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Proceedings of the Royal Irish Academy: Archaeology, Culture, History, Literature, Volume 120C, 2020, pp. 365-390 (Article)

Published by Royal Irish Academy

Reconstruction of hydrological drought in Irish catchments (1850–2015)

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[Accepted 24 August 2020. Published 15 October 2020.]

Abstract

While long-term records that extend into the nineteenth century exist for various meteorological variables, river flow records of concurrent length do not exist on the island of Ireland. This work attempts to reconstruct monthly river flows for twelve Irish catchments using quality assured long-term precipitation records for the period 1850–2015. A conceptual rainfall-runoff model calibrated and verified on contemporary flow records is used to reconstruct monthly flows for each catchment. Reconstructions are then analysed to identify periods of drought using a threshold-based drought indicator. Results show that the catchments examined experienced protracted drought episodes with seven major drought rich periods identified in 1887–88, 1891–94, 1902–12, 1933–34, 1944, 1953, 1971–76. The timing and severity of hydrological droughts are consistent with previous work that has examined meteorological drought. This work thus provides a first attempt to reconstruct historical river flows to examine hydrological drought in Ireland. We tease out directions for future work and the opportunities presented for using such reconstructions for drought risk management.

Introduction

In recent years significant progress has been made in developing long-term, quality assured records of precipitation for the island of Ireland that stretch back to the eighteenth and nineteenth centuries. These records have been used to extend understanding of past climate variability and change, and to provide further insight into extremes of floods and droughts. For such hydro-climatic extremes it is particularly beneficial to have long river flow records to examine, among other things, how meteorological extremes propagate into hydrological extremes. However, river flow records of concurrent length do not exist on the island. The commencement of river flow monitoring typically coincided with the onset of arterial drainage in the 1940s/1950s and with the occurrence of drought in the

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doi: https://doi.org/10.3318/PRIAC.2020.120.11

mid-1970s when local authorities became concerned about ensuring adequate supply to meet demand.[1]

In the UK and elsewhere, researchers have used long rainfall records to reconstruct river flows for numerous catchments with the derived series being employed to assess variability and change in flow sequences and to investigate past extremes.[2] Reconstructed flows have also been used to assess the resilience of water company drought plans, noting that severe droughts of the nineteenth century are particularly useful for testing current and future water supply systems and to provide a baseline for climate change adaptation planning.[3] For instance, river flow reconstruction and drought analysis for the Anglian Region, United Kingdom (UK) highlighted periods of prolonged drought in 1854–60 and 1893–1907.[4] While similar work for the Severn Trent water supply region in the UK identified several notable drought periods in the reconstructed flow series in 1887–89, 1892–97, 1921–23, 1933–35, 1975–77 and 1995–98.[5] Each of these studies highlights the utility of long-term reconstructed river flows to water planning and to understanding variability and change in catchment hydrology.

This paper aims, firstly, to use the Island of Ireland Precipitation (IIP) network 1850–2015 to reconstruct monthly river flows for selected catchments and, secondly, to identify hydrological droughts in reconstructed flow records.[6] The paper is organised as follows; first we describe the study catchments and detail the data used in reconstructing river flows. Next, we describe the methods, including the hydrological model employed, its calibration and verification. The drought indicators employed are also described. Following the presentation of

[1] Murphy *et al.*, 'Climate-driven trends in mean and high flows from a network of reference stations in Ireland', *Journal of Hydrological Science*, 58:4 (2013), 755–72, doi: 10.1080/02626667.2013.782407

[2] P.D. Jones, 'Riverflow reconstruction from precipitation data', *Journal of Climatology*, 4 (1984), 171–86; P.D. Jones and D.H. Lister, 'Riverflow reconstructions for 15 catchments over England and Wales and an assessment of hydrological drought since 1865', *International Journal of Climatology*, 18 (1998), 999–1013; Spraggs *et al.*, 'Re-construction of historic drought in the Anglian Region (UK) over the period 1798–2010 and the implications for water resources and drought management', *Journal of Hydrology,* 526 (2015), 231–52, doi: 10.1016/j.jhydrol.2015.01.015; Jones *et al.*, 'Extended riverflow reconstructions for England and Wales, 1865–2002', *International Journal of Climatology*, 26 (2006), 219–31.

[3] Watts *et al.*, 'Testing the resilience of water supply systems to long droughts', *Journal of Hydrology*, 414–5 (2012), 255–67, doi: 10.1016/j.jhydrol.2011.10.038.

[4] Spraggs *et al.*, 'Re-construction of historic drought in the Anglian Region', 231–52.

[5] Lennard *et al.*, 'The application of a drought reconstruction in water resource management', *Hydrology Research*, 47:3 (2015), 646–59, doi:10.2166/nh.2015.090.

[6] Noone *et al.*, 'A 250-year drought catalogue for the island of Ireland (1765–2015)', *International Journal of Climatology*, 37 (2017), 239–54, doi:10.1002/joc.4999.

results we provide some discussion of key insights and future research directions, before drawing conclusions.

Study catchments and data

In reconstructing river flows, suitable catchments were selected from the Irish Reference Network (IRN), which consists of 35 river flow gauges from the Republic, together with 8 stations from Northern Ireland contained in the UK Benchmark Network.[7] Catchments within the IRN have good quality observed data of at least 25 years duration and are relatively free from confounding factors such as urbanisation and river regulation.[8] Based on proximity to rainfall gauges within the IIP, twelve catchments (see Fig 1) were chosen from the IRN, representing, as far as possible, diversity in catchment characteristics (see Table 1). For each catchment daily mean flow data was obtained from the Office of Public Works (OPW) and the Environmental Protection Agency and converted to mean monthly flows.[9] Fig 1 shows the location of the IIP stations in relation to each catchment. Note that Shannon Airport is matched to two catchments (27002, 23002) and for some catchments the rainfall gauge is located outside of the catchment boundary.

Potential Evapotranspiration (PET) observations are limited across Ireland and rely on approaches to estimate approximate losses. The Penman-Monteith method is recommended by the United Nations Food and Agriculture organisation (FAO). It calculates PET by combining both energy and mass balances to model evapotranspiration. However, the Penman-Monteith method is data intensive to calculate and due to a lack of required long-term data for Ireland it is not possible to derive estimates dating back to 1850 using this approach. While there are other methods for calculating PET, most have significant input data requirements such as temperature, wind speed and radiation. More stringent PET calculation methods that only require mean daily/monthly temperature and the latitude of the site are available.[10] However, given the lack of long-term quality assured temperature records for Ireland this study employs constant monthly PET over the period of reconstruction (1850–2015) as a first pass approach. Long-term average PET (LTA_PET) is calculated from Penman-Monteith

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[7] Harrigan *et al*., 'Designation and trend analysis of the updated UK Benchmark Network of river flow stations: the UKBN2 dataset', *Hydrology Research*, 49:2 (2018), 552–67, doi: 10.2166/nh.2017.058; J. Hannaford and G. Buys, 'Trends in seasonal river flow regimes in the UK', *Journal of Hydrology*, 475 (2012), 158–74.

[8] Murphy, *et al*., 'Climate-driven trends in mean and high flows', 755–72.

[9] Office of Public Works, OPW Hydrodata: http://waterlevel.ie/hydro-data/home.html; Environmental Protection Agency 2016, http://www.epa.ie/water/wm/hydrometrics/network/

[10] C.W. Thornthwaite, 'An approach toward a rational classification of climate', *Geographical Review*, 38:1 (1948), 55–94; H.F. Blaney and W.D. Criddle, 'Determining water needs from climatological data', USDA Soil Conservation Service (1950), SOS–TP, USA, pp 8–9.

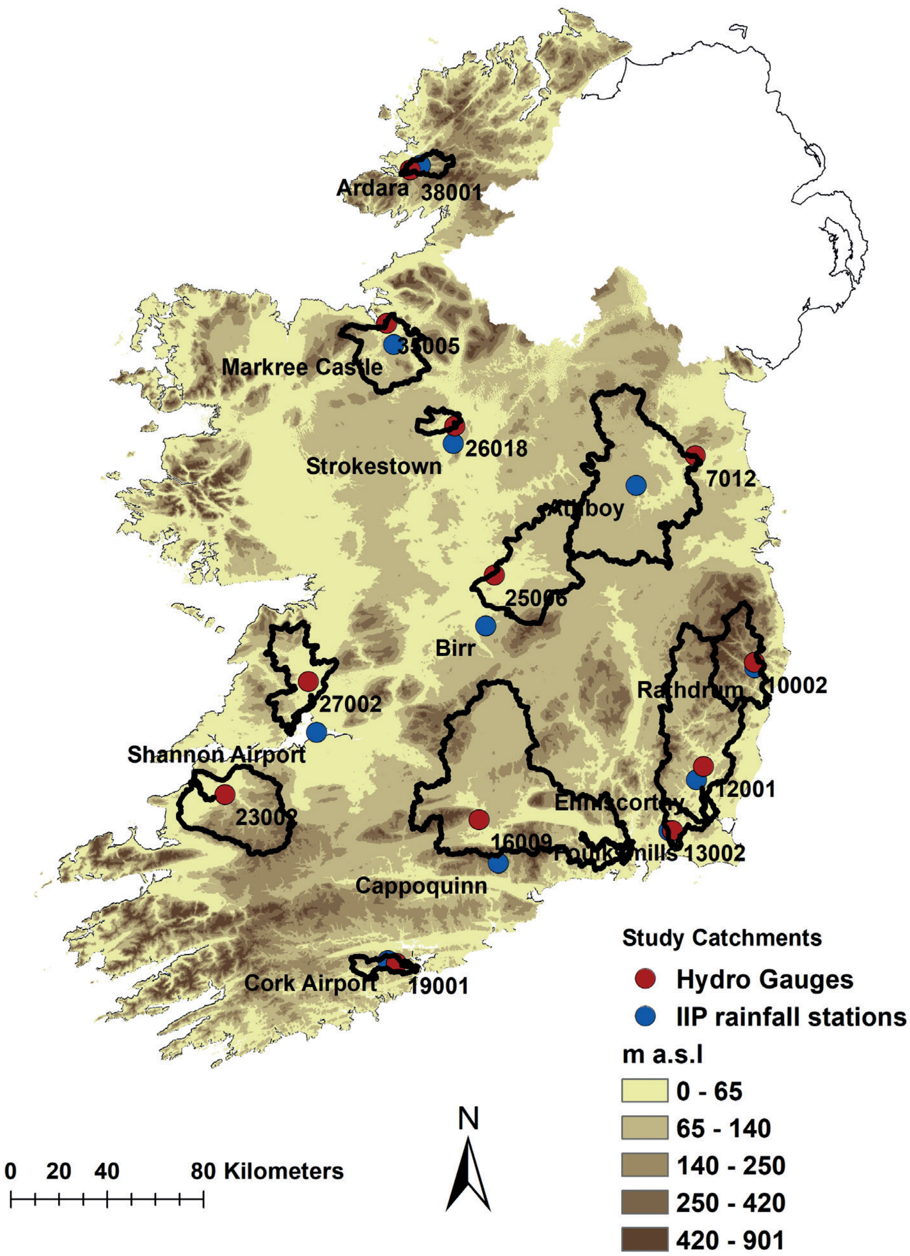

FIG. 1—The location of the 12 study catchments (black outline) with the gauge location (red circle) and gauge number. The blue circles represent each of the Island of Ireland precipitation stations used in reconstructing river flow at each study catchment.

estimates for seven synoptic station records (1955–2015) representing inland and coastal locations (see Fig 2). Firstly, the monthly mean of each station was calculated and then averaged across all stations to obtain the long-term monthly averages employed for reconstruction of flows for each catchment (see Fig 2). The monthly mean PET derived for this study closely corresponds to those

TABLE 1—Details of key catchment characteristics for each of the 12 selected study catchments. The portion of flow (m^3/s^1) during low flow periods that derives from stored sources such as groundwater is defined by the Base Flow Index (BFI). Low BFI indicates a river which has lower storage with flow being runoff dominated. In contrast a higher BFI means that flows have a greater groundwater component.

Catchment Gauge ID												
Key Catchment Descriptors	*7012*	*10002*	*12001*	*13002*	*16009*	*19001*	*23002*	*25006*	*26018*	*27002*	*35005*	*38001*
Catchment Area (km^2)	2460	231	1031	63	1583	106	647	1163	119	564	640	111
Standard-period (1961–1990) average annual potential evapotranspiration (mm)	890	1530	1167	1044	1079	1176	1345	932	1044	1336	1198	1753
Standard-period (1961–1990) average annual rainfall (mm)	504	511	522	537	518	527	514	495	458	533	463	498
BFI soils	0.68	0.54	0.72	0.73	0.63	0.68	0.31	0.71	0.72	0.70	0.61	0.28
Total length of river network above gauge (km)	2146	239	1101	65	1585	108	719	846	99	303	836	264
Main stream length (km)	94	35	89	16	85	24	51	67	25	40	41	26
Slope of main stream (m/km)	0.70	6.90	2.10	4.95	1.00	3.74	4.31	0.75	0.55	1.22	1.15	5.95
Proportion of catchment area mapped as benefitting from arterial drainage schemes	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.28	0.00	0.00	0.00	0.00
Proportion (as a %) of river network length included in arterial drainage schemes	61	00	00	00	00	**0**	00	51	00	00	00	00

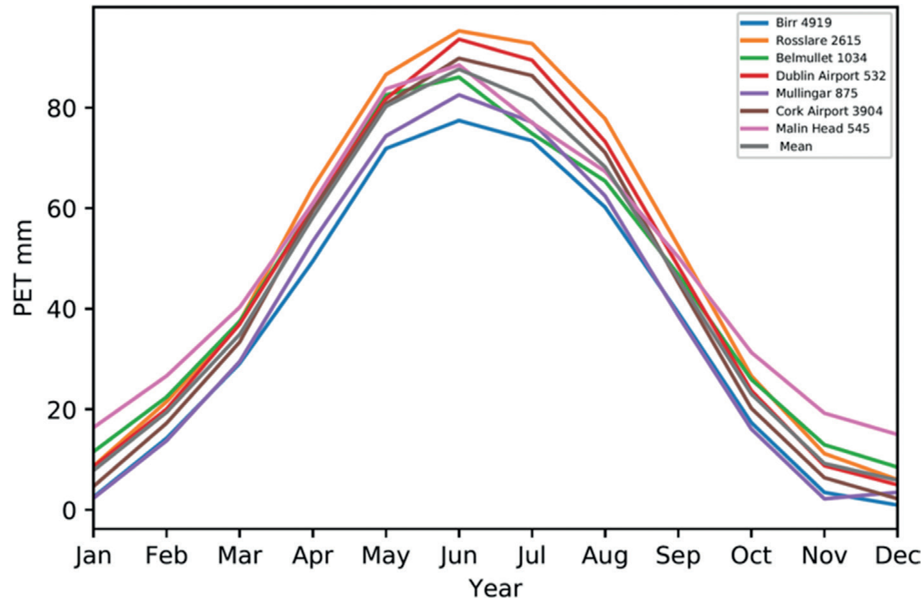

FIG. 2—Long-term monthly mean PET from seven Met Éireann synoptic stations for the period 1955–2015. The black line represents the mean of all seven stations.

values presented in previous work.[11] Other river flow reconstruction work has also used this approach noting that constant evapotranspiration is useful for past reconstructions when only rainfall data are available.[12]

Methods

The hydrological model

The hydrological model HYSIM was chosen to reconstruct monthly river flows for each catchment. HYSIM is a lumped conceptual rainfall runoff model (CRR) that requires monthly/daily precipitation and PET data to simulate river flow.[13] HYSIM has previously been used to model Irish catchments and has also been widely employed in the United Kingdom and elsewhere.[14] HYSIM uses parame-

[11] T. Keane, 'Climate, weather and Irish agriculture', Joint Working Group on Applied Meteorology (AGMET) (1986) (Dublin Mount Salus Press, 1986) available at Meterological Service, Dublin 9.

[12] Jones *et al*., 'Riverflow reconstructions for 15 catchments over England and Wales', 999–1013; Jones *et al*., 'Extended riverflow reconstructions for England and Wales, 1865–2002', 219–31.

[13] R.E. Manley, 'Calibration of hydrological model using optimization technique', *Journal of the Hydraulics Division* (American Society of Civil Engineers), 104 (1978), 189–202.

[14] Rosemary Charlton and Sonja Moore, 'The impact of climate change on water resources in Ireland' in John Sweeney *et al*., *Climate Change, scenarios and impacts for Ireland* (EPA Publication, Johnstown Castle, 2003), 81–102; Murphy *et al*., 'The

ters for hydrology and hydraulics that characterize the catchment rainfall-runoff response. The model represents the catchment as a set of linked storage functions which connect seven hydrological stores (snow storage, interception, upper and lower soil horizon, transitional groundwater, groundwater storage and minor channel storage). HYSIM has two main groups of parameters; physical parameters and process parameters. The physical parameters are measurable properties of the watershed; the process parameters represent the characteristics that are not directly measurable and estimated via calibration against observations. Physically based parameters were set using prior knowledge of soil type, catchment size and observed flow records. Process parameters were calibrated by comparing observed and simulated flows. These include two interflow parameters and two permeability parameters which control movement of water in the soil layers. Fig 3 provides an overview of the model structure.[15]

Before being used for reconstruction, HYSIM was calibrated and validated for each catchment with 75 per cent of available observations used to calibrate the model and the remaining independent data used to verify model performance. For parameters that needed to be estimated by minimising the difference between observed and simulated flows, the Extremes Error of Estimate (EEE) objective function was used to identify optimum parameter values. To assess model performance we employ the Nash Sutcliffe Efficiency (NSE).[16] The NSE is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance. An NSE value of 1 indicates a perfect model fit, whereas a value of 0 indicates that the model performs as well as the mean of the observations. Several other goodness of fit criteria were also calculated across the range of flow conditions, including the Mean Absolute Error (MAE), Percent Bias (PBIAS) and

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reliability of an "off-the-shelf" conceptual rainfall runoff model for use in climate impact assessment: uncertainty quantification using Latin hypercube sampling', *Area*, 38:1 (2006), 65–78; Murphy *et al.*, 'Climate-driven trends in mean and high flows', 755–72; C.G. Pilling and J.A.A. Jones, 'The impact of future climate change on seasonal discharge, hydrological processes and extreme flows in the Upper Wye experimental catchment, mid-Wales', *Hydrological Processes*, 16:6 (2002), 1201–13; Lennard *et al.*, 'The application of a drought reconstruction in water resource management', 646–59; R. Remesan and I.P. Holman, 'Effect of baseline meteorological data selection on hydrological modelling of climate change scenarios', *Journal of Hydrology*, 528 (2015), 631–42; B.S. Soundharajan, A.J. Adeloye and R. Remesan, 'Evaluating the variability in surface water reservoir planning characteristics during climate change impacts assessment', *Journal of Hydrology*, 538 (2016), 625–39.

[15] Manley, 'Calibration of hydrological model using optimization technique', 189–202; Murphy *et al.*, 'Climate-driven trends in mean and high flows from a network of reference stations in Ireland', 755–72.

[16] J.E. Nash and J.V. Sutcliffe, 'River flow forecasting through conceptual models part I—a discussion of principles', *Journal of Hydrology*, 10:3 (1970), 282–90. doi:10.1016/0022-1694(70)90255-6.

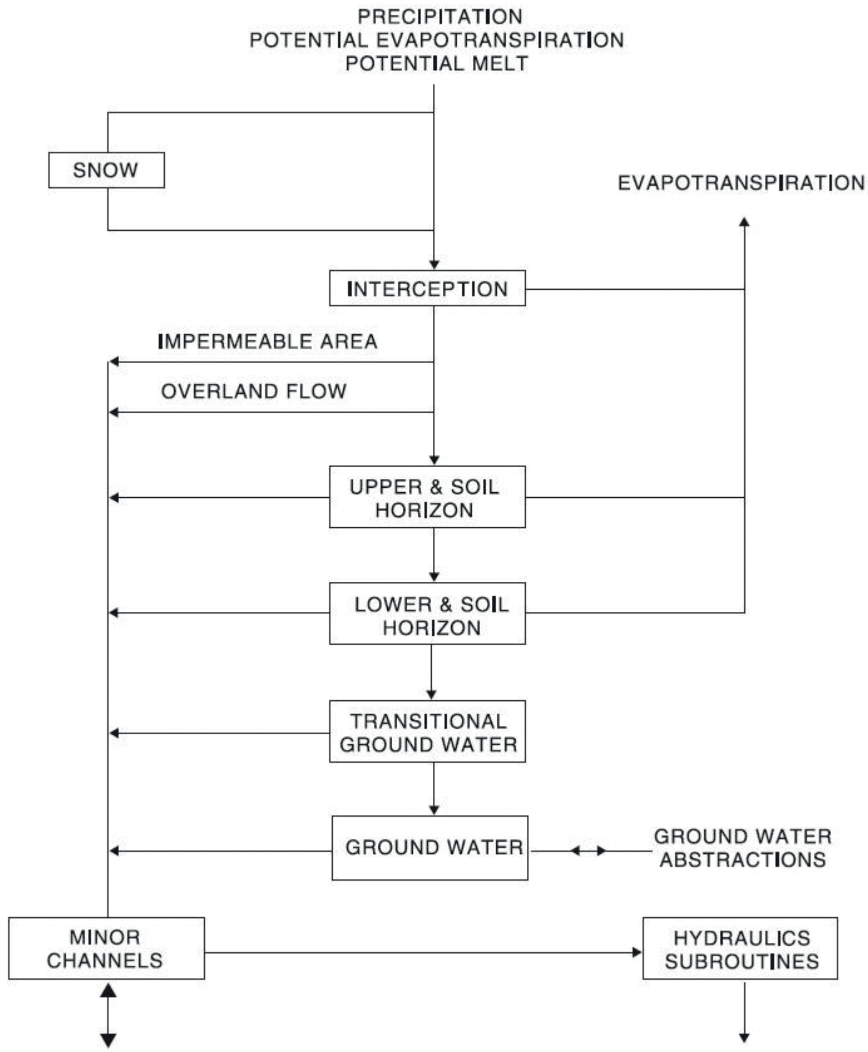

Fig. 3—HYSIM model structure.

coefficient of determination (R^2).[17] Model performance was evaluated for winter (ONDJFM) and summer (AMJJAS) half years.

Drought indicator

There are a wide variety of drought metrics for assessing various types of drought. A commonly used method for drought identification in river flows is

[17] Remesan and Holman, 'Effect of baseline meteorological data selection on hydrological modelling of climate change scenarios', 631–42; M.K. Muleta 'Model performance sensitivity to objective function during automated calibrations', *Journal of Hydrologic Engineering*, 17:6 (2011), 756–67.

the threshold level approach where the start and end of a drought is defined by a period when flow is below a certain threshold.[18] The Q95 (the 5th percentile flow) relates to the flow rate equalled or exceeded for 95 percent of the flow record and is an important low flow indicator. Q95 is widely used for monitoring water quality and supply and is thus adopted as a flow threshold here to identify drought events. To implement this procedure, Q95 thresholds were produced by first calculating the 5th percentile for each month (January, February, March etc.) of reconstructed flow from 1850–2015 at each catchment. Next the reconstructed monthly flow was deducted from the 5th percentile value to give the Q95 deficit or surplus for that month at each catchment.[19] The identification of thresholds for each month allows multi-season droughts to be identified. The start of a drought is defined when the reconstructed monthly flow drops below the long term Q95 threshold value for that month, resulting in a Q95 deficit and ends when the reconstructed monthly flow exceeds the Q95 threshold for that month (i.e. returns to surplus relative to Q95 threshold). The drought duration is calculated by summing the number of months from the first month where the simulated flow drops below the Q95 threshold value and ends at the month where the Q95 threshold value is exceeded (note that the first month is inclusive in the drought duration but the end month noted is not inclusive in the drought duration).

Results

Model calibration and validation

The annual model calibration and validation results are presented in Table 2. Overall HYSIM performs well during calibration with NSE values for monthly flows ranging from 0.76 at 12001-Slaney (Co. Wexford) to 0.91 at 38001-Owenea (county Donegal). NSE values for verification range from 0.67 at 12001-Slaney to 0.92 at 26018-Owenure (county Roscommon). The results indicate that the model tends to underestimate flows with PBIAS ranging from -0.6% to -11.2%. The largest underestimation for 23002-Feale (county Kerry) is likely due to the precipitation gauge being located outside the catchment area. For most catchments model performance during verification is in line with calibration results, indicating a robust model. The largest reduction in performance (see Table 2) during verification is for 16009-Suir (county Tipperary) where again the rainfall station may not be adequately representative of the catchment. Fig 4 compares scatter plots of simulated and observed flows for the summer half year during the verification period for each catchment. Despite a slightly weaker performance at

[18] Hisdal *et al*., 'Have streamflow droughts in Europe become more severe or frequent?', *International Journal of Climatology*, 21:3 (2001), 317–33; Fleig *et al*., 'A global evaluation of streamflow drought characteristics', *Hydrology and Earth System Sciences*, 10:4 (2006), 535–52.
[19] Watts *et al*., 'Climate change and water in the UK–past changes and future prospects', *Progress in Physical Geography*, 39:1 (2015), 6–28.

TABLE 2—Annual model calibration (Cal) and validation (Val) performance at each catchment.

Catchment	*Catchment Area (km²)*	*Model*	*Period*	*NSE*	*R^2*	*MAE m^3/s^1*	*PBIAS m^3/s^1*
7012-Boyne at Slane Castle, Co. Meath	2460	Cal	1942–1960	0.88	0.89	6.76	3.1
		Val	1961–1970	0.90	0.93	5.43	0.6
10002-Avonmore at Laragh, Co. Wicklow	231	Cal	1953–1964	0.77	0.93	2.13	-1.3
		Val	1965–1970	0.88	0.86	2.13	-6
12001-Slaney at Scarrawalsh, Co. Wexford	1031	Cal	1990–2010	0.76	0.74	5.61	-2.6
		Val	1970–1980	0.67	0.77	5.12	5.6
13002-Corock at Foulksmill, Co. Wexford	63	Cal	1977–1982	0.88	0.92	0.21	-1.1
		Val	1983–1985	0.83	0.83	0.20	-3.4
16009-Suir at Cahir Park, Co. Tipperary	1583	Cal	1953–1980	0.84	0.84	6.16	-0.6
		Val	1991–2000	0.68	0.77	9.12	-12.1
19001-Owenboy at Ballea, Co. Cork	106	Cal	1974–1990	0.84	0.84	0.64	-1.9
		Val	1991–2010	0.83	0.88	0.57	-1.7
23002-Feale at Listowel, Co. Kerry	647	Cal	1974–1990	0.84	0.87	4.86	-11.2
		Val	1991–2010	0.87	0.88	4.61	-2.41
25006-Brosna at Ferbane, Co. Offaly	1163	Cal	1952–1960	0.89	0.85	3.58	-1.7
		Val	1961–1970	0.77	0.84	4.09	-5.4
26018-Owenure at Bellavahan, Co. Roscommon	119	Cal	1992–2000	0.89	0.87	0.59	1.3
		Val	1976–1980	0.92	0.93	0.39	0.8
27002-Fergus at Ballycorey, Co. Clare	564	Cal	1974–1985	0.88	0.88	2.18	6.4
		Val	1986–1990	0.79	0.81	2.44	-0.8
35005-Ballysadare at Ballysadare, Co. Sligo	640	Cal	1947–1960	0.84	0.84	2.84	-0.7
		Val	2002–2008	0.76	0.82	3.21	-4.6
38001-Owenea at Clonconwall Ford, Co. Donegal	111	Cal	1994–2000	0.91	0.95	0.88	1.7
		Val	2001–2003	0.89	0.91	0.78	-0.7

a couple of catchments (16009, 12001), overall models show an acceptable level of performance during both calibration and verification. The derived models for each catchment were then used to reconstruct monthly river flows at all twelve study catchments for the period 1850–2015. Fig 5 and Fig 6 show the reconstructed flows for the entire reconstructed period for winter and summer half years with observed flows overlaid for each study catchment.

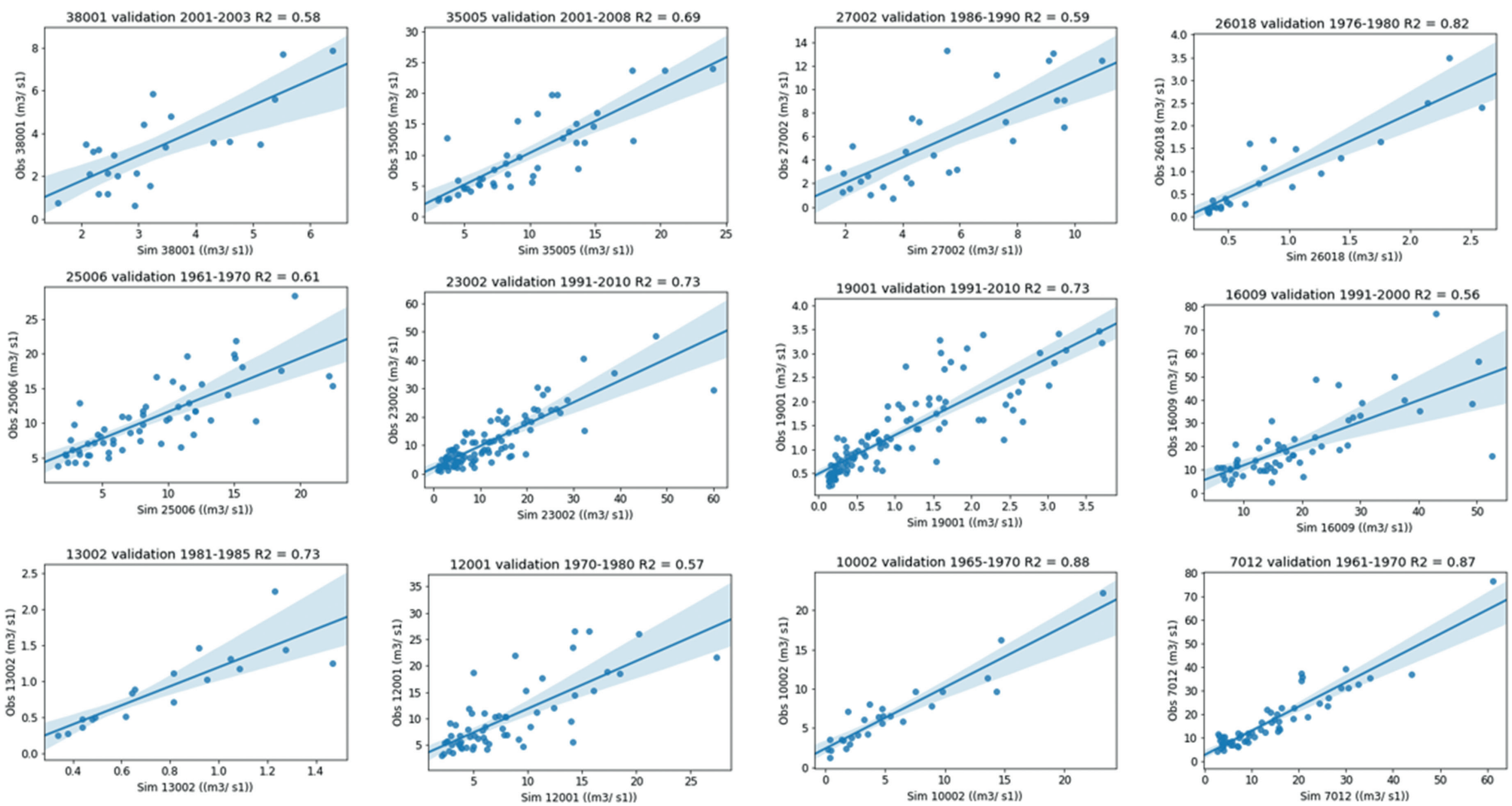

FIG. 4—Scatter plots of simulated and observed summer (April, May, June, July, August and September) half year flows (m^3/s^1) for the verification period indicating the R^2 value at each study catchment between observed (Obs) and simulated (Sim) flows. The solid line indicates the best fit.

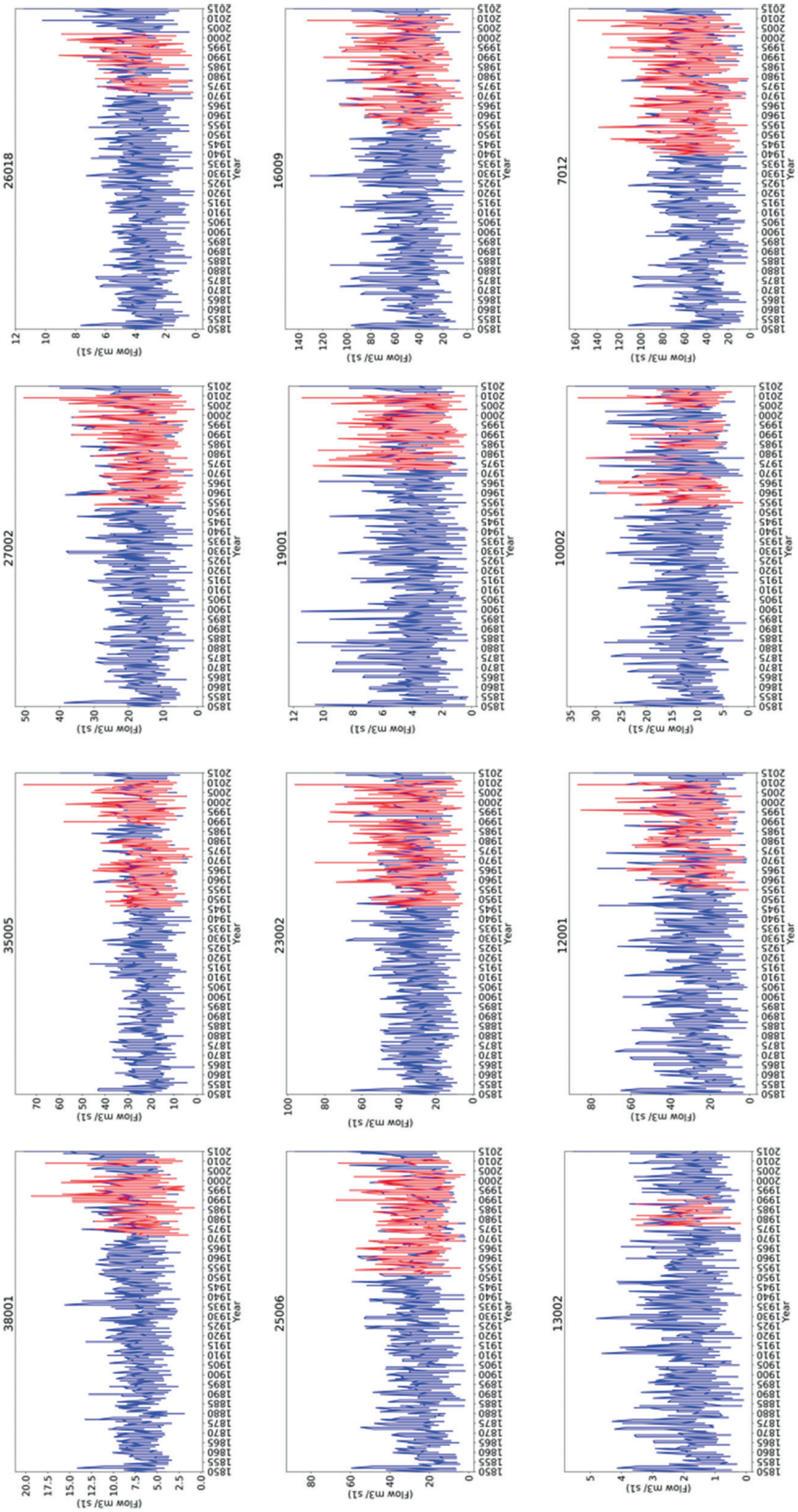

FIG. 5—Reconstructed (1850–2015) (blue line) and observed (red line) flows (m^3/s^1) for the winter (October, November, December, January, February and March) half year for each of the twelve catchments.

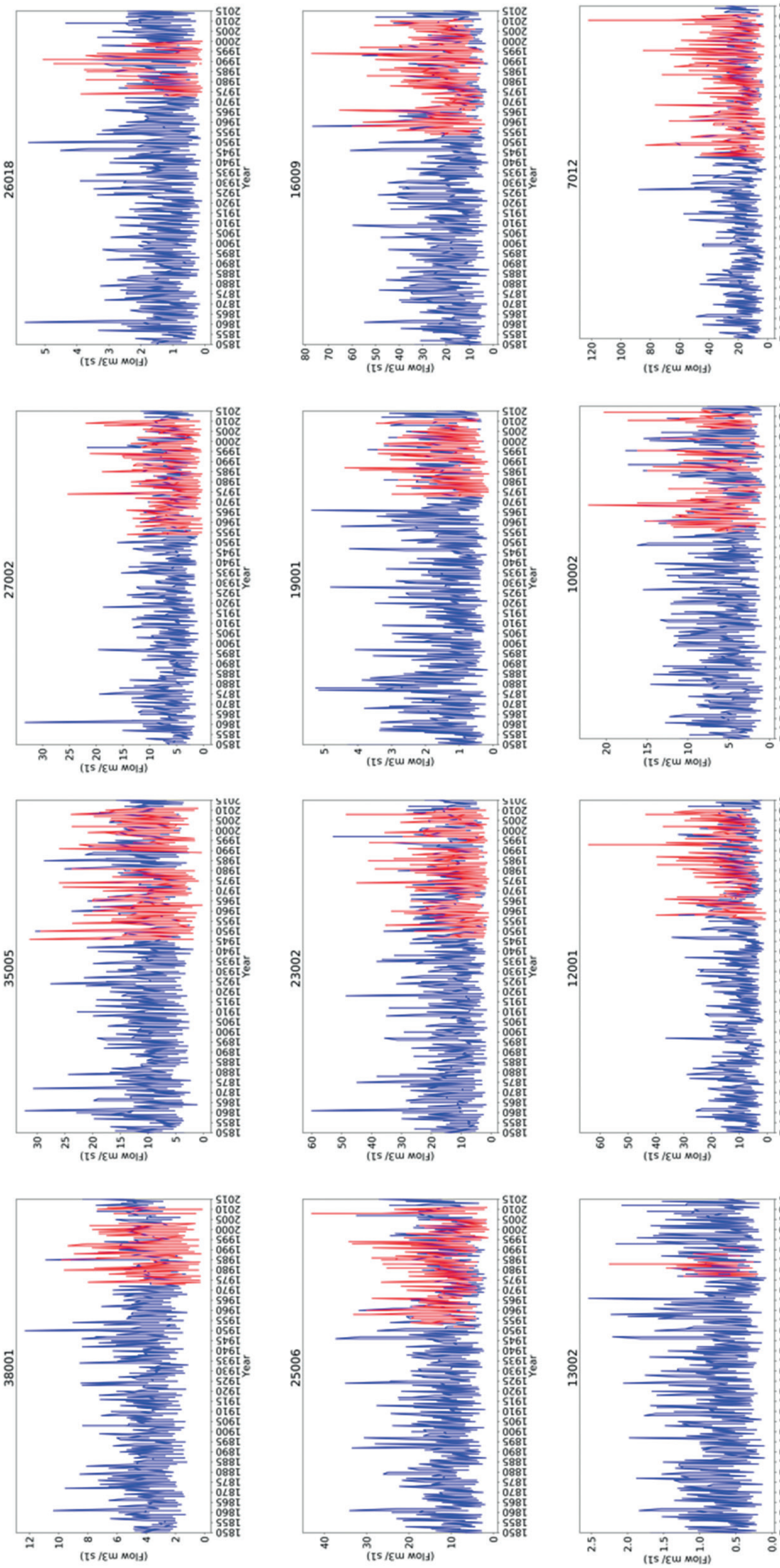

FIG. 6—Same as Fig 5 but for summer (April, May, June, July, August and September) half year flows (m^3/s^1).

Q95 Threshold drought results

For the purpose of the drought analysis the following section will focus upon presenting detailed results and analysis for a selection of six study catchments. These have been chosen based on their location to provide good geographical coverage across Ireland and the selection includes catchments of varying size and characteristics. The six selected catchments are as follows: 38001-Owenea at Clonconwall Ford, County Donegal (North-West); 26018-Owenure at Bellavahan, County Roscommon (Mid-West); 7012-Boyne at Slane Castle, County Meath (East); 10002-Avonmore at Laragh, County Wicklow (East); 13002-Corock at Foulksmills, County Wexford (South-East), and 19001-Owenboy at Ballea, County Cork (South) (Fig. 1). We present the top ten ranked Q95 threshold deficit droughts based on drought duration for all twelve catchments in Table 6 of the Appendix of this paper.

Table 3 presents the top ten ranked droughts based on duration for catchments 38001 (North-West) and 26018 (Mid-West). Table 3 also shows the drought period start and end dates, together with the duration in months, the mean flow deficit in m^3/s^1 over the drought duration and the accumulated or total flow deficit in m^3/s^1 over the drought duration.

The results show that catchment 38001-Owenea, County Donegal (North-West) experienced the longest drought from January 1953 to the start of June 1953 with a duration of 5-months below the Q95 threshold. Other noteworthy droughts, each lasting four months, were experienced at 38001-Owenea during 1929, 1933, 1975 and 1984. The largest accumulated deficit at 38001-Owenea (-3.99 m^3/s^1) was experienced from September 1933 to January 1934. The results for 38001-Owenea also show a 3-month drought from March 1875 to the start of June 1875. There were also four two-month droughts with two occurring in 1855 and one each in 1856 and 1873.

The results shown in Table 3 for 26018-Owenure, County Roscommon, demonstrate that the longest drought, which was of seven months duration, occurred between May 1921 and December 1921. The largest accumulated deficit (-1.84 m^3/s^1) was also experienced during the drought of 1953. Droughts lasting six months occurred from April 1893 to the beginning of October 1893 and then again from February 1953 to the start of August 1953. There were three more four-month long droughts during 1891, 1941 and 1944. A further four droughts lasting three-months were identified during 1870, 1879 and 1887.

Table 4 shows the top ten drought events, ranked by duration, for the catchments 7012-Boyne, county Meath and 10002-Avonmore, county Wicklow both in the eastern region of the island. The longest drought at catchment 7012-Boyne occurred from January 1891 to September 1891 with flows persisting below simulated monthly Q95 threshold for eight months. The largest accumulated deficit (-51.82 m^3/s^1) also occurred during this drought period. Several droughts of 7-months duration were experienced in 1893–94, 1934, and again during 1953. In addition, droughts lasting four months were experienced during 1857–58,

TABLE 3—Top ten ranked Q95 drought events based on duration for catchments 38001 and 26018. The drought deficits are negative values derived from the Q95 (5^{th} percentile) threshold across all months. A drought start period is defined when the reconstructed monthly flow value falls below the Q95 threshold and drought ends when the monthly flow value returns above the Q95 threshold. Table shows the drought period start and end dates together with the duration in months, mean low-flow deficit (m^3/s^1) and accumulated deficit (m^3/s^1 over the drought period. Note that the first month is inclusive in the drought duration but the end month noted is not inclusive in the drought duration.

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m^3/s^1 deficit*	*Accumulated Q95 m^3/s^1 Deficit*	*Drought duration months*
38001 Owenea North-west BFI (0.28)	1	1953-01	1953-06	-0.20	-0.99	5
	2	1929-03	1929-07	-0.42	-1.66	4
	3	1933-09	1934-01	-1.00	-3.99	4
	4	1975-06	1975-10	-0.23	-0.94	4
	5	1984-06	1984-10	-0.51	-2.06	4
	6	1875-03	1875-06	-0.15	-0.45	3
	7	1855-01	1855-03	-0.28	-0.56	2
	8	1855-11	1856-01	-0.17	-0.35	2
	9	1856-03	1856-05	-0.06	-0.12	2
	10	1873-12	1874-02	-0.14	-0.28	2
26018 Owenure Mid-west BFI (0.72)	1	1921-05	1921-12	-0.26	-1.84	7
	2	1893-04	1893-10	-0.02	-0.12	6
	3	1953-02	1953-08	-0.22	-1.31	6
	4	1891-02	1891-06	-0.32	-1.27	4
	5	1941-07	1941-11	-0.03	-0.13	4
	6	1944-03	1944-07	-0.14	-0.55	4
	7	1858-01	1858-04	-0.03	-0.08	3
	8	1870-07	1870-10	-0.03	-0.08	3
	9	1879-11	1880-02	-0.33	-0.98	3
	10	1887-06	1887-09	-0.03	-0.08	3

1887, 1892 and 1933–34. Table 4 shows that catchment 10002-Avonmore experienced severe drought commencing at the start of April 1893 and lasting eight months until the beginning of December 1893. The same drought period produced the largest accumulated deficit (-6.18 m^3/s^1). There were three four-month long droughts during the years 1874, 1953 and 1976, several two-month droughts during in 1884, 1906–07, 1938, 1944 and 1978 and a two-month drought in 1854.

Table 5 shows the top ten Q95 drought events, ranked by duration, for catchments 13002-Corock at Foulksmills, county Wexford (South-East) and 19001-Owenboy at Ballea, county Cork (South). Results at catchment

TABLE 4—Same as Table 3 but for catchment 7012 and 10002.

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
7012 Boyne East BFI (0.68)	1	1891-01	1891-09	-6.48	-51.82	8
	2	1893-06	1894-01	-3.31	-23.19	7
	3	1934-02	1934-09	-6.12	-42.82	7
	4	1953-02	1953-09	-2.22	-15.56	7
	5	1857-12	1858-04	-1.69	-6.75	4
	6	1887-07	1887-11	-0.78	-3.12	4
	7	1892-03	1892-07	-0.93	-3.72	4
	8	1933-09	1934-01	-3.36	-13.45	4
	9	1870-07	1870-10	-0.62	-1.87	3
	10	1895-05	1895-08	-1.29	-3.88	3
10002 Avonmore East BFI (0.54)	1	1893-04	1893-12	-0.77	-6.18	8
	2	1874-04	1874-08	-0.41	-1.63	4
	3	1953-01	1953-05	-0.53	-2.13	4
	4	1976-05	1976-09	-0.38	-1.53	4
	5	1884-10	1885-01	-1.11	-3.34	3
	6	1906-12	1907-03	-1.17	-3.51	3
	7	1938-04	1938-07	-0.57	-1.70	3
	8	1944-06	1944-09	-0.06	-0.19	3
	9	1978-09	1978-12	-0.92	-2.77	3
	10	1854-03	1854-05	-0.13	-0.26	2

13002-Corock for December 1975 to the start of October 1976 indicate that the longest drought persisted for 10 months. The largest Q95 accumulated deficit (-1.98 m^3/s^1) also occurred during the drought of 1975–76. The drought from June 1887 to January 1888 was second longest, lasting 7 months. During 1891, 1893 and 1944 catchment 13002-Corock experienced a drought lasting 6 months.

In addition, between May 1905 and December 1906 drought persisted for 5 months and during May to October 1975 drought also lasted 5 months. Drought persisted for 4 months during 1888 and 1953 at catchment 13002-Corock and for 3 months during late 1854–55. For catchment 19001-Owenboy (Table 5) the longest drought started in February 1944 and persisted until September 1944. The second longest drought was experienced during 1887 from May to November and lasted 6 months. There were two 5-month long droughts during 1906–07 and in 1975. The results show that 19001-Owenboy experienced periods of drought with flows consistently below simulated Q95 for 6-months in 1854–55, 1874, 1891, 1921 and 1953, with the largest accumulated deficit (-2.55 m^3/s^1) occurring during the 1854–55 drought.

TABLE 5—Same as Table 4 but for catchment 13002 and 19001

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
13002 Corock South-east BFI (0.73)	1	1975-12	1976-10	-0.20	-1.98	10
	2	1887-06	1888-01	-0.07	-0.51	7
	3	1891-02	1891-08	-0.12	-0.73	6
	4	1893-06	1893-12	-0.04	-0.27	6
	5	1944-03	1944-09	-0.02	-0.10	6
	6	1906-12	1907-05	-0.22	-1.08	5
	7	1975-05	1975-10	-0.03	-0.14	5
	8	1888-02	1888-06	-0.12	-0.49	4
	9	1953-01	1953-05	-0.05	-0.21	4
	10	1854-12	1855-03	-0.17	-0.52	3
19001 Owenboy South BFI (0.68)	1	1944-02	1944-09	-0.16	-1.13	7
	2	1887-05	1887-11	-0.06	-0.36	6
	3	1906-12	1907-05	-0.51	-2.55	5
	4	1975-04	1975-09	-0.09	-0.45	5
	5	1854-03	1854-07	-0.05	-0.21	4
	6	1854-11	1855-03	-0.85	-3.39	4
	7	1874-06	1874-10	-0.06	-0.25	4
	8	1891-02	1891-06	-0.20	-0.81	4
	9	1921-06	1921-10	-0.05	-0.21	4
	10	1953-01	1953-05	-0.32	-1.29	4

Discussion

Key findings

This paper has reconstructed monthly river flows for twelve Irish catchments for the period 1850–2015. These catchments provide good spatial coverage and incorporate diverse catchment characteristics. Quality assured, long-term monthly precipitation records and long-term average PET data were used to reconstruct historical river flows for each catchment. Using the threshold method to identify droughts as periods during which flows fall below the long-term simulated monthly Q95 threshold, we identify notable drought events in each catchment. The results at six selected catchments are presented and discussed in detail, while the top 10 droughts (by duration) for all catchments are provided in Table 6 in the Appendix.

The results show that the most noteworthy drought years based on the drought indicator used were 1887–88, 1891–94, 1902–12, 1933–34, 1944, 1953, 1971–76. Previous work has compiled a 250-year historical meteorological drought catalogue for Ireland using the Standardised Precipitation Index (SPI) applied to 25 precipitation series contained in the Island of Ireland precipitation network (1850–2015) and a reconstructed precipitation series from 1765 representing the island of Ireland. Although, the previous study used a different drought indicator and concerned only meteorological drought, the periods highlighted as drought rich for the period 1850–2015 are generally consistent across both studies.[20]

Moreover, the identified drought years in this study show good coherence with studies conducted in the United Kingdom, which highlight the large spatial extent of some of the historical droughts. Drought rich periods are noted for many rivers in England and Wales during 1887–89, 1892–97, 1933–34 and 1975–76, which closely correspond to droughts identified in this study.[21] Our results also show that these Irish catchments have experienced a relatively drought sparse period since the 1980s up to 2015.

Limitations of this study and opportunities for future work

This work provides a first pass reconstruction of long-term river flows and as such there is much scope for improving this analysis. Conceptual Rainfall Runoff (CRR) models are a simplified representation of a complex catchment system and the selection of model structure is usually a subjective decision made by the modeller.[22] Some model parameters cannot be measured and need to be estimated; they are also assumed to be constant over time. It is widely acknowledged that most uncertainty in CRR models comes from model structures and parameter selection.[23] Equifinality exists where many model parameter combinations can generate a satisfactory simulation. [24] In addition, only one CRR model was employed in

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[20] Noone *et al*., 'A 250-year drought catalogue for the island of Ireland (1765–2015)', 239–54.

[21] Lennard *et al*., 'The application of a drought reconstruction in water resource management', 646–59; Spraggs, 'Re-construction of historic drought in the Anglian Region (UK) over the period 1798–2010 and the implications for water resources and drought management', 231–52; T. Marsh, G. Cole and R. Wilby, 'Major droughts in England and Wales, 1800–2006', *Weather*, 62 (2007), 87–93; Todd *et al*., 'Severity, duration and frequency of drought in SE England from 1697 to 2011', *Climate Change*, 121:4 (2013), 673–87. doi:10.1007/s10584-013-0970-6.

[22] Murphy *et al*., 'The reliability of an "off-the-shelf" conceptual rainfall runoff model for use in climate impact assessment: uncertainty quantification using Latin hypercube sampling', 65-78; Wagener *et al*., 'Towards reduced uncertainty in conceptual rainfall-runoff modelling: Dynamic identifiability analysis', *Hydrological Processes*, 17:2 (2003), 455–76.

[23] Murphy *et al*., 'The reliability of an "off-the-shelf" conceptual rainfall runoff model for use in climate impact assessment: uncertainty quantification using Latin hypercube sampling', 65–78.

[24] Wagener *et al*., 'Towards reduced uncertainty in conceptual rainfall-runoff modelling: Dynamic identifiability analysis', 455–76; R. Wilby, 'Uncertainty in water resource model parameters used for climate change impact assessment', *Hydrological Processes*, 19 (2005), 3201–19.

this study; future work could use other CRR models and modelling techniques to explore additional model structures in reconstructing Irish river flow.

Overall good model performance was maintained even when this study was required to use rainfall stations outside of catchment boundaries. However, increasing the number of long-term rainfall stations available as part of the IIP would also increase confidence in reconstructed flows. Furthermore, gridded reconstructions of precipitation and temperature exist for Europe over the period 1766 to present and their potential for reconstructing river flows should be investigated.[25] A greater spatial distribution of rainfall data would also facilitate an increased sample of catchments for reconstruction so that a more in depth understanding of the role of catchment characteristics in drought propagation could be explored. Here longer droughts seem to be associated with catchments with higher groundwater contribution to river flows; our sample size is too small to draw robust results.

Work is ongoing at the Irish Climate Analysis and Research Units (ICARUS) at Maynooth University in collaboration with Met Éireann to digitise and transcribe daily precipitation records dating back to the nineteenth century in Ireland.[26] These daily precipitation records could be used to expand the IIP monthly network. These daily precipitation records could also be employed to run catchment rainfall runoff models to produce daily reconstructed flow records back to the late nineteenth century to examine variability and change in hydrological extremes more closely.

Another limitation of this study is the lack of long-term temperature records for Ireland. There are monthly temperature records available at Markree (West), Birr (Midlands) and Dublin (East) with records dating back to 1830 but these have not yet been homogenised or quality assured. There are further long-term hard copy daily temperature records in the Met Éireann archives. Researchers at the National University of Galway are in the process of digitising and transcribing these records and they will apply homogenisation methods for data quality assurance.[27] Given that PET is temperature driven, the long-term average PET data used in this study does not take any increase in temperature over the period into account. Future work could address this limitation. Furthermore, the influence of snow during colder periods can cause modelling output errors.[28] In addressing this

[25] Pauling *et al*., 'Five hundred years of gridded high-resolution precipitation reconstructions over Europe and the connection to large-scale circulation', *Climate Dynamics*, 26 (2006), 387–405.

[26] Ryan *et al*., 'Ireland's pre-1940 rainfall records', *Geoscience Data Journal*, (2020), forthcoming; Ryan *et al*., 'Integrating data rescue into the classroom', *Bulletin of the American Meteorological Society*, 99:9 (2018), 1757–64.

[27] C. Mateus, A. Potito and M. Curley, 'Reconstruction of a long-term historical daily maximum and minimum air temperature network dataset for Ireland (1831–1968)', *Geoscience Data Journal* (2020), 1–14. https://doi.org/10.1002/gdj3.92.

[28] P.D. Jones, 'Riverflow reconstruction from precipitation data', *Journal of Climatology*, 4 (1984), 171–86.

issue future work could incorporate the long-term temperature records into the CRR models to simulate snow and snow melt. Finally, as with any approach to river flow reconstruction we assume consistent land-use and channel geomorphology over the period of reconstruction. These assumptions are unlikely to hold, but nonetheless assessment of reconstructed flows for catchments in their contemporary state is a useful endeavour for informing variability and change.

Implications

The 1995 drought is often used as the event of record from a water management perspective.[29] Yet the 1995 drought does not feature in the top ten ranked drought events based on duration, as more severe droughts have been identified during the nineteenth century. The past 40 years appear to have been a relatively drought poor period in hydrological terms. However, during 2018 Ireland experienced a very dry summer with the combined three-month rainfall totals (May, June and July) at Phoenix Park, Dublin the lowest on record.[30] The study used the Standardised Precipitation and Evapotranspiration Index (SPEI) to calculate the three-month accumulated deficit (SPEI-3).[31] The value for SPEI-3 for May to July 2018 was -2.70, the most extreme value on record at Phoenix Park. The drought of 2018 caused water supply issues with restrictions in place for most of the summer. As the situation worsened, the utility company Irish Water warned in early August that Dublin would run out of water supply within 70 days if drought conditions continued.[32] During 2020 the east and Dublin region experienced the lowest spring (March, April and May (MAM)) rainfall totals since records began in 1837 at Phoenix Park. In addition, the combined rainfall totals for April to May ranked as the driest consecutive two months ever recorded at Phoenix Park.[33] In the past three years Ireland, and especially the densely populated regions across the east and Dublin, have experienced two extreme three-month drought periods due to rainfall deficits. These recent droughts

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[29] M. MacCarthaigh, *An assessment of the 1995 drought including a comparison with other known drought years* (Environmental Protection Agency, Wexford, 1996), 70.
[30] S. Noone, C. Murphy and P. Thorne, 'The ongoing flash drought is (probably) the most intense experienced at Phoenix Park since records began', Irish Climate Analysis and Research Units, Maynooth University, Ireland, 2018), http://icarus-maynooth.blogspot.com/2018/08/the-ongoing-flash-drought-is-probably.html (accessed 28/05/2019).
[31] Beguería *et al*., 'Standardized precipitation evapotranspiration index (SPEI) revisited: parameter fitting, evapotranspiration models, tools, datasets and drought monitoring', *International Journal of Climatology*, 34 (2014), 3001–23. doi:10.1002/joc.3887
[32] *Irish Times*, 7 Aug. 2018: https://www.irishtimes.com/news/ireland/irish-news/dublin-could-run-out-of-water-in-70-days-irish-water-warns-1.3589156 (accessed 28/05/2019).
[33] S. Noone and C. Murphy '2020: the driest spring in Dublin since records began in 1837', Irish Climate Analysis and Research Units, Maynooth University, Ireland, 2020. http://icarus-maynooth.blogspot.com/2020/05/2020-driest-spring-in-dublin-since.html (accessed 29/07/2020).

caused severe water supply issues but are significantly shorter than the historical droughts identified in recent research.[34]

The results of this study indicate that catchments located in the south, midlands, east and south-east have been prone to long duration hydrological droughts in the past. For example, flows persisted below monthly Q95 for a period of ten months at 13002-Corock in the south-east from the start of December 1975 to beginning of October 1976. In addition, drought at 7012-Boyne in the east lasted for eight months during 1891. Therefore, if future droughts like those experienced in the past reoccur, they may have serious implications for water supply and water quality in vulnerable regions.

Conclusion

Reconstructed monthly flows for twelve catchments were derived and analysed to identify historical hydrological droughts. The results identified seven major hydrological drought rich periods which affected most study catchments. While the methods available to reconstruct flows are subject to limitations, the consistency of the timing of these drought periods with those identified in previous work, both in Ireland and the UK, builds confidence in the subsequent results, which provide new insights into historical river flow and droughts in Ireland. This work also provides a basis from which future research can build, to expand the spatial and temporal context of river flow reconstructions and to develop fuller estimates of the uncertainties associated with reconstructions and hydrological droughts.

[34] Noone *et al.*, 'A 250-year drought catalogue for the island of Ireland (1765–2015)', 239–54.

Appendix supplementary material

Appendix tables present the top ten ranked Q95 drought events based on duration for all catchments. The drought deficits are negative values derived from the Q95 (5th percentile) threshold across all months. A drought start period is defined when the reconstructed monthly flow value falls below the Q95 threshold and drought ends when the monthly flow value returns above the Q95 threshold. The tables show the drought period start and end dates together with the duration in months, mean low-flow deficit (*m^3/s^1*) and accumulated deficit (*m^3/s^1*) over the drought period. Note that the first month is inclusive in the drought duration but the end month noted is not inclusive in the drought duration.

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m^3/s^1 deficit*	*Accumulated Q95 m^3/s^1 Deficit*	*Drought duration months*
38001 Northwest BFI (0.28)	1	1953-01	1953-06	-0.20	-0.99	5
	2	1929-03	1929-07	-0.42	-1.66	4
	3	1933-09	1934-01	-1.00	-3.99	4
	4	1975-06	1975-10	-0.23	-0.94	4
	5	1984-06	1984-10	-0.51	-2.06	4
	6	1875-03	1875-06	-0.15	-0.45	3
	7	1855-01	1855-03	-0.28	-0.56	2
	8	1855-11	1856-01	-0.17	-0.35	2
	9	1856-03	1856-05	-0.06	-0.12	2
	10	1873-12	1874-02	-0.14	-0.28	2

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m^3/s^1 deficit*	*Accumulated Q95 m^3/s^1 Deficit*	*Drought duration months*
35005 West BFI (0.61)	1	1864-02	1864-11	-1.08	-9.70	9
	2	1953-01	1953-08	-1.69	-11.85	7
	3	1956-02	1956-07	-1.17	-5.87	5
	4	1941-07	1941-11	-0.60	-2.41	4
	5	1856-10	1857-01	-1.37	-4.11	3
	6	1890-05	1890-08	-0.07	-0.22	3
	7	1891-02	1891-05	-1.17	-3.51	3
	8	1893-06	1893-09	-0.02	-0.05	3
	9	1929-04	1929-07	-0.73	-2.20	3
	10	1975-07	1975-08	-0.34	-0.69	2

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
27002 West BFI (0.70)	1	1891-02	1891-08	-0.57	-3.40	6
	2	1893-04	1893-10	-0.24	-1.42	6
	3	1953-02	1953-08	-1.25	-7.51	6
	4	1879-11	1880-03	-1.34	-5.38	4
	5	1887-06	1887-10	-0.17	-0.67	4
	6	1895-06	1895-10	-0.19	-0.78	4
	7	1944-03	1944-07	-0.41	-1.64	4
	8	1902-08	1902-11	-0.38	-1.14	3
	9	1905-07	1905-10	-0.21	-0.62	3
	10	1933-10	1934-01	-3.47	-10.41	3

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
26018 West BFI (0.72)	1	1921-05	1921-12	-0.26	-1.84	7
	2	1893-04	1893-10	-0.02	-0.12	6
	3	1953-02	1953-08	-0.22	-1.31	6
	4	1891-02	1891-06	-0.32	-1.27	4
	5	1941-07	1941-11	-0.03	-0.13	4
	6	1944-03	1944-07	-0.14	-0.55	4
	7	1858-01	1858-04	-0.03	-0.08	3
	8	1870-07	1870-10	-0.03	-0.08	3
	9	1879-11	1880-02	-0.33	-0.98	3
	10	1887-06	1887-09	-0.03	-0.08	3

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
25006 Midlands BFI (0.71)	1	1887-07	1888-04	-1.29964	-11.6968	9
	2	1850-01	1850-08	-1.71125	-11.9788	7
	3	1864-04	1864-10	-0.29988	-1.79925	6
	4	1973-03	1973-09	-1.00088	-6.00525	6
	5	1976-04	1976-10	-0.83921	-5.03525	6
	6	1891-02	1891-07	-1.4809	-7.4045	5
	7	1953-03	1953-08	-0.63385	-3.16925	5
	8	2004-05	2004-10	-0.4824	-2.412	5
	9	1911-06	1911-10	-0.10513	-0.4205	4
	10	1956-04	1956-08	-0.25294	-1.01175	4

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
23002 Southwest BFI (0.31)	1	1893-03	1893-08	-0.61	-3.06	5
	2	1902-07	1902-11	-0.82	-3.27	4
	3	1933-09	1934-01	-2.63	-10.53	4
	4	1953-03	1953-07	-1.95	-7.78	4
	5	1971-05	1971-09	-0.15	-0.60	4
	6	1879-11	1880-02	-2.97	-8.91	3
	7	1887-06	1887-09	-0.33	-0.98	3
	8	1895-05	1895-08	-0.31	-0.92	3
	9	1929-04	1929-07	-0.37	-1.12	3
	10	1852-04	1852-06	-0.15	-0.31	2

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
19001 South BFI (0.68)	1	1944-02	1944-09	-0.16	-1.13	7
	2	1887-05	1887-11	-0.06	-0.36	6
	3	1906-12	1907-05	-0.51	-2.55	5
	4	1975-04	1975-09	-0.09	-0.45	5
	5	1854-03	1854-07	-0.05	-0.21	4
	6	1854-11	1855-03	-0.85	-3.39	4
	7	1874-06	1874-10	-0.06	-0.25	4
	8	1891-02	1891-06	-0.20	-0.81	4
	9	1921-06	1921-10	-0.05	-0.21	4
	10	1953-01	1953-05	-0.32	-1.29	4

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
16009 South BFI (0.63)	1	1887-05	1887-11	-1.25	-7.50	6
	2	1921-07	1922-01	-4.12	-24.70	6
	3	1854-11	1855-03	-5.28	-21.10	4
	4	1864-06	1864-10	-0.07	-0.29	4
	5	1893-04	1893-08	-1.62	-6.49	4
	6	1850-01	1850-04	-5.27	-15.80	3
	7	1854-03	1854-06	-3.23	-9.70	3
	8	1874-05	1874-08	-0.31	-0.94	3
	9	1879-11	1880-02	-6.31	-18.94	3
	10	1884-09	1884-12	-3.29	-9.87	3

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
13002 Southeast BFI (0.73)	1	1975-12	1976-10	-0.20	-1.98	10
	2	1887-06	1888-01	-0.07	-0.51	7
	3	1891-02	1891-08	-0.12	-0.73	6
	4	1893-06	1893-12	-0.04	-0.27	6
	5	1944-03	1944-09	-0.02	-0.10	6
	6	1906-12	1907-05	-0.22	-1.08	5
	7	1975-05	1975-10	-0.03	-0.14	5
	8	1888-02	1888-06	-0.12	-0.49	4
	9	1953-01	1953-05	-0.05	-0.21	4
	10	1854-12	1855-03	-0.17	-0.52	3

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
12001 Southeast BFI (0.72)	1	1893-06	1894-01	-1.43	-10.01	7
	2	1944-03	1944-10	-1.05	-7.38	7
	3	2015-01	2015-08	-1.03	-7.19	7
	4	1887-07	1888-01	-0.42	-2.55	6
	5	1953-02	1953-07	-1.15	-5.75	5
	6	1874-06	1874-10	-0.39	-1.58	4
	7	1891-03	1891-07	-1.09	-4.36	4
	8	1907-01	1907-05	-5.19	-20.77	4
	9	1941-07	1941-11	-0.36	-1.42	4
	10	1854-12	1855-03	-3.58	-10.74	3

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
10002 Southeast BFI (0.54)	1	1893-04	1893-12	-0.77	-6.18	8
	2	1874-04	1874-08	-0.41	-1.63	4
	3	1953-01	1953-05	-0.53	-2.13	4
	4	1976-05	1976-09	-0.38	-1.53	4
	5	1884-10	1885-01	-1.11	-3.34	3
	6	1906-12	1907-03	-1.17	-3.51	3
	7	1938-04	1938-07	-0.57	-1.70	3
	8	1944-06	1944-09	-0.06	-0.19	3
	9	1978-09	1978-12	-0.92	-2.77	3
	10	1854-03	1854-05	-0.13	-0.26	2

Catchment	*Rank*	*Drought Start*	*Drought end*	*Mean Q95 m³/s¹ deficit*	*Accumulated Q95 m³/s¹ Deficit*	*Drought duration months*
7012 East BFI (0.68)	1	1891-01	1891-09	-6.48	-51.82	8
	2	1893-06	1894-01	-3.31	-23.19	7
	3	1934-02	1934-09	-6.12	-42.82	7
	4	1953-02	1953-09	-2.22	-15.56	7
	5	1857-12	1858-04	-1.69	-6.75	4
	6	1887-07	1887-11	-0.78	-3.12	4
	7	1892-03	1892-07	-0.93	-3.72	4
	8	1933-09	1934-01	-3.36	-13.45	4
	9	1870-07	1870-10	-0.62	-1.87	3
	10	1895-05	1895-08	-1.29	-3.88	3