Received: 8 May 2021 | Revised: 4 November 2021 | Accepted: 14 January 2022 | Published on: 11 February 2022

DOI: 10.1002/joc.7542

RESEARCH ARTICLE

International Journal of Climatology RMetS

Historical droughts in Irish catchments 1767–2016

Paul O'Connor[1] | **Conor Murphy**[1] | **Tom Matthews**[2] | **Robert L. Wilby**[2]

[1]Irish Climate Analysis and Research Units, Department of Geography, Maynooth University, Maynooth, Ireland

[2]Department of Geography and Environment, Loughborough University, Loughborough, UK

Correspondence
Paul O'Connor, Irish Climate Analysis and Research Units, Maynooth University, Rm 1.9., Laraghbryan House, Maynooth, County Kildare, Ireland.
Email: pkoconnor@gmail.com

Funding information
Irish Environmental Protection Agency, Grant/Award Number: 2019-CCRP-MS.60; Irish Research Council, Grant/Award Numbers: GOIPG/2017/421, COALESCE/2019/43

Abstract

Recent prolonged dry periods in summer 2018 and spring 2020 have reawakened interest in drought in Ireland, prompting questions regarding historical drought occurrence and potential long-term risks. Employing 250 years of monthly precipitation and flow reconstructions, we investigate historical drought in Irish catchments evaluating the characteristics (number of events, duration, and deficits) of moderate, severe, and extreme droughts as well as the propagation of meteorological to hydrological drought. Using standardized indices, we identify three distinct catchment types. Cluster 1 catchments, located in the wetter northwest are characterized by small areas, low groundwater storage, and the highest frequency of hydrological drought relative to other catchments. Cluster 3 catchments, located in the drier east and southeast have larger areas, greater groundwater storage, the highest frequency of meteorological drought but the least hydrological droughts. However, once established, droughts in Cluster 3 tend to be more persistent with large accumulated deficits. Cluster 2 catchments, located in the southwest and west, are intermediate to Clusters 1 and 3, with hydrological droughts typically of shorter durations, reduced accumulated deficits but greater mean deficits. The most extreme droughts based on accumulated deficits across all catchments occurred in 1803–1806, 1854–1859, 1933–1935, 1944–1945, 1953–1954, and 1975–1977. Although not as severe, droughts in 1887–1888, 1891–1894, and 1971–1974 also appear as significant extremes. Changes in drought characteristics reveal a complex picture with the direction, magnitude, and significance of trends dependent on the accumulation period used to define drought, the period of record analysed, and the reference period used to standardize indices. Of particular note is a tendency towards shorter, more intense meteorological and hydrological droughts. Our findings offer important insight for drought and water management in Ireland given the paucity of extreme droughts in short observed river flow records.

KEYWORDS

drought analysis, drought propagation, hydrological drought, Ireland, meteorological drought, reconstruction

1 | INTRODUCTION

Drought is a complex hazard (Van Loon *et al.*, 2016), typically characterized by the component of the hydrological cycle affected (e.g., atmosphere [meteorological], soil moisture [agricultural], or river flows [hydrological] droughts) (Haile *et al.*, 2020). Impacts can unfold slowly, with propagation of meteorological to hydrological drought dependent on controls governing catchment response, including land cover, geology, and rainfall–runoff relationships (Lorenzo-Lacruz *et al.*, 2013; Wong *et al.*, 2013; Barker *et al.*, 2016; Huang *et al.*, 2017; Guo *et al.*, 2020). Recently, there has been greater attention to evaluating historical droughts, facilitated by increased information availability from data rescue efforts (Noone *et al.*, 2017; Tanguy *et al.*, 2021); use of extreme droughts for stress testing models of water supply systems (Wilby and Murphy, 2019; Murphy *et al.*, 2020b); interest in placing recent extremes in a long-term context (Lhotka *et al.*, 2020; Moravec *et al.*, 2021); and evaluations of variability and change in drought occurrence and characteristics (Hanel *et al.*, 2018; Vicente-Serrano *et al.*, 2021a).

Although most work has focused on meteorological drought, increasingly researchers are using long-term precipitation and temperature records to study hydrological droughts for periods before systematic river flow measurements. For example, Caillouet *et al.* (2017) reconstructed 140 years (1871–2011) of river flow for 600 French catchments. This information was then screened for hydrological droughts using a threshold level approach, and uncovered well known European droughts of 1921, 1945, 1949, 1954, 1976, and 1989–1990 events, as well as less well-known events in 1878 and 1893. Multicentennial reconstructions have been produced elsewhere in Europe (Hanel *et al.*, 2018; Moravec *et al.*, 2019; Erfurt *et al.*, 2020) and assessed for drought occurrence using hydrological drought indicators. An overarching theme of these studies is that, despite variations in temporal and spatial extents, extreme hydrological droughts have been a regular feature in long-term reconstructions for mainland Europe.

Trends in meteorological drought across Europe have been extensively investigated (e.g., Gudmundsson and Seneviratne, 2015; Stagge *et al.*, 2017; Hänsel *et al.*, 2019; Oikonomou *et al.*, 2020; Vicente-Serrano *et al.*, 2021a). However, research into hydrological drought trends are less common (Sutanto and Van Lanen, 2020) because long records are not as readily available for observed river flow as for meteorological variables (Mediero *et al.*, 2015). Across Europe, trends in low flows have been found to vary considerably between regions with a general lack of clear patterns (Stahl *et al.*, 2010; Van Loon, 2015). Such inconsistencies are the result of changing temporal characteristics of precipitation deficits which impact directly on low flows and result in spatio-temporal variability in hydrological drought intensities (Hanel *et al.*, 2018).

Historical droughts in UK catchments have also been the subject of much research (e.g., Jones and Lister, 1998; Jones *et al.*, 2006; Spraggs *et al.*, 2015; Wilby *et al.*, 2015; Parry *et al.*, 2016). For instance, Rudd *et al.* (2017) assessed hydrological drought over the period 1891–2015 and found that, while there was considerable spatial and temporal variability between individual events, few changes in drought characteristics were identifiable. More recently, Barker *et al.* (2019) assessed hydrological drought occurrence in 108 UK catchments for the same period and found regionally distinctive drought characteristics. Significant drought episodes included 1890–1910, 1921–1922, 1933–1934, in the 1940s, and early 1970s prior to the notable 1975–1976 event. Overall, evidence of trends in hydrological drought occurrence and severity in the UK is limited (Hannaford, 2015).

Research in Ireland has focused on historical meteorological drought (e.g., Wilby *et al.*, 2016; Noone *et al.*, 2017; Murphy *et al.*, 2018; 2020a), with relatively little attention to long-term hydrological drought. One exception is Noone and Murphy (2020) who used rescued and transcribed monthly precipitation data (Noone *et al.*, 2017) to reconstruct river flows in 12 catchments during the period 1850–2015. Drought events were identified using the low flow Q95 threshold, with major episodes in 1887–1888, 1891–1894, 1902–1912, 1933–1934, 1944, 1953, and 1971–1976. Murphy *et al.* (2013) investigated trends in observed river flows for 43 catchments. However, they found that the short records hindered robust assessment, highlighting the value of reconstruction techniques for understanding multidecadal (or even multicentennial) variability and change in river flows.

Recently, O'Connor *et al.* (2021) produced monthly reconstructions of river flow for 51 catchments in Ireland. We employ these reconstructions to assess historical meteorological and hydrological drought by fitting standardized indices to precipitation series and reconstructed river flows spanning the period 1767–2016. As well as identifying major drought events, we evaluate changes in drought characteristics (severity, duration, maximum intensity, accumulated and mean deficits) and investigate regional controls on drought propagation. This is the first assessment of multicentennial drought properties for Ireland—a place where drought has been popularly overlooked as a recurrent threat to water security and the wider socio-economy.

The remainder of the paper is structured as follows: section 2 describes the catchments, datasets and methods employed. Section 3 presents the results, with details

TABLE 1 Details of the 51 study catchments

River flow station ID	Station name	Waterbody name	Cluster No.	SPI-1 vs. SSI-1	SPI-3 vs. SSI-1	SPI-6 vs. SSI-1	SPI-12 vs. SSI-1	SAAR (mm)	BFIsoil (index)	Area (km²)
21002	Coomhola	Coomhola	2	0.98	0.65	0.46	0.32	2,158	0.37	65
38001	Clonconwal	Ownea	1	0.97	0.68	0.48	0.34	1795	0.28	111
22006	Flesk	Flesk (Laune)	2	0.96	0.71	0.51	0.35	1741	0.39	329
26029	Dowra	Shannon	1	0.96	0.69	0.48	0.34	1,546	0.46	117
33001	Glenamoy	Glenamoy	1	0.95	0.68	0.47	0.33	1,509	0.29	76
35002	Billa Bridge	Owenbeg	1	0.95	0.73	0.53	0.38	1,458	0.42	81
22035	Laune Bridge	Laune	2	0.94	0.75	0.55	0.38	1858	0.64	560
23002	Listowel	Feale	2	0.94	0.74	0.53	0.37	1,388	0.31	647
3051	Faulkland	Blackwater (Mon)	1	0.93	0.76	0.57	0.41	1,049	0.42	143
18050	Duarrigle	Blackwater	2	0.93	0.75	0.53	0.36	1,511	0.41	250
32012	Newport Weir	Newport	1	0.93	0.76	0.55	0.39	1,652	0.59	146
6030	Ballygoly	Big	1	0.92	0.75	0.54	0.38	1,106	0.45	10
39006	Lennan	Claragh	1	0.92	0.76	0.54	0.38	1,435	0.44	245
39009	Aghawoney	Fern O/L	1	0.92	0.76	0.55	0.39	1,485	0.4	207
18006	Cset Mallow	Blackwater	2	0.91	0.77	0.56	0.38	1,311	0.5	1,055
15003	Dinin Bridge	Dinin	3	0.90	0.76	0.56	0.39	992	0.38	299
16013	Fourmilewater	Nire	3	0.90	0.78	0.57	0.39	1,303	0.54	94
25002	Barrington S Br.	Newport (Mun)	2	0.90	0.77	0.56	0.38	1,229	0.54	222
25030	Scarriff	Graney	2	0.90	0.78	0.57	0.40	1,183	0.54	280
36015	Anlore	Finn	1	0.90	0.77	0.58	0.41	1,009	0.42	154
25001	Annacotty	Mulkear	2	0.89	0.78	0.58	0.39	1,138	0.52	648
15007	Kilbricken	Nore	3	0.88	0.81	0.60	0.42	1,078	0.59	340
18003	Killavullen	Blackwater	2	0.87	0.81	0.61	0.42	1,287	0.46	1,257
24030	Danganbeg	Deel	2	0.87	0.80	0.60	0.41	1,013	0.53	259
35005	Ballysadare	Ballysadare	1	0.87	0.81	0.61	0.43	1,212	0.61	640
16012	Tar Bridge	Tar	3	0.84	0.85	0.67	0.48	1,222	0.63	230
18002	Ballyduff	Blackwater	2	0.84	0.83	0.63	0.44	1,213	0.62	2,334
30007	Ballygaddy	Clare	1	0.84	0.84	0.65	0.45	1,097	0.65	470
16011	Clonmel	Suir	3	0.83	0.84	0.65	0.45	1,072	0.67	2,144
27002	Ballycorey	Fergus	2	0.83	0.84	0.64	0.44	1,262	0.7	511
12001	Scarrawalsh	Slaney	3	0.82	0.86	0.67	0.47	1,068	0.72	1,031
14007	Derrybrock	Stradbally	3	0.82	0.84	0.67	0.47	869	0.64	95
15001	Annamult	Kings	3	0.82	0.83	0.63	0.43	955	0.51	444
15006	Brownsbarn	Nore	3	0.82	0.83	0.64	0.45	950	0.63	2,418
16008	New Bridge	Suir	3	0.82	0.84	0.65	0.44	1,002	0.64	1,090
16009	Caher Park	Suir	3	0.82	0.85	0.65	0.45	1,047	0.63	1,583
19001	Ballea	Owenboy	2	0.82	0.84	0.65	0.45	1,199	0.68	103
6014	Tallanstown	Glyde	3	0.81	0.85	0.67	0.48	913	0.63	270
14019	Levitstown	Barrow	3	0.81	0.85	0.67	0.47	839	0.62	1,697

TABLE 1 (Continued)

River flow station ID	Station name	Waterbody name	Cluster No.	SPI-1 vs. SSI-1	SPI-3 vs. SSI-1	SPI-6 vs. SSI-1	SPI-12 vs. SSI-1	SAAR (mm)	BFIsoil (index)	Area (km^2)
24008	Castleroberts	Maigue	2	0.81	0.84	0.64	0.45	948	0.54	806
34001	Rahans	Moy	1	0.81	0.86	0.65	0.45	1,290	0.78	1975
6013	Charleville	Dee	3	0.80	0.84	0.67	0.48	880	0.62	309
25034	Rochfort	L. Ennell Trib	3	0.80	0.85	0.68	0.47	958	0.76	11
26058	Ballyrink Br.	Inny Upper	3	0.80	0.87	0.68	0.49	971	0.77	60
7012	Slane Castle	Boyne	3	0.79	0.85	0.68	0.48	888	0.68	2,408
16010	Anner	Anner	3	0.79	0.86	0.69	0.48	961	0.62	437
25006	Ferbane	Brosna	3	0.78	0.86	0.68	0.47	898	0.71	1,163
7009	Navan Weir	Boyne	3	0.77	0.85	0.68	0.48	869	0.71	1,684
15005	Durrow Ft. Br.	Erkina	3	0.75	0.86	0.69	0.48	889	0.71	379
36019	Belturbet	Erne	3	0.74	0.86	0.67	0.47	991	0.79	1,492
26021	Ballymahon	Inny	3	0.73	0.87	0.71	0.50	942	0.83	1,099

Note: The cluster number, Pearson correlation value between SSI-1 and SPI-1, 3, 6, and 12 month accumulation values, standard period average annual rainfall (SAAR) value, base flow index (BFIsoil) and area (km^2) are displayed. Rows are ordered by correlation scores between SPI-1 and SSI-1 from highest (blue) to lowest (red) allowing correlation scores at higher SPI accumulations, SAAR, BFI and area values to be compared. All correlation values are significant ($p \leq .05$).

about the characteristics of historical droughts across catchments then an assessment of variability and change. Section 4 discusses the detected trends, study caveats, potential applications, and scope for further research. Finally, section 5 concludes with a summary of key findings.

2 | DATA AND METHODS

2.1 | Catchments and data

We evaluate historical droughts for 51 catchments across Ireland, employing reconstructed monthly precipitation and discharge estimates for each catchment for the period 1767–2016, derived by O'Connor *et al.* (2021). The choice of end year was determined by the availability of concurrent hydrological and meteorological data. The sample represents diverse hydrological conditions in Ireland, including catchments that have good quality data and limited evidence of disturbance/river regulation during the period of the observational record (Murphy *et al.*, 2013). Table 1 lists the catchments considered and Figure 1 shows their spatial distribution. Full details of the construction of the long-term precipitation and discharge series are provided by O'Connor *et al.* (2021). Briefly, monthly gridded (0.5° × 0.5°) reconstructed precipitation and temperature datasets developed by Casty *et al.* (2007) were bias-corrected to observed catchment data, before being used to force a conceptual hydrological model and an Artificial Neural Network to reconstruct monthly river flows. We employ the ensemble median of the reconstructed discharge series for each of the 51 catchments assessed.

To aid interpretation, we employ hierarchical agglomerative clustering to identify a reduced subset of catchments following previous studies (e.g., Schmitt *et al.*, 2007; Berhanu *et al.*, 2015; Clubb *et al.*, 2019). Clustering was undertaken based on the Standardized Streamflow Index (SSI; see section 2.2) with Euclidean distance determining dissimilarities between catchments and Ward's (Ward Jr, 1963) linkage criterion used to identify clusters. Silhouette information (Rousseeuw, 1987), which interprets the consistency of clustered data, was also derived to confirm the optimum number of clusters. Median SPI and SSI series were extracted for catchments comprising each identified cluster.

Physical catchment descriptors (PCDs), derived by Mills *et al.* (2014), were compiled for each cluster grouping to determine the importance of catchment characteristics in modifying the occurrence and propagation of hydrological droughts. The PCDs were the standard period average annual rainfall, 1961–1990 (SAAR); baseflow index derived using catchment soil type (BFIsoil); Taylor-Schwartz measurement of mainstream slope

(TAYSLO); proportion of area covered by peat (PEAT); proportion of time soils are typically wet (FLATWET); and mainstream length in kilometres (MSL). These six PCDs were previously used by Broderick *et al.* (2019) to classify Irish catchments.

2.2 | Standardized drought indices

We derive the standardized precipitation index (SPI; McKee *et al.*, 1993) and standardized streamflow index (SSI; Vicente-Serrano *et al.*, 2012) for the 51 catchments and clusters for the period 1767–2016 using the "SCI" package in R (Gudmundsson and Stagge, 2016). Both SPI and SSI series were extracted for accumulation periods of 1, 3, 6, and 12 months. Two key decisions when applying standardized indices are (a) the statistical distribution and (b) the reference period for standardizing data. The effect of distribution has been previously investigated (Vicente-Serrano *et al.*, 2012; Bloomfield and Marchant, 2013; Soľáková *et al.*, 2014; Stagge *et al.*, 2015; Svensson *et al.*, 2017). We evaluate the performance of three distributions when deriving the SPI and SSI, namely the Gamma distribution, commonly used for long-term precipitation series (Shiau, 2020); the Log-logistic distribution, which has been used in fitting precipitation and streamflow series (e.g., (Vicente-Serrano and Beguería, 2016); and the Tweedie distribution, which has been found to perform well for SSI (Svensson *et al.*, 2017) due to the ability to constrain the lower bound to zero (Tweedie, 1984).

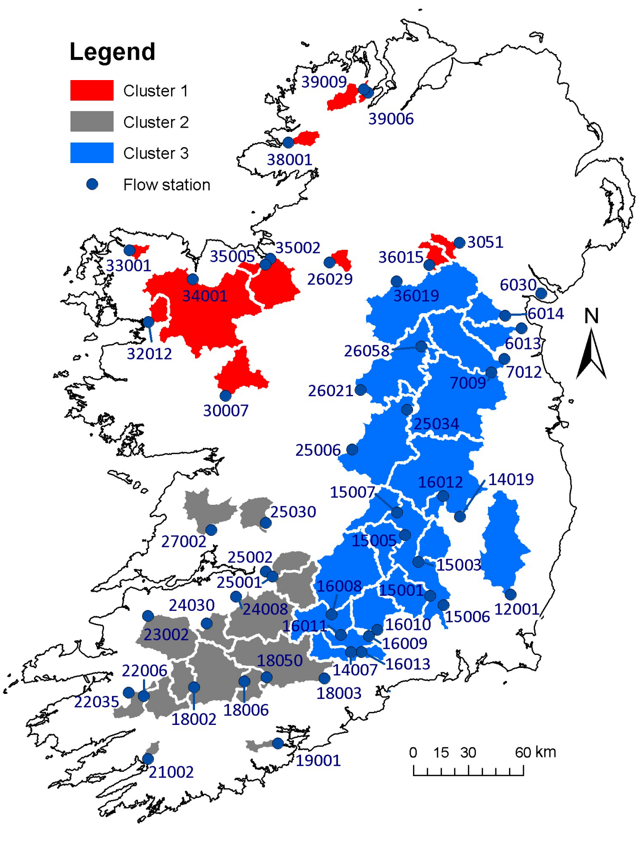

FIGURE 1 Catchment areas with flow station codes and cluster membership [Colour figure can be viewed at wileyonlinelibrary.com]

Others have highlighted the importance of the reference period used to derive SPI for the detection of historical droughts (Núñez *et al.*, 2014; Paulo *et al.*, 2016; Um *et al.*, 2017). The selection of a representative benchmark is particularly important for Ireland given the influence of low-frequency ocean–atmosphere variability (Murphy *et al.*, 2013; McCarthy *et al.*, 2015). Here, the optimum reference period, which most closely matched average conditions, was specified by minimizing the mean of positive and negative SSI values for 1, 3, 6, and 12 month accumulations for different start years (1767–1990) and reference period durations (30–250 years). We found the reference period 1930–1999 to be optimum. Moreover, a 70-year window is consistent with the wavelength of the Atlantic Multidecadal Oscillation (AMO), which has been shown to modulate the frequency of drought across northwestern Europe (Sutton and Dong, 2012; Wilby *et al.*, 2015). To test the sensitivity of our results to the reference period, we considered three other periods: 1767–2016 (250 years), 1900–1999 (100 years), and 1981–2010 (30 years), with the latter as recommended by the World Meteorological Organisation (WMO, 2017).

We categorize drought severity for both SPI and SSI following McKee *et al.* (1993) with values of −1.00 to −1.49 representing moderate drought, −1.50 to −1.99 representing severe drought, and values ≤−2.00 representing extreme drought. We examine the occurrence of hydrological droughts across the 51 catchments over the period 1767–2016 by generating heatmaps for SSI accumulations over 3 (SSI-3), 6 (SSI-6), and 12 (SSI-12) months. For each drought category (i.e., moderate, severe, and extreme) and accumulation period we extract meteorological (SPI) and hydrological (SSI) drought indices. Individual droughts commence when the respective standardized index falls below the drought category's upper value and terminate when recovered to zero. Events are categorized as moderate, severe, or extreme according to the maximum deficit recorded. For each drought index, accumulation period, and severity category we derive the following statistics:

- Number of events: sum of drought event numbers.
- Duration: number of months from the start until the end of the drought event.
- Maximum intensity: minimum index value attained during the event.

- Accumulated deficit: sum of monthly deficits during the drought event.
- Mean deficit: accumulated deficit divided by duration.

For our assessment of *extreme* historical droughts we focus on event duration, accumulated deficit, and maximum intensity; for our analysis of *average* historical drought characteristics we investigate the number of events (total), drought durations (mean), accumulated deficits (mean), and mean deficits (mean) for each catchment cluster.

Trends in the number of events (per year), duration (months), and deficits (accumulated and mean) of moderate and severe droughts for both SSI and SPI at 1, 3, 6, and 12 month accumulations were assessed for all catchments and clusters using a modified version of the Mann–Kendall (MK) test (Yue and Wang, 2004) which employs variance correction to address serial correlation. Trends were evaluated at the 0.05 significance level with a MK Z statistic >1.96 indicating a significant positive trend and a score <−1.96 indicating a significant negative trend. Following Wilby (2006) and Murphy *et al*. (2013), the sensitivity of trends to the period of record was evaluated by considering different start and end dates with a minimum record length of 30 years.

Finally, we examine the propagation of meteorological to hydrological drought using a similar approach to Barker *et al*. (2016). We compute Pearson correlation coefficients between SSI-1 and SPI- 1, 3, 6, 12 for each catchment within each cluster. Stronger correlations between SSI-1 and SPI series over longer accumulation periods indicate a delay in drought propagation from precipitation to discharge, signalling a nonlinear drought response due to catchment storage.

3 | RESULTS

3.1 | Fitting standardized indices

To select the most appropriate distribution for deriving SPI and SSI, the Gamma, Tweedie, and Log-logistic distribution functions were evaluated for 1, 3, 6, and 12 month accumulations using median precipitation and river flow series. Following Svensson *et al*. (2017), function performance was assessed using Anderson–Darling and Shapiro–Wilk scores (see Table S1, Supporting Information). Although the Gamma and Tweedie functions performed well for standardized precipitation, Tweedie performed markedly better for flow standardization. Visual assessment of the fitted distributions was also undertaken (see Figures S1 and S2). All three functions replicate the distribution of precipitation but the Tweedie and Log-Logistic are better for flow. The Tweedie function was best at capturing the lower tails of flow distributions, particularly in summer months, so was selected for use as in Barker *et al*. (2018). Sample plots of SPI and SSI indices for each distribution for the mid-1970s drought (Figure S3) indicate that sensitivity to distribution is greatest for maximum drought intensity over shorter accumulation periods.

3.2 | Cluster analysis

The optimum number of catchment clusters was determined through visual and numerical assessment of the height between nodes in the dendrogram derived from the agglomerative cluster analysis. We determined that a three-cluster grouping best distinguished SSI values (at 1, 3, 6, and 12 month accumulations) across the 51 catchments. K-means clustering, with the use of silhouette information, also confirmed three groups as optimal. Figure 1 displays each of the clusters and catchment IDs, with further details of cluster membership given in Table 1. Cluster 1 catchments (n = 13) tend to be in the northwest and are relatively small and wet, with low groundwater storage (characterised by BFIsoil), steeper slopes, and a higher proportion of peat and wetter soils (see Figure 2a). Catchments in Cluster 2 (n = 15) tend to be in the southwest and are intermediate between Cluster 1 and 3 in terms of the PCDs evaluated. Cluster 3 catchments (n = 23) are in the east and southeast, tend to be larger and drier, have greater groundwater storage, with shallow slopes and a low proportion of peat cover.

3.3 | Drought propagation

The propensity for meteorological drought to propagate to hydrological drought was assessed for catchments in each cluster by deriving Pearson correlation scores between SSI-1 and SPI-1, 3, 6, and 12 over the full period of reconstructions. Boxplots of derived Pearson scores for each of the clusters are displayed in Figure 2b. Cluster 1 catchments show strongest correlations between SSI-1 and SPI-1, consistent with their low groundwater storage and more rapid propagation of drought. Cluster 3 catchments have strongest correlations between SSI-1 and SPI-3, but remain strong for SPI accumulations over 6 and 12 months, highlighting the slower propagation of drought in larger catchments with greater groundwater storage. Cluster 2 catchments are intermediate, with correlations between SSI and SPI decreasing for longer accumulation periods. In terms of the influence of PCDs, we find a strong association between SAAR and likelihood of

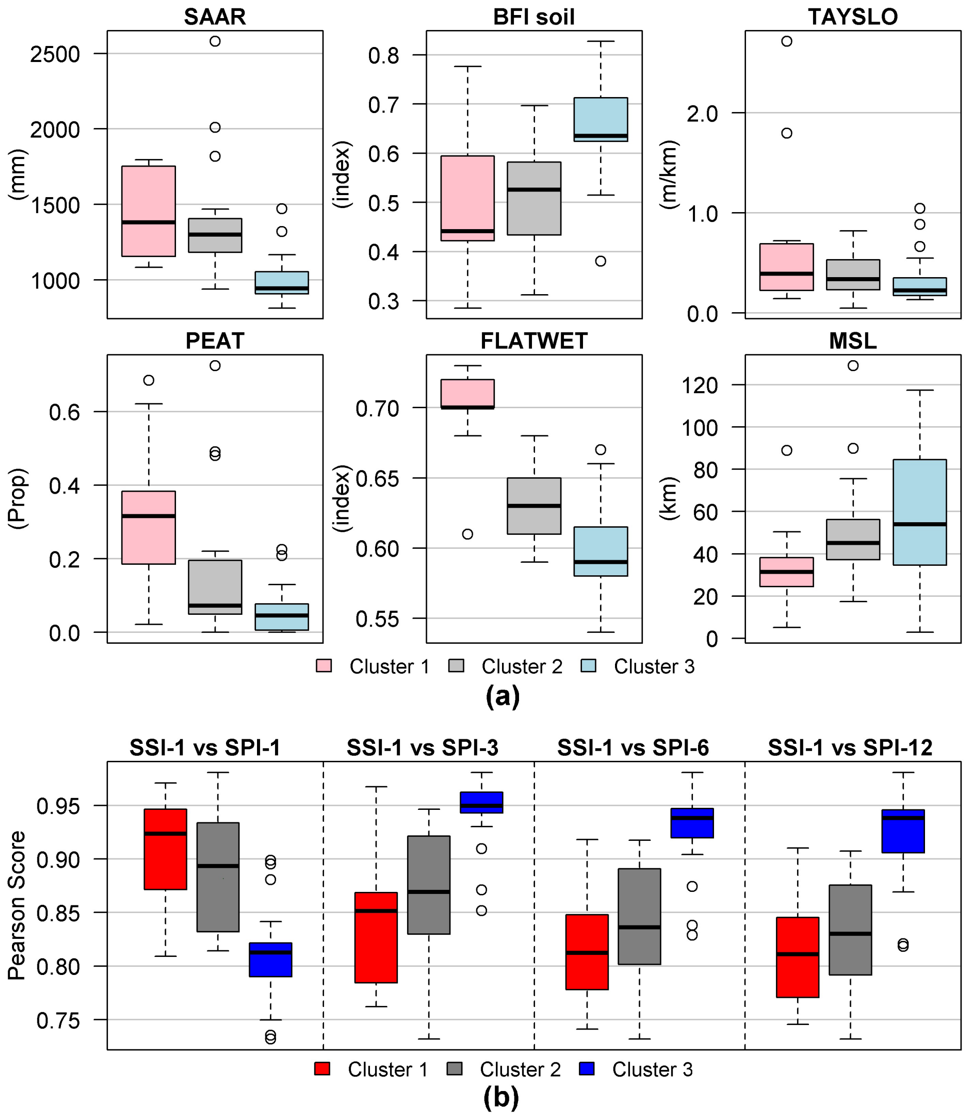

FIGURE 2 (a) Distributions of the six physical catchment descriptors for each cluster and (b) Pearson correlation coefficients scores between SSI-1 and SPI-1, 3, 6, and 12 for each cluster [Colour figure can be viewed at wileyonlinelibrary.com]

a drought, with total annual rainfall correlating strongly with the risk of drought occurrence at 1-month accumulation (Table 1). Also evident is the link between groundwater storage and delayed drought onset, whereby catchments with greater groundwater storage (higher BFIsoil) show stronger correlations between SSI-1 and SPI over longer accumulations.

3.4 | Historical hydrological droughts

Figure 3 displays SSI-1, 3, 6, and 12 generated from the median flow values of each cluster. The variability of SSI between clusters is apparent with different responses in drought event intensity as a function of accumulation period. High variability in SSI-1 values is a feature of the short accumulation period, resulting in more moderate, severe, and extreme events. This is evidenced by SSI values falling below the previously defined McKee *et al.* (1993) thresholds more frequently than for other accumulation periods. Persistent and extreme droughts are more easily detected in the SSI-12 series which produces the lowest number of events across all intensities. Differences in drought intensities between catchment groupings are also visible. For example, while Cluster 1 and 2 catchments register an extreme SSI-6 drought in 1984, this event only reaches severe classification in Cluster 3. Furthermore, while Cluster 2 catchments experience no SSI-12 drought exceeding moderate intensity in the period 1978–2016, both Cluster 1 and 3 return at least one severe and one extreme event. Cluster 1 generates the most hydrological droughts of all intensities (102 SSI-12 events), followed by Cluster 2 (94 SSI-12 events), and Cluster 3 generating the least (83 SSI-12 events).

Figure 4 displays heatmaps of SSI-3, 6, and 12 for the full 250-year period for individual catchments, organized by cluster membership. The most prominent events include the 1803–1806, 1855–1859, 1887–1890, 1933–1935, 1953–1954, 1971–1974, and 1975–1977 droughts. Conversely, the periods 1860–1885 and 1978–2004 were

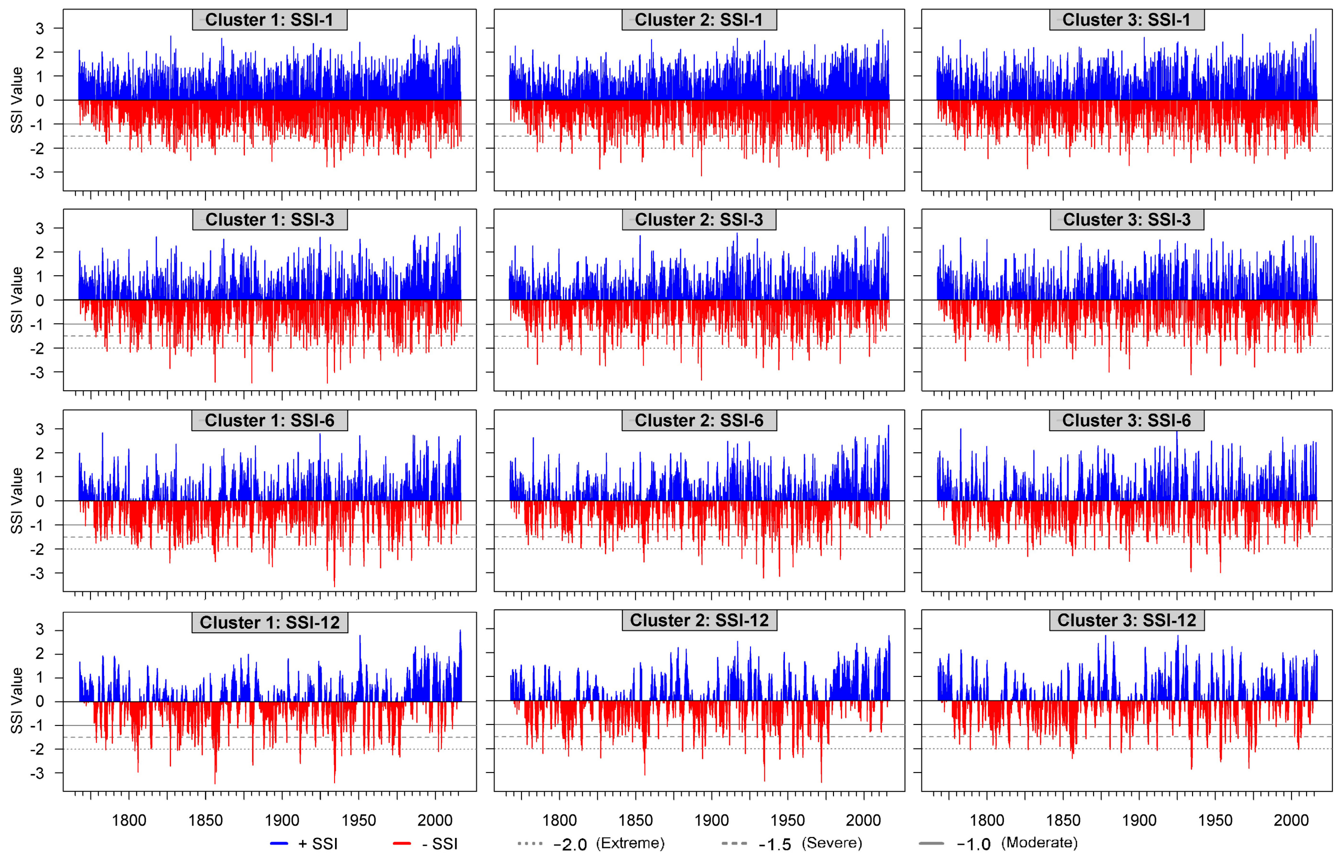

FIGURE 3 Time-series of SSI-1, 3, 6, and 12 derived from median flows for each cluster for the period 1767–2016, using the Tweedie distribution and 1930–1999 reference period. Horizontal lines represent moderate (SSI = −1), severe (SSI = −1.5), and extreme (SSI = −2) drought thresholds [Colour figure can be viewed at wileyonlinelibrary.com]

notably drought poor. Catchment specific variations in drought durations and deficits align closely within clusters, particularly in the case of Cluster 1 which differ noticeably from Cluster 2 and 3. For example, in the SSI-6 and 12 reconstructions, the 1921–1923 drought shows much greater intensity in Cluster 1 compared with other clusters. Differences between Cluster 2 and 3 are also evident. For instance, deficits in the 2004 drought (SSI-12) were severe/extreme in most Cluster 3 catchments but less so in Cluster 2 catchments. Although differences in drought numbers, durations, and deficits *between* clusters are considerable, similarities in drought characteristics for catchments *within* clusters are high.

3.5 | Meteorological and hydrological drought characteristics

A summary of moderate, severe, and extreme meteorological (SPI) and hydrological (SSI) historical drought characteristics is presented in Figure 5. For equivalent intensities and accumulations, the number of SSI drought events (Figure 5a) is consistently lower than for SPI. Although the number of SPI events is often highest in Cluster 3 catchments, SSI event numbers are consistently lower, indicating that meteorological droughts in Cluster 3 do not always translate into hydrological drought. Conversely, Cluster 1 catchments have the highest overall number of SSI drought events despite the number of SPI drought events being similar to Cluster 3, suggesting that the former are more vulnerable to hydrological drought onset. Cluster 2 catchments consistently have the lowest meteorological drought numbers but register more hydrological droughts than Cluster 3. Mean drought duration statistics (Figure 5b) show that SSI events tend to persist longer than corresponding SPI events. However, for Cluster 3 catchments SSI drought durations are longer, suggesting this cluster is susceptible to more persistent droughts once deficits become established.

Accumulated deficit statistics (Figure 5c) indicate that, on average, SSI events produce greater deficits than SPI events. Drought deficits are typically greatest in Cluster 1 for meteorological drought but rank behind Cluster 3 for hydrological drought, highlighting that while more susceptible to drought, Cluster 1 catchments recover quicker than Cluster 3 catchments. Cluster 2 catchments

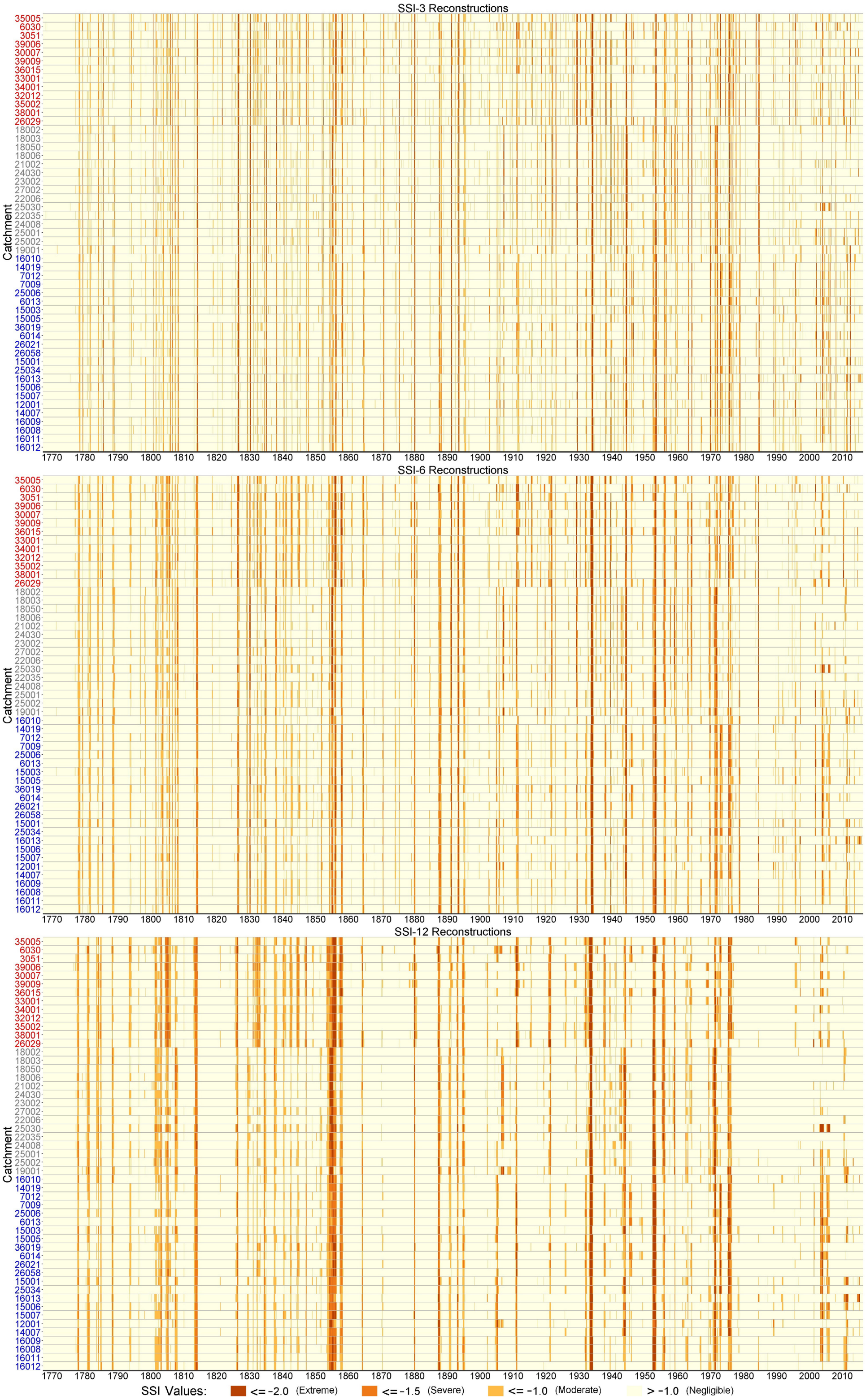

FIGURE 4 Heatmaps of SSI-3, 6, and 12 reconstructions for all 51 catchments grouped by cluster (Cluster 1, red; Cluster 2, dark grey; Cluster 3, blue). Colour coded are the main drought severity categories (moderate: −1.00 to −1.49; severe: −1.50 to −1.99; extreme: ≤−2.00) [Colour figure can be viewed at wileyonlinelibrary.com]

tend to show intermediate accumulated deficits. Cluster 3 catchments consistently show lower accumulated deficit values for SSI-1, 3, 6, and 12 compared to equivalent SPI accumulations which is directly related to longer drought durations in this grouping. Mean drought deficit statistics (Figure 5d) indicate that most SPI events produce greater mean deficits than equivalent SSI events. For almost all SSI accumulation periods, mean drought deficits in Cluster 3 catchments are less than Clusters 1 and 2 despite being equal or greater than the equivalent SPI mean deficits. This results from longer drought durations in these catchments.

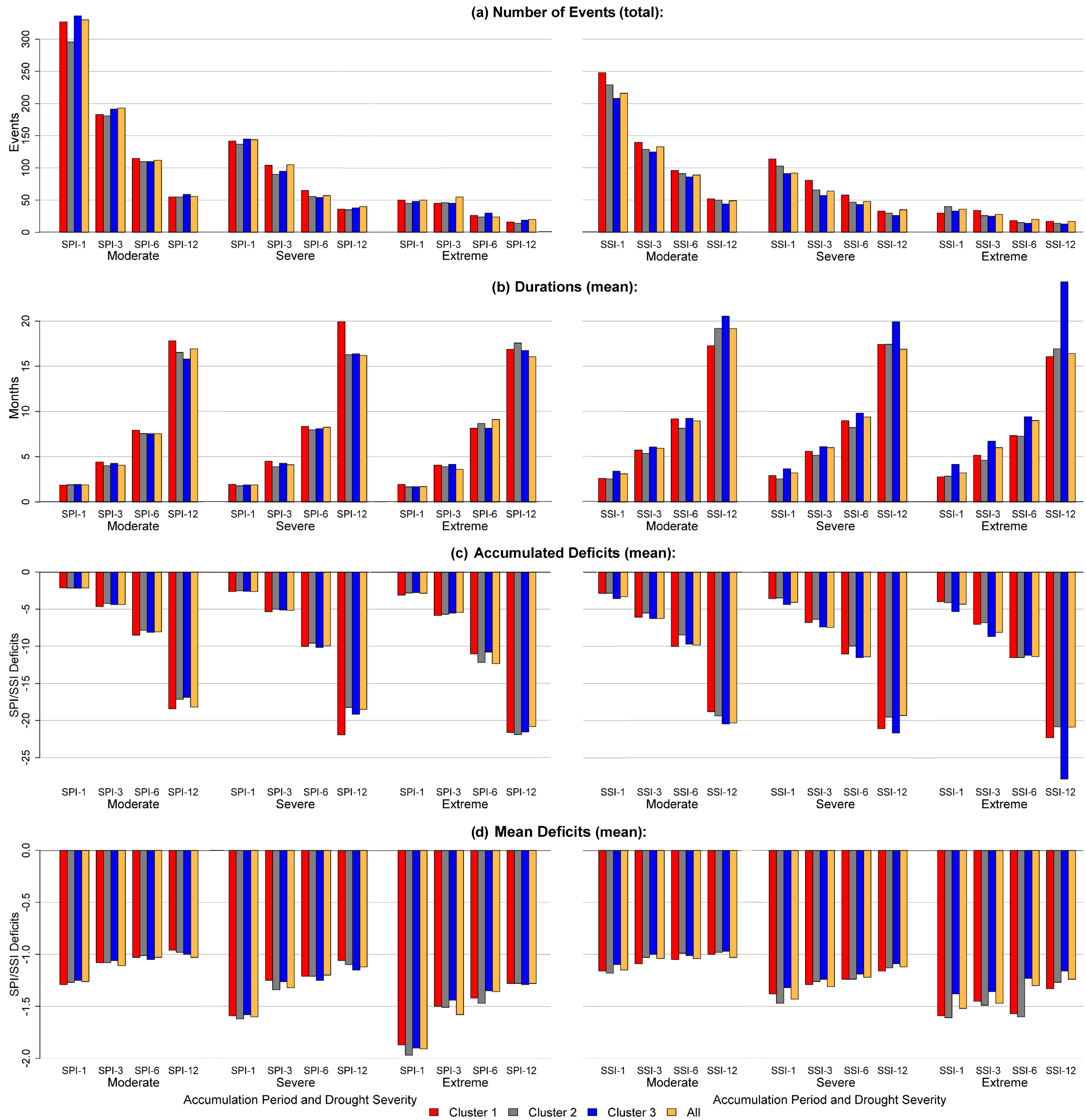

FIGURE 5 Meteorological (SPI) and hydrological (SSI) droughts, (a) total number of events, (b) mean durations, (c) mean accumulated deficits and (d) mean deficits for moderate, severe, and extreme droughts derived from median SPI and SSI series for each cluster grouping (Cluster 1, red; Cluster 2, dark grey; Cluster 3, blue; all clusters, orange). SPI and SSI event characteristics are derived for accumulation periods of 1, 3, 6, and 12 months [Colour figure can be viewed at wileyonlinelibrary.com]

Numbers of moderate, severe, and extreme hydrological drought events, their durations, accumulated deficits and mean deficits, for SSI-1, 6, and 12, were also derived for each catchment. Results display similar patterns to those found in the cluster analysis above, albeit with catchment specific variations (see Figures S4–S6). The Inny at Ballymahon (ID: 26021; Cluster 3) has the least number of moderate, severe, and extreme drought events for SSI-1, 6, and 12, whereas the Shannon at Dowra (ID: 26029; Cluster 1) has the most (n = 740). Catchments in the southwest have on average the shortest drought durations, the greatest mean deficits, and least accumulated deficits, with the Blackwater at Killavullen (ID: 18050; Cluster 2) having the shortest mean drought duration

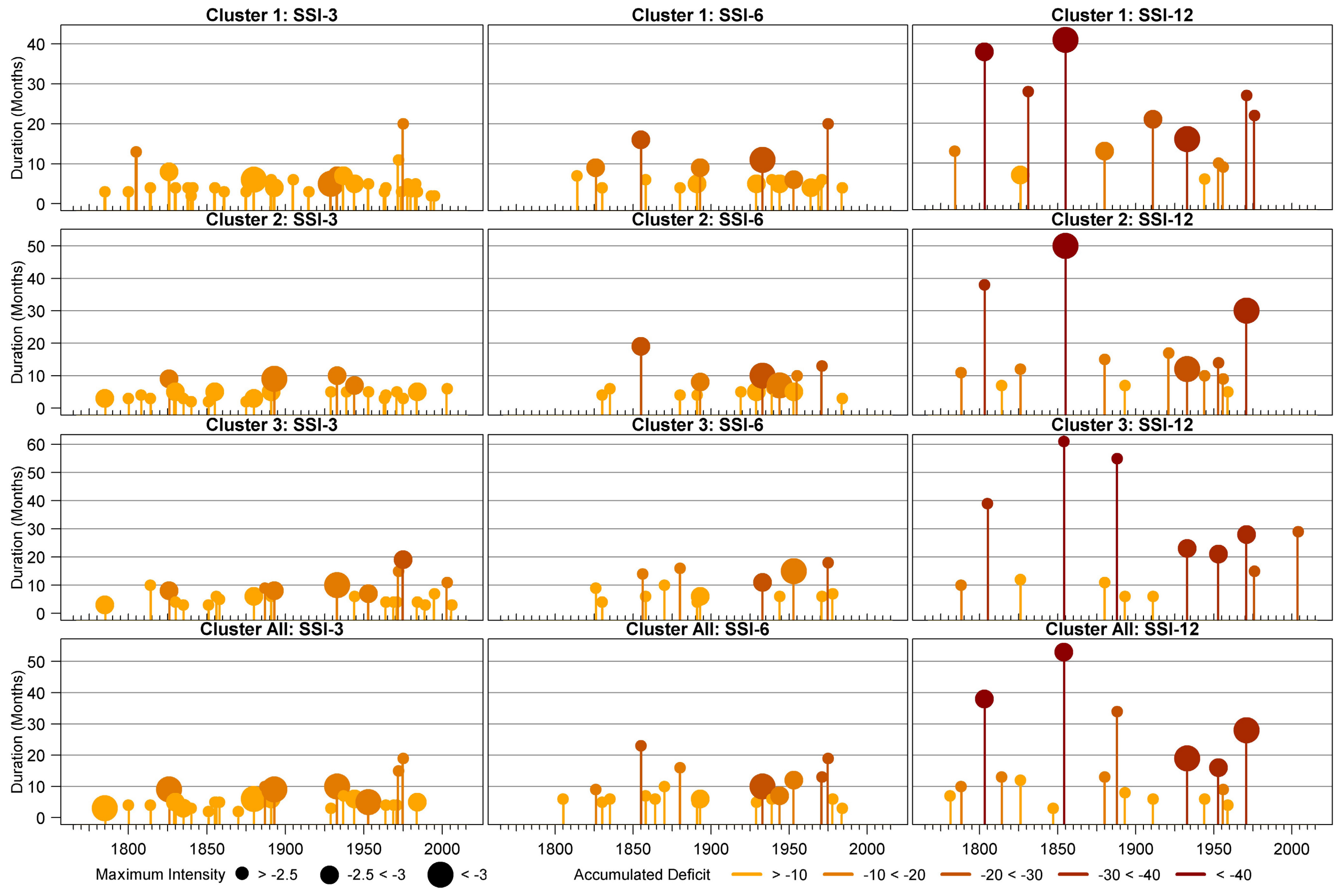

FIGURE 6 Extreme SSI-3, 6, and 12 drought events derived from median flow reconstructions for each cluster and all catchments for the period 1767–2016. For each extreme drought event the duration, maximum intensity, and accumulated deficit are provided [Colour figure can be viewed at wileyonlinelibrary.com]

and least accumulated deficits (8.27 months; −9.94 SSI). The Coomhola at Coomhola (ID: 21002) has the greatest mean deficits (−1.30 SSI) and is a Cluster 2 catchment. At the other extreme, the Erne at Belturbet (ID: 36019) has the longest durations (12.33 months), the Glyde at Tallanstown (ID: 6014) has the greatest accumulated deficits (−13.65 SSI) and the Erkina at Durrow (ID: 15005) has the least mean deficits (−1.14 SSI), with all three catchments belonging to Cluster 3. Overall, catchments in the northwest display the most variability in numbers of hydrological drought events, durations, and deficits.

3.6 | Extreme hydrological drought events

Figure 6 displays extreme SSI-3, 6, and 12 drought events for each cluster with details about the number of events, their durations, maximum intensities, and accumulated deficits. For SSI-12, the 1854–1860 drought period is most notable, having the greatest duration and accumulated deficits in each cluster. The event is less prominent for SSI-6, particularly in Cluster 3, and is not distinguishable from other events at SSI-3. Although not as remarkable for SSI-12, the 1975–1977 drought is a prominent SSI-3 and SSI-6 event in terms of deficits and duration for Clusters 1 and 3, with the longest duration of all extreme droughts in both clusters at that accumulation, and the greatest accumulated deficits of all droughts in Cluster 3. The 1933–1935 drought is notable for the intensity and accumulated deficits despite the relatively short duration, particularly for SSI-6 and SSI-12 in Cluster 1. Cluster 3 catchments have the most extreme droughts by accumulated deficit and duration for SSI-3 and SSI-12, whereas for SSI-6 it is Cluster 1. On average, maximum intensity values are most extreme in Cluster 2 for SSI-3 and Cluster 1 for SSI-6 and 12. Across all clusters, there is a remarkable lack of extreme hydrological droughts since the mid-1970s.

Of the top 10 most extreme hydrological droughts per cluster grouping and accumulation period listed in Table 2, the 1854–1859 event is the most prominent having the longest duration (53 months) and greatest accumulated deficits (−84.81) for SSI-12. Based on SSI-3, this

TABLE 2 Top 10 SSI-3, 6, and 12 drought events, derived from median flow across all catchments and for clusters during the period 1767–2016. Included are the maximum intensity (Max INT), accumulated SSI deficit (Accum SSI) and duration (months) of each event

Cluster 1 (SSI-3)	Start date	End date	Max INT	Accum SSI	Months	Cluster 1 (SSI-6)	Start date	End date	Max INT	Accum SSI	Months	Cluster 1 (SSI-12)	Start date	End date	Max INT	Accum SSI	Months
1st	07/1975	03/1977	−2.33	−19.90	20	1st	10/1933	09/1934	−3.64	−26.87	11	1st	11/1855	04/1859	−3.46	−70.53	41
2nd	10/1933	05/1934	−3.00	−15.34	7	2nd	07/1975	03/1977	−2.44	−26.75	20	2nd	10/1803	12/1806	−2.98	−50.95	38
3rd	01/1805	02/1806	−2.16	−13.50	13	3rd	05/1855	09/1856	−2.53	−25.02	16	3rd	09/1831	01/1834	−2.05	−37.59	28
4th	12/1855	06/1856	−3.42	−12.39	6	4th	06/1826	03/1827	−2.58	−15.47	9	4th	10/1933	02/1935	−3.43	−34.49	16
5th	03/1929	08/1929	−3.46	−11.61	5	5th	05/1893	02/1894	−2.74	−14.41	9	5th	11/1971	02/1974	−2.24	−33.04	27
6th	12/1937	07/1938	−2.90	−9.83	7	6th	04/1953	10/1953	−2.72	−11.54	6	6th	01/1976	11/1977	−2.34	−32.34	22
7th	02/1891	08/1891	−2.17	−8.92	6	7th	05/1944	10/1944	−2.67	−9.64	5	7th	08/1911	05/1913	−2.62	−25.54	21
8th	07/1826	03/1827	−2.85	−8.90	8	8th	05/1929	10/1929	−2.89	−9.36	5	8th	05/1953	03/1954	−2.18	−15.91	10
9th	05/1893	09/1893	−2.96	−8.68	4	9th	12/1971	06/1972	−2.11	−9.02	6	9th	10/1784	11/1785	−2.03	−15.32	13
10th	03/1953	08/1953	−2.41	−8.31	5	10th	02/1858	08/1858	−2.10	−8.23	6	10th	09/1880	10/1881	−2.68	−15.10	13
Cluster 2 (SSI-3)	**Start date**	**End date**	**Max INT**	**Accum SSI**	**Months**	**Cluster 2 (SSI-6)**	**Start date**	**End date**	**Max INT**	**Accum SSI**	**Months**	**Cluster 2 (SSI-12)**	**Start date**	**End date**	**Max INT**	**Accum SSI**	**Months**
1st	03/1944	10/1944	−2.89	−14.09	7	1st	02/1855	09/1856	−2.55	−26.77	19	1st	02/1855	04/1859	−3.10	−68.64	50
2nd	11/1933	09/1934	−2.81	−13.80	10	2nd	11/1933	09/1934	−3.21	−21.46	10	2nd	10/1803	12/1806	−2.31	−39.63	38
3rd	06/1826	03/1827	−2.70	−12.07	9	3rd	05/1971	06/1972	−2.28	−21.14	13	3rd	09/1971	03/1974	−3.40	−33.23	30
4th	05/1893	02/1894	−3.32	−11.03	9	4th	11/1955	09/1956	−2.15	−15.54	10	4th	01/1953	03/1954	−2.37	−26.95	14
5th	06/1984	11/1984	−2.64	−9.14	5	5th	04/1944	11/1944	−3.15	−15.47	7	5th	12/1933	12/1934	−3.35	−26.93	12
6th	03/1929	08/1929	−2.41	−9.02	5	6th	06/1893	02/1894	−2.66	−11.45	8	6th	05/1956	02/1957	−2.21	−13.02	9
7th	01/1830	06/1830	−2.74	−8.66	5	7th	04/1953	09/1953	−2.76	−9.80	5	7th	09/1880	12/1881	−2.12	−12.36	15
8th	03/1953	08/1953	−2.62	−8.43	5	8th	06/1929	11/1929	−2.64	−8.28	5	8th	12/1921	05/1923	−2.21	−12.16	17
9th	02/1891	07/1891	−2.48	−8.43	5	9th	03/1830	07/1830	−2.21	−7.57	4	9th	08/1944	06/1945	−2.44	−11.82	10
10th	10/1971	03/1972	−2.04	−7.56	5	10th	01/1835	07/1835	−2.10	−7.05	6	10th	12/1788	11/1789	−2.20	−11.58	11
Cluster 3 (SSI-3)	**Start date**	**End date**	**Max INT**	**Accum SSI**	**Months**	**Cluster 3 (SSI-6)**	**Start date**	**End date**	**Max INT**	**Accum SSI**	**Months**	**Cluster 3 (SSI-12)**	**Start date**	**End date**	**Max INT**	**Accum SSI**	**Months**
1st	07/1975	02/1977	−2.78	−20.47	19	1st	08/1975	02/1977	−2.21	−23.37	18	1st	11/1854	12/1859	−2.41	−82.87	61
2nd	11/1933	09/1934	−3.10	−16.42	10	2nd	11/1933	10/1934	−2.96	−21.83	11	2nd	01/1888	08/1892	−2.17	−40.85	55
3rd	10/1972	01/1974	−2.00	−14.83	15	3rd	03/1953	06/1954	−3.01	−19.29	15	3rd	11/1971	03/1974	−2.81	−38.64	28
4th	02/1953	09/1953	−2.73	−14.11	7	4th	03/1856	05/1857	−2.29	−15.08	14	4th	11/1805	02/1809	−2.02	−37.21	39
5th	11/2003	10/2004	−2.19	−11.96	11	5th	03/1880	07/1881	−2.01	−11.00	16	5th	01/1953	10/1954	−2.54	−34.34	21
6th	08/1887	05/1888	−2.09	−11.79	9	6th	05/1944	11/1944	−2.22	−9.95	6	6th	12/1933	11/1935	−2.86	−32.85	23
7th	05/1893	01/1894	−2.86	−10.93	8	7th	12/1971	06/1972	−2.32	−8.40	6	7th	07/2004	12/2006	−2.04	−29.75	29

(Continues)

TABLE 2 (Continued)

Cluster 3 (SSI-3)	Start date	End date	Max INT	Accum SSI	Months	Cluster 3 (SSI-6)	Start date	End date	Max INT	Accum SSI	Months	Cluster 3 (SSI-12)	Start date	End date	Max INT	Accum SSI	Months
8th	07/1826	03/1827	−2.74	−10.31	8	8th	09/1826	06/1827	−2.10	−8.40	9	8th	01/1976	04/1977	−2.14	−23.27	15
9th	01/1856	07/1856	−2.45	−8.85	6	9th	08/1893	02/1894	−2.52	−8.01	6	9th	12/1788	10/1789	−2.05	−10.93	10
10th	02/1891	08/1891	−2.24	−8.48	6	10th	03/1858	09/1858	−2.02	−7.67	6	10th	12/1826	12/1827	−2.04	−9.80	12
All Clusters (SSI-3)	**Start date**	**End date**	**Max INT**	**Accum SSI**	**Months**	**All Clusters (SSI-6)**	**Start date**	**End date**	**Max INT**	**Accum SSI**	**Months**	**All Clusters (SSI-12)**	**Start date**	**End date**	**Max INT**	**Accum SSI**	**Months**
1st	07/1975	02/1977	−2.41	−17.47	19	1st	06/1855	05/1857	−2.32	−27.44	23	1st	11/1854	04/1859	−2.71	−84.81	53
2nd	11/1933	09/1934	−3.22	−16.18	10	2nd	11/1933	09/1934	−3.33	−23.24	10	2nd	10/1803	12/1806	−2.74	−45.01	38
3rd	07/1887	05/1888	−2.24	−13.99	10	3rd	05/1971	06/1972	−2.30	−21.34	13	3rd	10/1971	02/1974	−3.13	−37.88	28
4th	06/1826	03/1827	−3.10	−13.84	9	4th	08/1975	03/1977	−2.18	−21.02	19	4th	12/1933	07/1935	−3.02	−32.40	19
5th	05/1893	02/1894	−3.45	−11.64	9	5th	03/1953	03/1954	−2.98	−15.86	12	5th	01/1953	05/1954	−2.64	−31.35	16
6th	03/1953	08/1953	−3.19	−11.57	5	6th	04/1944	11/1944	−2.65	−13.46	7	6th	01/1888	11/1890	−2.30	−25.76	34
7th	10/1972	01/1974	−2.03	−10.65	15	7th	03/1880	07/1881	−2.18	−12.46	16	7th	05/1956	02/1957	−2.22	−12.55	9
8th	04/1944	10/1944	−2.63	−9.60	6	8th	08/1826	05/1827	−2.39	−11.30	9	8th	09/1880	10/1881	−2.50	−12.02	13
9th	06/1984	11/1984	−2.72	−9.28	5	9th	02/1858	09/1858	−2.15	−9.58	7	9th	12/1788	10/1789	−2.10	−11.41	10
10th	01/1830	06/1830	−2.85	−9.23	5	10th	08/1893	02/1894	−2.98	−8.32	6	10th	08/1814	09/1815	−2.33	−11.23	13

event fails to make the top 10 extreme droughts for Cluster 2. This is primarily due to the length of the drought and the sporadic deficits accumulated over shorter periods during its occurrence. Spatially and temporally, the drought was uneven with Cluster 1 catchments experiencing extreme SSI-12 drought approximately 12 months after Cluster 3, and 9 months after Cluster 2. Despite this, maximum SSI-12 deficits are greatest in Cluster 1 catchments reaching −3.46 SSI.

The 1933–1935 event is the most spatially coherent drought in the record, as it is identified as a top six SSI-3, -6, and -12 event in all clusters. The relatively short duration of this event (23 months for SSI-12), results in high ranks across lower accumulations (consistently within the top two events). Cluster 1 catchments are most impacted with a maximum intensity of −3.43 SSI, the second most extreme of all SSI-12 events across each cluster grouping. Extreme drought conditions consistently began earliest in Cluster 1 catchments, 2 months before Clusters 2 and 3 catchments in the case of SSI-12 and 1 month in the case of SSI-3 and 6. Consequently, Cluster 1 catchments experience the greatest accumulated deficits reaching −34.49 for SSI-12.

The 1944 drought, although not as extreme as others in terms of duration or deficits, is most significant in Cluster 2 particularly for SSI-3 where accumulated deficits exceed values attained by all other droughts. For SSI-6, the event is notable in all groupings, as it is consistently within the top seven events despite having a relatively short duration (7 months).

The 1953–1954 drought is another prominent event in the series which, despite a relatively short duration, produced considerable accumulated deficits. The event is registered as a top 10 drought in each cluster and accumulation period. Cluster 3 catchments show the greatest accumulated deficits (−34.34 SSI-12) and duration (maximum of 21 months). The event does not start simultaneously across the three clusters, with Cluster 1 reaching extreme conditions 4 months after Cluster 2 and 3 and ending 7 months earlier compared to SSI-12 in Cluster 3. This highlights the potential for temporal differences in drought event numbers across the island.

The 1975–1977 drought is the most recent extreme identified in our series, coming at the end of a drought rich period during the early to mid-1970s. With a maximum duration of 22 months (Cluster 1, SSI-12) the spatial impact of the event is uneven. While for Cluster 1 and 3 it is identified as a top 10 event for all accumulation periods, this drought does not rank highly over any accumulation period for Cluster 2. The greatest severity is seen in Cluster 3 where it is the top-ranking drought by accumulated deficit for SSI-3 and 6. While extreme drought conditions commenced at a similar time across Clusters 1 and 3 (consistently summer 1975 for SSI-3 and SSI-6 and winter 1975/1976 for SSI-12), the duration was considerably longer for Cluster 1 catchments (7 months in the case of SSI-12 compared to Cluster 3). As a result, accumulated deficits were greatest in this cluster reaching −32.34 for SSI-12.

3.6.1 | Sensitivity of drought characteristic results to reference period

Sensitivity of drought characteristics to reference period was investigated using four test periods (1767–2016, 1900–1999, 1930–1999, and 1981–2010) to calculate SSI-1, 3, 6, and 12. The indices, derived from median flow series across all catchments, were assessed for numbers of drought events, their durations, and accumulated deficits at moderate and severe thresholds. Figure 7 shows that

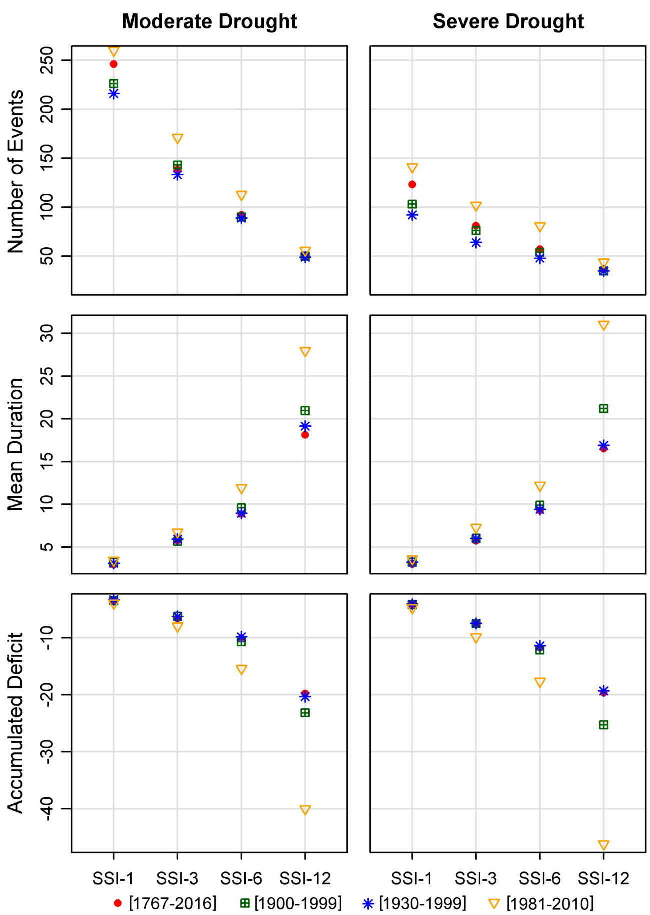

FIGURE 7 The number, duration, and accumulated deficit of drought events for SSI-1, 3, 6, and 12 values derived from median reconstructions for all catchments. Values are derived from the 1767–2016 (red dot), 1900–1999 (dark green square), 1930–1999 (blue star), and 1981–2010 (orange triangle) reference periods [Colour figure can be viewed at wileyonlinelibrary.com]

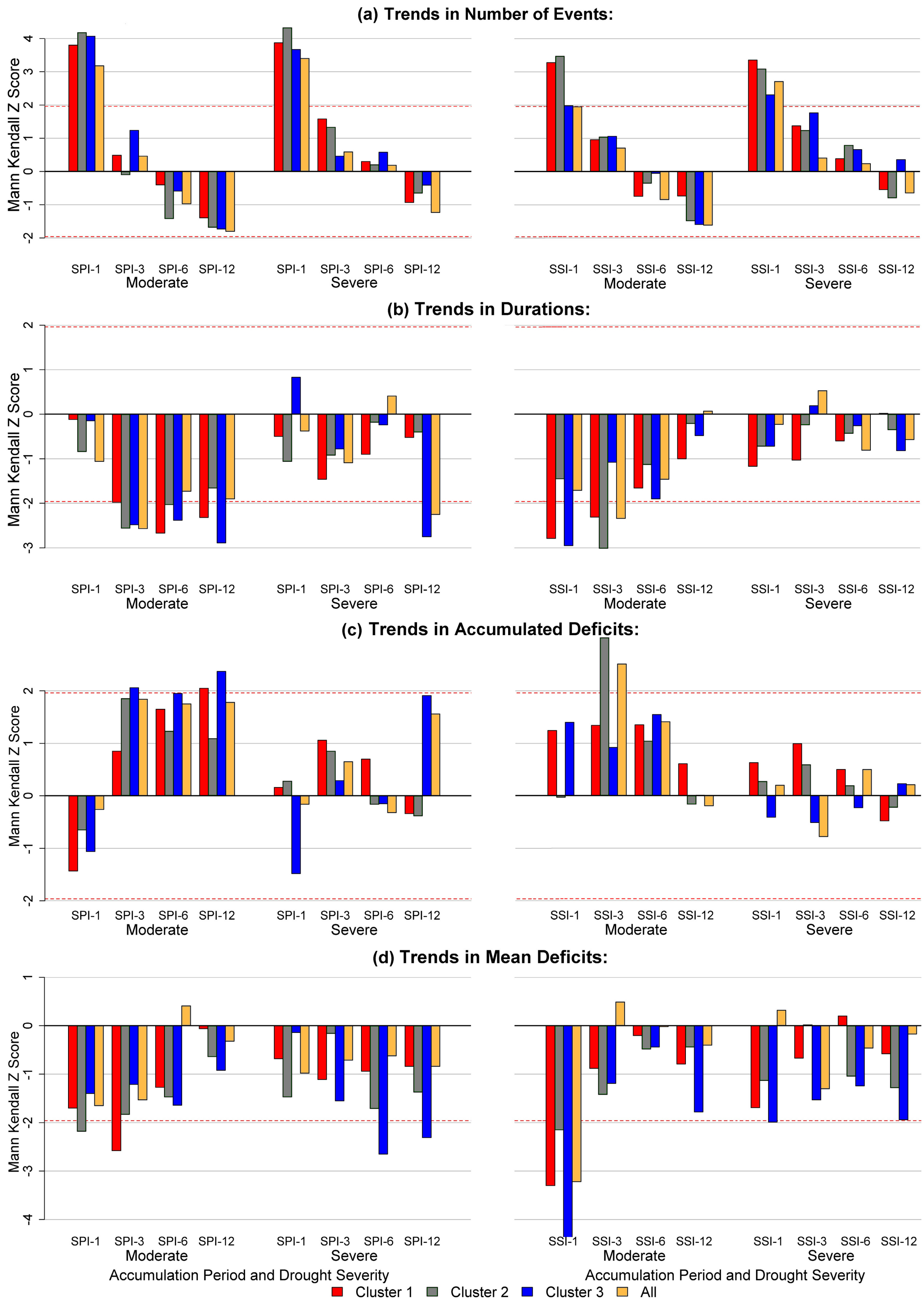

FIGURE 8 Mann–Kendall *Zs* scores for trends in moderate and severe meteorological (SPI) (left) and hydrological (SSI) (right) drought (a) number of events, (b) durations, (c) accumulated and (d) mean deficits for each cluster and all catchments (Cluster 1, red; Cluster 2, dark grey; Cluster 3, blue; all clusters, orange). Event characteristics are derived for accumulation periods of 1, 3, 6, and 12 months. Dashed red horizontal lines represent the 0.05 level significance thresholds (±1.96) [Colour figure can be viewed at wileyonlinelibrary.com]

the reference period has a discernible impact on all three metrics but particularly on the number of events at 1, 3, and 6 month accumulations and on durations and deficits at 6 and 12 month accumulations.

For occurrence, the 1930–1999 baseline consistently generates the least number of events across all accumulations and severities ($n = 726$, compared with $n = 968$ for the 1981–2010 reference). Differences in the number of droughts derived for SSI-1, 3, 6, and 12 range from a minimum of seven events between all four reference periods for moderate SSI-12 to a maximum of 49 events between the 1930–1999 and 1981–2010 reference periods for severe SSI-1. All four references produce similar drought duration values for SSI-1 and 3 at moderate and severe intensities. For SSI-6, the 1981–2010 baseline produces longer mean drought durations. The greatest differences in duration between reference periods are for SSI-12. Severe droughts calculated using the 1930–1999 baseline have a mean duration of 17 months, compared with 31 months for 1981–2010.

Accumulated deficits emulate those of duration with SSI-1 showing similar values for all four reference periods at both severities. The 1981–2010 reference period again deviates from others by producing greater accumulated deficits for SSI-3 and 6. SSI-12 is very sensitive to the baseline, with 1930–1999 producing a mean accumulated deficit of SSI = −19 compared with mean SSI = −46 for 1981–2010. For each accumulation period and severity category the 1981–2010 reference period generates the greatest deficits overall while the 1930–1999 period generates the least (excluding moderate SSI-12 droughts).

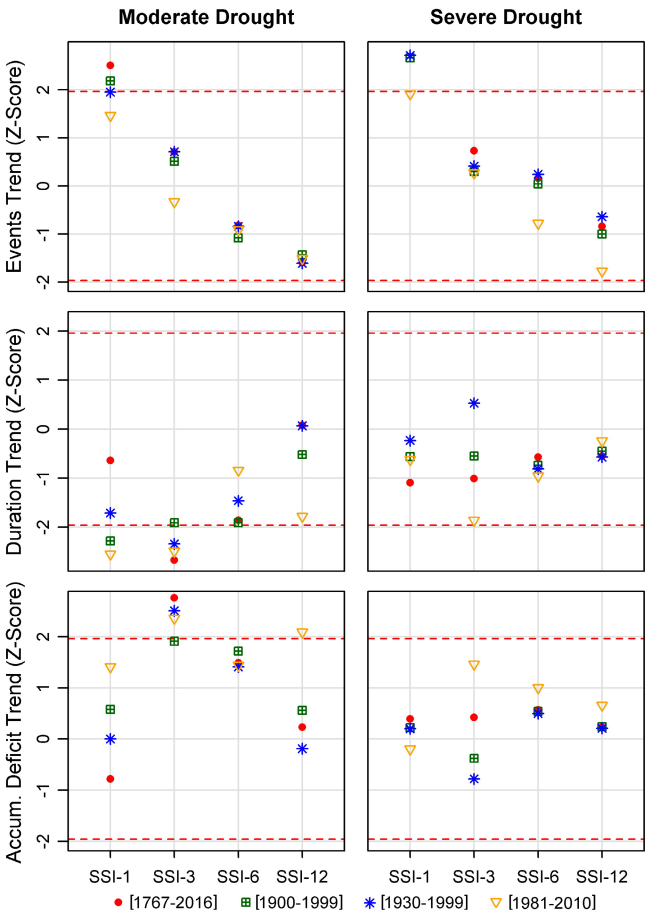

FIGURE 9 Sensitivity of trends in the number, duration and accumulated deficits of moderate (left) and severe (right) drought events to reference period used in fitting SSI indices. Results are presented for accumulation periods of 1, 3, 6, and 12 months for median reconstructions across all catchments. MK *Zs* scores returned for trends are derived from the 1767–2016 (red dot), 1900–1999 (dark green square), 1930–1999 (blue star), and 1981–2010 (orange triangle) reference periods. Dashed red horizontal lines represent the 0.05 level significance thresholds (±1.96) [Colour figure can be viewed at wileyonlinelibrary.com]

3.7 | Trends in drought characteristics

Trends in the number of events, durations, accumulated and mean deficits of moderate and severe droughts for SSI and SPI at 1, 3, 6, and 12 month accumulations were evaluated for each cluster as well as for all clusters combined. Extreme drought was excluded due to the small number of events. Results for the full period (1767–2016) are displayed in Figure 8. For each cluster, a significant ($p \leq .05$) increasing trend in the number of moderate and severe drought events is found for SPI and SSI-1, but nonsignificant trends are found for SPI and SSI-3 (increasing except for Cluster 2 SPI-3) and SPI and SSI-6 (decreasing for moderate and increasing for severe SPI and SSI). Strong decreasing trends in the number of moderate SPI and SSI-12 drought events (Figure 8a) are evident for all clusters and all catchments combined. Trends in the number of severe SPI and SSI-12 events are weaker and are all nonsignificant.

Decreasing trends in duration (Figure 8b) are evident for meteorological (SPI) and hydrological (SSI) droughts for most accumulation periods and clusters. Significant ($p \leq .05$) decreasing trends in the duration of moderate meteorological droughts are evident for SPI-3 and 6 (all clusters) and SPI-12 (Clusters 1 and 3). For severe droughts, despite overall decreasing trends in duration, significant decreases are limited to SPI-12 in Cluster 3. In terms of hydrological droughts only moderate events show significant decreasing trends in duration for SSI-1 (Clusters 1 and 3) and SSI-3 (Clusters 1 and 2). No significant changes in duration are found for severe hydrological droughts for any accumulation period.

For accumulated deficits (Figure 8c), trends are almost the inverse of those found for duration, highlighting the close association between these indices. A significant ($p \leq .05$) increasing trend (i.e., towards smaller accumulated deficits) is found for moderate SPI-3 droughts (Cluster 3) and moderate SPI-12 (Clusters 1 and 3), however this does not translate into significant increases in SSI-3 or 12 for either cluster. For hydrological droughts, changes are again confined to moderate droughts, with significant increasing trends in accumulated deficits in SSI-3 for Cluster 2 and the all-clusters sample. Other accumulation periods are also dominated by increasing trends in moderate drought deficits, though these are nonsignificant. By contrast, mean deficits (Figure 8d) for moderate and severe droughts show trends towards more negative values (i.e., more intense droughts), with the exception of severe SSI-6 droughts in Cluster 1. The strength of trends is generally greater for hydrological drought. Specifically, the largest hydrological trends are found for SSI-1 in all clusters, and for Cluster 3 for all severe drought accumulation periods.

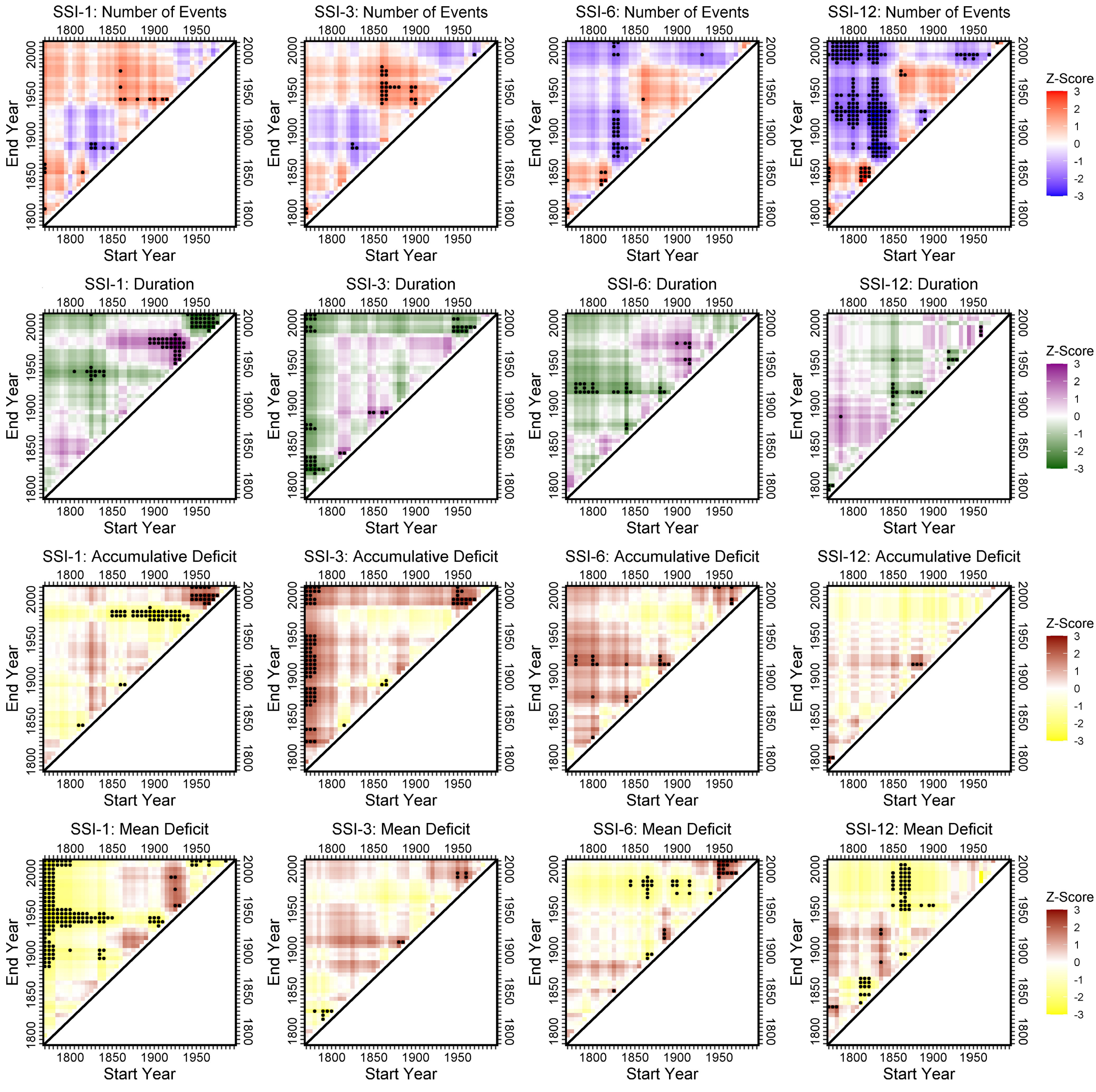

FIGURE 10 MK *Zs* scores for trends in the number of events, durations, accumulated and mean deficits of moderate hydrological droughts for varying start and end dates. Results are displayed for median reconstructions across all catchments with SSI values, derived from the Tweedie distribution and 1930–1999 reference period. MK *Zs* values are calculated for periods ranging from 30 to 245 years in 5 year increments for accumulation periods of 1, 3, 6, and 12 months. Black dots indicate test periods for which trends are significant at the 0.05 level [Colour figure can be viewed at wileyonlinelibrary.com]

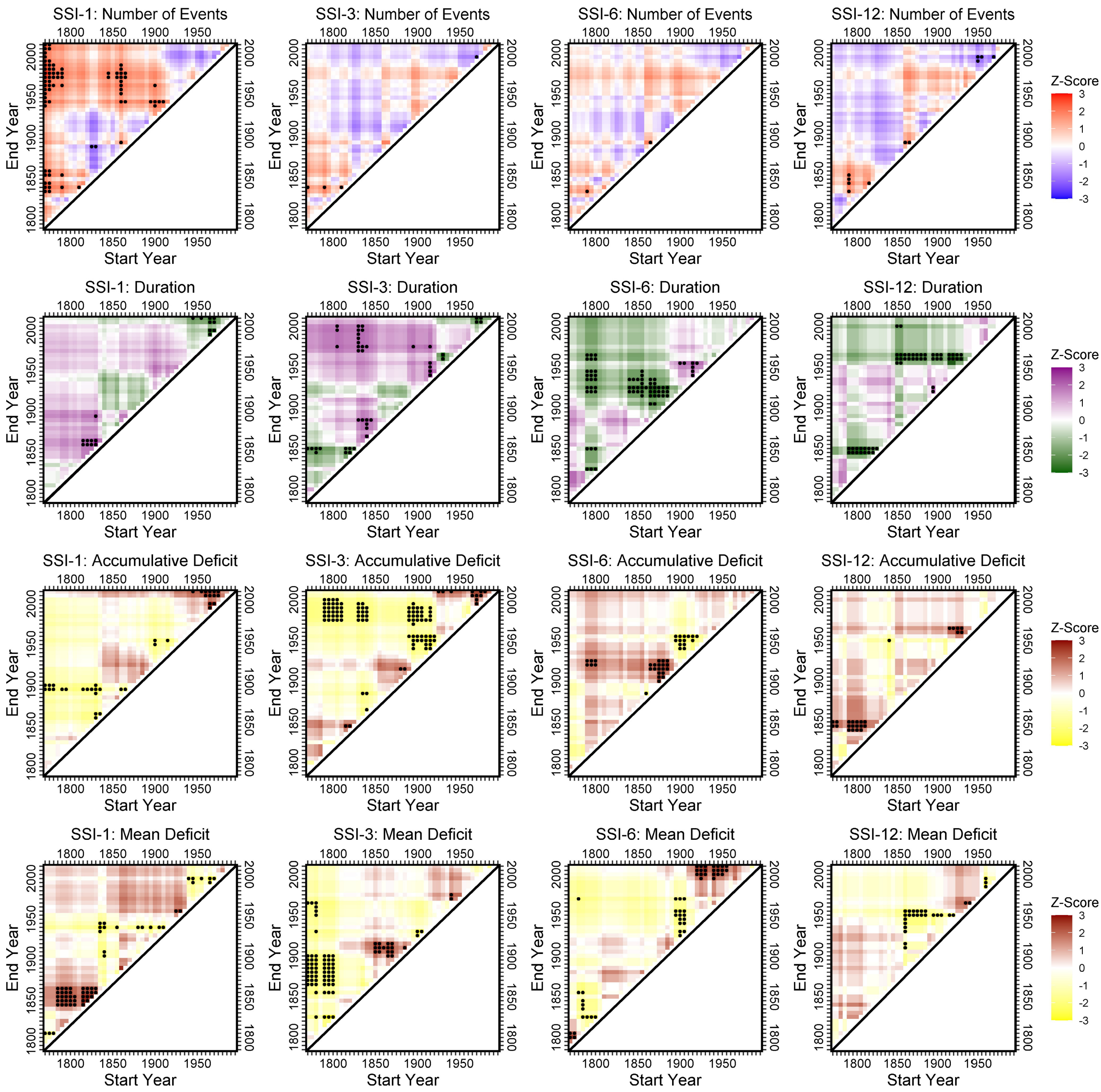

FIGURE 11 As Figure 10 but for severe droughts [Colour figure can be viewed at wileyonlinelibrary.com]

Catchment specific trends in numbers of hydrological droughtevents, durations, and deficits for SSI-1, 6, and 12 at moderate and severe intensities were also derived (Figures S7 and S8). Results align with patterns identified in the cluster analysis described above, with the number of moderate and severe SSI-1 drought events showing significant ($p \leq .05$) increasing trends across catchments. SSI-6 drought shows overall nonsignificant increasing trends while SSI-12 shows decreasing trends with decreases strongest for moderate drought. Decreasing trends in the duration of moderate SSI-1, 6, and 12 events are identifiable across nearly all catchments with corresponding reductions in accumulated deficits. Mean deficits show more negative values (i.e., more intense droughts) especially for moderate SSI-1.

3.7.1 | Sensitivity of trend results to reference period

Sensitivity of trends in numbers of hydrological (SSI) drought events, durations, and deficits to reference period are shown for each cluster in Figure 9. Variations in the magnitude, significance and direction of trends, derived for each reference period, are considerable. For the number of drought events, similar trends are identifiable across all four periods with the greatest deviations evident for the 1981–2010 reference period. The most notable differences are apparent for SSI-3 moderate and SSI-6 severe drought events where the 1981–2010 period gives decreasing trends while other reference periods produce increasing trends. Most reference periods show decreasing trends in moderate drought duration (the 1767–2016 and 1930–1999 periods show weak increasing trends for SSI-12). The significance of decreasing trends in duration and accumulated deficits is dependent on the reference period used for both moderate and severe events. Furthermore, the direction of change in accumulated deficits is also sensitive to the reference period.

3.7.2 | Sensitivity of trends to start and end dates

The sensitivity of trends to the period of record analysed was assessed using SSI-1, 3, 6, and 12 derived from the median flow across all catchments. Trends in the number of hydrological drought events, durations, accumulated and mean deficits were evaluated for moderate and severe droughts across the 1770–2015 period, for a minimum length of 30 years to a maximum of 215 years, incremented at steps of 5 years. Figures 10 and 11 show results for moderate and severe droughts, respectively. The strong influence of record length on the direction, magnitude, and significance of trends is evident. For moderate droughts, increasing trends in the number of SSI-1 events are seen for tests commencing prior to 1920, with decreasing trends found for tests starting after 1920. Similar patterns are seen for SSI-3, while for SSI-6 and 12, tests commencing prior to 1860 also display persistent decreasing trends (significantly for many SSI-12 tests). Significant decreases in the duration of moderate SSI-1 and 3 events are evident for start years after 1945 while SSI-1 tests with start years between 1895 and 1940 and end years in the 1950s and 1980s show significant ($p \leq .05$) decreasing trends, with a notable shift in duration trends in recent decades. For SSI-1, significant increases in accumulated deficit values are evident for tests commencing after 1945, similar to trends in duration. In contrast, decreases in SSI-1 mean deficits are identified for tests commencing pre-1845 and post-1945, significantly for a number of these.

The strongest (increasing) trends in the number of severe drought events are for SSI-1, especially for tests commencing prior to 1910, as well as those commencing before 1795 and from 1855–1865 (Figure 11). Severe SSI-1 drought duration shows decreasing trends for tests commencing post-1945. Increases in accumulated deficit values are evident for the same period. Despite these changes, mean deficit trends show significant decreases in SSI-1 for start years from 1940 to 1975 indicating trends towards greater intensity of SSI-1 droughts over this period. While limited significant trends are evident in the number of severe SSI-3 events, some significant changes are evident for SSI-3 duration, accumulated deficits and mean deficits. For duration, increases are evident for tests commencing prior to 1925, but decreases after 1965. Similarly, for severe SSI-3 accumulated deficits, decreases are evident for tests commencing prior to 1925, but increases after 1960.

4 | DISCUSSION

This research reconstructs hydrological and meteorological droughts for Irish catchments during the period 1767–2016. Consistent with other studies, we find that catchment characteristics play a critical role in moderating hydrological drought (Van Loon and Laaha, 2015; Barker *et al.*, 2016; Tijdeman *et al.*, 2018). Three distinct clusters of catchments were identified using the standardized streamflow index (SSI). Cluster 1 catchments in the northwest were found to be susceptible to hydrological drought onset with event duration often lowest of the three clusters. Eastern and southeastern, Cluster 3, catchments have the fewest hydrological droughts, but these tend to last longer and produce greater accumulated and reduced mean deficits than other clusters, especially for extreme droughts. Cluster 2 catchments in the southwest had the lowest drought durations overall, with the number of drought events being intermediate between Clusters 1 and 3.

Examination of the propagation of meteorological to hydrological drought confirmed the importance of groundwater storage in mediating drought incidence. Furthermore, we find a somewhat inverse manifestation of meteorological and hydrological drought across our clusters. Cluster 3 catchments consistently show the lowest frequency of hydrological drought despite having a higher frequency of meteorological drought when compared to other clusters. The opposite is true for Cluster 1 catchments, which experience the highest frequency of hydrological drought with, on average, fewer meteorological droughts than Cluster 3 catchments. Drought duration was generally longer for hydrological events in comparison to meteorological drought, with Cluster 3 catchments showing the greatest drought duration, indicating that these catchments are susceptible to long droughts once deficits become established.

We identified the top 10 droughts for each cluster at 3, 6, and 12 month accumulations. The most notable extreme droughts were the 1803–1806, 1854–1859, 1933–1935, 1944–1945, 1953–1954, and 1975–1977 events. Noone *et al.* (2017) also identified the same post-1850 events as experiencing extreme meteorological drought (except 1944–1945). All three droughts (1806, 1887, and 1893) investigated by Murphy *et al.* (2017) using documentary evidence appear as top 10 events here, with 1806 being prominent at the 12-month accumulation in Clusters 1 and 2, and 1887 at 3 and 12 month accumulations in Cluster 3. The 1893 event, which has been described as a "relatively forgotten" drought in France by Caillouet *et al.* (2017), is detectable at 3- and 6-month accumulations in all our clusters. The Noone and Murphy (2020) assessments of hydrological drought in Ireland also identified 1933–1935, 1944–1945, 1953–1954, and 1971–1977 as notable drought periods. While not as highly ranked, the 1887–1888 and 1891–1894 droughts also emerge as significant events in our study.

European analysis has identified similar historical hydrological droughts to those in this work, particularly in northern/central European regions (Moravec *et al.*, 2019). In the UK, the long drought from 1890 to 1910, the historic 1933–1934 event, and the drought of 1976 are the most prominent extreme events identified by Marsh *et al.* (2007) and Barker *et al.* (2019) that correspond with droughts identified in our study. The 1854–1859 event was similarly identified as one of the most extreme meteorological, hydrological and soil moisture droughts on the European continent in the last 250 years by Hanel *et al.* (2018). In the UK, the same event ranks highly (Spraggs *et al.*, 2015), with considerable groundwater impacts reported (Marsh *et al.*, 2007). The 1933–1934 drought, which was found to be the most spatially consistent of all events in this study, also had notable impacts on UK flows (Barker *et al.*, 2019) but has less prominence in historic drought records for continental Europe (Moravec *et al.*, 2019). Another notable event identified in our research is the 1953–1954 drought which also impacted central and western Europe (Sheffield *et al.*, 2009). However, for the UK, this drought only impacted Northern Ireland and western Scotland (Barker *et al.*, 2019), highlighting how hydrological drought impacts can vary considerably over relatively small spatial scales, dependent on catchment properties and local climate conditions.

Analysis of trends in the number, duration, mean and accumulated deficits of moderate and severe drought events revealed a complex picture with the direction, magnitude and significance often dependent on the accumulation period used to define drought, the period of record analysed, and the reference period used in fitting standardized indices. The most consistent results identified were for shorter accumulation periods (1 and 3 months) at moderate intensity. Decreasing durations and smaller accumulated deficits (i.e., less severe droughts) were found for the full period of record and in the moving window assessment for tests commencing after 1940. However, we find strong negative trends in mean deficits (i.e., more intense droughts) for both moderate and severe meteorological and hydrological droughts, especially over shorter accumulation periods.

Vicente-Serrano *et al.* (2021a) found similar trends for summer SPI-3 for long-term rainfall records in Ireland (1871–2018), particularly in southern and eastern regions, with decreasing trends in the magnitude of August SPI-3 (i.e., increased summer drought), despite predominantly decreasing trends in drought duration. In their assessment of the E-OBS dataset for Europe, Gudmundsson and Seneviratne (2015) found overall decreasing trends in drought event occurrence in northern regions, particularly for SPI-12 with some variance between trends evident in central and western regions. Overall decreases in drought occurrence, particularly at higher accumulations, including SSI-12 were also found in our study for trends commencing in the latter half of 20th century, however their significance is limited. Hanel *et al.* (2018) showed that the spatial/temporal variability of drought intensities across the continent may conceal localized impacts, particularly for meteorological to hydrological drought propagation because catchments react differently to drought events (Stoelzle *et al.*, 2014).

Periods marked by an absence of drought are also evident, especially for longer accumulation periods. The period 1767–1800 had few extreme hydrological droughts with the exception of events in 1784–1785 (Cluster 1) and 1788–1789 (Clusters 2 and 3) which rank as top 10 droughts for SSI-12. This is consistent with identified SPI-12 droughts from reconstructions of Island of Ireland precipitation by Murphy *et al.* (2020a). Furthermore, a drought-poor period in the late 1700s is also evident in the series generated by Todd *et al.* (2013) from the Kew, Oxford, and Spalding rainfall series, for southeast England. Another drought-poor period is evident in 1860–1885, as reported for SPI-12 events by Noone *et al.* (2017). The lack of extreme droughts (particularly for longer accumulation periods) since the mid-1970s found here is consistent with studies showing decreasing trends in meteorological drought in northern European regions for SPI-3, 6, 12, 24, and 36 month accumulations (Gudmundsson and Seneviratne, 2015; Stagge *et al.*, 2017). In the UK, Barker *et al.* (2019) found a decrease in hydrological drought occurrence (SSI-3 and 12) post the 1980s in northern and western catchments, which aligns with our findings. The presence of drought-rich and

-poor periods in our reconstructions suggests that a return to an era of more frequent extreme droughts is possible. This raises questions regarding the preparedness of water managers in Ireland for such change. The Irish Water (2021) 25-year plan acknowledges substantial vulnerability to drought due to the major expansion of infrastructure during the current drought-poor period (post mid-1970s) combined with insufficient recognition of the historical propensity for droughts.

There are a number of limitations to note. O'Connor *et al.* (2021) highlight key assumptions regarding the reconstruction of river flows including land-use change, changes in channel geometry (Slater *et al.*, 2019), and reductions in precipitation and temperature station density in early records (Ryan *et al.*, 2021), among others. Moreover, Murphy *et al.* (2020b) raise questions about the under measurement of snowfall in early precipitation records. Therefore, pre-1850 results should be treated with caution. Nonetheless, the coherence of drought events across clusters increases confidence in the results, as does consistency with inventories of major droughts in the UK and western Europe.

There is potential for further research too. For instance, given the typically short (∼45 years) records of observed river flow in Ireland, our reconstructions provide a multicentury catalogue of major droughts for stress-testing infrastructure, water and drought management plans. The various indices could also be used for national drought monitoring and reporting of emergent trends (Wilby, 2021). Similarly, there have been considerable efforts in Europe to link drought metrics and impacts to better inform drought monitoring and management (e.g., Bachmair *et al.*, 2016; Haro-Monteagudo *et al.*, 2018; Erfurt *et al.*, 2019; Parente *et al.*, 2019; Parsons *et al.*, 2019; Vicente-Serrano *et al.*, 2021b). As noted by Noone *et al.* (2017), Irish newspaper archives hold valuable information about cross-sectoral drought impacts. Potential therefore exists to systematically identify droughts from newspaper records dating back to the 1700s, to understand vulnerability and identify which metrics and accumulation periods best describe societal impacts at the catchment scale. Such work could shed light on the changing nature of drought vulnerability and inform development of monitoring and early warning systems (Hannaford *et al.*, 2019).

Having a multicentury catalogue of meteorological and hydrological droughts at the catchment scale also offers potential to inform and evaluate climate change adaptation. As previously highlighted, the most extreme hydrological events identified here tend to occur before the availability of digital discharge records and, therefore, offer new insight into the range of variability in drought characteristics. Recent research is highlighting the utility of storylines (plausible changes to the factors that impacted the unfolding of past events) for informing adaptation to credible extreme events (Shepherd *et al.*, 2018); others have used such approaches to evaluate how extreme drought events may change in a warmer world (e.g., Chan *et al.*, 2021). Our work provides a foundation for such approaches to adaptation planning across Irish catchments. Finally, future work should examine the climatological drivers behind drought-rich and -poor periods, as well as for the emergent pattern of shorter, sharper droughts identified here over recent decades. The AMO is known to influence summer precipitation variability in Ireland (McCarthy *et al.*, 2015) and has been linked to hydrological drought occurrence in the UK (Svensson and Hannaford, 2019). The role such phenomena play in drought variability, together with impacts of observed temperature increases should be further examined, as changing drought characteristics may have consequences for water management in Ireland, particularly where limited catchment storage increases vulnerability.

5 | CONCLUSIONS

We used reconstructed monthly precipitation and river flows to evaluate historical and hydrological drought in 51 Irish catchments over the period 1767–2016. Using standardized indices of varying accumulation periods applied to reconstructions for individual catchments and cluster groupings we found that physical catchment descriptors such as average rainfall and groundwater storage play a critical role in determining the propagation of meteorological to hydrological drought. Runoff dominated catchments tend to experience the highest drought frequency and intensity, but shorter durations. Groundwater dominated catchments tend to experience droughts of longer duration with greater accumulated deficits and reduced mean deficits. Accounting for the differential signatures of droughts at the catchment scale, the most significant hydrological droughts were identified in 1803–1806, 1854–1859, 1933–1935, 1944–1945, 1953–1954, and 1975–1977. Although not as highly ranked, events in 1826–1827, 1887–1888, 1891–1894, and 1971–1974 also emerged as significant hydrological extremes in our study. However, the evaluation of drought characteristics was shown to be sensitive to the reference period used in standardizing drought indices. The most appropriate reference period should be identified with the wavelength of key modes of variability in mind. Here, we recommend a 70-year reference period, which matches observed AMO periodicity. Despite trends in the number of drought events, durations and deficits being additionally sensitive to the period of record tested, we found that shorter droughts show evidence of increasing mean deficits, despite decreasing duration, indicating a tendency towards shorter, more intense hydrological droughts. For longer accumulation periods, we found a lack of significant trends and, at times, a lack of coherence between trends in meteorological and hydrological drought even within the same types of catchment (cluster). The dataset developed here offers an important reference set for drought and water management in Ireland, particularly given the paucity of extreme droughts present in the observational records currently used for drought planning (Irish Water, 2021).

AUTHOR CONTRIBUTIONS

Paul O'Connor: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; validation; visualization; writing – original draft. **Conor Murphy:** Conceptualization; project administration; resources; supervision; validation; writing – review and editing. **Tom Matthews:** Conceptualization; supervision; validation; writing – review and editing. **Robert L. Wilby:** Conceptualization; validation; writing – review and editing.

ACKNOWLEDGEMENTS

Paul O'Connor acknowledges funding from the Irish Research Council (IRC). Conor Murphy acknowledges funding from the Irish Environmental Protection Agency through the JPI/AXIS project CROSSDRO (2019-CCRP-MS.60) and IRC Coalesce Project COALESCE/2019/43. We thank the OPW, EPA, and Met Éireann for their data and UK CEH for Tweedie distribution code. Open access funding provided by IReL. [Correction added on 20 May 2022, after first online publication: IReL funding statement has been added.]

ORCID

Paul O'Connor https://orcid.org/0000-0002-7755-0831
Conor Murphy https://orcid.org/0000-0003-4891-2650
Tom Matthews https://orcid.org/0000-0001-6295-1870

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How to cite this article: O'Connor, P., Murphy, C., Matthews, T., & Wilby, R. L. (2022). Historical droughts in Irish catchments 1767–2016. *International Journal of Climatology*, *42*(11), 5442–5466. https://doi.org/10.1002/joc.7542