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The Irish Hydrometric Reference Network, Version 2.0

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ABSTRACT

We present an update of the Irish Hydrometric Reference Network (IHRN) of river gauging stations from across the Republic of Ireland that have been deemed suitable for assessing climate-driven changes in high, mean and low flows. Selection criteria, analysis of metadata and historical flows, and stakeholder feedback are applied to identify 51 stations for inclusion in the network. Missing daily data were infilled using a conceptual hydrological model and an Artificial Neural Network. As well as providing a dataset for monitoring and detecting the impact of changing climatic conditions on Irish catchments, the updated IHRN offers utility for assessing extremes of flood and drought and for modelling future flow regimes via climate change impact assessments.

1 | Introduction

High quality, long-term observational records are fundamental for understanding the impact of climate variability and change on river flows (Dixon et al. 2006; Chiverton et al. 2015; Garner et al. 2015). Flow records with notable anthropogenic influences (e.g., drainage, irrigation, abstractions and discharges, river flow management), inaccurate rating curves at extremes, limited length and/or containing considerable missing data, may provide inaccurate or misleading assessments of change over time (Hannaford et al. 2013; Hall et al. 2014; Wilby et al. 2017). Hydrometric reference networks comprise quality-assured, long-term flow gauges that provide reliable observational records from near-natural river flow regimes (Whitfield et al. 2012) and have been developed for many countries such as the US, Australia, and New Zealand (Slack and Landwehr 1992; Turner et al. 2012; Queen et al. 2023), and in some studies have been grouped for larger areas such as the Nordic region, Europe,

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Dataset Details
Metadata relating each of the 51 IHRN V2 stations are given including details on each station's flow data, their catchment characteristics and a rating of each station's performance at high, mean, and low flows. Also included are daily observed, modelled, and infilled river flow data (station start year till 2022). Modelled data includes median flows generated using the Artificial Neural Network (ANN) together with upper/lower uncertainty bounds. Data are presented in six tab-delimited TEXT files (ASCII) containing the station metadata, observed flows, ANN modelled flows, modelled flows' 2.5% quantile, modelled flows' 97.5% quantile and infilled observed flows.

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and globally (Wilson et al. 2010; Stahl et al. 2010; Turner 2024). Such networks typically cover the full range of possible flows but have also been developed to target a specific flow regime, for example, low flows in France (Giuntoli et al. 2013).

Whilst selection criteria for reference networks often reflect local data limitations, there are standard criteria which are typically considered. These include the degree of basin development (ideally pristine with stable land-use), water use (limited regulations, diversions and abstractions), record length (at least 20 years), data collection (active stations), good data quality, and adequate supporting metadata (Whitfield et al. 2012). Secondary considerations often relate to sufficient spatial coverage and representativeness of the range of catchment characteristics, with incomplete or low spatial coverage being identified as a particular source of uncertainty when using networks for assessing historic change (Easterling et al. 2016). Reference networks are commonly employed in studies assessing catchment responses to climate variability and change at high (e.g., Burn and Whitfield 2017; Hodgkins et al. 2017; Mazer et al. 2021) and low (e.g., Hannaford and Marsh 2006; Dudley et al. 2020; O'Connor et al. 2022) flows.

The utility of flow records, including those from reference networks, can be compromised by missing data and extended gaps in the record (Harvey et al. 2012). Discharge series can contain missing data due to issues such as equipment malfunction, loss during transmission/storage, human error or because data are of insufficient accuracy, precision or reliability (Wilby et al. 2017). When carrying out statistical analysis of flow series, missing values can lead to biassed results (Zhang and Thorburn 2022). It is therefore pertinent that gaps in any record be limited and infilled when possible. Techniques employed to infill missing data include nearest neighbour approaches, (e.g., Giustarini et al. 2016), interpolation techniques (e.g., Peterson and Western 2018), linear regression techniques (e.g., Durocher et al. 2019), hydrological modelling (e.g., Zhang and Post 2018) and machine learning (e.g., Dahmani and Latif 2024).

In Ireland, the first hydrometric reference network, consisting of 43 stations, was developed by Murphy et al. (2013a). These stations have been employed in numerous studies including the investigation of flow extremes, historical trends, links to external hydroclimatic drivers, streamflow forecasting, hydrologically modelling, and river flow reconstructions (e.g., Hodgkins et al. 2024; Mediero et al. 2015; Murphy et al. 2013a; Donegan et al. 2021; Foran Quinn et al. 2021; Broderick et al. 2016; Noone and Murphy 2020). An optimal reference network requires periodical review to ensure it remains fit for purpose (Mishra and Coulibaly 2010). Given the passage of > 10 years since the creation of the first Irish reference network this paper provides a revised network to ensure that all stations are fit for purpose and that stations that may not have been of sufficient length in Version 1 are included in this update.

In the remainder of this article we present the Irish Hydrometric Reference Network (IHRN) Version 2. We outline the criteria applied for inclusion, present the derived networks for high, mean and low flows, detail the modelling process employed to infill missing flow data and provide an outline of the main characteristics of the network catchments. Finally, we present an analysis of annual and seasonal trends in flows from across the IHRN V2.

2 | Irish Hydrometric Reference Network Version 2 (IHRN V2)—Station Selection

2.1 | IHRN V2—Data Gathering

Daily Mean Flows (DMFs) for 366 catchments were available for assessment, comprising 143 gauges overseen by the Irish Environmental Protection Agency (EPA) and Local Authorities and 223 gauges maintained by the Office of Public Works (OPW). In Ireland the OPW are responsible for flood risk management and maintain hydrometric stations for this purpose. The EPA has an important remit for water quality, while local authorities historically had responsibility for water management. Therefore, different hydrometric agencies have an historical focus on different parts of the flow regime. Flow series are available for download from the EPA (http://www.epa.ie/hydronet/) and the OPW (http://waterlevel.ie/).

2.2 | IHRN V2—Application of Criteria

DMFs for all available stations were assessed for inclusion based on the criteria outlined in Table 1. Specific requirements included that station series be at least 30 years in length, have < 10% missing data, have < 2.5% urban extent, < 10% extractions/discharges (Q95 or the flow exceeded 95% of the time), be active or if suspended, that this is temporary. In Ireland, arterial drainage, an activity used to improve land drainage and to reduce the frequency and extent of overland flooding (Bhattarai and O'Connor 2004), has historically impacted many catchments (Murphy et al. 2013a) and can influence rainfall-runoff response (Harrigan et al. 2014). For catchments with a documented history of arterial drainage, only the post-drainage data were included for analysis.

Trends in annual and seasonal flows for each station were also examined, using a modified version of the non-parametric Mann–Kendall test (Mann 1945; Kendall 1955) that addresses autocorrelation (Yue and Wang 2004). The deviation of a single station's trends from others and/or the identification of excessively large trends resulted in further investigation of the relevant station's metadata as appropriate. When deciding upon the final listing of IHRN stations, the application of certain selection criteria was relaxed for a small number of catchments so that the final list covered a broad range of catchment characteristics, representative of differing hydroclimatological conditions on the island and had a good geographical distribution (see Table 2).

2.3 | IHRN V2—Rating Curve Performance Across the Flow Regime

To address requirements of different users who often have specific interest in high, mean or low flows, together with different priorities of the main hydrometric agencies in Ireland,

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TABLE 1 | Selection criteria used to identify suitable stations to include in the IHRN V2.

Key selection criteria	Comment
Active	Stations must be active and collecting data and expected to continue to do so into the future. Note: temporarily suspended stations were considered for inclusion
Hydrometric data quality	High quality, consistent hydrometric data, with adequate supporting metadata are required. A well-defined stage-discharge relationship particularly at high and low flows (identified with rating curve) is desirable with details on gauge type, performance in supporting metadata (e.g., detail on weed growth, high flow bypassing and other channel disturbances) required
Record length	Long continuous record lengths are essential (at least 30 years) with continuity of ongoing measurements without significant gaps (< 10% gap in the record overall)
Near-natural flow regime	Catchments should be subjected to limited flow regulation, extractions, or discharges. When unavoidable a threshold of 10% influence on flow values at/below Q95 is applicable for low flow stations
Limited land-use change and drainage	Flow regimes that are relatively free from development and other anthropogenic influences (here we classify relatively free from development as the catchment having < 2.5% urban extent). Catchments subject to arterial drainage are flagged, with only post-drainage records employed
Geographical location	Geographical spread that encompasses the entirety of the island (all eight Water Framework Directive river basin districts), in locations with differing rainfall regimes, underlying geology, catchment orientation, and vegetation cover. The spatial distribution of candidate stations, record length, data quality at high, mean and low flows and overall hydrological representativeness were considered when choosing stations with importance adjusted depending on circumstances
Confirmation	Station nomination is flagged with the relevant hydrometric authority overseeing its operation (i.e., EPA, OPW). Feedback on station selection also attained using a related query sheet with questionnaire addressing all issues identified through previous examination

rating curve quality of IHRN V2 stations was assessed at those three flow regimes using a classification approach similar to Harrigan et al. (2018) for the UK Benchmark Network. The rating curves for candidate stations were graded separately for high (Q05), mean (Q50) and low (Q95) flows, with a value of 1 (good performance), 2 (moderate performance), or 3 (poor performance) assigned to each station. Grading was undertaken via a questionnaire distributed to hydrometric experts within Local Authorities, the EPA and OPW. An overall score was then obtained by averaging scores across each of the three flow regimes and rounding to the nearest whole number. Stations that obtained an overall score of 3 were dropped from the final listing of IHRN V2 stations. Similarly, stations were removed from a given flow regime if their performance was poor.

Table 2 provides the final list of stations, detailing their characteristics, ratings for high, mean, and low flows, and their overall performance scores. In total, 51 stations were identified as suitable for inclusion in the IHRN V2, 17 of which are high quality and 34 of which are moderate quality overall (see Table 3 for a more detailed breakdown). Using this information, different networks are defined for low, mean, and high flows. Suitable stations for mean flow are most numerous (50), followed by high flow (45), and low flows (42). Of the 51 stations, only 12 have a high-quality rating across all three flow regimes (see Table 2), indicating the importance of defining unique networks for high, mean, and low flows to maximise spatial coverage. Table 2 also identifies nested catchments (gauges monitoring sub-catchments within the same larger catchment).

2.4 | IHRN V2—Spatial Distribution and Catchment Characteristics

The spatial distribution of networks for the three flow regimes can be seen in Figure 1. Green points represent good performing stations whilst orange represent moderate performing stations. It is evident that without relaxation of rules to include moderate quality stations, significant spatial gaps would occur in the network, particularly in inland regions at high flows. Some minor spatial gaps remain, particularly in the east (close to the Dublin region with its high urban extent), the west (close to the Galway region), and in the northwest (in county Donegal) and are the result of no stations meeting basic selection criteria in these locations. As records mature it is anticipated that these gaps will be filled in future versions of the IHRN (see Section 5.2).

Six key catchment descriptors, extracted for the final list of IHRN stations are shown in Figure 2. Standard Annual Average Rainfall (SAAR), derived using the 1961–1990 baseline for consistency with other Irish national datasets (e.g., the Flood Studies Update), ranges from 879.6 to 1924.7 mm, the Base Flow Index (BFIsoil: a measure of catchment permeability; see Mills et al. 2014) ranges from 0.29 to 0.83, the main channel slope (Tayslo; derived from Taylor–Schwartz method) ranges from 0.12 to 2.71, the proportion of peatland in the catchment (Peat) ranges from 0 to 0.80, catchment area (Area) ranges from 10.4 to 2333.7 km^2 and the average catchment elevation (Elevation) ranges from 84.0 to 493.4 m. The range of catchment descriptors show good consistency across the three flow regimes, though the high flow network tends to have slightly larger catchment areas, higher BFI values and lower mean elevations.

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TABLE 2 | Details of the 51 stations included in the Irish Hydrometric Reference Network Version 2 (IHRN V2).

Station	Station name	River name	Latitude	Longitude	Start year	Total years (till end 2022)	Missing flows (%)	Maximum consecutive missing days	Nested within	High flow rating	Mean flow rating	Low flow rating	Overall performance score	Arterial drainage	Urban extent (p)
6012	Clarebane	Fane	54.093	−6.665	1972	50.25	4.89	334	NA	1	1	1	1	—	0.013
6013	Charleville	Dee	53.856	−6.413	1975	47.18	1.8	73	NA	1	1	1	1	1950–1957	0.009
6014	Tallanstown	Glyde	53.921	−6.549	1975	47.19	2.83	111	NA	1	1	2	1	1950–1957	0.012
6030	Ballygoly	Big [Louth]	54.026	−6.243	1975	47.96	9.28	296	NA	3	1	1	2	—	0.000
7002	Killyon	Deel [Raharney]	53.488	−6.970	1979	43.57	4.95	189	7005	2	1	3	2	1973–1978	0.003
7005	Trim	Boyne	53.556	−6.791	1975	47.35	3.61	369	NA	2	2	3	2	1971–1974	0.007
7006	Fyanstown	Moynalty	53.726	−6.802	1986	36.18	4.4	185	NA	2	2	2	2	1982–1985	0.004
7033	Virginia Hatchery	Blackwater [Kells]	53.834	−7.078	1980	42.98	5.7	735	7006	2	1	2	2	—	0.006
11,001	Boleany	Owenavorragh	52.643	−6.270	1972	50.78	3.34	254	NA	3	2	2	2	—	0.017
12,001	Scarawalsh	Slaney	52.548	−6.549	1955	67.33	3.71	108	NA	2	2	3	2	—	0.006
14,007	Derrybrock	Stradbally	53.039	−7.084	1980	42.92	1.86	71	14,019	1	1	1	1	—	0.007
14,019	Levitstown	Barrow	52.935	−6.949	1954	69	6.98	1169	NA	2	1	3	2	—	0.018
15,011	Mount Juliet	Nore	52.531	−7.188	1990	32.13	0.93	22	NA	2	1	1	1	—	0.013
16,009	Caher Park	Suir	52.357	−7.922	1954	68.25	3.21	271	16,011	2	1	2	2	—	0.008
16,011	Clonmel	Suir	52.351	−7.694	1972	50.87	3.02	193	NA	1	1	3	2	—	0.007
18,002	Ballyduff	Blackwater [Munster]	52.144	−8.051	1972	51	1.55	78	NA	1	1	1	1	—	0.006
18,003	Killavullen	Blackwater [Munster]	52.149	−8.515	1972	51	3.8	194	18,002	2	2	1	2	—	0.007
18,005	Downing Br.	Funshion	52.168	−8.258	1972	51	1.32	75	18,002	2	3	2	2	—	0.004
19,001	Ballea	Owenboy	51.822	−8.421	1972	50.25	6.99	373	NA	1	1	1	1	—	0.019
20,002	Curranure	Bandon	51.765	−8.682	1975	48	4.88	456	NA	1	1	1	1	—	0.008
22,035	Laune Br.	Laune	52.061	−9.617	1991	31.45	6.57	231	NA	3	1	1	2	—	0.010
23,001	Inch Br.	Galey	52.468	−9.534	1972	50.57	3.84	222	NA	1	2	2	2	1951–1959	0.003
24,030	Danganbeg	Deel	52.409	−9.002	1980	42.66	8.12	186	NA	2	2	2	2	1962–1968	0.011

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TABLE 2 | (Continued)

Station	Station name	River name	Latitude	Longitude	Start year	Total years (till end 2022)	Missing flows (%)	Maximum consecutive missing days	Nested within	High flow rating	Mean flow rating	Low flow rating	Overall performance score	Arterial drainage	Urban extent (p)
25,002	Barrington S Br.	Newport	52.645	−8.474	1953	69.25	4.37	287	NA	2	2	2	2	—	0.002
25,006	Ferbane	Brosna	53.270	−7.827	1952	71	7.38	944	NA	1	1	3	2	1948–1951	0.019
25,022	Syngefield	Camcor	53.093	−7.881	1953	69.27	4.13	339	NA	2	2	1	2	—	0.002
25,030	Scarriff	Graney	52.908	−8.532	1972	50.25	4.66	263	NA	2	2	2	2	—	0.001
25,038	Tyone	Nenagh	52.851	−8.185	1990	32.25	3.12	41	NA	1	1	1	1	—	0.002
26,005	Derrycahill	Suck	53.432	−8.262	1954	68.25	2.6	172	NA	2	2	2	2	—	0.002
26,008	Johnston S Br.	Rinn	53.828	−7.862	1979	43.27	7.43	775	NA	2	2	2	2	—	0.003
26,019	Mullagh	Camlin	53.733	−7.823	1953	69.29	3.64	141	NA	3	2	2	2	—	0.013
26,021	Ballymahon	Inny	53.563	−7.757	1972	50.25	5.03	488	NA	2	2	3	2	1959–1963	0.004
26,029	Dowra	Shannon	54.191	−8.014	1975	47.55	2.3	139	NA	3	1	1	2	—	0.000
26,058	Ballinrink Br.	Inny Upper	53.776	−7.250	1981	41.14	3.63	131	26,021	2	2	2	2	1959–1963	0.010
26,108	Boyle Abbey Br.	Boyle	53.973	−8.296	1990	32.09	4.92	200	NA	1	2	2	2	1982–1992	0.004
27,002	Ballycorey	Fergus	52.870	−8.974	1954	68.67	2.7	322	NA	1	1	1	1	—	0.001
30,002	Ower Br.	Black [Shrule]	53.481	−9.159	1974	48.38	6.64	372	NA	2	2	2	2	—	0.000
30,007	Ballygaddy	Clare	53.531	−8.874	1974	48.12	4.1	198	NA	2	2	1	2	1954–1974	0.005
30,020	Ballyhaunis	Dalgan	53.762	−8.764	1988	34.05	3.39	76	30,021	2	1	2	2	—	0.010
30,021	Christina S Br.	Robe	53.685	−8.992	1985	37.09	5.65	188	NA	2	2	2	2	—	0.002
31,002	Cashla	Cashla	53.288	−9.530	1979	43.74	6.57	664	NA	1	1	1	1	—	0.000
32,012	Newport Weir	Newport [Mayo]	53.889	−9.524	1981	41.62	6.33	382	NA	1	1	1	1	—	0.000
33,001	Glenamoy	Glenamoy	54.240	−9.696	1977	45.83	4.62	280	NA	2	1	2	2	—	0.000
34,001	Rahans	Moy	54.104	−9.157	1972	51	1.27	57	NA	1	1	2	1	1960–1971	0.008
34,007	Ballycarroon	Deel [Crossmolina]	54.086	−9.344	1972	50.25	6.94	334	NA	1	1	3	2	1960–1971	0.000
34,010	Cloonacannana	Moy	53.967	−8.930	1972	50.69	3.93	457	34,001	2	1	1	1	1954–1971	0.009
34,024	Kiltimagh	Pollagh	53.848	−9.013	1977	45.91	7.47	841	34,001	3	2	2	2	—	0.008

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Station	Station name	River name	Latitude	Longitude	Start year	Total years (till end 2022)	Missing flows (%)	Maximum consecutive missing days	Nested within	High flow rating	Mean flow rating	Low flow rating	Overall performance score	Arterial drainage	Urban extent (*p*)
35,005	Ballysadare	Ballysadare	54.209	−8.509	1989	33.25	2.12	52	NA	1	2	3	2	—	0.002
35,011	Dromahair	Bonet	54.227	−8.299	1986	36.97	4.24	334	NA	1	1	1	1	1983–1986	0.002
36,019	Belturbet	Erne	54.098	−7.450	1957	65.04	6.43	803	NA	1	1	1	1	—	0.007
39,006	Claragh	Leannan	55.028	−7.684	1977	46	4.34	158	NA	2	1	1	1	—	0.012

Note: High, mean, low flow rating values and overall performance scores are categorised for each station as being good (1), moderate (2) or poor (3).

TABLE 3 | Performance ratings of the 51 stations included in the IHRN V2 at high, mean, and low flows.

Station performance	High flow	Mean flow	Low flow
Good (1)	20	29	21
Moderate (2)	25	21	21
Poor[a] (3)	6	1	9

Note: Stations were graded as performing good (score of 1), moderate (score of 2), and poor (score of 3) at each flow regime.

[a] Stations with a *poor* performance at a given flow regime were excluded from the final network for that flow regime.

3 | Infilling Missing Data

3.1 | Series Length and Missing Data

Figure 3 displays the number of stations in operation for each year in the updated IHRN. The earliest gauge (ID: 25006) commenced recording in 1952. While ten stations date to the 1950s, most records commenced in the 1970s, with notable increases in 1972 and 1975, aligning with an increase in hydrometric observations following extreme drought at that time (Murphy et al. 2013a). Figure 4 maps the record length of IHRN V2 stations (a), together with the percentage of missing data (b), and the maximum consecutive days missing at each station (c). Record length (up to the end of 2022) range from 31 to 71 years (averaging 49.2 years), with longer records reasonably well distributed geographically. Missing data averages 4.5% (range: 0.9%–9.3%) and shows no spatially dependent suggesting that no particular region is subject to large consistent gaps in observations. Furthermore, gaps in the record are not temporally dependent, with only a small number of occasions when numerous stations are missing data concurrently (e.g., a 13-day period in April 2001 involving 16 stations).

3.2 | Hydrological Modelling

Missing data can severely impact analysis of flow variability and change detection (Harvey et al. 2010), particularly at extremes (Gao et al. 2018). To address this, we employed a conceptual hydrological model and an artificial neural network (ANN) to infill missing flows. The GR4J (Génie Rural à 4 paramètres Journalier; Perrin et al. 2003) is a four-parameter bucket-type water balance model that partitions rainfall between production (soil moisture) and routing stores, using a water exchange function to account for groundwater interaction. We ran the GR4J model using the airGR package (Coron et al. 2017). Catchment average precipitation was extracted from gridded (1 × 1 km) Met Éireann precipitation (1941–2022; see Walsh 2012). Catchment specific potential-evapotranspiration was calculated using Oudin's formula (Oudin et al. 2005). As Met Éireann's gridded (1 × 1 km) temperature data (Walsh 2012) only commences in 1961, a subset of gridded (0.25° × 0.25°) ERA5 surface temperature reanalysis data (Hersbach et al. 2020) was extracted for the catchment area for the period 1941–2022. Bias correction was carried out using the *qmap* quantile mapping package (Gudmundsson 2016) with local linear least square regression

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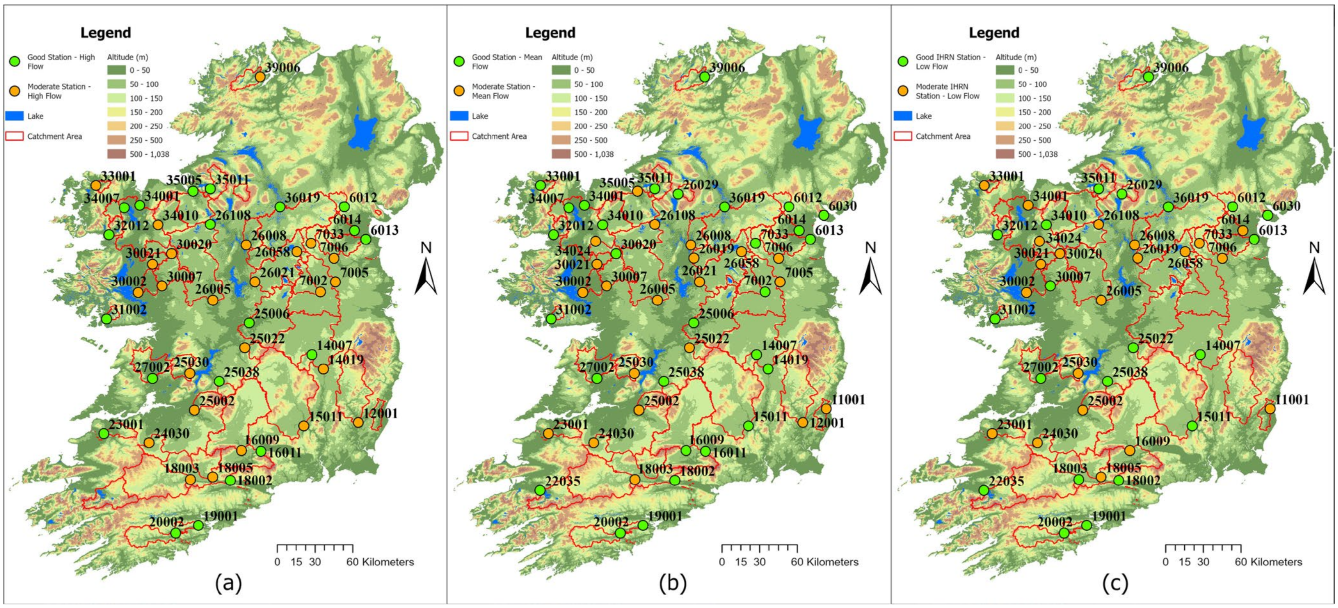

FIGURE 1 | Maps of IHRN V2 stations selected for (a) high, (b) mean, and (c) low flows. Station performance for each flow regime is indicated by the station colour with green representative of good performing stations and orange of moderate performing stations.

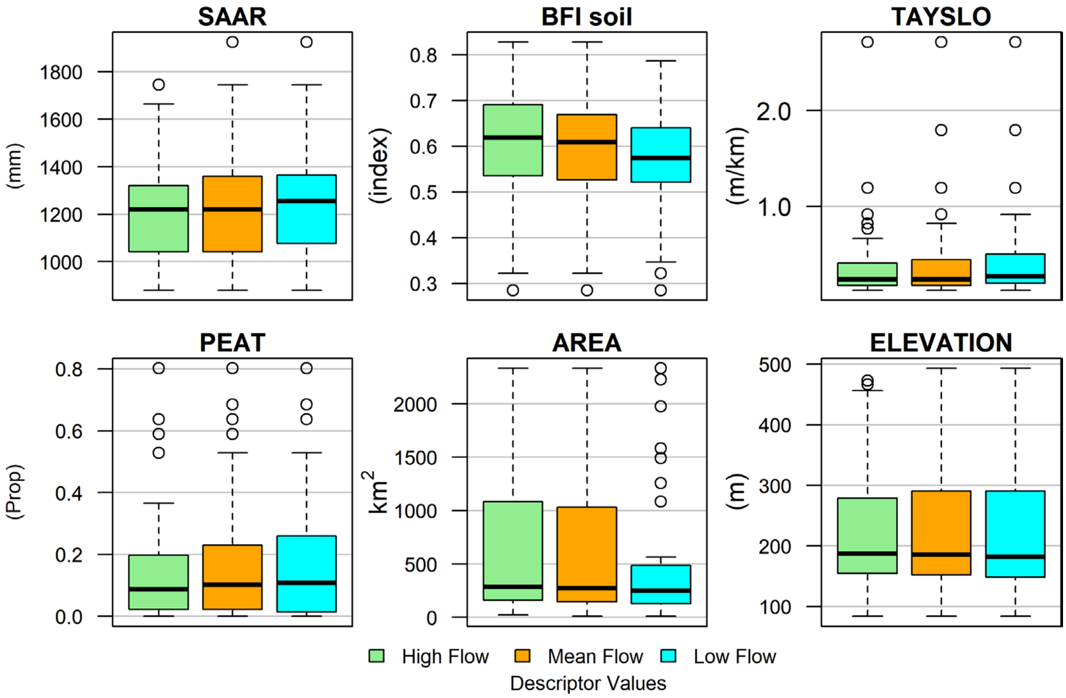

FIGURE 2 | Boxplots of selected catchment descriptors for the Irish Hydrometric Reference Network (IHRN) version 2 stations, grouped by high, mean, and low flows. Descriptors include standard annual average rainfall (SAAR), base flow index (BFIsoil), channel slope (TAYSLO; derived from Taylor-Schwartz method), peatland (PEAT), catchment area (AREA), and catchment elevation (Elevation).

interpolation mapping catchment specific ERA5 temperature data to the Met Éireann equivalent.

To calibrate the model, 80,000 parameter sets were generated from a uniform distribution using Monte Carlo methods. Table 4 summarises the range of values employed for each of the four parameters. This ensemble approach allowed for a broad assessment of model performance across a plausible range of values. Calibration was subsequently performed using observed daily flows from the start of each record till the end of 1999 (including a one-year warm-up period). The Nash Sutcliffe Efficiency (NSE) (Nash and Sutcliffe 1970) and Kling Gupta Efficiency (KGE) (Gupta et al. 2009; Kling et al. 2012) objective functions were applied to identify the 200 best performing parameter sets. Median flows from these top 200 sets for each objective function were extracted for each station.

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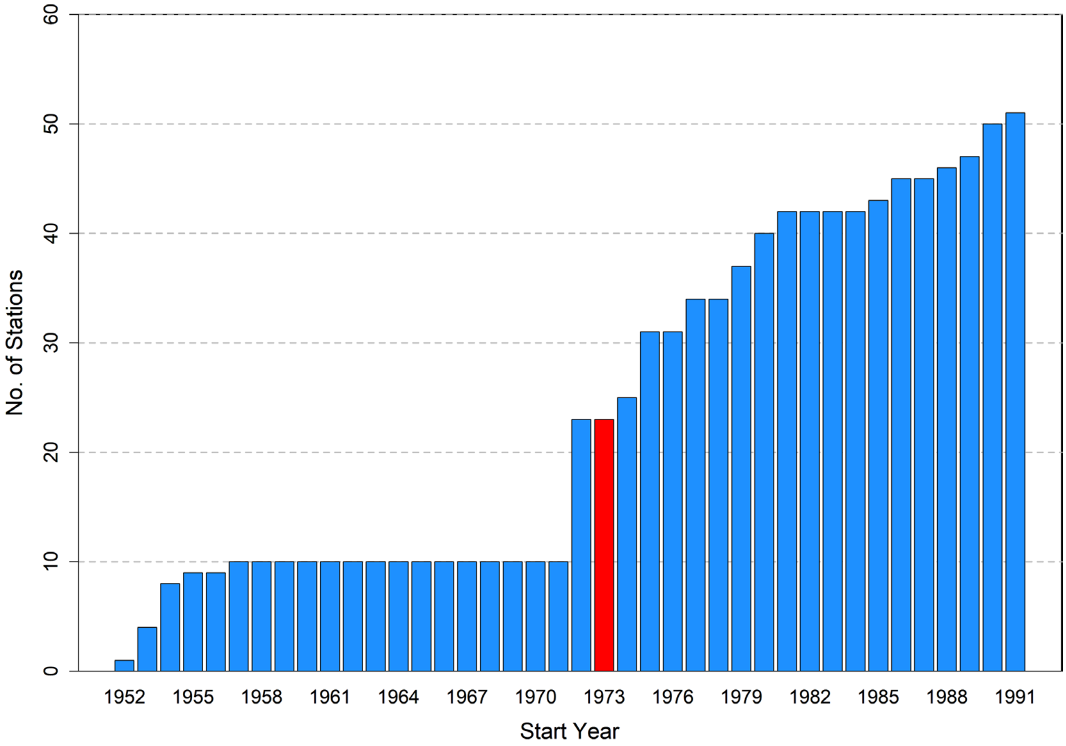

FIGURE 3 | Start year of flow measurements for each of the IHRN V2 stations, ranging from 1952 to 1991. The average start year of all 51 stations, highlighted in red, is 1973.

Flows generated from the GR4J model were subsequently employed as inputs (1-day lag) to the ANN, along with daily temperature, precipitation and precipitation lagged by one to 4 days for the entire observational period. The ANN was developed using the *neuralnet* package (Fritsch et al. 2019) in R. Model structures consisting of two hidden layers with combinations of one to eight neurons in each were generated. Performance was evaluated during the calibration period using the NSE and KGE objective functions, with the top 20 best performing ANN models retained from each objective function. Median simulated flow values from the combined GR4J and ANN ensembles were used to represent the final flow outputs for each catchment, with 95th percentile confidence intervals (i.e., lower and upper uncertainty bounds) also derived (these data are available in the *Modelled_Flows.txt*, *2.5_Quantile_Modelled_Flows.txt*, and *97.5_Quantile_Modelled_Flows.txt* files in the Zenodo repository).

3.3 | Model Performance and Validation

Model performance scores, including NSE, KGE, Mean Absolute Error (MAE), and R-Squared for the GR4J model and the ANN model (employing the GR4J model outputs as a predictor), were extracted for each station for the calibration period and a 22-year independent validation period (2000–2022 inclusive; see Figure 5). Comparing GR4J and ANN model performances across all stations, we find average NSE values increase from 0.81 to 0.91, KGE values increase from 0.85 to 0.93, MAE values decrease from 0.57 to 0.40, and R-squared values increase from 0.82 to 0.91 for the calibration period, indicating improved performance using the ANN model. For the validation period, average NSE values increase from 0.82 to 0.90, KGE values increase from 0.83 to 0.89, MAE values decrease from 0.59 to 0.42, and R-squared values increase from 0.83 to 0.91. As the ANN model consistently outperformed the GR4J model, the ANN was used to infill gaps in observations for all selected stations.

4 | Assessment of Trends

The impact of infilling missing data on trends was assessed for each IHRN V2 station. Annual and seasonal mean flows were extracted and trends identified using a modified version of the non-parametric Mann-Kendall (MK) test that accounts for autocorrelation (Yue and Wang 2004). MK Z-scores, representing trend direction and magnitude, were obtained for observed flows (with gaps) and infilled flows (available as *Observed_Flows.txt* and *Infilled_Flows.txt* files in the Zenodo repository) and results compared (Figure 6). MK Z-scores exceeding $|1.96|$ indicate significant trends at the 0.05 level. While some stations show moderate deviations from the 1:1 line, most of the network displays very similar MK Z-scores for both observed and infilled data. For instance, station ID 14019 shows minimal deviation despite a gap exceeding 100 days, suggesting that infilling has limited impact on trends. Overall, mean flows exhibit a general tendency toward positive trends across all seasons except spring, with a limited number of statistically significant trends evident.

Trend persistence in annual and seasonal mean flows was also assessed to identify if individual stations showed deviations over the observational period that were inconsistent with other stations. For these tests the start year was dropped consecutively

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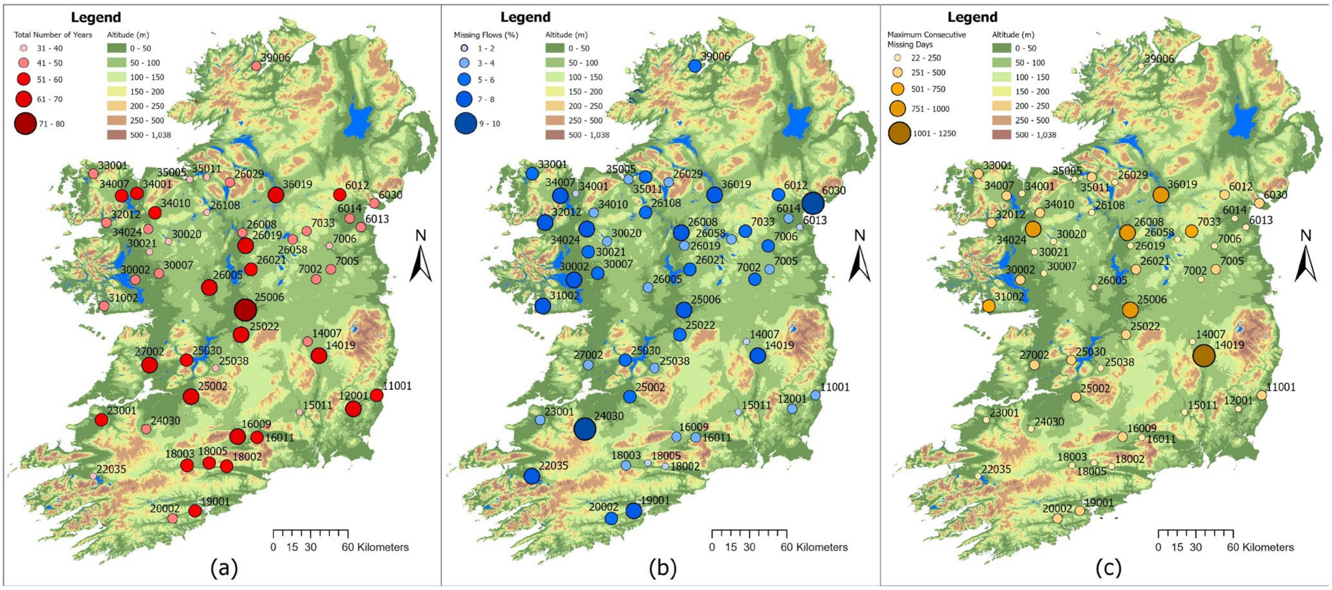

FIGURE 4 | Maps of flow metrics for the 51 IHRN V2 stations, including details on (a) the length of each station's flow record (in years), (b) the percentage of the station's flow record that is missing, and (c) the maximum number of consecutive missing days per station.

TABLE 4 | List of parameters used in the GR4J hydrological model. Included are their description, units, and the range of calibrated values from which 80,000 random values were generated.

Parameter	Description	Units	Range of calibrated values
X1	Maximum capacity of the production (soil moisture) store	mm	0–1100
X2	Groundwater exchange coefficient	mm/day	0–10
X3	Maximum capacity of the routing store	mm	0–1000
X4	Time base of the unit hydrograph	days	0–10

for each station until the year 2000 and the MK *Z* statistic noted. Figure 7 shows a persistence plot of MK *Z*-scores for annual flows, with good performing stations shown in green and moderate performing in orange. Both categories show similar *Z*-score patterns with no obvious outliers, increasing confidence in results from moderately ranked stations.

Across the network increasing trends in average annual flows are evident, particularly for longer records (e.g., pre-1965 were of the 10 stations all show positive trends (consistently statistically significant for 4 of them)). A similar pattern is for raw observed flows (see Figure S1). The most negative trends occur for tests commencing in 1993, where 17 stations show decreasing trends, however none are statistically significant.

Figure 8 presents a seasonal breakdown of MK persistence plots for IHRN V2 stations. Both good and moderate performing stations show comparable trends in each season. The importance of start year is clear in seasonal trends with earlier start years tending to produce stronger trend patterns than shorter records. Winter mean flows are dominated by increasing trends, particularly for tests commencing pre-1973. For the post-1970s period winter mean flow trends are generally non-significant. Spring shows considerable fluctuation in the significance and direction of trends depending on the start year. For tests commencing pre-1974 and post-1994 most trends are increasing, for tests commencing from 1974 to 1994 the majority are decreasing. For summer mean flows, increasing trends are particularly evident for longer records. Autumn shows strong similarities with summer, with increasing trends dominating for longer records. However, in both instances flow trends are statistically non-significant. Seasonal flows also show similar results for raw observed flow series (see Figure S2).

5 | Discussion

5.1 | IHRN V2 Strengths and Weaknesses

The inclusion of 51 gauging stations, representative of a wide range of catchment characteristics, allows for detailed analysis of climate variability and change in Irish river flows. The average length of series in the network has been extended from 40 years in IHRN V1 to 49 years (average start year is 1973), with only 4.6% of flow data missing on average (previously 4.7%). Infilling via the ANN model showed that missing data had little impact on mean flow trends. Future work will investigate impacts on high and low flows. As per Harrigan et al. (2018), the IHRN V2 provides unique networks for high, mean, and low flows. This allows for the best performing stations for each regime to be identified for trend assessment. A smaller number of stations (17) are classified as having high-quality ratings across all flow regimes. Along with evaluation of the station flow and

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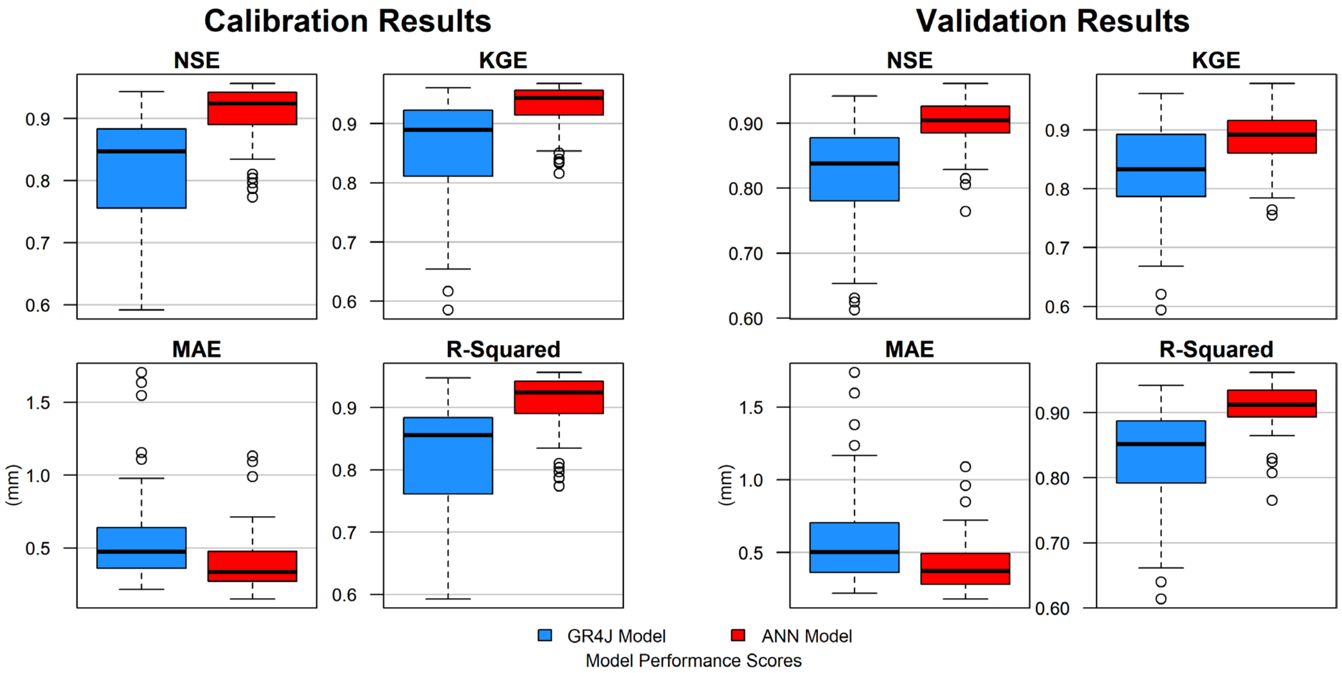

FIGURE 5 | Model performance indicators for the Génie Rural à 4 paramètres Journalier (GR4J) and Artificial Neural Network (ANN) models used to infill flows for all 51 IHRN V2 stations. The four panels on the left represent scores for the calibration period (from start of record to end of 1999) while the four on the right represent scores for the validation period (2000–2022). Metrics include the Nash Sutcliffe Efficiency (NSE), Kling Gupta Efficiency (KGE), Mean Absolute Error (MAE), and Coefficient of Determination (R^2).

metadata, coherence in trends across the network over the historical record suggests that the IHRN V2 is fit for purpose. That said, there are some weaknesses in the network that need consideration. Many Irish catchments have been subject to arterial drainage (Bhattarai and O'Connor 2004), with drainage maintenance often ongoing in these catchments. It is unavoidable that some IHRN catchments were subject to these activities (see Table 2). However, none of the 16 stations impacted (noted in Table 2) had drainage occur post the commencement of the flow record used here. Another potential weakness is gaps in network coverage in certain regions. To address this, some criteria were relaxed, specifically in relation to the amount of missing data in some stations, the inclusion of post-drainage flow series and the inclusion of moderately good rating curves where necessary for spatial coverage. These aspects and associated metadata (available in the *IHRN_Station_Metadata.txt* file in the Zenodo repository) should be considered by potential users.

To quantify the impact of relaxing selection criteria, a comparative analysis of physical catchment descriptors and station performance was conducted across high, mean, and low flow regimes (see Figure S3). Results show that the physical attributes remain relatively consistent regardless of station quality ratings. Furthermore, Mann–Whitney U tests found no significant difference ($p > 0.05$) in annual and seasonal mean flow trends between good and moderate stations. This suggests that while a moderate rating may introduce localised uncertainty, it does not undermine the detection of broader climatic trends across the network. However, users should consider the implications of poor data quality at extremes, with uncertainties in high flows, particularly in larger catchments, having consequences for flood risk assessment, while uncertainties in low flow can hinder the detection and addressing of water quality and quantity issues associated with drought, particularly in smaller catchments (Coxon et al. 2015).

The average station start year is 1973, with only 10 dating to 1971 or earlier. Consequently, assessments of pre-1972 flows face significant geographical gaps (especially in the northwest, southwest and east), which may hide important regional trends. The lack of significant trends in records starting in the early 1970s suggests a change in flows around this time, consistent with observations in North America (Ryberg et al. 2020), and Ireland, where a climatic change point in the mid-1970s, linked to a shift in the North Atlantic Oscillation (NAO), resulted in increased precipitation and flows (Murphy et al. 2013a, 2013b). While the Mann–Kendall test identifies monotonic trends, results can be influenced by these abrupt shifts, which may also be driven by changes in high flow events that disproportionately affect mean values. Consequently, users should consider these spatial and temporal constraints when employing the IHRN V2 for long-term climate impact assessments. Furthermore, there is under-representation of upland catchments which may limit research on flow responses to climate variability in such regions, something that has been flagged with relevant hydrometric authorities. Finally, as with many reference networks (Whitfield et al. 2012) assessing land-use impacts remains challenging due to limited long-term data. It is certain that activities like peat extraction and changing agricultural practices have impacted flows, but the extent of impact remains unclear. While consistency in trends across the network suggests that changes in mean flows are primarily climate-driven, low flow trends may be significantly more affected by land-use changes, making them harder to attribute to external climate drivers alone.

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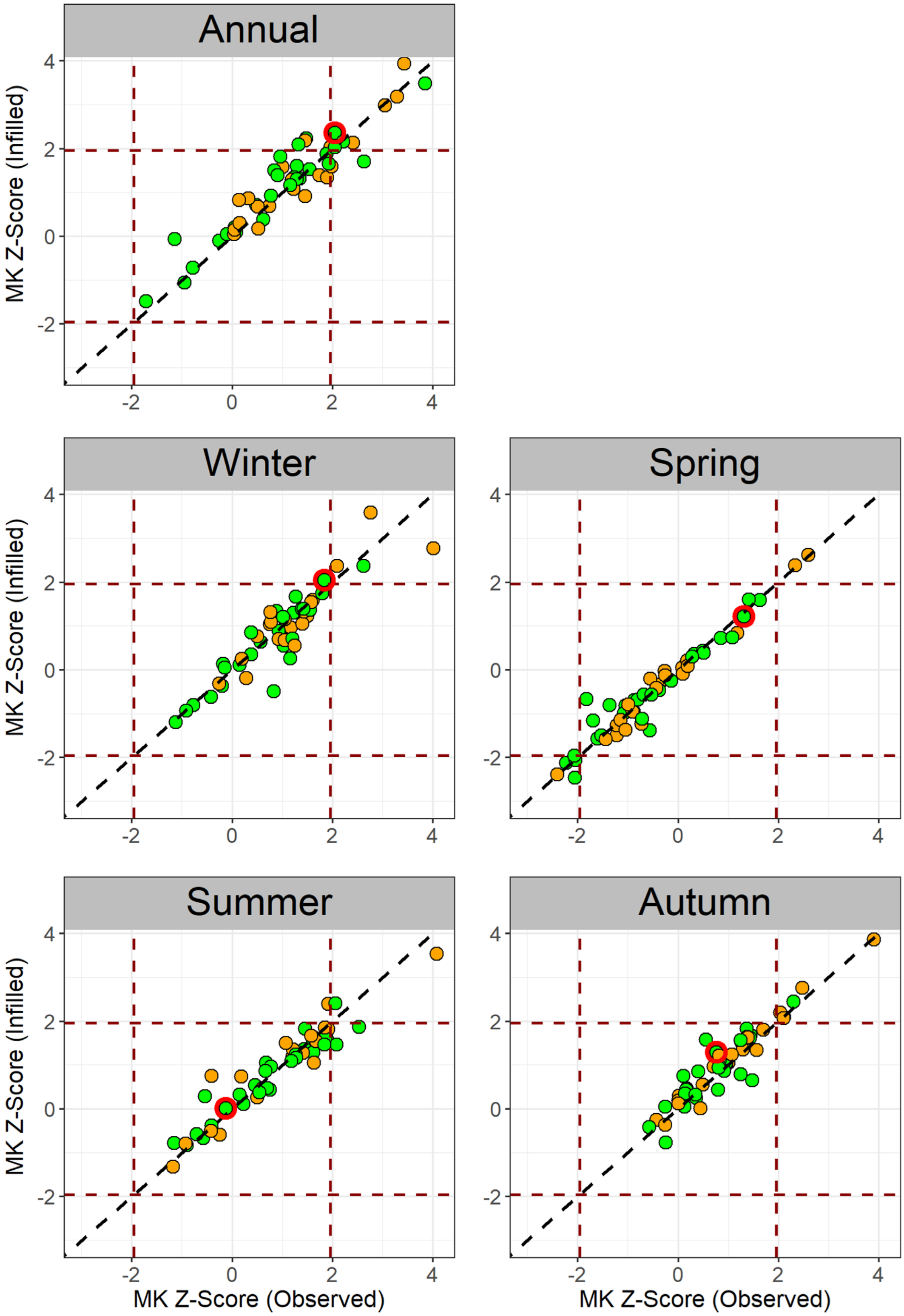

FIGURE 6 | Mann–Kendall *Z*-scores derived from annual, winter [DJF], spring [MAM], summer [JJA], and autumn [SON] observed (including missing data) and infilled (observed with missing data infilled) mean flows for the entire length of the record for each of the 51 IHRN V2 stations. Dashed red lines highlight the value at which trends become significant (i.e., > 1.96 or < −1.96). Stations classified as good are shown in green and moderate are shown in orange. Station ID 14019, which contains a data gap exceeding 100 consecutive days, is circled in red.

5.2 | Utility and Future Work

We have demonstrated the network's utility in identifying annual and seasonal mean flow trends. Since stations suitable for high and low flow analysis are now identified, assessments can easily expand to these extremes and explore links to key modes of climate variability, such as the North Atlantic Oscillation (Murphy et al. 2013a, 2013b). By limiting confounding factors and ensuring good quality data, reference networks can play an important role in climate change attribution studies. Accurate

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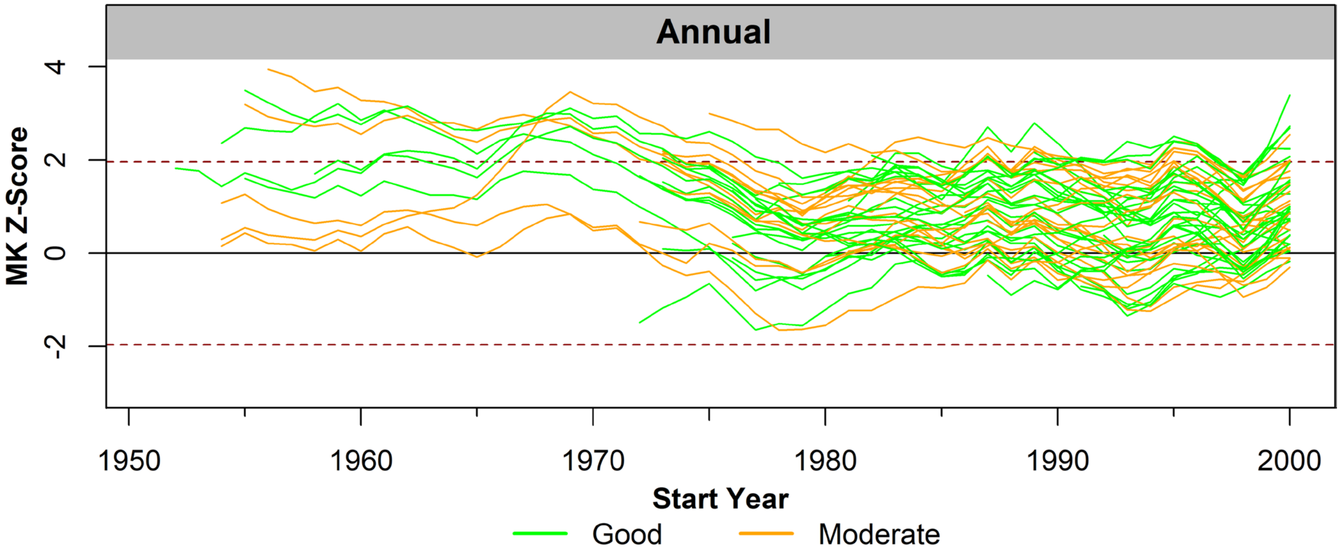

FIGURE 7 | Mann–Kendall *Z*-scores derived from annual mean flows for 51 IHRN V2 stations. MK Z-scores are derived from infilled flows for the given start year till the end of 2022. Stations classified as *good* are shown in green and *moderate* are shown in orange.

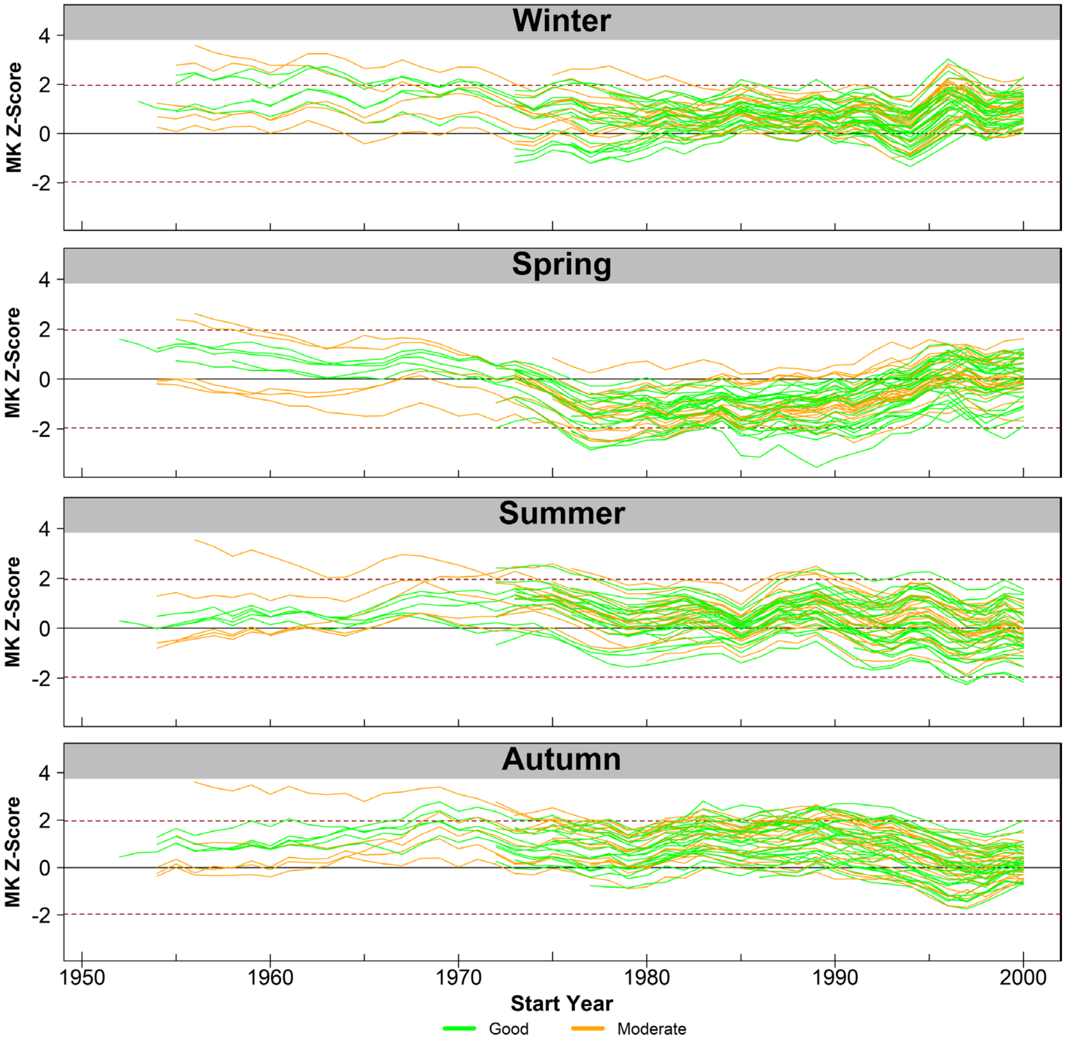

FIGURE 8 | As Figure 7 but for seasonal mean flows.

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application of seasonal forecasts at the catchment scale is reliant on high-quality river flow data. Reference stations such as those in the IHRN V2 offer a means to increase the accuracy of seasonal flow forecasting activities. As the IHRN V2 specifies a set of catchments that meet reference network criteria, it can be used in the generation of historical reconstructions and future climate change projections, bringing together past, present and future flows across a wide set of catchment characteristics.

Finally, we identify 13 fledgling stations that meet most criteria but are too short for inclusion in this iteration of the IHRN. These have been flagged as fledgling stations with the relevant organisations for prioritisation for monitoring for future inclusion. A number of these stations are in regions where spatial gaps have been identified (see Section 2.4 and Figure S4). Using the same datasets and models employed in this study, the authors intend to extend the record of IHRN V2 stations using flow reconstruction techniques (as per O'Connor et al. 2023), enabling the identification of trend patterns over longer time periods.

6 | Summary

This paper presents the Irish Hydrometric Reference Network (IHRN) Version 2, an updated, quality-assured dataset designed for monitoring Irish river flows. Stations were selected based on widely established criteria including record length, quality, minimal urban development, limited missing data, and the representativeness of Irish catchment characteristics. Through engagement with hydrometric experts, independent networks were identified for high, mean, and low flows, enabling targeted assessment across the flow regimes. To ensure data continuity, an artificial neural network was developed to infill observational gaps. Resultant annual and seasonal flow series were assessed for trends. The observed continuity of trends in mean flows confirms both the data quality and the network's utility for detecting climate-driven variability and change. While increasing trends dominate annual and winter mean flows for the observational period, these trends are generally non-significant for records commencing after the 1970s.

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Data Availability Statement

The data that support the findings of this study are openly available in Zenodo at https://doi.org/10.5281/zenodo.13943987.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Mann–Kendall Z-scores derived from annual mean flows for 51 IHRN V2 stations. MK Z-scores are derived from observed flows for the given start year till the end of 2022. Stations classified as good are shown in green and moderate are shown in orange. **Figure S2:** As Figure S1 but for seasonal mean flows. **Figure S3:** Boxplots of selected catchment descriptors as per Figure 2 in the main manuscript but including values for all individual catchments and their related performance at high mean and low flows. **Figure S4:** Map of potential future IHRN stations.

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