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DATA ARTICLE

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Hydrometric data rescue and extension of river flow records: Method development and application to catchments modified by arterial drainage

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Abstract

Extended hydrometric (water level and flow) records are presented for eight Irish catchments subject to arterial drainage. The procedures employed to collect and process historical data, extend flow records and compile key metadata and information about each gauging station are described. Procedures are developed to handle data quality issues related to hydrometric practices and equipment malfunction and to quality assure rescued data using quality codes that complement modern hydrometric practices. The workflow developed will assist other hydrometric data rescue efforts and minimize subjectivity during the rescue process. The newly extended records represent the longest continuous river flow series available in Ireland, extending to the commencement of formal hydrometric monitoring in the country in 1940. The resultant data sets add 150 years of daily data across eight stations and will provide a key new resource for hydrological studies into the impacts of arterial drainage and flow nonstationarity.

KEYWORDS

data rescue, drainage, historical hydrometry, Ireland, river flow

JEL CLASSIFICATION

Climate, Land Surface

Dataset Identifier: https://doi.org/10.1594/PANGAEA.950792

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Title: Extended river flow and water level records from 1939–2021 for eight arterially drained catchments in Ireland.

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Resource type: Dataset.

Version: 1.0.

1 | INTRODUCTION

The availability of long, high-quality hydroclimatic records is critical for detection and attribution of nonstationary dynamics (Slater et al., 2021). To detect change, studies require observed datasets that are sufficiently long to reflect the timeframe of hypothesised drivers of change (Slater et al., 2021) and to identify statistically significant deviation from natural variability (Merz et al., 2012).

Work to rescue historical data and extend available records is an important component of hydroclimatic research, with a growing number of data rescue projects internationally (e.g. Hawkins et al., 2022). In Ireland, historical data rescue has led to new insights into precipitation (Ryan et al., 2021, 2022) and temperature (Mateus et al., 2020; Mateus & Potito, 2022) variability and change. In climatology, much attention has been paid to data rescue procedures and workflows (Brönnimann et al., 2018), including the development of best practice guidelines (WMO, 2016) and international efforts to facilitate data rescue efforts and data storage (e.g. Copernicus Climate Change Service [C3S]).

Despite the World Meteorological Organization (WMO) identifying the need for hydrometric data rescue globally, primarily due to record deterioration, and the development of generalized guidelines to support hydrometric data rescue (WMO, 2014), there remain few examples of formal data rescue of historical streamflow data (e.g., Antico et al., 2018). There is much potential, therefore, for data rescue to contribute to hydrological studies and understanding (e.g. Antico & Vuille, 2022).

In Ireland, most river flow data are publicly available only from the early 1970s, despite commencement of hydrometric monitoring in the early 1940s. This is particularly problematic for research into long-term variability and change and understanding the impacts of human interventions. For instance, a state-sponsored arterial drainage programme was implemented in Ireland after 1945 involving catchment-scale schemes to widen and/or deepen thousands of kilometres of Irish rivers with the intention of reducing waterlogging, supporting drainage during the spring-autumn growing season and mitigating flood events (Bruton & Convery, 1982). The lack of available gauged river flows in the period before installation limits understanding of the impact of arterial drainage on the hydrological regime.

The primary aim of this paper is to develop an approach for historical hydrometric data rescue for eight arterially drained catchments from the Office of Public Works' hydrometric archives (OPW). In doing so, we develop a workflow for hydrometric data rescue that builds off existing WMO guidance and will be of use in different contexts. The extended water level and river flow records are then presented and opportunities for further use explored.

The remainder of the paper is structured as follows: Section 2 provides detail on catchment selection. Section 3 presents an overview of the workflow adopted and then describes in detail each stage of the data rescue process and the development of extended river flow records using historical rating relationships. Section 4 provides an overview of quality assurance protocols. Section 5 outlines data access and summarizes overall data quality. Section 6 discusses future data use and limitations. Section 7 presents key lessons learned for future hydrometric data rescue efforts both in Ireland and further afield, before final conclusions are drawn in Section 8.

2 | CATCHMENT SELECTION AND WORKFLOW

Here we focus data rescue activities on arterially drained catchments in Ireland to extend the pre-drainage records. Across Ireland, 34 catchments were subject to arterial drainage, totalling 2,600 km^2 of drained land, covering ~20% of the country (OPW, 2021). All arterially drained catchments were considered for selection with the following criteria applied using metadata from the digital Register of Hydrometric Stations in Ireland 2020 (Environmental Protection Agency, 2020) and additional information held by the OPW (including OPW, 2018):

- The catchment must be actively maintained as part of the OPW's arterial drainage programme.
- A minimum of 5 years of pre-drainage water level or flow data must be available for data rescue.
- Historical paper records are legible.
- Station metadata (datums, level checks, alteration of controls) is available from the start of the record.
- Either rating relationships for the earliest available data have previously been developed, or there is a sufficient quantity and quality of flow gaugings to produce an historical rating curve.
- If multiple stations in a single catchment meet the above criteria, then the most downstream station was selected.

Using these criteria, eight catchments were identified with at least one suitable station for data rescue (Table 1, Figure 1). Together, selected catchments represent the full period of arterial drainage works in Ireland from the earliest works in the 1940s (Brosna), to the most recent scheme in the mid-1980s (Monaghan Blackwater). The most common reasons for catchment exclusion were a lack of flow gauging data during the pre-drainage period, while many smaller catchments (<100 km^2) also lacked continuous water level data.

TABLE 1 Stations selected for data rescue.

Station #	Station name	Waterbody	Catchment area (km^2)	Arterial drainage scheme	Scheme works	Drained area (km^2)
03051	FAULKLAND	BLACKWATER (MONAGHAN)	143.2	Blackwater Monaghan	1984–1992	23.67
23001	INCH BR.	GALEY	191.9	Feale	1951–1959	107.24
24012	GRANGE BR.	DEEL	366.28	Deel	1962–1968	202.34
25006	FERBANE	BROSNA	1,162.76	Brosna	1948–1955	348.83
26021	BALLYMAHON	INNY	1,098.78	Inny	1959–1963	46.94
30004	CORROFIN	CLARE	706	Corrib-Clare	1951–1959	107.24
30005	FOXHILL	ROBE	237.9	Corrib-Mask	1979–1986	97.12
34004	BALLYLAHAN	MOY	935.45	Moy	1960–1971	48.16

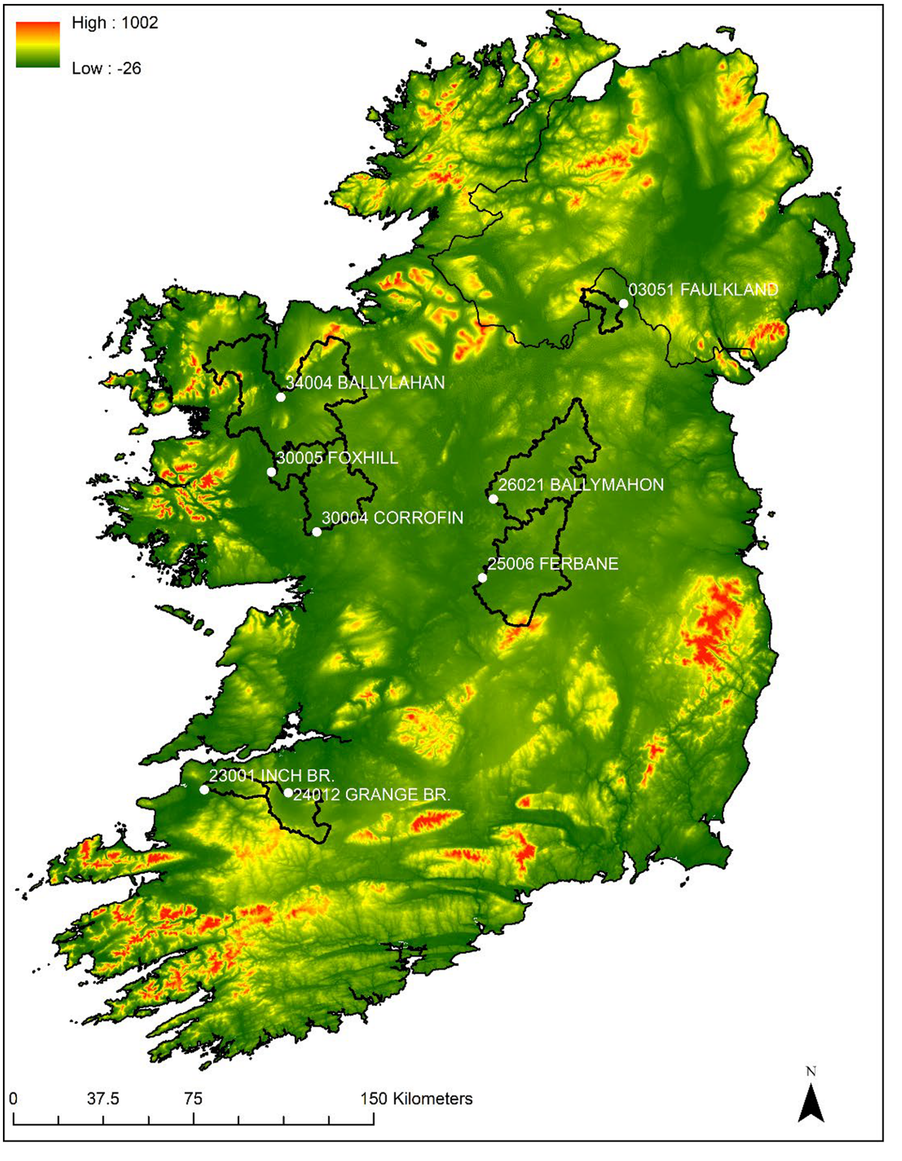


FIGURE 1 Catchments and associated gauges selected for data rescue (Source topographic data: Copernicus Land Monitoring Service, 2016).

3 | DATA RESCUE WORKFLOW

Figure 2 provides an overview of the data rescue workflow employed, comprising three key phases of data collection and review, data processing and quality assurance. Each of these phases is outlined in detail.

3.1 | Phase 1: Data collection and review

Water level data (i.e. the height of water above a local datum, also referred to as stage) were sourced from OPW's hydrometric archives in two hardcopy paper formats. Earliest data are stored as single-sheet annual summaries

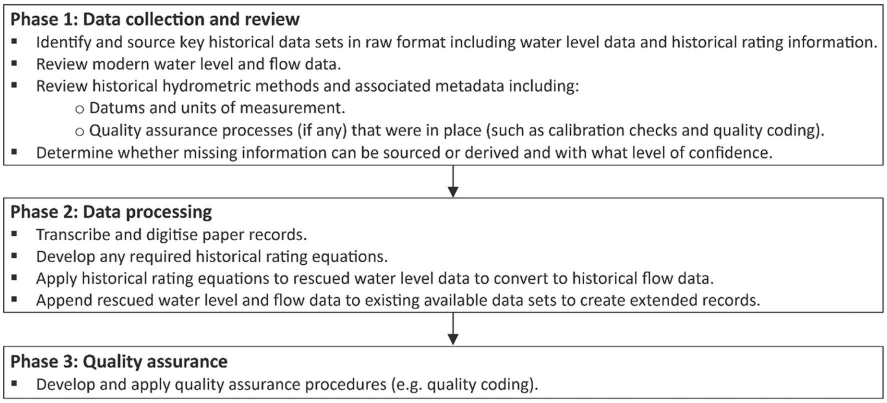


FIGURE 2 Overview of the data rescue process comprising three phases of data collection and review, data processing and quality assurance.

of daily staff gauge readings (termed 'staff data', see Figure 3). These are in imperial units of measurement and available for all eight stations from hydrometric year 1939/1940 to the late 1940s/early 1950s (depending on the station). Station #03051 Faulkland is an exception with this data format extending until 1977. In Ireland, the Hydrometric Year (HY) runs 1st October through to 30th September, e.g. 01/10/1939–30/09/1940 is HY1939.

For three stations (#23001 Inch Bridge, #26021 Ballymahon and #34004 Ballylahan), continuous water level data through the 1950s and 1960s were also collected. In the early 1950s, float and weight autographic recorders replaced the daily staff gauge reading as the primary hydrometric method. These recorders traced a continuous water level line on A3 graph paper representing approximately 7 days (termed 'chart data', see Figure 4). Charts were changed weekly and organized into books per hydrometric year. Chart data may be imperial, decimal feet (i.e. feet and tenths of a foot) or metric depending on the station and year.

Hydrometric metadata (e.g. datums, dates of autographic recorder installation, level checks and units of measurement), flow gauging data, hydrometric reports and historical rating curve data are held in mixed paper and digital format in the OPW archives. For station #03051 Faulkland historical flow gauging and rating curve data were also sourced from the Environmental Protection Agency (EPA), who have been responsible for the station since 1975. Existing available quality assured water level and flow data for each station were provided by the OPW and EPA.

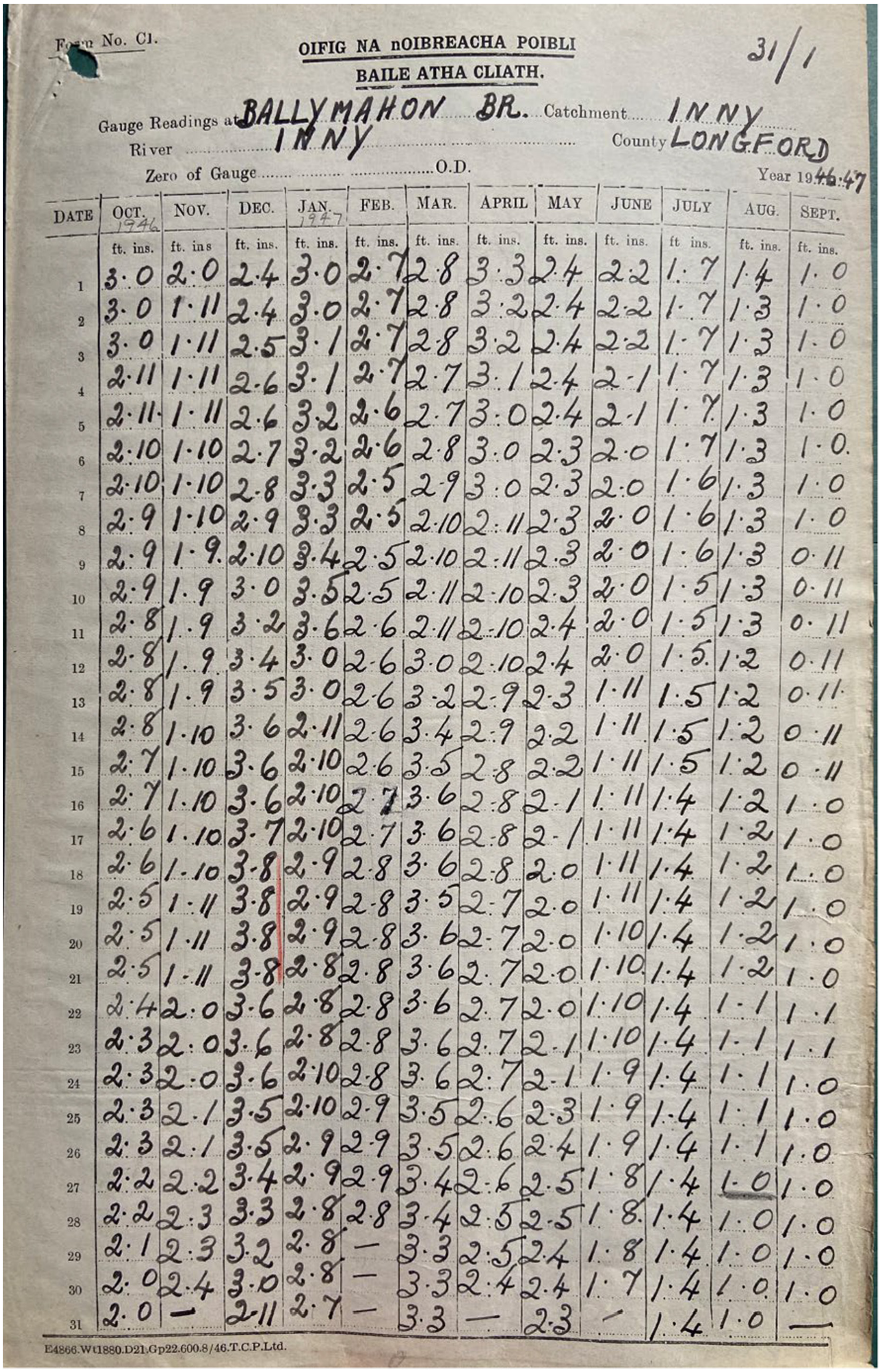
3.2 | Phase 2: Data processing

3.2.1 | Transcription of historical water levels

Transcription methods were tailored to each format of historical water level data. Staff data were manually transcribed into an MS Excel document. Care was required in the period 1939–1941 where the typesetting used often recorded imperial staff gauge readings under 1 foot as e.g., '11' rather than '0.11' (for 0′11″). Transcribed records were checked against the raw data by a second person and updated with any corrections. Data were then converted to metric values.

Transcription of the chart data followed standard OPW practices and involved two steps: editing and digitisation. Editing both prepared data for digitisation and served as a quality assurance check. It involved the addition of annotations to each weekly chart to record the start time, date and staff gauge water level (as a metric value) corresponding to when the chart was placed on the autographic recorder, and the end time, date and water level when the chart was taken off the recorder after 7 days. The end date for one chart should match the start date for the next week (i.e. charts should 'tie in' to each other to create a seamless water level record). These annotations were used during digitisation to adjust the digitized chart water level line upwards or downwards if required, e.g. when (due to human error) the chart line had not been set to the correct starting water level as per the staff gauge.

Editing effectively determined whether the chart water level line could be digitized as it appeared on the paper record or if it required correction, and if so, what correction should be applied. Data utilized during editing included: (i) annotations by the local person employed to change the weekly charts who was required to record the start/end time, date and water level as per the station staff gauge; (ii) calibration checks conducted by OPW Engineers including correction notes; and (iii) datums for staff gauges and autographic recorders. Calibration checks were considered more reliable than local person annotations and took precedence if disparities between these two sets of annotations occurred. Once edited, charts were digitized using a specialist scanning board and KiDiGi™ software. Staff and chart data were then imported into the specialist hydrometric software WISKI™ (Water Information Systems by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OIFIG NA nOIBREACHA POIBLI
BAILE ATHA CLIATH.

31/1

Gauge Readings at BALLYMAHON BR. Catchment INNY
River INNY County LONGFORD
Zero of Gauge .... O.D. Year 1946:47

DATE	OCT. 1946	NOV.	DEC.	JAN. 1947	FEB.	MAR.	APRIL	MAY	JUNE	JULY	AUG.	SEPT.
	ft. ins.	ft. ins	ft. ins.	ft. ins.	ft. ins.	ft. ins.	ft. ins.	ft. ins.	ft. ins.	ft ins.	ft. ins.	ft. ins.
1	3.0	2.0	2.4	3.0	2.7	2.8	3.3	2.4	2.2	1.7	1.4	1.0
2	3.0	1.11	2.4	3.0	2.7	2.8	3.2	2.4	2.2	1.7	1.3	1.0
3	3.0	1.11	2.5	3.1	2.7	2.8	3.2	2.4	2.2	1.7	1.3	1.0
4	2.11	1.11	2.6	3.1	2.7	2.7	3.1	2.4	2.1	1.7	1.3	1.0
5	2.11	1.11	2.6	3.2	2.6	2.7	3.0	2.4	2.1	1.7	1.3	1.0
6	2.10	1.10	2.7	3.2	2.6	2.8	3.0	2.3	2.0	1.7	1.3	1.0
7	2.10	1.10	2.8	3.3	2.5	2.9	3.0	2.3	2.0	1.6	1.3	1.0
8	2.9	1.10	2.9	3.3	2.5	2.10	2.11	2.3	2.0	1.6	1.3	1.0
9	2.9	1.9	2.10	3.4	2.5	2.10	2.11	2.3	2.0	1.6	1.3	0.11
10	2.9	1.9	3.0	3.5	2.5	2.11	2.10	2.3	2.0	1.5	1.3	0.11
11	2.8	1.9	3.2	3.6	2.6	2.11	2.10	2.4	2.0	1.5	1.3	0.11
12	2.8	1.9	3.4	3.0	2.6	3.0	2.10	2.4	2.0	1.5	1.2	0.11
13	2.8	1.9	3.5	3.0	2.6	3.2	2.9	2.3	1.11	1.5	1.2	0.11
14	2.8	1.10	3.6	2.11	2.6	3.4	2.9	2.2	1.11	1.5	1.2	0.11
15	2.7	1.10	3.6	2.10	2.6	3.5	2.8	2.2	1.11	1.5	1.2	0.11
16	2.7	1.10	3.6	2.10	2.7	3.6	2.8	2.1	1.11	1.4	1.2	1.0
17	2.6	1.10	3.7	2.10	2.7	3.6	2.8	2.1	1.11	1.4	1.2	1.0
18	2.6	1.10	3.8	2.9	2.8	3.6	2.8	2.0	1.11	1.4	1.2	1.0
19	2.5	1.11	3.8	2.9	2.8	3.5	2.7	2.0	1.11	1.4	1.2	1.0
20	2.5	1.11	3.8	2.9	2.8	3.6	2.7	2.0	1.10	1.4	1.2	1.0
21	2.5	1.11	3.8	2.8	2.8	3.6	2.7	2.0	1.10	1.4	1.2	1.0
22	2.4	2.0	3.6	2.8	2.8	3.6	2.7	2.0	1.10	1.4	1.1	1.1
23	2.3	2.0	3.6	2.8	2.8	3.6	2.7	2.1	1.10	1.4	1.1	1.1
24	2.3	2.0	3.6	2.10	2.8	3.6	2.7	2.1	1.9	1.4	1.1	1.0
25	2.3	2.1	3.5	2.10	2.9	3.5	2.6	2.3	1.9	1.4	1.1	1.0
26	2.3	2.1	3.5	2.9	2.9	3.5	2.6	2.4	1.9	1.4	1.1	1.0
27	2.2	2.2	3.4	2.9	2.9	3.4	2.6	2.5	1.8	1.4	1.0	1.0
28	2.2	2.3	3.3	2.8	2.8	3.4	2.5	2.5	1.8	1.4	1.0	1.0
29	2.1	2.3	3.2	2.8	—	3.3	2.5	2.4	1.8	1.4	1.0	1.0
30	2.0	2.4	3.0	2.8	—	3.3	2.4	2.4	1.7	1.4	1.0	1.0
31	2.0	—	2.11	2.7	—	3.3	—	2.3	—	1.4	1.0	—

E4866.Wt1880.D21.Gp22.600.8/46.T.C.P.Ltd.

FIGURE 3 Sample annual summary of daily staff gauge readings for station #26021 Ballymahon during the Irish hydrometric year 1946–1947.

KISTERS) and converted to absolute water levels using the appropriate Ordnance Datum(s).

3.2.2 | Specific issues related to chart data

Table 2 summarizes the data quality issues encountered during the editing of chart data and the Standard Operating Procedure (SOP) applied to resolve them. These quality issues can be broadly categorized as either Hydrometric (denoted 'H') or Equipment (denoted 'E'). The former related to aspects within the control of the hydrometric practitioner and the latter related to unforeseen malfunction in the technology employed. The category 'Other' (denoted 'O') refers to issues that do not fall within these categories. Hydrometric data issues were generally resolvable, and data could be rescued; however, several equipment issues rendered data unusable and effectively lost.

3.2.3 | Historical rating curves

To convert the rescued water level data to flow for each station, a rating curve was required that described the

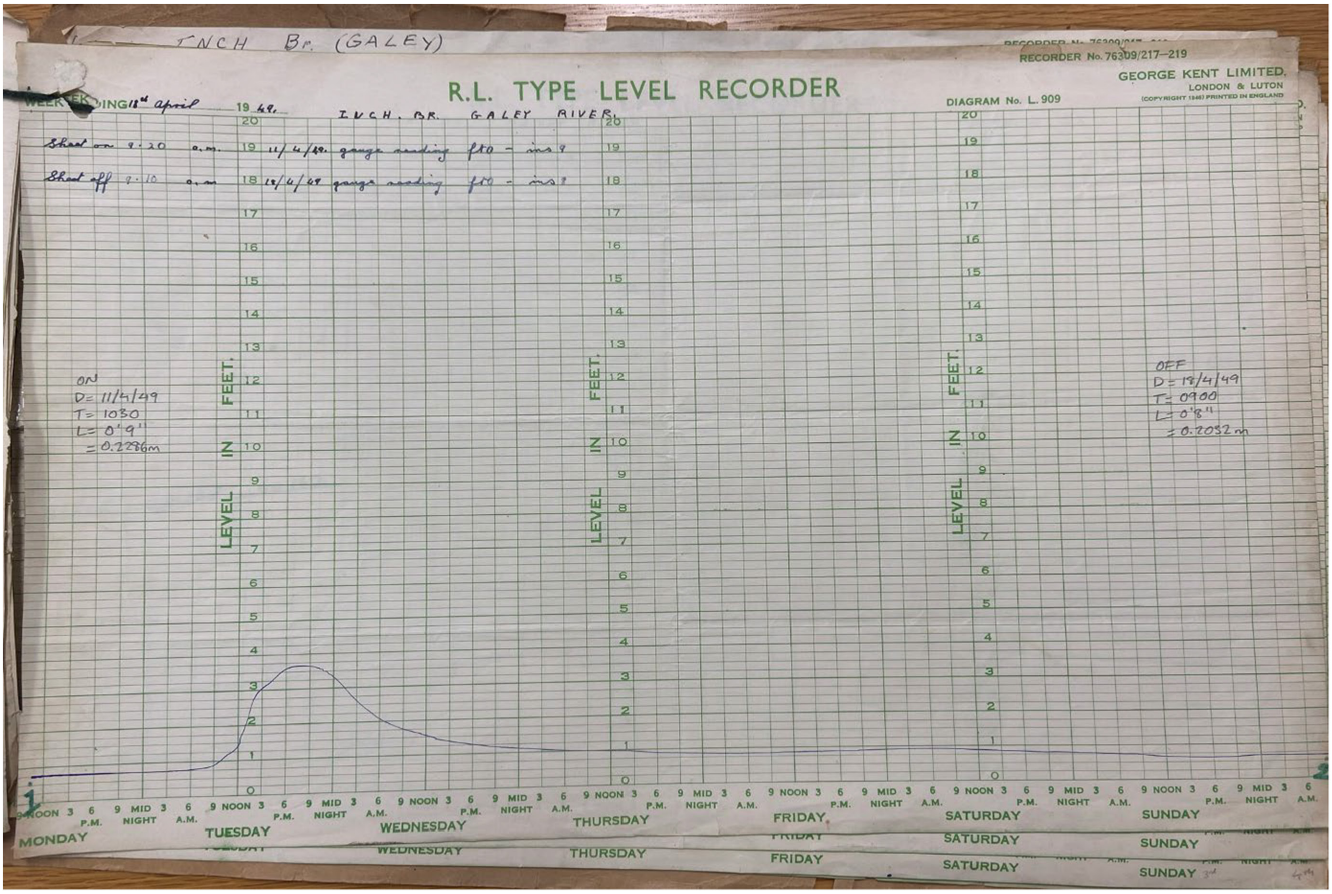

FIGURE 4 Sample weekly autographic recorder chart of continuous water level data for station #23001 Inch Bridge dated 11/04/1949–18/04/1949.

water level-flow relationship during that period. For five stations, historical rating curves were provided by the OPW. Consistent with their ISO 9001:2015 accredited procedure, these were developed with a minimum of nine flow gaugings for the historical period covering low, medium and high flow conditions. Each rating curve is valid for the period associated with the flow gaugings used in its construction. Given the channel geometry changes associated with the arterial drainage schemes, stations were re-rated after the works and each station has two sets of rating curves: pre- and post-drainage. These earliest rating curves describe pre-drainage conditions.

Historical pre-drainage rating curves were developed for stations #03051 Faulkland, #25006 Ferbane and #34004 Ballylahan because none were available. Representing low, medium and high flow conditions, 9 historical flow gaugings collected by the OPW and EPA were used to derive the rating equation for #03051 Faulkland, whereas 14 flow gaugings were used for #34004 Ballylahan. The rating curve for #25006 Ferbane was sourced from O'Kelly (1945) based on 28 flow gaugings conducted between 01/01/1940 up to and including the winter of 1944. Further details about each derived rating curve are available in the README file for each station's published data set.

3.2.4 | Historical flow data and record extension

The rescued water level data were converted to historical flow data via application of the appropriate historical rating curve. Generally, the first flow gaugings were conducted in the early to mid-1940s. For five stations this meant the period between the start of the historical water level record and the first flow gauging was without an associated rating curve. To bridge this gap, the earliest rating curve has retrospectively been applied back to the start of the historical water level record to create an extended flow record that uses all available rescued data per station. This was justified on the basis that there is no evidence in the hydrometric records of significant channel modification during this period at any of these stations (e.g. as indicated by a change in staff gauge zero). It assumes that the catchment rainfall-runoff response was unchanged.

TABLE 2 Standard operating procedure to resolve data quality issues encountered in chart data (numbered and denoted H = Hydrometric, E = Equipment, O = Other).

Quality issue	Type	Description	Evidence on charts	Standard operating procedure during editing	Data rescued?
Loss of data	H	Water level line (pencil or pen) has degraded over time.	Faded water level line that is difficult to see. The indentation from the pen/pencil on the paper chart may be preserved. (H1)	Where the faded line could confidently be restored, it was traced with a red dashed pen line.	Yes
			No or minimal markings are present, chart is essentially blank. (H2)	Weekly chart could not be digitized, data are lost.	No
Missing annotations	H	Chart annotations by local person are partial or missing entirely.	Chart annotations by local person of the start and end staff gauge levels, dates and/or times are partial or missing. (H3)	Missing information was determined from contextual sources, e.g. dates, times and levels in the previous and following weeks, and annotations added to the charts.	Yes
Inconsistent datums	H	Staff gauge datum differs from the autographic recorder datum.	The start/end staff gauge water levels annotated by the local person do not match the chart line start/end water level because the data are different (i.e. they always differ by the mismatch in datum levels). This means the annotated staff gauge levels are not directly transferable to the chart line and a calculation is required. (H4)	Staff gauge start/end water levels and the datums for both staff gauge and autographic recorder were used to calculate the correct chart line start/end water levels. Annotations added to the charts.	Yes
Staff gauge unusable	H	Staff gauge unreadable either at all or below a certain level (e.g. due to siltation).	Start/end staff gauge water level readings are missing. Usually accompanied by an annotation from the local person but not always. (H5)	The chart was accepted as correct in time and level unless any calibration checks in nearby weeks indicated otherwise, or it did not tie into the weeks either side of it, in which case corrections were made.	Yes
Inconsistent station management	H	Local person has not changed the chart on a regular weekly basis.	There are multiple lines per weekly chart; however, they are distinguishable and levels tie in to the weeks either side. (H6)	Using contextual information from the previous and following weeks, the lines were distinguished from each other, and start/end annotations were added per line.	Yes
Clock malfunction	E	Clock does not run true to time but has run fast, over-rotating the drum and chart.	The length of the weekly water level line exceeds the period accounted for i.e. there may be two or three distinguishable water level lines captured on the one chart. (E1)	Using the start and end dates/times for the entire period and the total length of line recorded, the correct start/end dates, times and levels were calculated for each individual line and annotations added.	Yes
			Multiple indistinguishable water level lines are recorded. Usually occurs when the malfunction is more pronounced. (E2)	Cannot be used for any purpose except identifying AMAX events, and even then, the precise date, time and hydrograph shape will be unknown because no sense can be made of the different lines. Weekly chart could not be digitized.	No

(Continues)

TABLE 2 (Continued)

Quality issue	Type	Description	Evidence on charts	Standard operating procedure during editing	Data rescued?
Drum malfunction	E	Rotation of the drum appears affected, often accompanied by a note from the local person explaining the drum 'got stuck'.	Pen line runs up and down the y (water level) axis without moving along the x axis as time progresses. (E3)	The water level line was digitized in parts: as one entry up to the point of malfunction and then as a second entry with a corrected start time after this was calculated from the length of the vertical line (i.e. the duration of malfunction).	Yes
Pen malfunction	E	Pen appears to jump rather than smoothly track water level change.	Step change in water level line. (E4)	The water level line was digitized in parts: as one entry up to the step change and another entry beginning after the step change. This preserved the water level information but the hydrograph shape is unknown. Digitized as one line if the magnitude of the step change was very minor in the context of the water level variation across the weekly record.	Yes
		Pen not working or not firmly set to paper	Water level line is patchy but most of the day/week/event in question is present. (E5)	Consistent with OPW practices and based on careful examination of river behaviour across the hydrometric year, data gaps are interpolated using red dashed pen lines.	Yes
			Water level line is missing or very patchy. (E6)	Data are essentially missing, and chart could not be digitized.	No
Other malfunction	E	Annotation from local person or technician notes that the autorecorder is out of order but without an explanation.	Water level line is missing or patchy. (E7)	Data are essentially missing, and chart could not be digitized.	No
Pump test	O	Pump test carried out.	Water level lines spikes and then has characteristic drawdown shape. (O1)	Period relating to pumping event was discarded and not digitized.	No

TABLE 3 Quality codes assigned to historical water level data (Hx, Ex, refer to the quality issues outlined in Table 2 that may have been encountered).

Code	Symbol	Current OPW application		Application to historical data	
		Name	**Description**	**Name**	**Description**
NA	Missing	Missing	Data are missing.	Missing	Data are missing i.e. no staff gauge reading or chart record exists for this day.
31	31	Inspected (Good)	Inspected water level data – Data may contain some error but has been approved for general use.	Good	Data are considered Good quality. The date, time, and start/end water levels are consistent with calibration checks and tie in to the preceding and following week. No corrections were required. Regular calibration checks have ensured the gauge was working properly or, where calibration checks may have been less frequent, there is no evidence of data quality issues and consistent and accurate staff gauge annotations have been made by the local person. (H1, H3, H4, H6)
32	C	Inspected (Good -modified)	As per Code 31, but digitized water level data has been corrected.	Good (modified)	As per Code 31, however some corrections were made during editing due to Hydrometric quality issues. The digitized water level data have been corrected. (H1, H3, H4, H6)
41	B	Poor	Poor measured water level data.	Fair	Data are considered Fair quality, reflecting a relatively lower level of confidence than for codes 31/32. Calibration checks may be infrequent or missing entirely, however there is no evidence that the gauge was significantly malfunctioning. Hydrometric quality issues may be present. Given the low number of calibration checks, contextual information has been key to determining the reliability of the chart, for example, if local person staff gauge annotations are missing for a period of several weeks but when they are present they match the chart line consistently, this indicates the work of the local person was generally reliable and the charts with missing annotations are treated as such. In all instances, the water levels recorded during calibration checks take precedence over staff gauge annotations by the local person. (H1, H3, H4, H5, H6)
42	42	Poor (modified)	As per Code 41, but digitized water level data has been corrected.	Fair (modified)	As per Code 41, however, some corrections were made during editing due to Hydrometric or Equipment quality issues. (H1, H3, H4, H5, H6, E1, E3, E4, E5) Importantly, all daily staff gauge records from the earliest period of data rescue are coded 42. This reflects uncertainty around the underlying assumption that these values accurately represent the true daily mean.

(Continues)

TABLE 3 (Continued)

		Current OPW application		Application to historical data	
Code	**Symbol**	**Name**	**Description**	**Name**	**Description**
99	*	Unchecked	Superseded by Code 254.	N/A	Not used in historical data rescue.
101	!	Unreliable	Data are suspected of being erroneous or is artificially affected (e.g., noisy data, blockages causing elevated levels, temporary works).	Unreliable	Data are suspected to be unreliable and generally cannot be interpreted or rescued, usually associated with severe equipment malfunction. This code also applies to situations where there has been a significant step change in the water level line, but the new water level line recorded does not match with the water levels of the following week. Here it is assumed the gauge has malfunctioned for the remainder of the weekly chart and the data cannot be trusted. (E2, E4, O1)
150	Various	Partial	Data are not available as they are missing, erroneous or of unacceptable quality	Partial	Data are missing for an entire day due to hydrometric or equipment issues and cannot be interpolated or determined. This code is used to differentiate data missing due to quality issues versus that where the chart is missing entirely (i.e. coded NA). (H2, E6, E7)
254	*	Unchecked	Unchecked digitized or imported water level data. Data are provisional only and must be used with caution.	N/A	Not used in historical data rescue.

TABLE 4 Example of quality assurance metadata table for station #26021 Ballymahon.

HY	Chart type	Chart height	#local person notes	#technician notes	#calibration points	Staff gauge zero (SGZ)	Auto-zero (AGZ)	Quality notes	% missing data
26021 Ballymahon *Staff gauge is IMPERIAL and charts are in HYDROMETRIC FEET*									
1956	Hydrometric feet	10’	None	20/06/1957	18/01/1957 15/05/1957 12/06/1957 24/07/1957 05/09/1957 12/09/1957	147.47′ OD	147.00′ OD	There was only one calibration check between October and April, after which checks became more frequent. Generally correct water levels were determined by working forwards and backwards from calibration checks and comparison with the recorded water level line. Staff gauge annotations were generally not trusted because: (i) they implied more variation than the recorded water level line showed and Ballymahon is known for long stable periods of flow (this decision to favour the recorded water level line was agreed with OPW Hydrometrics); and (ii) several calibration checks showed a different annotated staff gauge level to the one annotated by the local person on the chart. We suspected that the staff gauge was not being consistently read accurately by the local person. Where there was missing data, or an absence of checks for several months, the start/end water levels were taken from the staff gauge annotations in the absence of other confirming information. If this resulted in a jump in water level at the next calibration check, then generally the error (i.e. the difference) was averaged out over several weeks so the water level tie-in was smooth.	3.56

TABLE 5 Quality codes assigned to extended flow records.

Code	Symbol	Current OPW application		Historical flow record	
		Name	Description	Name	Description
NA	Missing	Missing	Input water level data are missing.	Missing	Input water level data are missing.
31	31	Good	Flow data estimated using a rating curve that is of Excellent or Good quality and inspected (Good) water level data. Data may contain some error but are of acceptable quality for general use.	Good	Flow data estimated using an historical rating curve that is of Good quality and Good historical water level data. Data may contain some error but are of acceptable quality for general use.
32	C	Good	As per Code 31 but using water level data of Code 32.	Good	As per Code 31 but using water level data of Code 32.
36	F	Fair	Flow data estimated using a rating curve that it is of Fair quality and inspected or corrected (Good) water level data. Data may contain a fair degree of error and should therefore be treated with some caution.	Fair	Flow data estimated using an historical rating curve that it is of Fair quality and Good historical water level data. Data may contain a fair degree of error and should therefore be treated with some caution.
41	B	Fair	Flow data estimated using a rating curve that it is of Excellent or Good quality and Poor measured water level data. Data may contain a fair degree of error and should therefore be treated with some caution.	Fair	Flow data estimated using an historical rating curve that is of Good quality and Fair historical water level data. Data may contain a fair degree of error and should therefore be treated with some caution.
42	(42)	Fair	As per Code 41 but using water level data of Code 42.	Fair	As per Code 41 but using water level data of Code 42.
46	B	Poor	Flow data estimated using a rating curve that is of Poor quality and inspected or corrected water level data. Data may contain a significant degree of error and should therefore be used for indicative purposes only.	Poor	Flow data estimated using an historical rating curve that is of Poor quality and Good or Fair historical water level data. Data may contain a significant degree of error and should therefore be used for indicative purposes only.
56	X	Extrapolated	Flow data estimated using an extrapolated rating curve and inspected or corrected water level data. Reliability of data is unknown and it should therefore be treated with caution.	Extrapolated	Flow data estimated using an extrapolated rating curve and Good or Fair historical water level data. This includes flow data produced through retrospective application of rating curves beyond the earliest flow gauging date. Reliability of data is unknown and it should therefore be treated with caution.

TABLE 5 (Continued)

Code	Symbol	Current OPW application		Historical flow record	
		Name	Description	Name	Description
96	P	Provisional	Flow data estimated using a Provisional rating curve. Data may be subject to revision following retrospective assessment of rating curves with the most recently taken flow measurements.	N/A	Not used in historical data rescue.
101	!	Unreliable	Flow data that have been estimated using Unreliable water level data. Data are suspected of being erroneous and must only be used with caution.	Unreliable	Flow data that have been estimated using Unreliable water level data. Data are suspected of being erroneous and must only be used with caution.
254	*	Unchecked	Flow data have been estimated using unchecked water level data. Data are provisional only and must be used with caution.	N/A	Not used in historical data rescue.

The historical water level and flow data were then appended to the existing available data for each station to create extended water level and flow records.

4 | QUALITY ASSURANCE PROTOCOLS AND OVERALL DATA QUALITY

4.1 | Phase 3: Quality assurance

4.1.1 | Historical water level data

Quality assurance of the rescued water level data was undertaken via a Standard Operating Procedure to assign quality codes and record detailed summary metadata during editing and digitisation. Quality codes were assigned to indicate the reliability and level of confidence in the historical data and do not reflect any quantitative analysis of error. Codes were adapted from existing OPW quality assurance methods by re-defining a subset of codes to reflect the specific historical data quality issues encountered (Table 3). A single quality code was assigned to each day of rescued water level data and appended to the record in WISKI.

The existing OPW method classifies water level data as Good, Poor, Unreliable or Unusable. Differentiation between Good and Poor for contemporary data is possible due to real-time data monitoring that enables quality issues to be identified and confirmed with certainty when data issues are suspected. In contrast, historical data rescue relied solely on the editing process (and associated information) to judge data quality. As a result, designation of quality codes is somewhat subjective where we felt confident about the reliability of the rescued data (Good), relatively less confident (Fair) or deemed data compromised given the observed quality issues (Unreliable). Table 3 provides the rationale for each quality code and links these with the quality issues encountered.

Importantly staff data have been assigned code 42 (Fair) because: (i) raw staff data had no accompanying annotations or metadata to identify quality issues or differentiate between the daily values in terms of quality; (ii) it is unclear how regularly the staff gauges, or local hydrometric practice, were checked by OPW; and (iii) there is uncertainty about the underlying assumption that these values accurately represent the true daily mean, given they are a single reading in time rather than an average of daily conditions. Quality coding these data as Fair therefore represents a conservative approach and signals to data users to think carefully about how potential error in these data could affect their particular study e.g. analysis of peak flows or runoff response if the true magnitude of a high flow event is missed.

For rescued chart data, an Excel file was compiled containing detailed notes and photographs describing the quality issues of specific charts and the decision(s) taken during data editing and quality coding. This was summarized in a metadata table per station that describes the overall data quality per hydrometric year and key hydrometric information. An example of HY1956 for station #26021 Ballymahon is shown in Table 4.

4.1.2 | Historical rating curves

Each rating curve was quality coded to reflect the level of confidence held about its accuracy based on the number and scatter of relevant flow gauging points, the stability and/or seasonality of the rating and any other factors that might affect the reliability of flow data derived from the rating. Where a rating curve is defined by two or more equations (e.g. one equation for low flows and another for medium to high flows), then each equation is quality coded separately. The quality codes are: 6 – Excellent, 16 – Good, 36 – Fair, 46 – Poor, 56 – Extrapolated and 96 – Provisional. Code 56 refers to a rating defined for water levels beyond the measured range (i.e. for ungauged flow conditions) and code 96 refers to the modern provisional rating curve which has yet to be confirmed with a recent gauging.

4.1.3 | Historical flow data

Quality codes were assigned to each daily flow value to reflect both the quality of the input water level data and the rating curves applied. For example, if the water level data was coded 31 (Good) but the rating curve was coded 46 (Poor), then the output flow value was coded 46 (Poor). This conservative approach to quality coding flow data reflects the influence of the comparatively less reliable component on the final data output. All flow data associated with retrospective application of rating curves prior to the first flow gauging have been quality coded 56 (Extrapolated). Generally historical water levels with quality code 101 (Unreliable) or 150 (Partial) were not converted to flow and consequently flow values are NA (Missing) for those days. These quality codes appeared only in the rescued chart data at stations #23001 Inch Bridge, #26021 Ballymahon and #34004 Ballylahan and accounted for 15%, 2.9% and 0.4% of rescued water level data respectively. Table 5 summarizes the quality codes used for the historical flow data as adapted from the existing OPW approach.

4.1.4 | Extended records

Extended water level and flow records were quality screened using the R environment, including checked for missing dates and percentages of missing data calculated. A series of visual checks were performed to:

- identify obvious outliers and check these values against the raw data to ensure correct transcription (i.e. no outliers were removed, only confirmed as a true transcription, see README files for station specific comments);
- examine the tie-in between historical and existing records to identify issues such as a misapplied datum in either the historical or existing data;
- examine the range of values and the shape of hydrographs observed in the historical and existing data sets to identify whether the rescued data reflected what would be expected for each station; and
- identify any gaps or jumps in the data so that these could be investigated and accounted for, e.g. usually because of equipment or hydrometric quality issues.

5 | DATA SET ACCESS AND QUALITY

The data are freely available from the open access PANGAEA data publisher (https://doi.org/10.1594/PANGAEA.950792). Individual station folders include: (i) an ASCII format data file of the daily mean extended absolute water level series from HY1939 to HY2020; (ii) an ASCII format data file of daily mean extended flow series from HY1939 to HY2020; and (iii) a README text file containing station-specific information about the data rescue process (e.g. metadata, notes on data quality, rating curves, missing data etc). Data files contain three columns providing the date (DD/MM/YYYY), value in metric

FIGURE 5 (a) Extended flow records for stations #03051 Faulkland, #23001 Inch Bridge, #24021 Grange Bridge and #25006 Ferbane. Red lines display the historical flow series created from the rescued water level data, and black lines display the existing available flow record to which the rescued data have been appended. Green rectangles highlight indicative flow records due to retrospective application of historical rating curves. The period of arterial drainage installation is also indicated. (b) As per Figure 5a but for stations #26021 Ballymahon, #30004 Corrofin, #30005 Foxhill and #34004 Ballylahan.

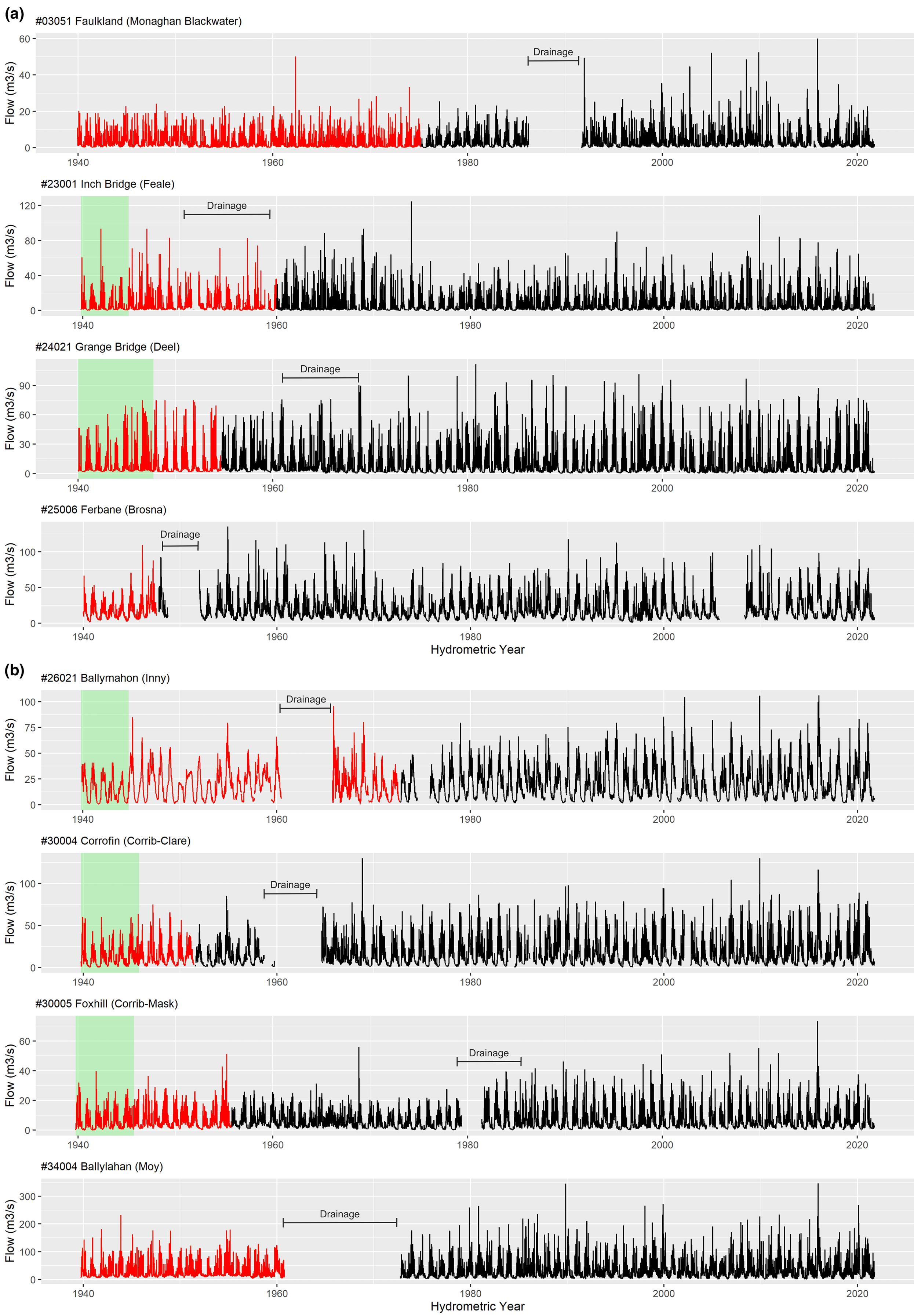
(a)
#03051 Faulkland (Monaghan Blackwater)
Drainage
Flow (m3/s)
#23001 Inch Bridge (Feale)
Drainage
Flow (m3/s)
#24021 Grange Bridge (Deel)
Drainage
Flow (m3/s)
#25006 Ferbane (Brosna)
Drainage
Flow (m3/s)
Hydrometric Year
(b)
#26021 Ballymahon (Inny)
Drainage
Flow (m3/s)
#30004 Corrofin (Corrib-Clare)
Drainage
Flow (m3/s)
#30005 Foxhill (Corrib-Mask)
Drainage
Flow (m3/s)
#34004 Ballylahan (Moy)
Drainage
Flow (m3/s)
Hydrometric Year

TABLE 6 Overview of the extended water level and flow records.

Station #	Station name	Previously available record – start date	Extended record: Total period	Extended record: Years added	Data rescued: Staff gauge (daily)	Data rescued: Autographic recorder (continuous)
03051	FAULKLAND	25/03/1975	Dec 1939 – Sept 2021	35	12/12/1939–23/04/1977	None
23001	INCH BR.	01/01/1960 (WL) 05/06/1972 (Q)	Oct 1939 – Sept 2021	20	15/10/1939–26/02/1949	10/03/1949–31/12/1959
24012	GRANGE BR.	01/10/1954	Jan 1940 – Sept 2021	14	05/01/1940–04/09/1954	None
25006	FERBANE	24/10/1947 (WL) 01/01/1952 (Q)	Jan 1940 – Sept 2021	8	01/01/1940–26/07/1947	None
26021	BALLYMAHON	01/10/1972	Nov 1939 – Sept 2021	27	28/11/1939–02/05/1953 09/10/1965–26/11/1966	16/05/1953–27/06/1960 17/11/1966–30/09/1972
30004	CORROFIN	04/08/1951	Oct 1939 – Sept 2021	11	08/10/1939–12/06/1951	None
30005	FOXHILL	14/10/1955	Oct 1939 – Sept 2021	16	01/10/1939–10/12/1955	None
34004	BALLYLAHAN	17/05/1974	Oct 1939 – Sept 2021	21	01/10/1939–24/11/1951	27/10/1951–30/09/1960 01/10/1972–16/05/1974

units (AbsWL = Absolute Water Level in metres Above Ordnance Datum, Q = Flow rate in cubic metres per second) and quality code (QC). Quality code keys are provided in Tables 3 and 5. For stations #23001 Inch Bridge, #26021 Ballymahon and #34004 Ballylahan, metadata summary tables relating to the rescue of the chart data are also provided in ASCII format.

Figure 5a, b shows the extended flow series, while Table 6 provides an overview including the number of years added to existing records and the length of each contributing data source. The stations that were removed during installation of arterial drainage works have been identified because they are missing water level and flow data for that period. For station #23001 Inch Bridge, water level data were previously available from 01/01/1960 but flow only from 05/06/1972. No reason was found as to why water level data for 1960–1972 had not previously been converted to flows. Given the rating curves for this period are considered suitable for use in flow calculations, this water level data was converted as part of this study. The same applies for the period 01/10/1972–16/05/1974 for station #34004 Ballylahan. For station #25006 Ferbane, the derived historical rating curve was also applied to chart data for HY1947 that had never been converted to flows. This added another year to the 7 years of rescued historical data. Also, the precise date of logger installation was not recorded for this station but was assumed to be the end of the missing data period 27/09/2005–23/04/2008 that correlates with recorded logger installation at nearby stations (e.g. #25016 Rahan, #25014 Millbrook).

5.1 | Summary of data quality

Every station has Good or Fair data for approximately 60% or more of the total extended flow record. For four stations (#03051 Faulkland, #25006 Ferbane, #23001 Inch Bridge and #26021 Ballymahon), this exceeds 80% of the extended record. Station #34004 Ballylahan contains the lowest proportion of Good or Fair data (56%), with 26% of the record rated Poor primarily due to some quality issues in the rescued chart data from 1951–1956 and scatter at the low flow end of the pre-drainage rating curve resulting in that rating curve being quality coded 46 (Poor). Figure 6a, b illustrate the proportions of each quality code per hydrometric year per station. Extrapolated data in the period of data rescue are largely related to retrospective application of rating curves.

On average there are 9% missing data across all extended flow series, ranging from 2.7% to 16.2% (#24012 Grange Bridge and #34004 Ballylahan respectively) (see Table 6). The most common reasons for missing data are equipment malfunction, gaps associated with changeover between hydrometric data collection methods and station removal during arterial drainage works. At Ballylahan, an

Start date of hydrometric data source used to create extended series					
Staff gauge (daily)	Autographic recorder (continuous)	Digital logger + pressure transducer (continuous)	Date of first flow gauging	Station removed during drainage installation?	Missing data in extended flow record (%)
12/12/1939	25/03/1975	17/01/2000	Unknown (suspect 1939–1948)	No	9.42
15/10/1939	10/03/1949	17/09/2001	08/01/1945	No	5.20
05/01/1940	01/10/1954	17/09/2001	26/01/1948	No	2.68
01/01/1940	24/10/1947	28/04/2008	04/01/1952	Yes	10.78
28/11/1939	16/05/1953* *Staff data 09/10/1965–16/11/1966	03/10/2001	05/03/1942	Yes	10.22
08/10/1939	04/08/1951	27/09/2002	07/03/1946	Yes	13.24
01/10/1939	14/10/1955	29/05/2001	01/03/1946	Yes	4.51
01/10/1939	27/10/1951	18/09/2002	14/06/1940	Yes	16.22

inability to define a rating relationship during the arterial drainage works meant all water level data from 1960–1972 were unable to be converted to flow and are missing from the final extended flow record.

6 | DATA SET USE AND LIMITATIONS

The extended river flow and water level records provide a valuable resource for investigating hydrological response to arterial drainage. The long records, which extend back to the commencement of hydrometric monitoring on the island will also be important for detection and attribution of changes across the flow regime, including low flows and drought (Nasr & Bruen, 2017), changing flood risk dynamics (Chen et al., 2021; Faulkner et al., 2019) and linking with changing riverine ecological conditions (Poff & Zimmerman, 2010). Furthermore, these long series offer empirical data to assist validation of flow reconstructions (O'Connor et al., 2021, 2022) and for training hydrological models across diverse hydrological and climatic conditions (Broderick et al., 2016). There is also opportunity for other research fields to cross-validate their historical data (e.g. water quality or ecology) with these river flow records.

The quality of extreme low or high flow data is affected by the success of flow gauging under these conditions. Some stations (e.g., #03051 Faulkland, #34004 Ballylahan) therefore have greater reliance on extrapolations at the lowest and highest range of flows, which may be relevant for extreme flow analysis. The extended water level data may serve as useful proxy for low flow investigations in these cases. Station #24012 Grange Bridge contains specific low flow limitations due to poor positioning of the staff gauge between HY1939 and HY1960 (further outlined in the README file for this station). These data points have been indicated with quality code 101 (Unreliable) in the extended series. All extended data sets utilize extrapolated rating curves for the highest flows.

Future users should be aware that any error in the rescued data will propagate through as uncertainty in derived metrics (Kennard et al., 2009). Although the methodology employed attempted to constrain subjectivity in decision-making, it cannot be fully eliminated. Data derived from the staff gauge are more likely to contain error than those derived from the continuous chart data. However, these are the only empirical data for the earliest years on record.

7 | GUIDANCE FOR FUTURE HYDROMETRIC DATA RESCUE

Based on insights from this work, Figure 7 provides a revised workflow as guidance for future hydrometric data rescue

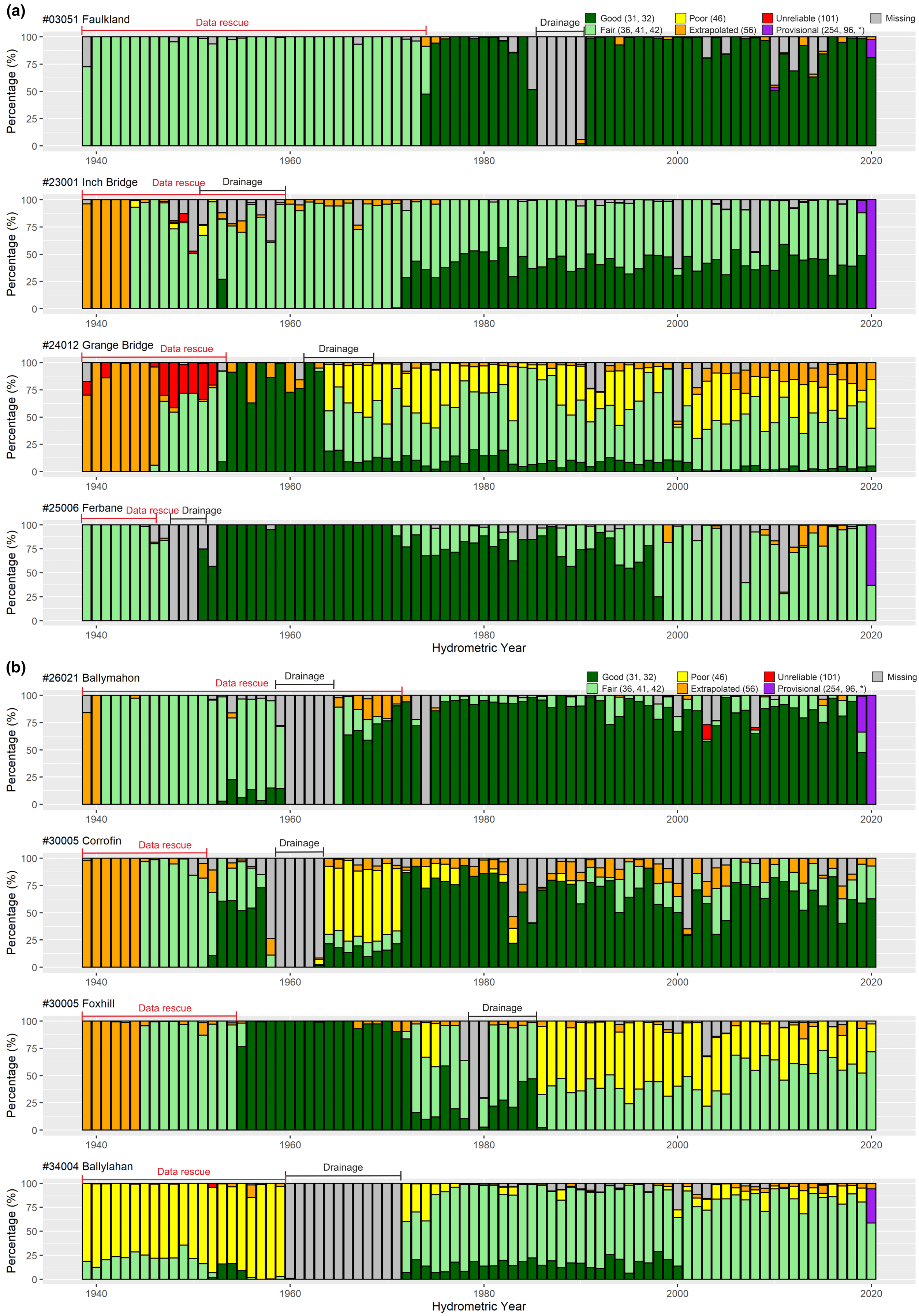
(a)
#03051 Faulkland
Data rescue
Drainage
Good (31, 32)
Fair (36, 41, 42)
Poor (46)
Extrapolated (56)
Unreliable (101)
Provisional (254, 96, *)
Missing
Percentage (%)
#23001 Inch Bridge
#24012 Grange Bridge
#25006 Ferbane
Hydrometric Year
(b)
#26021 Ballymahon
#30005 Corrofin
#30005 Foxhill
#34004 Ballylahan
1940
1960
1980
2000
2020

FIGURE 6 (a) Overview of quality codes across extended flow records for stations #03051 Faulkland, #23001 Inch Bridge, #24021 Grange Bridge and #25006 Ferbane with periods of data rescue and arterial drainage installation indicated. (b) As per Figure 6a but for stations #26021 Ballymahon, #30004 Corrofin, #30005 Foxhill and #34004 Ballylahan.

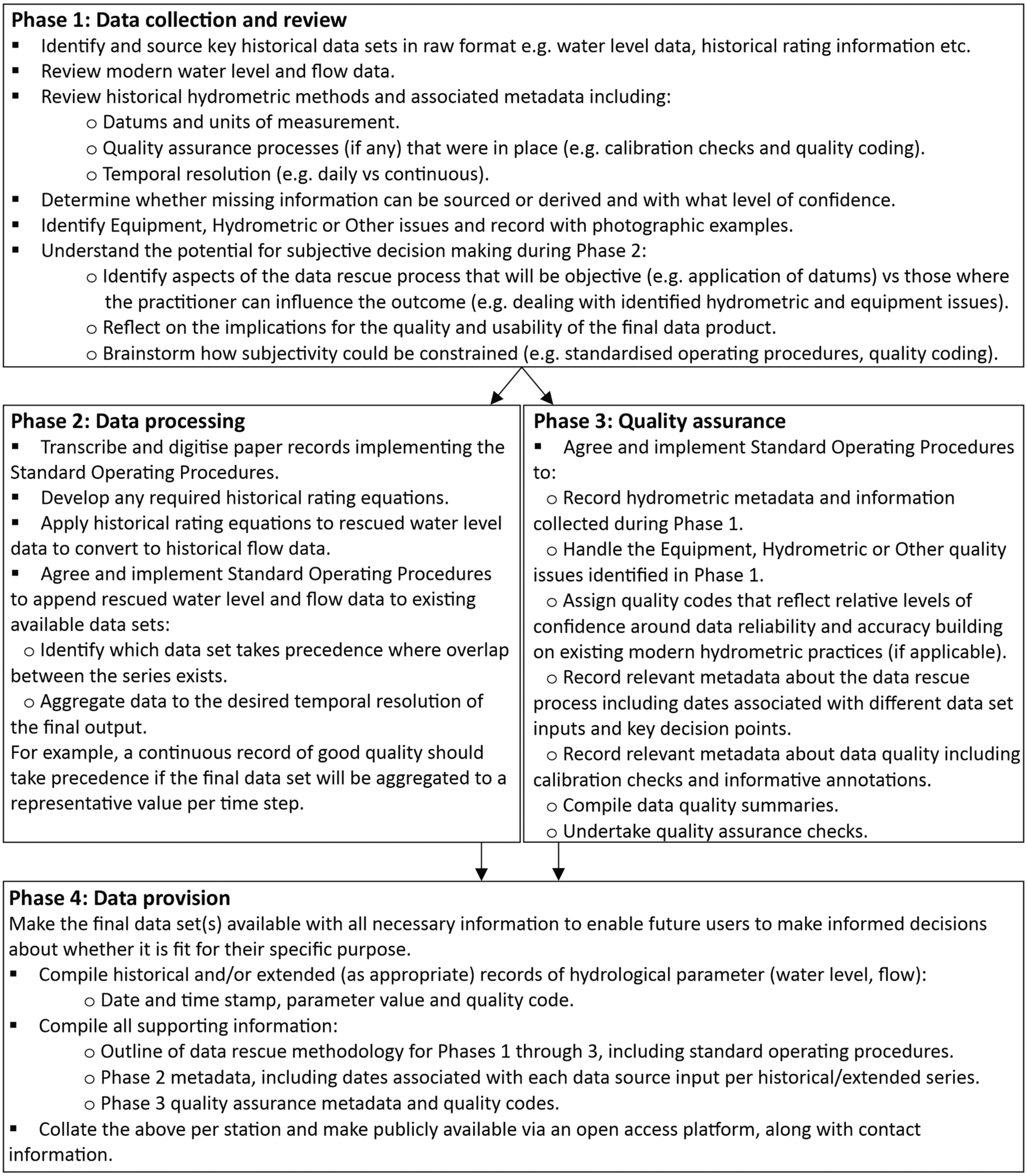

FIGURE 7 Revised workflow (from Figure 2) detailing key considerations during each phase of hydrometric data rescue, highlighting the concurrent nature of data processing and quality assurance phases and presenting data provision as a core fourth phase of the rescue process.

efforts, reflecting three key lessons learned. First, subjectivity during data rescue (such as deciding how to approach data quality issues (Table 2) and determining corrections during editing) can affect the accuracy of the final product. To constrain subjectivity and ensure decisions about data are reproducible, data processing requires standardized operating procedures that should be agreed between data rescue practitioners and data holders (e.g., agencies responsible for the hydrometric data). Importantly, standard procedures relating to quality assurance such as quality coding (Phase 3) must be conducted alongside the transcription, digitizing and record extension components of data processing (Phase 2), meaning these phases should occur concurrently with rather than sequentially.

Second, quality coding approaches for historical data should complement the existing approach employed by hydrometric agencies to ensure compatibility between contemporary and rescued records. Considering the intention behind different quality levels by thinking about data broadly grouped as 'best available', 'compromised' or 'estimated' (Commonwealth of Australia, 2019) can help to draw parallels between modern and historical data more easily than taking an overly prescriptive approach, especially given that data may be collected using several different hydrometric practices over time.

Third, provision of quality codes alone is an insufficient level of detail to allow future users to decide whether the data are suitable for intended purposes. For example, a researcher interested in low flow analysis needs to be aware that rescued data coded 'Unreliable' for #24012 Grange Bridge due to a badly positioned staff gauge are likely to be overestimates but are not necessarily unusable. Quality codes must be provided alongside more detailed metadata to communicate quality issues and decisions made during data rescue. Practitioners should explicitly consider, plan and allocate time for data provision as the fourth and final phase of the hydrometric data rescue process.

8 | CONCLUSION

This paper presents extended water level and flow records for eight arterially drained catchments in Ireland produced via data rescue from hydrometric archives. The standard operating procedures developed to handle specific data quality issues and quality assurance provide a methodology and workflow for future hydrometric data rescue work in Ireland and further afield.

The derived data sets, which extend to the commencement of hydrometric monitoring on the island, will offer better insights into nonstationary river dynamics, including hydrological responses to arterial drainage, and a key new resource for hydrological modelling (e.g. flow reconstructions). The addition of a total of 150 years of empirical data across eight stations provides a new window into past hydrological conditions in Ireland.

AUTHOR CONTRIBUTIONS

Kate de Smeth: Conceptualization (equal); data curation (lead); funding acquisition (equal); methodology (equal); project administration (lead); writing – original draft (lead); writing – review and editing (equal). **Joanne Comer:** Data curation (equal); methodology (equal); resources (lead); supervision (supporting); writing – review and editing (supporting). **Conor Murphy:** Conceptualization (equal); funding acquisition (supporting); methodology (equal); supervision (lead); writing – review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no conflict of interest in relation to this work.

OPEN RESEARCH BADGES

This article has been awarded Open Data Badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. Data is available at Open Science Framework

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