Trends in reconstructed monthly, seasonal and annual flows for Irish catchments (1900–2016)

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Introduction

Analysis of trends in historical river flows furthers understanding of variability and change for water management. In the United Kingdom (UK), Harrigan *et al.* (2018) examined trends in river flows finding increasing trends in autumn and winter, decreases in spring and contrasting northwest/southeast increasing/decreasing patterns in summer. In Ireland, Murphy *et al.* (2013) assessed trends in observed flows for 43 Irish catchments over the period 1976–2009, identifying decreasing trends in winter and spring flows and increasing trends in summer. However, such analyses can be hampered by short record lengths (e.g. Wilby, 2006; Slater *et al.*, 2021). In Europe, which has amongst the longest and most spatially dense flow records (Brönnimann *et al.*, 2019), average record length is 54 years (Mangini *et al.*, 2018). In Ireland, flow records typically commenced in the 1970s in response to severe drought at the time (Murphy *et al.*, 2013), with only a handful of gauges extending to earlier periods. Consequently, researchers have attempted to reconstruct flows to extend observed records and improve understanding of variability and change (e.g. Jones *et al.*, 2006; Spraggs *et al.*, 2015; Brigode *et al.*, 2016; Smith *et al.*, 2019). Here, we employ monthly flow reconstructions developed by O'Connor *et al.* (2021) for Irish catchments to assess trends in annual, seasonal and monthly mean flows and examine the sensitivity of trends to the period of record analysed.

Data and methods

Study catchments and flow data

Trends in flow reconstructions were found for 51 catchments across Ireland (see Table 1 for details of the flow stations and related catchment meteorological and hydrometric data). For a full background on how the monthly flows were reconstructed, see O'Connor *et al.* (2021). In brief, catchment precipitation and evapotranspiration were derived by bias correcting Casty *et al.*'s (2007) gridded (0.5°×0.5°) precipitation and temperature datasets and used as inputs to a conceptual rainfall–runoff model and artificial neural network to simulate monthly flows for the past 250 years for each catchment. The median simulation from across hydrological modelling approaches is employed here. Given large uncertainties in pre-1900 reconstructions, only data from 1900 to 2016 were used, with the choice of end year (i.e. 2016) determined by the availability of concurrent hydrological and meteorological data. Annual, seasonal (winter (DJF), spring (MAM), summer (JJA), and autumn (SON)) and monthly mean flow indices were extracted for all 51 catchments.

Trend analysis

Trends are assessed using a modified version of the non-parametric Mann–Kendall (MK) test that accounts for autocorrelation (Yue and Wang, 2004), with the threshold for significance set at the 0.05 level. The non-parametric Theil–Sen's slope (Theil, 1950; Sen, 1968) estimator was also derived to evaluate the magnitude of trends. Trends were evaluated in two ways. First, we use a fixed period of analysis (1900–2016) to examine trends over the full period. Slope magnitudes and directions for each catchment, at annual, seasonal and monthly timescales were calculated and mapped to identify regional patterns. Second, we examine the persistence of trends, or their dependency on the period of record analysed, by sequentially dropping the start year of analysis, to a minimum record length of 16 years, which provided a sufficient length of time to identify an accurate trend in the data whilst allowing all twentieth century values to be contained within the analysis. For each catchment and indicator, the resultant series of MK Z values were plotted and examined.

Results

Annual and seasonal trends

Figure 1 plots trend magnitude and significance for annual mean flows for the full period of record. Increasing trends predominate, with the exception of catchments in the southeast. Large and significant increasing trends are found for western, northern and southwestern catchments. By examining trend persistence (Figure 2), it is apparent that such large increasing trends are only evident for long records. For tests commencing post 1970, few significant trends are evident.

Seasonal trends for the full period are plotted in Figure 3. For winter, significant increasing trends are found for catchments in the northwest and along the Atlantic seaboard. Large increasing trends are also evident in the southwest but not significant at the 0.05 level. In the east and southeast decreasing trends in winter mean flows are evident, some of which are significant. For winter, in catchments showing increasing trends, these are relatively consistent irrespective of the period of record analysed (Figure 4), however significant increasing trends are more common in longer records. While trend tests commencing from the 1970s onwards generally show increases, they tend to be weaker and non-significant compared to those found in longer records.

Spring is marked by an absence of significant trends for the fixed period 1900–2016. Broadly speaking, the western half of the country tends to show increasing trends, largest in the northwest, while the eastern half of the country shows weak decreasing trends. However, trends in spring mean flows (Figure 4) are highly sensitive to the period of record analysed. Tests commencing in the 1920s and 1930s show large and significant increasing trends for many catchments. Conversely, tests commencing in the mid-1970s show widespread decreasing trends, often significant, across catchments.

Like spring, summer shows a marked absence of significant trends for the 1900–2016 fixed period (Figure 3). Most catchments show weak (non-significant) decreasing trends, with some catchments

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Table 1

Details of the 51 study catchments. As well as overall flow station data, catchment area (km^2), Standard period Average Annual Rainfall (SAAR) and annual runoff (mm) are displayed. Rows are ordered by SAAR values from lowest (blue) to highest (red) with similar colouring applied to annual runoff to allow for visual comparisons between values.

River flow station ID	*Station*	*Waterbody*	*Latitude (°)*	*Longitude (°)*	*Area (km^2)*	*SAAR (mm)*	*Annual runoff (mm)*
14019	Levitstown	Barrow	52.94	−6.95	1697	839.18	392.85
7009	Navan Weir	Boyne II	53.64	−6.67	1658	868.88	467.32
14007	Derrybrock	Stradbally	53.04	−7.09	115	869.39	511.51
6013	Charleville	Dee	53.86	−6.41	309	879.51	424.77
7012	Slane Castle	Boyne I	53.71	−6.56	2408	888.15	505.77
15005	Durrow Ft. Br.	Erkina	52.85	−7.40	379	889.40	477.33
25006	Ferbane	Brosna	53.27	−7.83	1163	898.01	465.74
6014	Tallanstown	Glyde	53.92	−6.55	270	913.06	508.42
26021	Ballymahon	Inny	53.56	−7.76	1099	942.42	545.98
24008	Castleroberts	Maigue	52.54	−8.77	806	948.22	498.14
15006	Brownsbarn	Nore I	52.50	−7.09	2418	950.18	513.76
15001	Annamult	Kings	52.55	−7.20	445	954.65	485.02
25034	Rochfort	L. Ennell Trib	53.47	−7.37	11	958.18	622.62
16010	Anner	Anner	52.38	−7.63	437	961.37	461.52
26058	Ballyrink Br.	Inny Upper	53.78	−7.25	60	971.33	609.28
36019	Belturbet	Erne	54.10	−7.45	1492	991.17	588.79
15003	Dinin Bridge	Dinin	52.72	−7.29	299	991.95	609.81
16008	New Bridge	Suir II	52.46	−8.00	1090	1001.64	662.97
36015	Anlore	Finn	54.18	−7.18	153	1009.16	689.58
24030	Danganbeg	Deel	52.41	−9.00	259	1013.26	537.15
16009	Caher Park	Suir I	52.36	−7.92	1583	1047.05	623.79
3051	Faulkland	Blackwater (Mon)	54.28	−6.92	143	1048.85	652.97
12001	Scarrawalsh	Slaney	52.55	−6.55	1031	1067.64	609.18
16011	Clonmel	Suir III	52.35	−7.69	2144	1072.13	713.24
15007	Kilbricken	Nore II	52.96	−7.46	340	1078.03	699.69
30007	Ballygaddy	Clare	53.53	−8.87	470	1096.77	713.12
6030	Ballygoly	Big	54.03	−6.24	10	1106.36	855.20
25001	Annacotty	Mulkear	52.67	−8.53	648	1138.26	749.58
25030	Scarriff	Graney	52.91	−8.53	279	1182.74	914.50
19001	Ballea	Owenboy	51.82	−8.42	103	1198.63	727.18
35005	Ballysadare	Ballysadare	54.21	−8.51	640	1211.79	848.16
18002	Ballyduff	Blackwater I	52.13	−8.69	2334	1212.61	792.55
16012	Tar Bridge	Tar	52.27	−7.84	230	1222.04	932.94
25002	Barrington S Br.	Newport (Munster)	52.64	−8.48	230	1228.72	822.23
27002	Ballycorey	Fergus	52.87	−8.97	511	1261.91	654.84
18003	Killavullen	Blackwater II	52.14	−8.05	1257	1287.50	871.17
34001	Rahans	Moy	54.10	−9.16	1975	1289.56	883.07
16013	Fourmilewater	Nire	52.27	−7.76	94	1303.17	1186.93
18006	Cset Mallow	Blackwater IV	52.10	−9.10	1052	1311.25	959.78
23002	Listowel	Feale	52.44	−9.48	647	1387.79	1089.43
39006	Lennan	Claragh	55.03	−7.68	245	1434.82	1094.59
35002	Billa Bridge	Owenbeg	54.18	−8.55	81	1458.15	1317.75
39009	Aghawoney	Fern O/L	55.04	−7.72	207	1485.30	1248.38
33001	Glenamoy	Glenamoy	54.24	−9.70	76	1509.06	1185.21
18050	Duarrigle	Blackwater III	52.15	−8.52	250	1511.34	1059.69

Table 1. (Continued)

River flow station ID	Station	Waterbody	Latitude (°)	Longitude (°)	Area (km²)	SAAR (mm)	Annual runoff (mm)
26029	Dowra	Shannon	54.19	−8.02	117	1545.73	1307.47
32012	Newport Weir	Newport	53.89	−9.52	146	1651.97	1268.71
22006	Flesk	Flesk (Laune)	52.05	−9.50	329	1741.05	1386.70
38001	Clonconwal	Ownea	54.78	−8.37	111	1795.14	1534.65
22035	Laune Bridge	Laune	52.06	−9.62	560	1858.03	1584.36
21002	Coomhola	Coomhola	51.74	−9.45	65	2157.84	1992.39

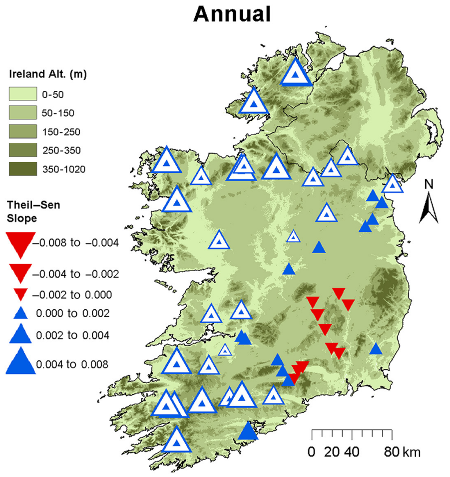

Figure 1. Theil–Sen slope estimates for mean annual flows for the 51 study catchments for the period 1900–2016. Trend directions are indicated by arrowhead direction and colour, with arrowhead size representative of slope magnitude. Significant trends, at the 0.05 level, are indicated using white triangles.

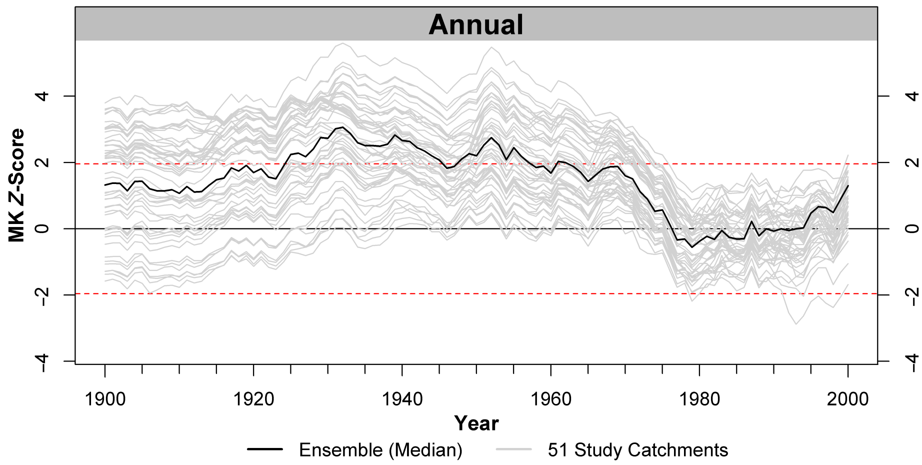

*Figure 2. Persistence of trends (sequentially varying start year of Mann–Kendall tests) for annual mean flows. Grey lines represent MK **Z** scores for each of the 51 study catchments. Trends for median flow values (black) across all 51 catchments are also displayed. Dashed red lines at +1.96/−1.96 represent thresholds above/below which trends are significant at the 0.05 level.*

in the upper Shannon basin showing weak (non-significant) increasing trends. Even the direction of trends in summer mean flows is dependent on the period of record analysed (Figure 4). Tests commencing prior to 1920 show a predominance of decreasing, non-significant trends. Tests commencing after ~1970, the period concurrent with available observed records, tend to show increasing trends in summer mean flows across most catchments.

In autumn, large and significant increasing trends are found for catchments in the northwest and north and for some catchments in the southwest for the fixed period 1900–2016. The remainder of catchments tends to show weak (non-significant) increasing trends, with the exception of catchments in the southeast where weak (non-significant) decreasing trends are apparent. Trends in autumn flows are, in general, of a consistent direction for test start years commencing prior to the 1970s. For tests commencing after the 1970s, there is a greater tendency towards negative trends, with many catchments showing significantly decreasing trends for tests commencing post 1995.

Monthly trends

Trends in monthly flows for the fixed period 1900–2016 are presented in Figure 5. For winter months, December shows significant increasing trends in northwestern catchments. The number and spatial extent of significant increasing trends increases in January with catchments across the north, northwest and along a considerable portion of the west coast all showing significant (increasing) trends. Large increasing trends are also evident in February but are not significant. In each winter month, catchments in the east and southeast show non-significant decreasing trends. For spring months, March shows the largest trends, with increases in the west and decreases in the east, however only two catchments (north and northwest) show significant increasing trends. For April and May, trends are weak and non-significant, with no clear spatial patterns. For summer months, June shows weak (non-significant) increasing trends across all catchments (significant for one catchment in the south). Both July and August flows are dominated by decreasing, mostly non-significant, trends. Largest decreasing trends are found for August in the southwest and west, with four catchments in the southwest and southeast showing significant decreases. For autumn months, trends are dominated by increases. September shows the greatest diversity of trends with large, though non-significant, increasing trends in the northwest, and weak decreasing trends in the east and southeast. Both October and November are dominated by increasing trends, particularly the latter, whereby catchments in the southwest show significant increases over the fixed period 1900–2016.

Figure 6 evaluates the persistence of trends in monthly mean flows for varying start years. While all months show sensitivity of results to the period used to assess trends, the months where trends are most sensitive to start year are March, April, July, August, September and October. In March, long-term records tend to return increasing trends (significant for tests commencing in the 1920s and 1930s). By contrast, tests commencing in the 1970s return significant decreasing trends. Similar results are obtained for April, with tests commencing in the mid-1980s returning significant decreasing trends for many catchments, while tests commencing in the first half of the twentieth century return large (often significant) increasing trends. July and August show similar results, with tests commencing in the early record dominated by decreasing trends, whereas tests commencing in the late 1960s typically

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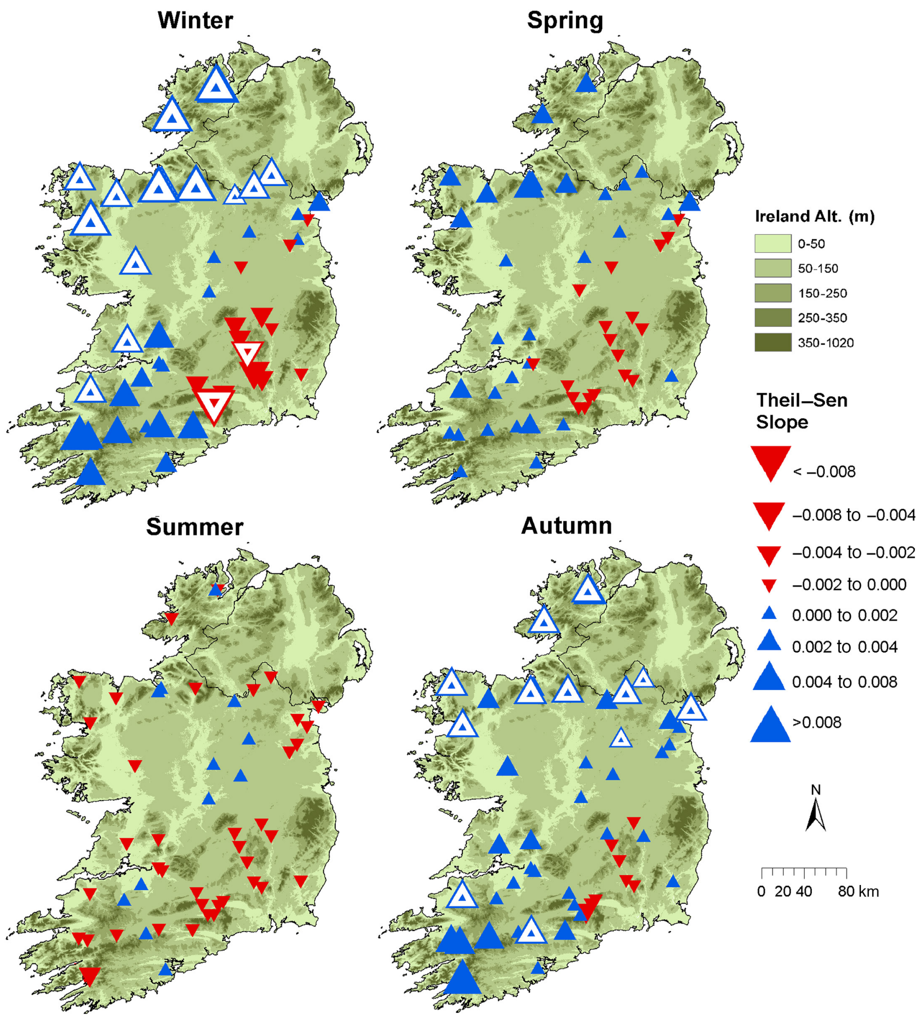

Figure 3. As per Figure 1 but for seasonal mean flows.

return large (often significant) increasing trends. In September, tests commencing between 1920 and 1960 show widespread decreasing trends across catchments, while tests commencing after 1960 show weak increasing and decreasing trends across catchments. Finally for October, tests commencing after 1970 tend to show large, often significant, decreasing trends, while tests commencing prior to the 1970 largely show increasing trends across catchments. These results highlight the importance of record length and again emphasise that the period of available observations is often unrepresentative of long-term trends in monthly flows.

Discussion

This research investigated annual, seasonal and monthly trends in reconstructed flows for 51 Irish catchments over the period 1900–2016. We find increasing trends in annual flows in the northwest, west and southwest. Our seasonal assessment found increases in autumn and winter flows consistent with those found for precipitation by McElwain and Sweeney (2003) and Murphy *et al.* (2018). Seasonal trends are also consistent with Murphy *et al.* (2013) for respective periods of records. Our monthly assessment confirmed seasonal findings, with prominent increasing trends evident in western catchments during the winter half year (October–March).

Our study shows the large variability in mean flows across Ireland. We find a change in the direction of trends in the mid-1970s, particularly in annual and spring mean flows. Ryan *et al.* (2021) found significant breakpoints between 1976 and 1979 for annual precipitation totals in their assessment of long-term trends in Irish precipitation. Similarly, Murphy *et al.* (2018) identified a step change in 1976 in their 1711–2016 rainfall series for Ireland. Both studies attribute this change to a switch to a predominantly positive phase of the North Atlantic Oscillation in the mid-1970s, previously noted in Ireland by Kiely (1999) and at a European scale by Lorenzo-Lacruz *et al.* (2022). Furthermore, McCarthy *et al.* (2015) highlight the influence of the Atlantic Multidecadal Oscillation (AMO) on summer precipitation in Ireland. Future research should prioritise investigating AMO influence on summer flows using these long-term reconstructions, with potential insights being useful for decadal forecasting and water management.

Our findings highlight the sensitivity of trends to the period of record examined. For annual, spring and summer mean flows, trends in reconstructions for the period concurrent with observations were often unrepresentative of long-term trends. This highlights the importance of flow reconstructions for contextualising findings from shorter observed records. Reconstructions are subject to uncertainty, principally from the hydrological models employed and the underlying precipitation data (O'Connor *et al.*, 2021). Close inspection of reconstructed and observed flows by O'Connor *et al.* (2021) and agreement between our results and those found in other studies suggest that our results are reliable.

Finally, assessment of climate change impacts on seasonal mean flows for Irish catchments using the CMIP6 ensemble by Meresa *et al.* (2021, 2022) suggests that anthropogenic climate change is likely to be associated with increases in winter mean flows. This is consistent with trends in winter identified here for the west and northwest. While the direction of change in summer is uncertain, the majority of future simulations suggest substantial decreases. Our results show little evidence of persistent trends in summer flows, while trends commencing in recent decades show a tendency towards increasing summer flows. Future work should further investigate the disparity between observed and simulated changes in summer flows. Similar issues have been raised elsewhere (e.g. Hannaford, 2015).

Conclusions

This study investigated trends in reconstructed river flows (1900–2016) for 51 catchments across the island of Ireland at annual, seasonal and monthly timescales. For the full period of record increasing trends are evident for annual, winter and autumn mean flows, particularly for catchments in the west and northwest. No significant trends are found for spring and summer mean flows. Analysis of trend persistence by sequentially varying the start year of analysis shows the sensitivity of trend results to the period of record tested. We find that trends in our reconstructions for the period concurrent with observations (typically the 1970s onwards) are often inconsistent with trends from longer records. This highlights the importance of long-term meteorological data in facilitating the development of flow reconstructions for contextualising trends from shorter observed records.

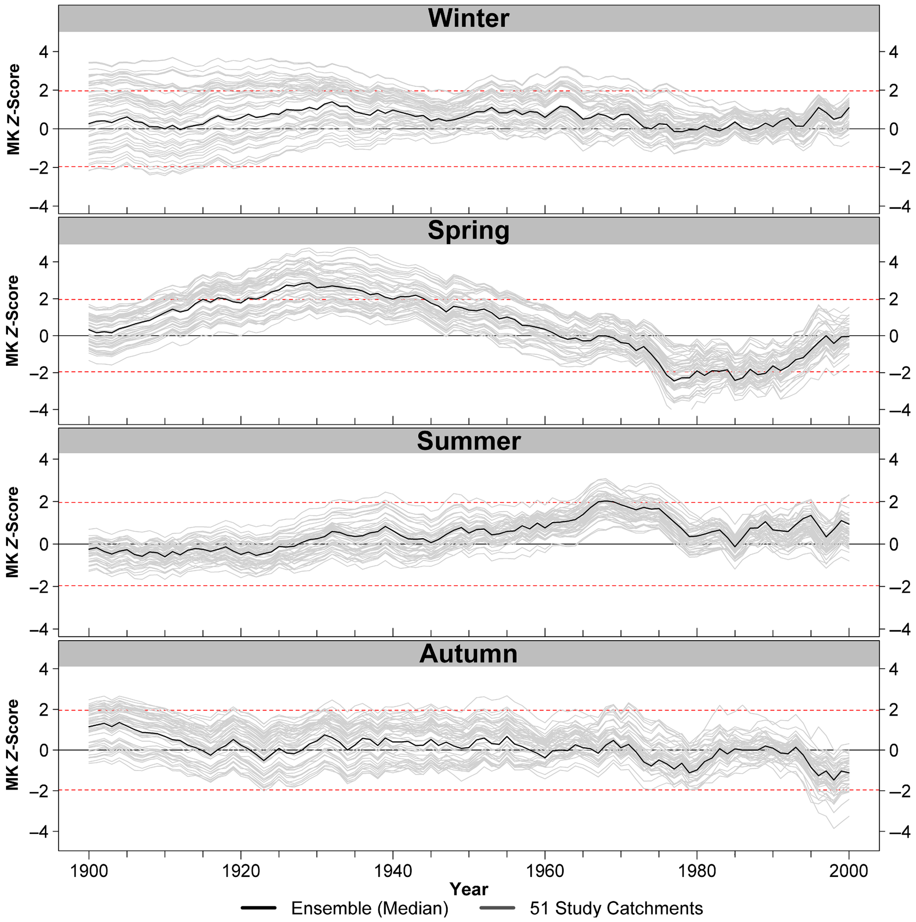

Figure 4. As per Figure 2 but for seasonal mean flows.

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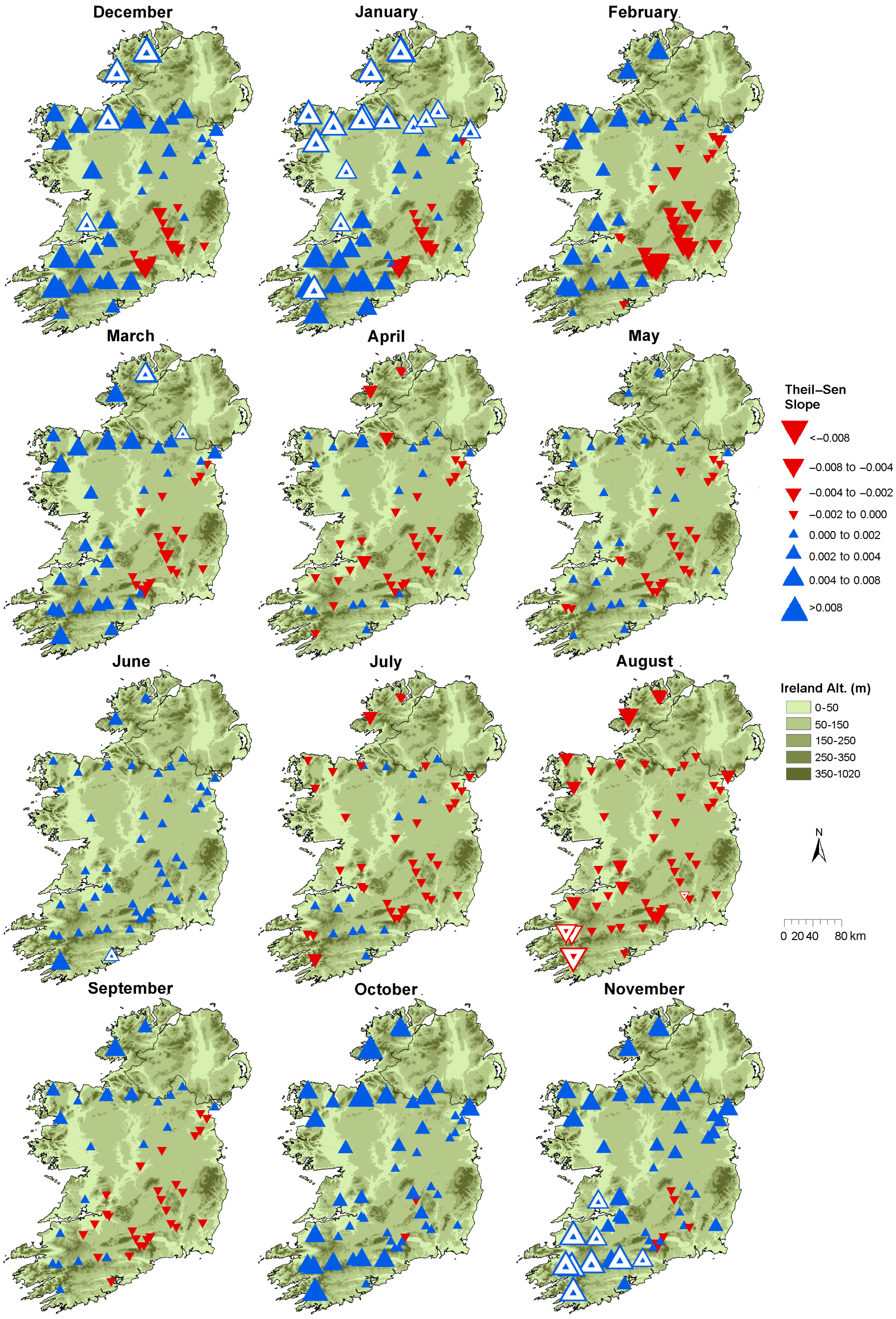

Figure 5. As per Figure 1 but for monthly mean flows.

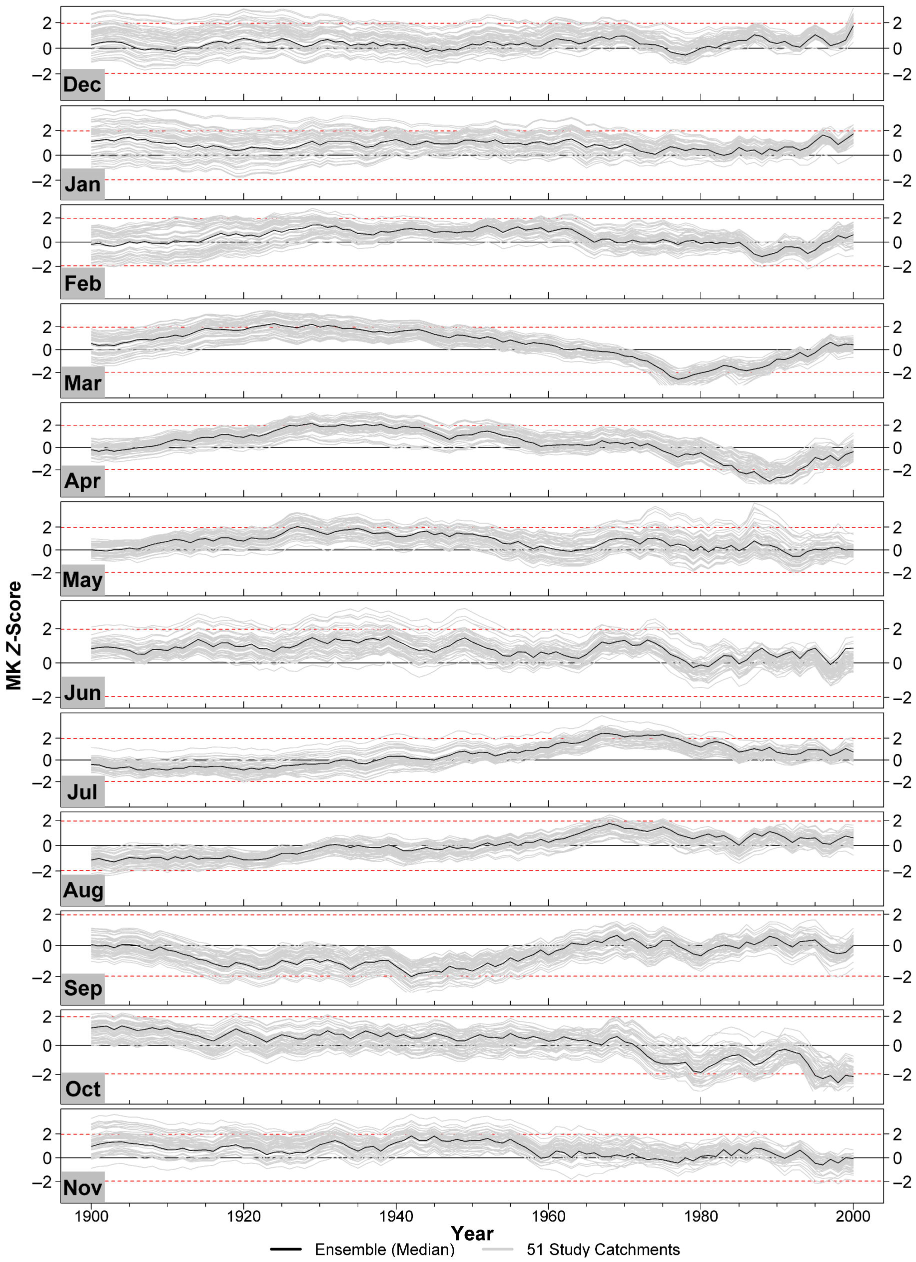

Figure 6. As per Figure 2 but for monthly mean flows.