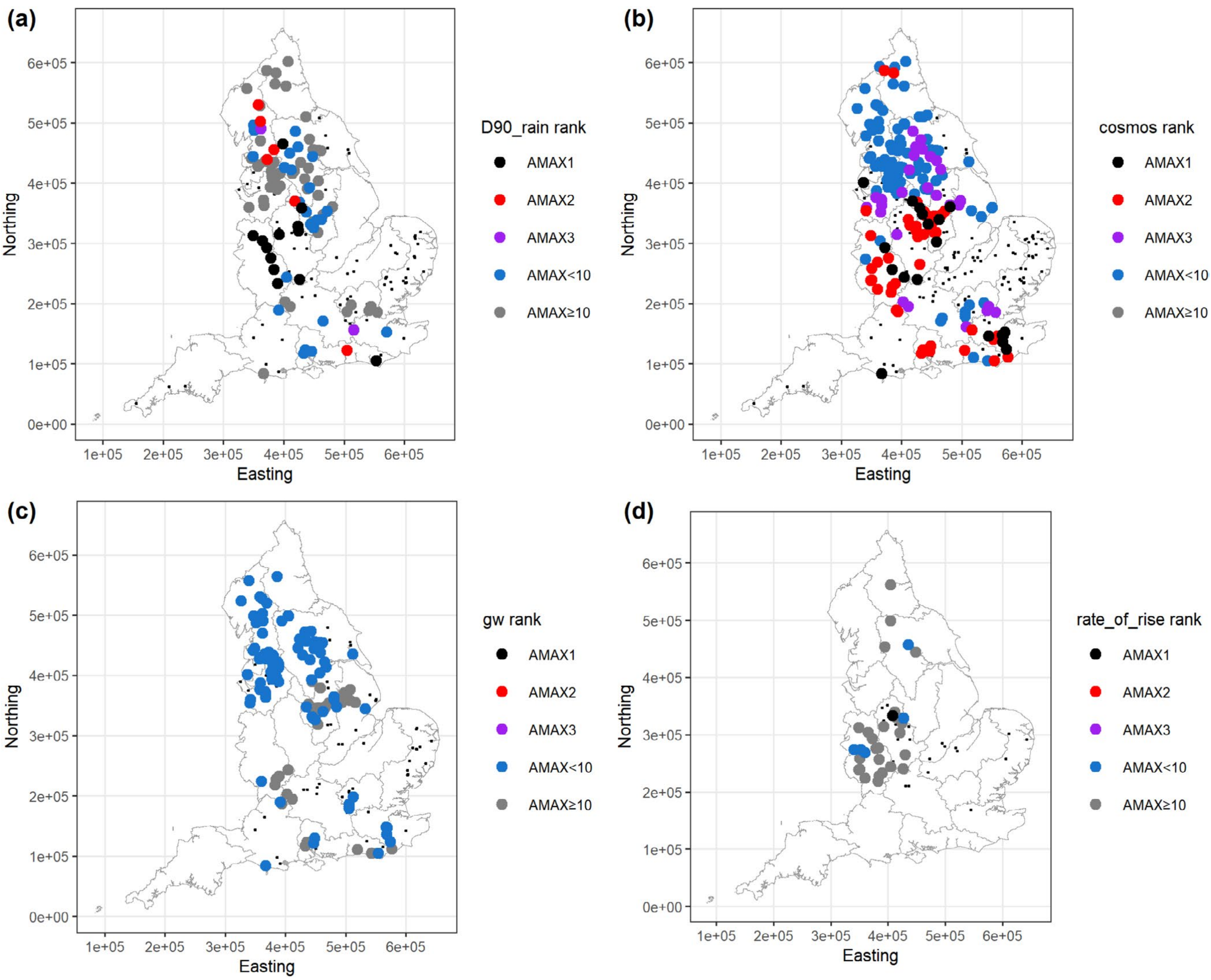

FIGURE 6 | (a) Maximum ranks of 90-day antecedent rainfall, (b) maximum relative rank (for the time of year) of volumetric water content, (c) maximum rank of peak groundwater level and (d) peak 1 h rate-of-rise rank during Spring 2020. Small black dots indicate other gauges (flow/level) that were included in this study but were not selected for events during this period.

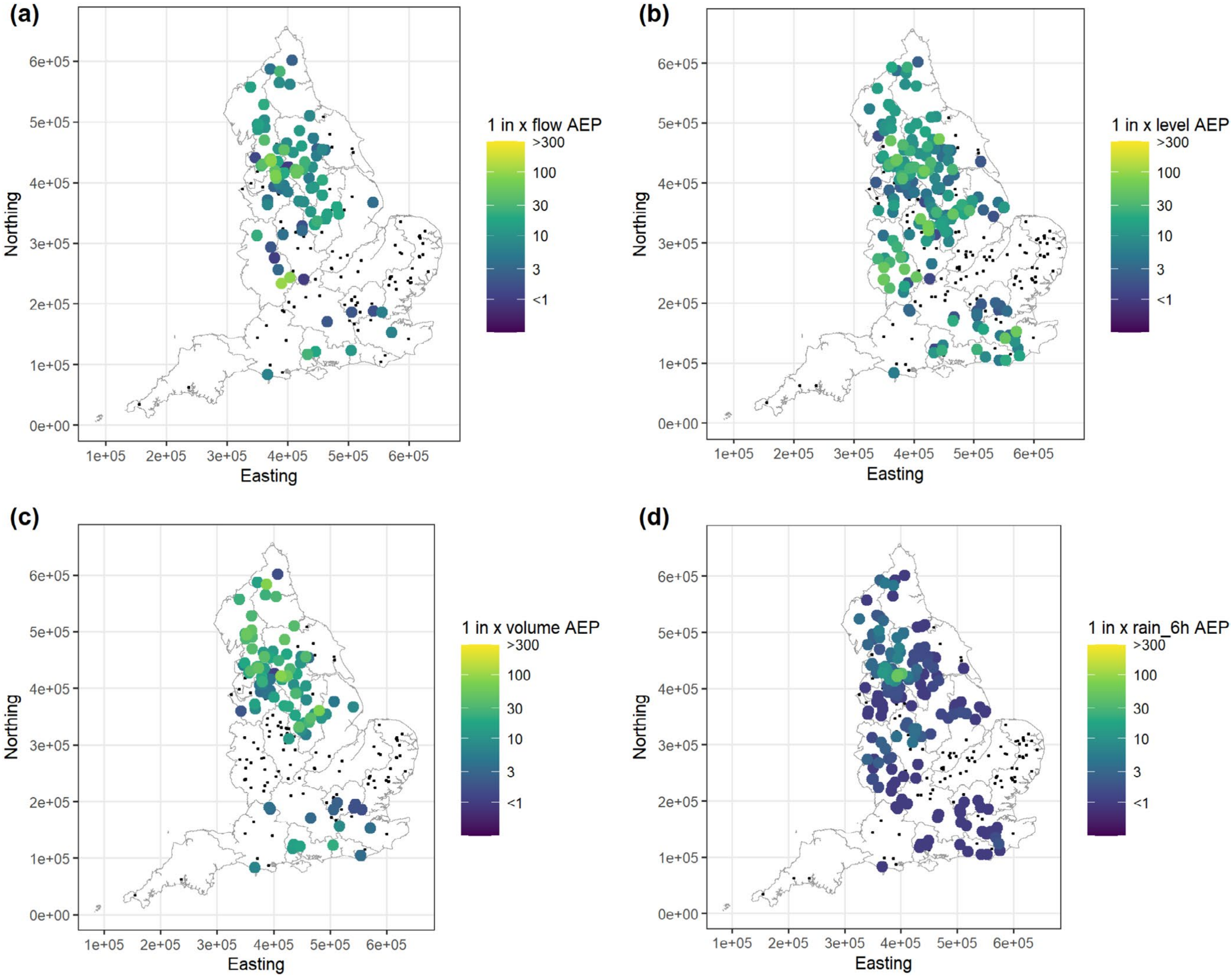

FIGURE 7 | Maximum AEPs of (a) flow, (b) level, (c) 2-week volume and (d) 6-h point rainfall during Spring 2020. Black dots indicate other gauges (flow/level/rainfall) that were included in this study but were not selected for events during this period.

4.5 | Autumn 2020

Storm Alex brought some of the heaviest rainfall of the year. Out of the 17 stations in the dataset that identified this event, 15 had a 4-day FEH22 rainfall AEP less than 1 in 10, and 7 had an AEP less than 1 in 30 (Table 5). Eight stations with records over 50 years experienced a new record 1-day October rainfall (Met Office 2020b), and nationally, 3rd October 2020 was the wettest day on record (Kendon and McCarthy 2021). However, following a dry summer, the antecedent conditions had become drier, with no high soil moisture or groundwater levels at these stations. Two stations experienced AMAX5 flow but these did not equate to an AEP less than 1 in 10.

Storm Aiden had significant effects at a number of stations in Cumbria and Yorkshire. Six of the 13 level stations for which Storm Aiden was identified as a key event experienced at least AMAX5 level, and 2 of the 7 flow stations had at least AMAX5 flow, which led to AEPs less than 1 in 14, despite the Met Office describing it as 'a fairly typical spell of stormy weather for the time of year' (Met Office 2020a). The high flows and levels may have been partially due to groundwater conditions. Moor Hall, the nearest groundwater station to these stations, had an AMAX4 groundwater level and Gisburn Forest, the nearest COSMOS station, had an AMAX2 soil moisture for the first quarter of November.

Between the 23rd and 27th of December, repeated rainfall events (Figure 8b shows 90-day accumulations) on top of ground saturated by previous events led to extreme flooding in many parts of the country. This was exacerbated by the arrival of Storm Bella on 26th December. Eight stations across Eastern England and Wessex experienced at least AMAX5 flow, with three stations reporting new record peak flows with AEPs less than 1 in 100. At level stations, 22 of the 48 stations, which noted this event experienced AMAX5 or greater events, with 7 new AMAX1 levels. On top of the extraordinary peaks, 16 of the 28 stations where 2-week volume was calculated had above AMAX5 volume. The number of flow and level stations affected far exceeded those affected by Desmond and Frank in 2016, and it is additionally notable that these effects happened in (drier) Eastern England rather than (wetter) Northwest England.

TABLE 5 | Rainfall depth and AEP (FEH22 grids) from sites identifying Storm Alex.

Raingauge name	Depth 6h	6h AEP	Depth 24h	24h AEP	Depth 96h	96h AEP
Heathrow Airport	17.2	< 2	41.2	3	75.4	10
Iver Heath	16.2	< 2	38.4	3	77.2	12
Radlett	21.1	2	53.9	9	99.1	64
Aylesbury	23.9	2	49.4	7	103.2	130
Priddy Chancellors Farm	29.2	2	49.4	3	135.8	53
Liverpool North STW	22.1	2	48.5	8	90.5	36
Markyate	17.4	< 2	45.6	4	91.0	44
Keynsham	20.0	2	41.0	3	87.8	15
Common Bank	31.2	4	47.0	5	90.8	16
Hoscar—Wigan S. Wks.	29.6	4	49.8	7	99.4	39
Barnacre	20.6	< 2	64.6	11	108.6	15

Note: Depth in mm, AEP express in 1 in *x* years.

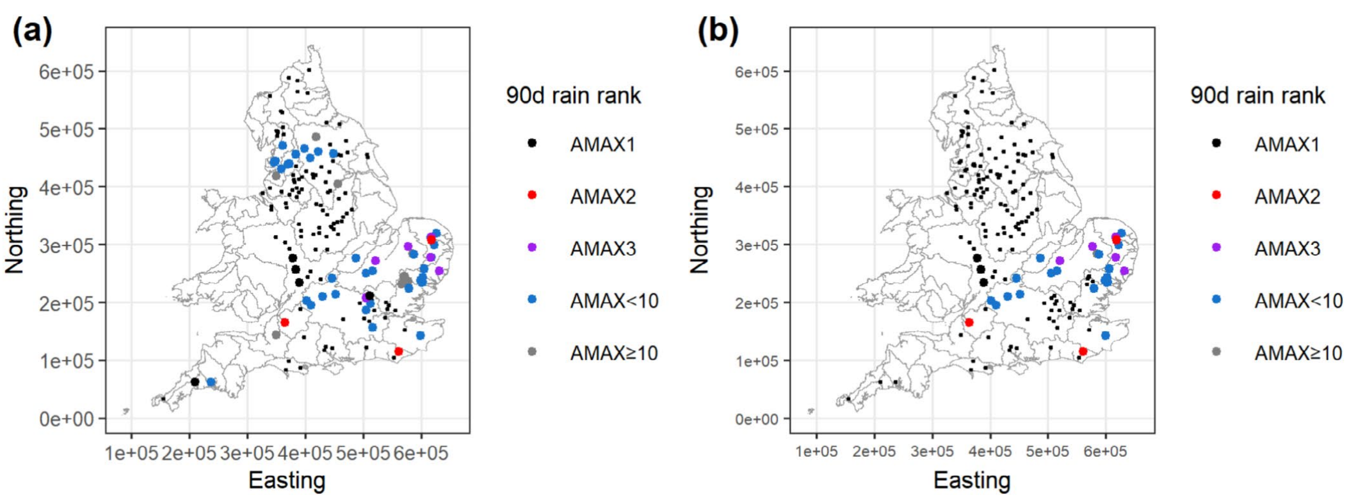

FIGURE 8 | Antecedent conditions of (a) Autumn 2020, (b) Storm Bella, showing maximum rank of 90-day accumulations of rainfall. Boundaries show UK hydrometric areas (NRFA 2014).

4.6 | Winter 2020–21

Storm Christoph brought exceptional rainfall to northern England and Wales in mid-January (Figure 9), which led to exceptional river flow volumes. Three stations in Greater Manchester experienced record flows (AMAX1), and five experienced peak flows with AEPs less than 1 in 30. In addition, 21 of the 31 stations in the study dataset for which volume was calculated experienced greater than AMAX5 2-week volume (Figure 10). Volumes were enhanced by the antecedent conditions: groundwater level, soil moisture and 90-day antecedent rainfalls were all high at many stations (Figure 12). This partially captured the heavy rainfall of December 2020.

This continued through the month, with 15 stations noting an event between the 28th January and 3rd February 2021. All of these stations had a 2-week volume of flow above AMAX10, and three showed record 2-week volumes. The instantaneous flow and level for this period was less pronounced, with only one level station identified with an AEP less than 1 in 10.

4.7 | Clustering of Events

Using the method outlined in Section 3.7, many stations were found to have experienced a statistically significant cluster of events over the 2019–21 period (Figure 11). In 2020, the year in which most events were identified, 80 of the 126 stations experienced a cluster of events, mostly on the western side of England. This spatial pattern was mostly followed in earlier and later events, which is unsurprising, as the 2-year kernel bandwidth somewhat encompassed events from across the study period. This was found to be largely independent of record length, but may also be linked to the start of many records being during a flood-dry period in the 1970s, inflating the rate of the POT events in the later record. This

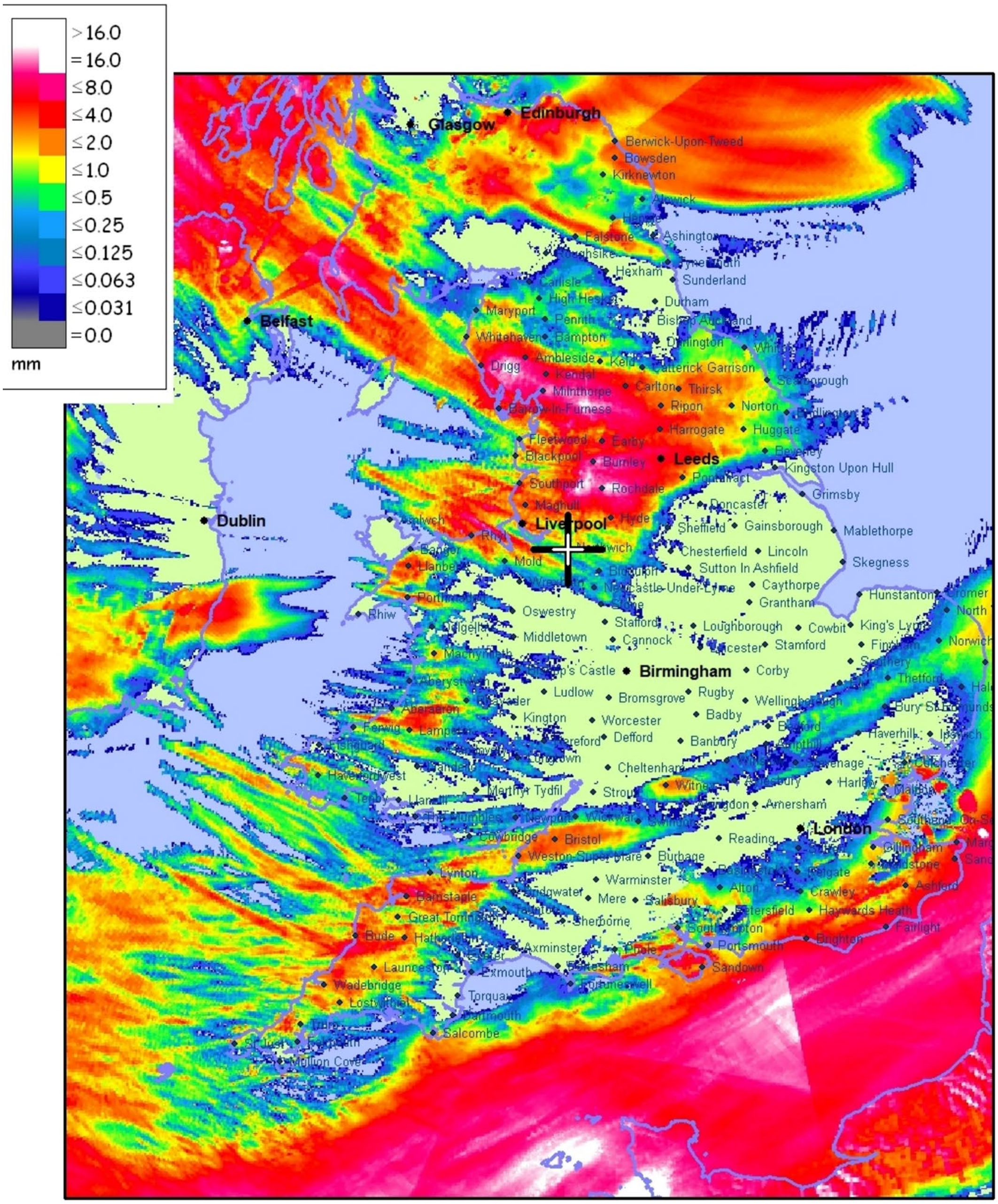

FIGURE 9 | Total rainfall in the 24 h up to 0900GMT 22nd January 2021, based on H24 gridded rainfall data. Figure produced through Hyrad V2.9.001.

is because a fixed percentile is used to determine POTs, rather than a fixed number of events in each year.

Formetta et al. (2024) showed that many locations in the UK have overdispersed POT records (exhibiting more clustering than would be expected by chance in a Poisson Process), and so finding so many stations with clustering is not surprising. However, what is notable is the number of stations for which this specific period was part of a cluster.

4.8 | Summary of Antecedent Conditions

In the previous sections, there was a pattern of more intense flooding occurring later in the study period despite a lack of extreme short-duration rainfall events to generate the events. However, the antecedent conditions, particularly the 90-day rainfall totals and soil moisture (VWC), increased over the study period. By looking at where both flood metrics and antecedent conditions (see Table 3) were very high (Figure 12), it can be seen that there was an increase in the co-occurrence of high levels of each over the study period, compared with the less extreme events in early 2019. Although coincidence between high flood metrics and wet antecedent conditions does not exceed 40%, the patterns suggest that the record high antecedent conditions (above AMAX5) led to record high magnitude flood events. In particular, more than 25% of stations showed a link between soil moisture (VWC) and both level and 2-week volume in Winter 2021. VWC had very strong links with level estimates with more than 20% coincidence for all the events in 2020

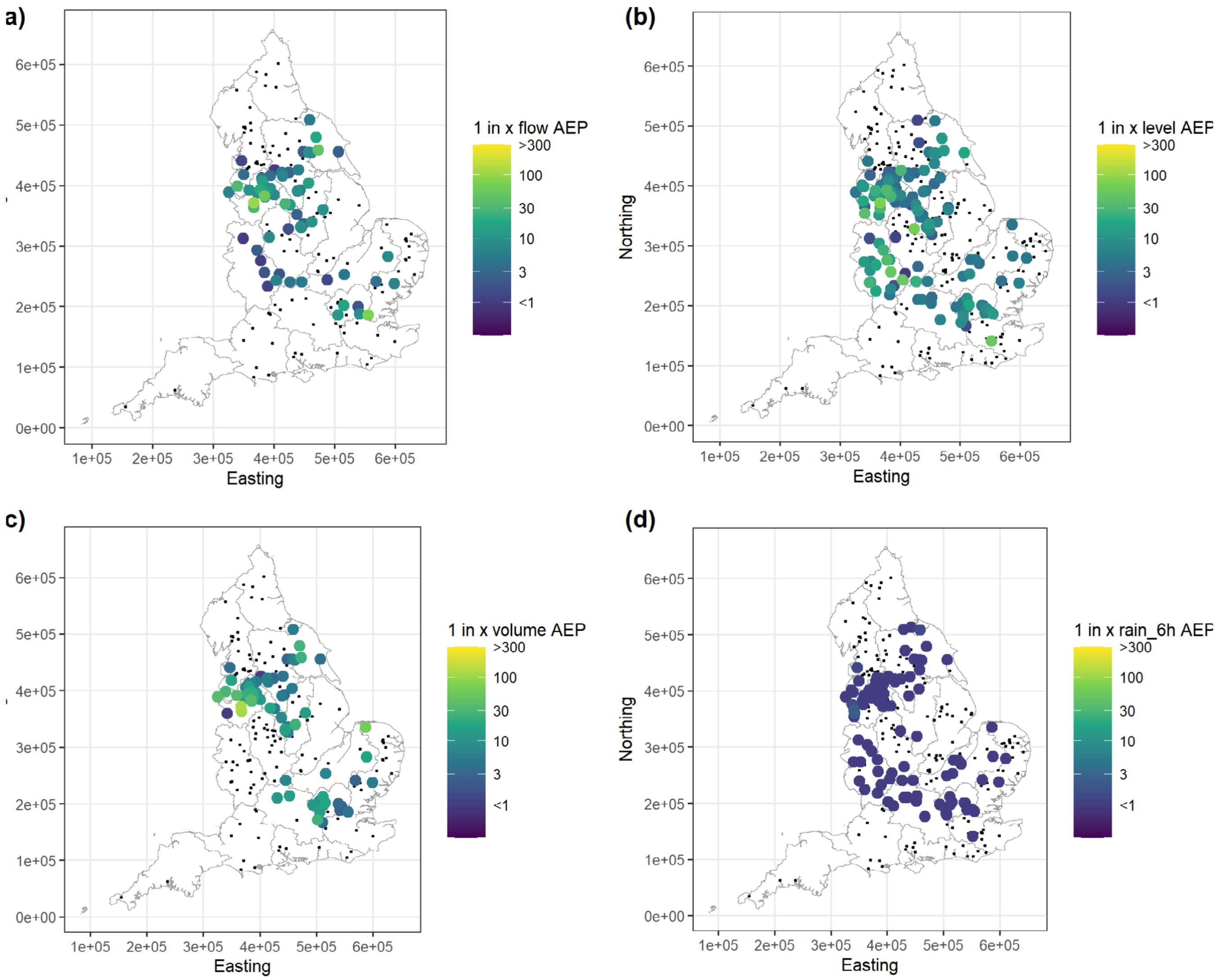

FIGURE 10 | Maximum AEPs of (a) flow, (b) level, (c) 2-week volume and (d) 6-h point rainfall during Winter 2020–21. Black dots indicate other gauges (flow/level/rainfall) that were included in this study but were not selected for events during this period.

and 2021. Compare this to the almost zero correlation in early 2019, where the conditions were still in a state of drought recovery. The number of impacted sites is also lower for these events, compared with Spring 2020 and Winter 2021 which impacted at least 39 sites under each of the flood metrics and had over 100 sites impacted by extreme level or volume accumulation in Spring 2020.

4.9 | Trends in Urban Areas

An investigation was also undertaken into the impact of urbanisation on flooding, by using Land Cover Maps (Marston et al. 2022) to compare current and previous urban extent and change against the existence of trends in the flow AMAX data. Although some catchments showed a large increase in the quantity of urban grid cells (Figure 13a), only 6 of the 15 stations with more than 6% increase in urbanisation showed significant trends. Looking purely at urbanisation in 2021, currently urbanised catchments are not statistically more likely to exhibit trends in peak flow.

Peak AEPs in 2019–21 were also investigated, but again there was no strong correlation between urban extent in catchments and the maximum AMAX rank observed. The most urban catchments were slightly more likely to experience flows with AEPs less than 1 in 5. However, this is more likely due to a bias in the catchments chosen. For local hydrometrists and hydrologists to have identified a key event it is more likely to have experienced an extreme event and/or be economically or socially relevant (and hence more likely to be urban or suburban).

5 | Discussion

The results in this paper highlight the importance of understanding the conditions antecedent to flooding events in order to better understand the possible impacts. Historically, flooding in the UK is typically mapped as an instantaneous, or very short, event. However, prolonged antecedent wet periods, where many regions far exceeded their monthly rainfall in a number of days (Turner, Muchan, et al. 2021), were the main contributing factor to widespread flooding. The

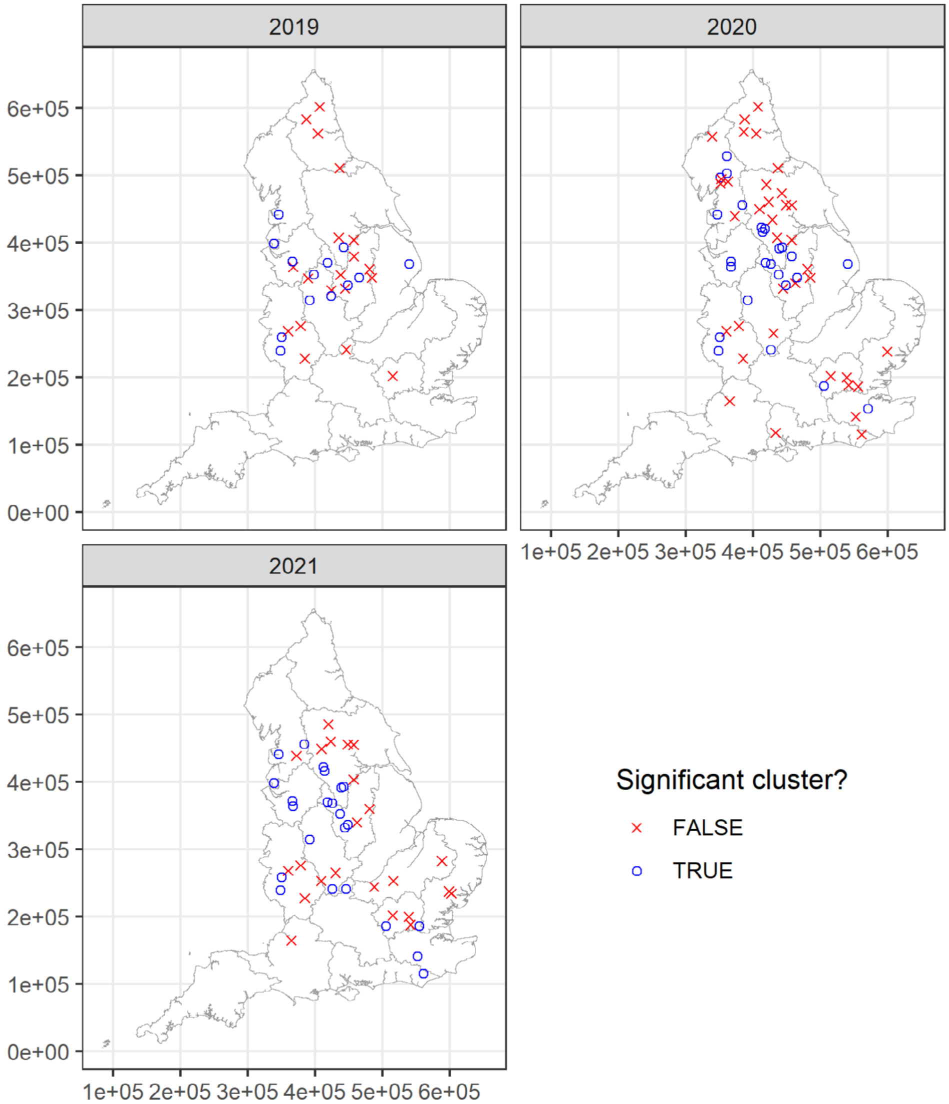

FIGURE 11 | Maps indicating flow stations which had key events identified in 2019, 2020 and 2021 that were part of a significant cluster of events (at 95% level) according to a kernel density analysis.

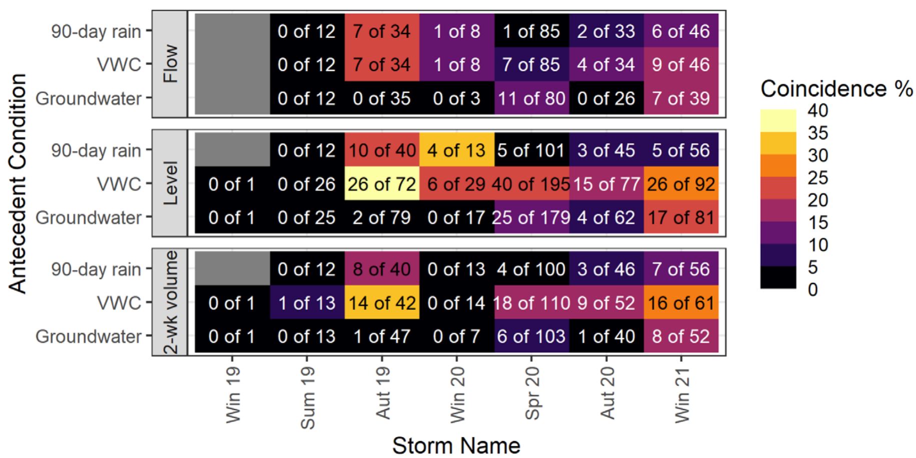

FIGURE 12 | Link between wet antecedent conditions and high flood metrics for different storm seasons, measured in percentage coincidence. Grey box indicates that no stations measured both metrics in that season. '*x* of *y*' indicates that *x* stations out of *y* measured both the flood metric and antecedent condition, and had high values for both (see Table 3).

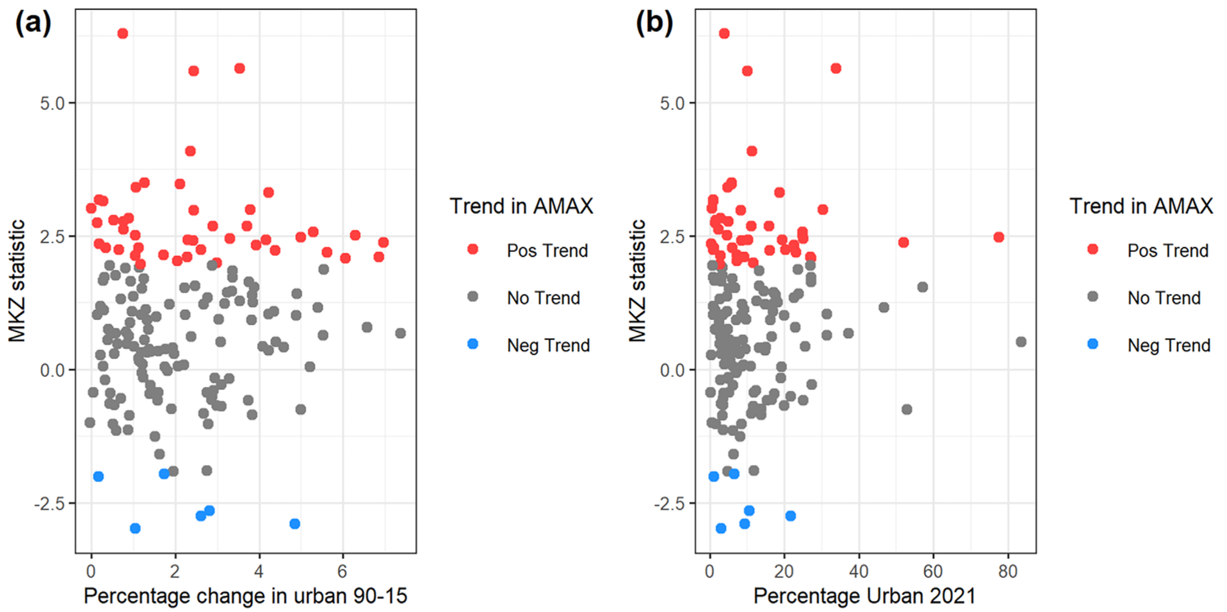

FIGURE 13 | Mann–Kendall statistics for flow catchments with different levels of urban change. (a) MKZ compared with change in percentage of urban gridcells between 1990 and 2015. (b) Urban extent in 2021 against MKZ statistic.

combination of widespread flooding and how it is impacted by wet antecedent conditions is well documented (Brunner and Dougherty 2022; Ledingham et al. 2019): evidence suggests that the coincidence of rainfall AMAX and flow AMAX in the UK is less pronounced when catchments have higher soil moisture.

The link between this pattern of repeated flooding and climate change has not been examined in this work, but should be considered in terms of whether this type of flooding is more frequent in the 21st century than historically. Davies et al. (2021) noted that four of the top ten wettest winters up to 2021 occurred in the preceding 14 years. However, trends in peak flow are still mixed across the UK (Griffin et al. 2019) and depend on many factors. For example, urbanisation is known to impact surface water flooding (Miller and Hutchins 2017), but showed mixed signals against trends in peak river flow in this study. Using rainfall depth as a proxy for surface water flooding can be greatly affected by specific urban ground cover. Response to extreme rainfall is impacted negatively by the impermeable surfaces of city centres and suburban areas—Kelly (2018) shows this for paved driveways—but positively by the use of sustainable drainage systems and green infrastructure (O'Donnell et al. 2020). Note that for the heaviest rainfall, trees intercepting rain can behave similarly to sloped roofs.

The clustering examined in this work is for a specific case study, but more widely clustering of flow events (temporally and spatially) is of key interest. It has been observed at both the national and European scale. Formetta et al. (2024) observe this in the POT data for the UK, with most stations experiencing more overdispersion than a Poisson process, especially when considered over shorter accumulation periods (1–2 years, rather than 4–5). This can be strongly linked to event seasonality. Hall and Blöschl (2018) show that most of Northern and Western Europe experience significant seasonal flood concentration (compared with uniformly distributed flood dates), which could lead to the clustering analysed in the present work.

One side issue with this kind of national study was the event selection process. All the events were hand-selected for analysis by local experts. This kind of event selection can be subject to any number of subconscious biases, similar to the issues of flood event perception being dependent on 'living memory' (Fanta et al. 2019). On the other hand, economic and social impact data are less available and less documented. It would be interesting in future work to understand whether there was a strong correlation in what events were selected against the impacts compared to non-reported peak flow events. Data-driven methods that automatically determine key flooding events (such as widespread flooding (Griffin, Kay, Stewart, et al. 2022)) may give a more comprehensive picture, especially if all types of analysis are possible at all sites of interest.

6 | Conclusions

Throughout the Summer 2019–Winter 2021 period, England experienced 17 different named storms, of which eight were highlighted by Environment Agency area teams, alongside a further 11 clusters of events. Following a dry period in 2019, this sequence of events highlighted the combined impacts of repeated storms over short time periods with long periods of sustained low-intensity rainfall between them. In order to better understand this, various antecedent conditions were investigated to determine how they affected the possible flooding hazards, and in turn the possible national impacts.

This work involved performing various types of flood frequency analysis, looking at river flow and level as well as groundwater, soil moisture and precipitation frequency, for more than 500 events across more than 300 stations in England. These analyses were used to identify notable peaks and national patterns of flooding over this period.

Initially, Autumn 2019 began with extreme rainfall events (AEP less than 1 in 50 in some cases) which led to extreme flow. This rainfall continued through the rest of the year and led to saturated ground conditions: exceptionally high soil moisture as recorded by COSMOS-UK, and examples of high groundwater levels, which in turn led to extreme levels and flows in late 2019. Before the ground could recover, Storms Ciara, Dennis and Jorge occurred in early 2020, again exhibiting consistent, sustained long-duration rainfall. By late 2020 and early 2021, more prolonged wet weather in Storm Christoph meant record 2-week flow volumes of water were recorded at some gauges, despite unremarkable peak rainfall rates.

Extreme antecedent conditions, relative to other years, were observed in the soil moisture and 90-day rainfall accumulations. For soil moisture, this might have been partly due to the short records in the COSMOS-UK network: some sensors have experienced only this one period of extreme storms. However, all long-duration rainfall accumulations were derived from a gridded dataset containing 131 years of daily rainfall data. By the end of the 2019–21 period, the impacts of these antecedent conditions led to greater fluvial impacts. It is clear in this case study that worsening antecedent conditions, such as those caused by repeated flooding events, are crucial in understanding likely flooding impacts, and should be investigated further across the whole period of record.

Overall, this set of storms seems to be part of an ongoing wet period in the UK, similar to the flood-rich periods of the early 1990s and early 2000s, driven increasingly by prolonged soil wetness over the course of 2–3 years. However, further work needs to be done to identify how best to analyse these spatially and temporally large event sets through a combination of expert hydrometrist knowledge and statistical application.

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Data Availability Statement

Most flow and level data are available from the National River Flow Archive, or the Hydrology Data Explorer API (https://environment.data.gov.uk/hydrology/explore). HadUK data are available from the Met Office. COSMOS-UK data are available from the COSMOS-UK website. Land Cover Data are available from the Environmental Informatics Data Centre (EIDC). Some groundwater, level, flow and rainfall data were granted by the Environment Agency directly, and are not available publically. Specifically, the H24 is not an openly available data product at the time of publication: it can be obtained through the HYRAD software (https://www.ceh.ac.uk/data/software-models/hyrad, UK Centre for Ecology and Hydrology 2024). The FEH22 rainfall frequency grids are available under licence from the UK Centre for Ecology & Hydrology. The code used to perform the analysis is available at https://github.com/NERC-CEH/WinterFloods.

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