07 - A STATISTICAL DESCRIPTION OF THE SMALL CATCHMENT (<30 km^2) HYDROMETRIC NETWORK IN IRELAND

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Abstract

Hydrological data are critical for understanding present conditions and predicting future changes within catchments, while an improved understanding of small river catchment hydrodynamics may be used to address a range of resource management challenges including water abstraction, flood risk management and water quality. Accordingly, an assessment of the current small catchment hydrometric network in Ireland was undertaken, in order to evaluate current fitness for purpose and necessary future network amendments. Statistical analyses were undertaken for all (active and inactive) hydrometric stations associated with a catchment area ≤30 km^2 during the period 1942-2015. The assessment database was populated by 744 stations, of which 76.6% are currently inactive, equating to an active small catchment hydrometric network of 174 stations. The current network is predominantly comprised of river (85%) and lake (10%) gauging stations; within the active network, 59.4% of stations are classified as recorder stations, with the remainder being 'gauge-only' stations (i.e. only water level monitored), of which 98.5% are managed by Local Authorities. A significantly greater proportion of "gauge only" stations have been inactivated during the record period, resulting in a decreased network density but increased data availability associated with the active network. A paucity of available continuous flow data currently exists, for example, low flow data (95th %) are available for just 45% of active stations, while dry weather flow (DWF) data are available for less than half (47.7%) of monitored small catchments. A disproportionately high small catchment network density is associated with the Shannon River Basin District (RBD) which comprises 38.5% of the total active network and 21.5% of national land area. Low monitoring levels are associated with the North Western, South Western and Neagh Bann RBDs ($p < 0.001$). Study findings may be used in concurrence with meteorological and physical catchment descriptors to aid decision making in terms of hydrometric network development (i.e. station reactivation, inactivation and, in the case of new installation, optimal station location) with respect to current and future data requirements.

1. INTRODUCTION

Due to inherently significant levels of (geological and hydrological) homogeneity associated with small catchments, flow pathways are typically sensitive to prevailing local climactic conditions and the primary physical catchment characteristics (e.g. elevation, land cover, topography, etc.) (Chiverton *et al*., 2015). Thus, successful characterisation of catchment behaviour under varying climactic and hydrological conditions is frequently conducted via integrated hydrological analyses and modelling of all hydrodynamic elements. This approach requires extensive hydrometric, meteorological and catchment-specific dataset availability, in order to appropriately represent the complexity of small catchment hydrodynamics. Moreover, it is considered that successful up-scaling of hydrological processes from the small catchment scale to the large catchment scale will lead to an increased understanding of and ability to effectively characterise large catchment hydrodynamics. In-depth evaluation of the hydrodynamic behaviour of small catchments in Ireland may be used to inform previous and ongoing research carried out in larger catchments including the Flood Studies Update (FSU) Programme carried out by the Office of Public Works (OPW) and the development of HydroTool (Flow Duration Curve Estimation Model for un-gauged catchments) by the Environmental Protection Agency (EPA) and Electricity Supply Board (ESB). Additionally, the development of empirical relationships between the hydrodynamic behaviours of small and large catchments will aid determination of the required levels of monitoring for small sub-catchments nested within larger individual catchments. Previous studies in both Ireland (OPW, 2012) and the UK (Faulkner *el al*., 2012) have identified the current paucity of small stream monitoring data as a fundamental obstacle to undertaking any rigorous investigation of the hydrodynamic behaviours of small catchments.

Hydrometric monitoring in Ireland dates back to the 19th century, with organisation of the network initiated in the early 1940s; the current network is considered to have good spatial coverage, having been driven by arterial drainage works, electricity generation, infrastructural development and warning and control of extreme events (MacCárthaigh, 2002). Both the Environmental Protection Agency (EPA) and the Office of Public Works (OPW) are responsible for the collection and provision of hydrometric data. The EPA-LA hydrometric network was originally established as a direct result of the 1976 drought experienced in Ireland and the UK, which highlighted the need for closer monitoring of river flows, particularly low flows, for the purposes of water provision. The EPA-LA network is currently maintained and managed under the auspices of the Environmental Protection Agency Act 1992 which requires the EPA, in consultation and collaboration with several agencies including Local Authorities, the Office of Public Works (OPW), the Electricity Supply Board (ESB), the Geological Survey of Ireland (GSI), the Marine Institute, Met Eireann, and the Northern Ireland Rivers Agency (NIRA) to prepare a national programme for the collection, analysis and distribution of surface water quantity data. Moreover, the Local Government (Water Pollution) Act 1977 placed responsibility for the monitoring, management and control of quality in water bodies with LAs (MacCárthaigh, 2002), leading to significant increases in the density and spatial coverage of the hydrometric network during the 1970s. The EPA also has an advisory capacity in the development of LA river flow networks. The primary objective of the EPA–LA network is low flow monitoring; conversely, the overarching objective of the OPW network has largely focused on flood-risk management (i.e. flood monitoring, arterial drainage and development of early warning systems). According to a recent review of the EPA hydrometric network (EPA, 2011) the combined EPA-LA and OPW hydrometric networks currently consist of 804 hydrometric stations; there are 262 hydrometric stations in the EPA–LA network where continuous water-level recording is taking place, with flow data derived from 232 of these stations. Additionally, there are 940 EPA-LA hydrometric stations which are no longer active (130 recorder stations and 810 staff gauge only stations); however, these data are available within the active station database (EPA, 2011). The OPW network comprises 379 hydrometric stations where continuous water-level recording is taking place, with flow data derived from 245 of these. A recent review of the Irish river hydrometric network was undertaken by Murphy *et al*. (2013) in order to identify suitable benchmark stations for monitoring and detection of climate driven hydrological change. Both the length of record and rating curve quality for flow value estimation were considered as part of this identification process. Typically, OPW hydrometric stations are older than their EPA-LA counterparts, and therefore tend to have longer records. However, many OPW stations have been adversely affected by the impacts of arterial drainage including river channel widening and deepening. Furthermore, OPW stations were more frequently installed in large catchments to monitor flooding occurrences and arterial drainage. The Environmental Protection Agency maintains the *Register of Hydrometric Stations in Ireland* all active and retired/inactive hydrometric stations on the island of Ireland since initiation of the hydrometric monitoring network (Available at: www.epa.ie/pubs/reports/water/flows/registerofhydrometricstationsinireland.html#.VijiZHFViko).

Effective hydrological monitoring is vital in order to provide information for the assessment, development and management of water resources and the water-related environment (e.g. dry weather flows, flood prevention, bridge design, nutrient management, groundwater resource assessment, etc.). Additionally, a functional hydrometric network is central to national compliance with the EU Water Framework Directive and provision of data pertaining to the current and projected effects of climate change at multiple scales. Mishra and Coilibaly (2009) recommend that national and local hydrometric networks be periodically reviewed to account for the "reduction in hydrological uncertainty brought about by the data since the last network analysis" and changes related to budget, data requirements and users, etc. Accordingly, the current study sought to statistically review both the existing and historical small catchment hydrometric network in order to assess the current status of small catchment monitoring in Ireland and place this in an historical context. Additionally, it is considered that the presented review will permit the identification of current monitoring gaps at the small catchment scale, thus resulting in recommendations pertaining to additional necessary monitoring and the potential efficacy of hydrodynamic up-scaling from small to large catchment scale in Ireland, which to date has not been examined.

2. METHODS

In order to effectively assess the current small catchment hydrometric network in Ireland, statistical analyses were conducted for all (active and inactive) hydrometric stations associated with a catchment area ≤30km^2 during the period 1942-2015. The primary data source used for the current study was the aforementioned *Register of Hydrometric Stations in Ireland.* The register is freely available online and comprises all active and retired hydrometric stations in the Republic of Ireland and Northern Ireland since the early 1940s (n = 2225). The complete register includes 33 variables per active/inactive station; as part of the current study, 19 variables were extracted and coded in order to determine spatial and temporal trends pertaining to the following issues:

- hydrometric network size,
- catchment (waterbody) type,
- responsible monitoring/management agencies,
- operational status,
- range of mean annual rainfall,
- range of 50th and 95th flow percentiles including dry weather (low) flows,
- station type and data availability,
- geographic distribution at multiple scales, and
- monitored catchment size

Previous international studies have used a wide range of maximum catchment areas to define what exactly a "small catchment" comprises (Chen *et al.*, 2001; Kannan *et al., 2007*; Sun *et al.*, 2013; Kalantari *et al.*, 2014; Pierret *et al.*, 2014). To date, no explicit definition or upper limit has been agreed upon within the literature. Faulkner *et al*. (2012) utilised a maximum catchment area of 25km^2 for small catchment definition and delineation while investigating flood estimation in small rural and urban catchments in the UK. In their investigation of ten existing flood estimation methods in small and urbanised Irish catchments, Gebre and Nicholson (2012) developed a regression equation was developed and tested on 38 gauged small catchments ranging from 5 to 30km^2; this study represents one of the few which has solely focused on small catchment hydrodynamics in Ireland. Accordingly, a maximum catchment area of 30km^2 has been employed in the current study to define the upper limit of a "small catchment". Following collation of all available data from the Register of Hydrometric Stations, statistical analyses were undertaken using the *R* statistical package (*FactoMineR*, *compareGroups* and *MVN* packages). All data collation and numerical data coding were carried out in Excel 2010 using conditional formatting and developed macros.

3. RESULTS AND DISCUSSION

3.1 Descriptive Summary

Within the currently available hydrometric database, 329 catchments are not assigned an explicit catchment area (i.e. 0 km^2) and were thus excluded from analyses. Overall, the database for assessment of the small catchment hydrometric network was populated by 744 stations in catchments ≤30km^2, with a mean catchment area of 11.65km^2 (Std. Dev. 8.37km^2) and minimum and maximum catchment areas of 0.1km^2 and 30km^2, respectively. The majority (76.6%) of stations located in small catchments are currently inactive; of those active stations, 59.4% (n = 104) are classified as recorder station (1 recorder station per 811.7km^2), with 70 "gauge only" stations currently in operation (1 gauge only station per 1206km^2). Almost 89% of active stations are associated with river catchments (Table 1). Just under 65% (n = 483) of small catchments had data available for flow (Q) only, while 15.2% (n = 113) and 8.5% (n = 63) had data available for water level (m) and both flow and level, respectively. These proportions have been altered significantly due to recent network amendments (widespread inactivation of "gauge only" stations), with 39.7% (n = 69), 13.2% (n = 23) and 43.1% (n = 75) of catchments associated with the availability of flow data, level data and both flow and level data, respectively. There is a notable paucity of available flow data for small catchments e.g. 50th percentile flow data are only available for 30.4% (n = 53) of currently active stations (Table 2). In total, 8.6% (n = 15) of active stations (6.2% of all stations) reported zero dry weather flow (DWF). This national trend mirrors a recent global pattern represented by a marked decline in the volume of river flow data being collected in many parts of the world (Mishra and Coulibaly, 2009). Typically, this trend has been driven by insufficient funding, inadequate institutional frameworks and a lack of appreciation of the worth of long-term hydrological data (Stokstad, 1999; Mishra and Coilibaly, 2009).

Descriptive statistics (Min, Max, Mean, Std. Dev.) associated with measured hydrological variables were not significantly different when active and inactive stations were compared. As previously outlined (Section 1), the majority of stations are and traditionally have been operated by Local Authorities, with approximately 82% of currently operational stations managed by the relevant County Council (Table 3). Structured small catchment hydrometric data measurement was initiated in 1942 (Figure 3), with the construction of the Torc Weir by the Office of Public Works at Owengariff, Co. Cork. A significant increase of the network size begun in 1975 with the installation of 28 stations; this increase continued over the ensuing 5 to 6 years period. A peak occurred during 1998 when 65 individual stations (10% of total) were installed nationwide, followed by a significant decrease starting in 2000 and continuing over the next decade.

Table 1. *Catchment type assigned to all (active and inactive) small catchments (n = 744)*

Catchment Type	Total (%)	Active (%)	Decrease (%)
River	661 (88.8)	148 (85.1)	77.6
Lake	68 (9.1)	17 (9.8)	75
Tidal	7 (0.9)	4 (2.3)	42.8
Well	1 (0.1)	1 (0.6)	-
Spring	7 (0.9)	4 (2.3)	42.8

Table 2. *Descriptive statistics for continuous hydrological variables associated with currently active stations (n = 174)*

	N	Minimum	Maximum	Mean	Std. Dev.
Pmm_61-90 (mm)	158	725	2332	1142.6	330
50% Flow (m^3/s)	53	0	0.869	0.237	0.194
95% Flow (m^3/s)	79	0	0.449	0.037	0.065
DWF (m^3/s)	83	0	0.2	0.018	0.034

NOTE: Pmm_61-90: Mean 30-year (1961-1990) annual precipitation (Pmm_61-90); 50% Flow: 50th Percentile (Median) Flow; 95% Flow: 95th Percentile Flow; DWF: Mean Dry Weather Flow

Table 3. *Management agency associated with small catchments in Ireland (n = 744)*

Agency	Total Stations		Active Stations	
	N	%	N	%
Local Authorities	662	89	143	82.2
OPW	35	4.7	21	12.1
NI Rivers Agency	16	2.2	7	4
Marine Institute	12	1.6	1	0.6
ESB	9	1.2	1	0.6
Other	10	1.3	1	0.6

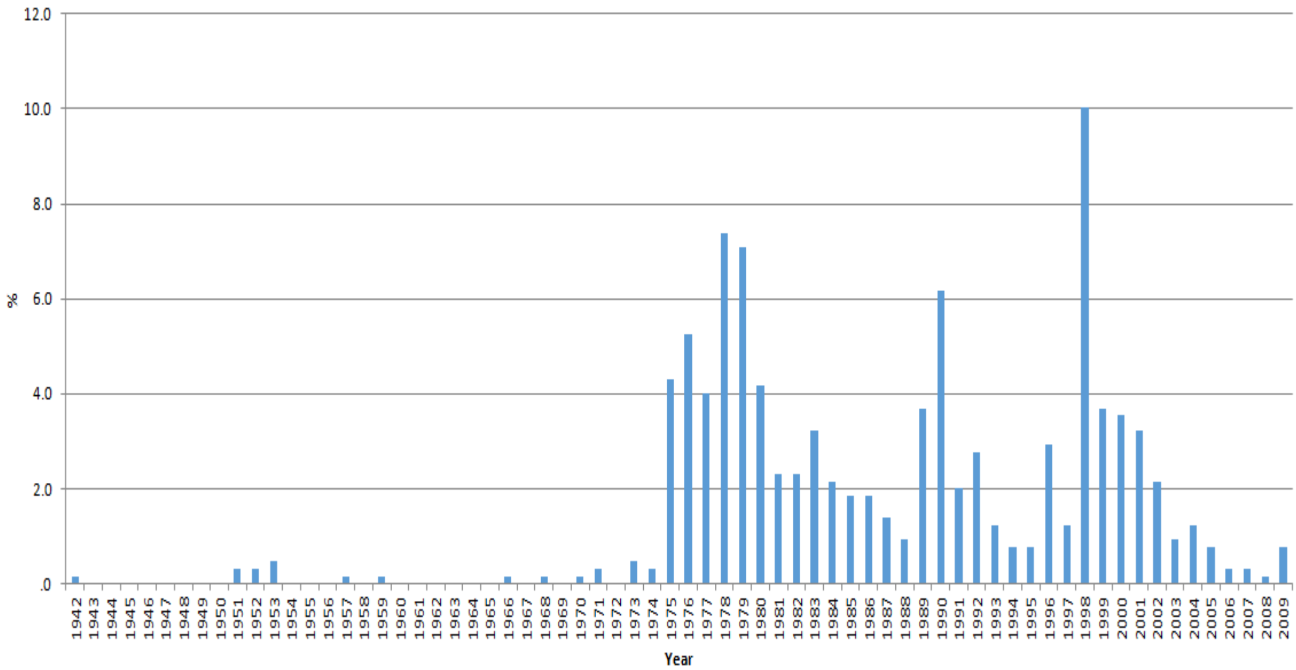

Figure 1. *Year of installation assigned to (active and inactive) small catchment hydrometric stations in Ireland, 1942-2009 (n = 744)*

3.2 Network Distribution

The Shannon RBD is associated with the highest percentage of active stations (38.5%, n = 67); in terms of hydrometric density, this is an unrepresentative proportion, with this RBD accounting for approximately 21.5% of the national land surface area (18,000km^2). The Eastern and Western RBDs are also somewhat over-represented, while the North Western, South Eastern, Neagh Bann, South Western and North Eastern RBDs are associated with disproportionately low levels of small catchment monitoring (Figure 2). The highest numbers of active small catchment stations are currently operating in counties Westmeath (9.2%, N = 16), Tipperary (8%, N = 14) and Kerry (6.9%, N = 11), while Derry, Armagh and Kilkenny all have just one active station.

Higher levels of annual mean precipitation are associated with administrative areas (RBDs and counties) located along the western seaboard ($F(6) = 17.364$, $p < 0.001$), thus reflecting national meteorological patterns. No association was found with regard to administrative area and the availability of monitored continuous hydrometric variables (50th and 95th flow percentile flows, mean dry weather flows). Similarly, no association was apparent between geographical area and continuous hydrometric means or standard deviations.

Within the total (active and inactive) dataset, a significant association existed between catchment/gauged waterbody type and geographical location (χ^2 (28) = 78.272, $p < 0.001$) thus reflecting national topography/hydromorphology; while mean RBDs comprised approximately 91% and 8% gauged river and lake catchments, respectively, the North Western RBD comprised 71.2% (n = 57) and 27.5% (n = 22) river and lake catchments (i.e. significantly higher proportion of gauged lakes). Similarly, the Western RBD historically contained a high number of lake catchments (12.8%, n = 16). Interestingly, amendments to the small catchment hydrometric network over the past two decades have led to this "lack of proportionality" no longer being in evidence (p = 0.331) (Table 4) i.e. catchment location no longer indicative of gauged waterbody type and may therefore denote a lack of hydromorphological representivity within the currently active network.

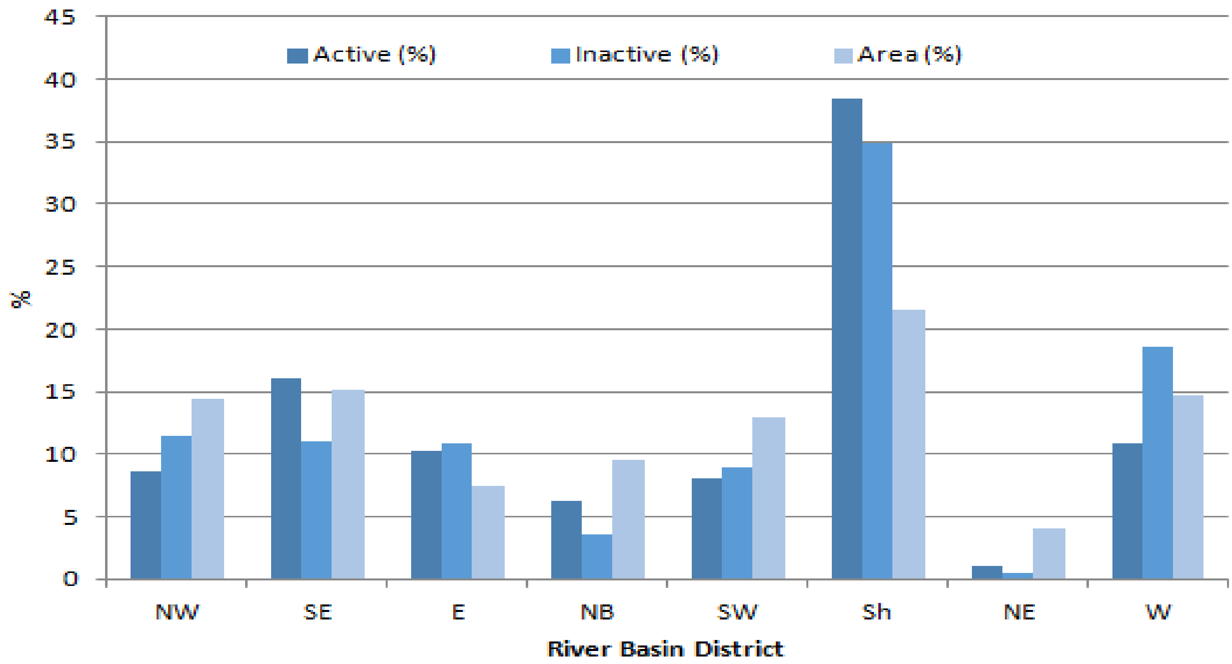

Figure 2. *Spatial distribution (River Basin District) of all actively monitored small catchments (n = 174)*

Table 4. *Catchment type and River Basin District associated with actively monitored small catchments (n = 174)*

RBD	River	Lake	Tidal	Well	Spring
North West	11	4	-	-	-
South East	25	-	2	1	-
East	14	4	-	-	-
Neagh Bann	10	1	-	-	-
South West	13	-	-	-	1
Shannon	58	4	2	-	3
North East	2	-	-	-	-
West	15	4	-	-	-

3.3 Station Inactivation

Since initiation of small catchment monitoring, 490 stations have been inactivated (Figure 3). A statistically significant association exists between the occurrence of station inactivation and station type (χ^2 (1) = 106.565, p <0.001); a significantly greater proportion of gauge only stations (i.e. only water level monitored) (OR 6.2; 95% CI 4.3-8.9) have been inactivated during the record period. Subsequently, while active network density has decreased substantially, a significantly higher proportion of active stations and associated small catchments are now associated with both level (m) and flow (Q) data availability (χ^2 (5) = 691.308, p <0.001) than previously the case. Similarly, a significantly greater proportion of gauging stations associated with rivers and lakes have been inactivated during the record period (χ^2 (4) = 12.644, p = 0.013) than other waterbody/catchment types (Table 1). A significant relationship (at the 95% level) was not found between operational status and catchment size (p = 0.06) (i.e. stations not inactivated solely based upon catchment size), with currently active stations associated with catchments which are only slightly larger than inactive stations (12.7km^2 vs. 11.3km^2). Network amendments have been more frequent in the Shannon RBD, with lowest levels of station inactivation occurring in the Neagh Bann (3.3%) and North Eastern RBDs (0%) (χ^2 (192) = 259.89, p = 0.001) (Table 5). A number of counties including Fermanagh (100%), Clare (92%) and Wicklow (89.3%) are currently associated with a disproportionately high percentage of inactive stations (χ^2 (31) = 46.030, p = 0.04).

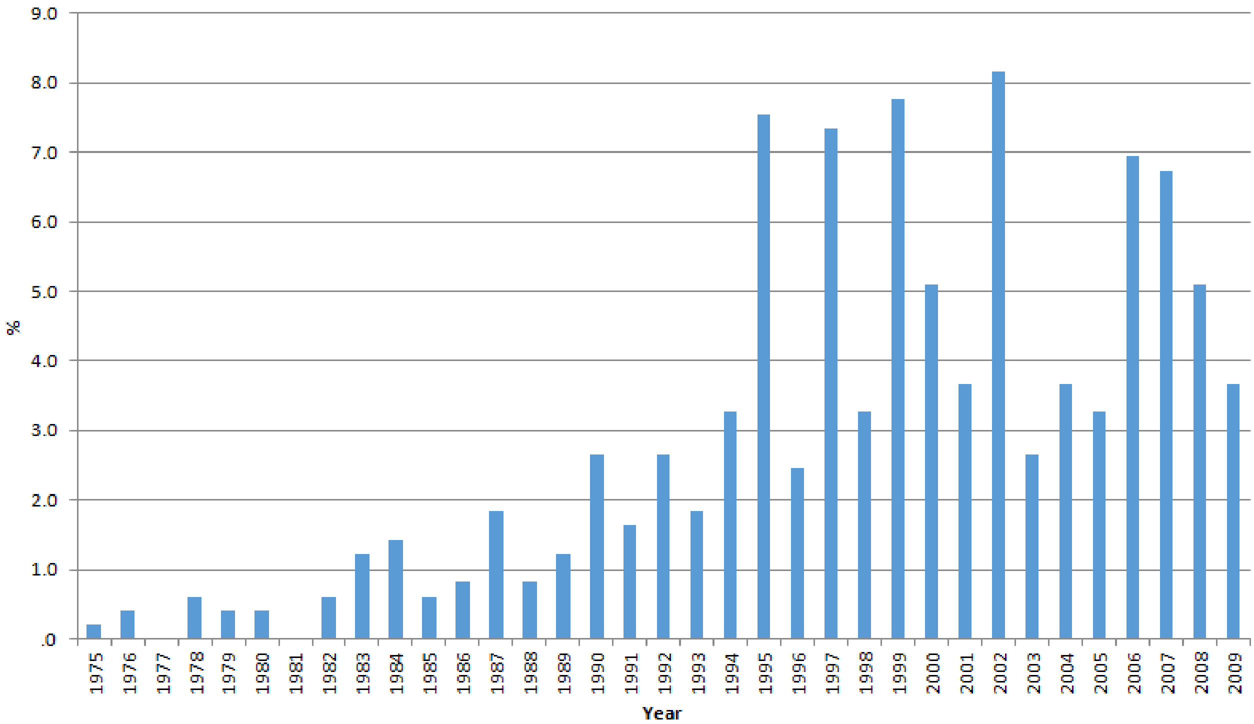

Figure 3. *Year of deactivation associated with inactive small catchments in Ireland, 1975-2009 (n = 490)*

Table 5. *River Basin District associated with inactive stations (n = 490)*

RBD	Inactive (n)	Inactive (%)
North West	45	9.2
South East	59	12
East	55	11.2
Neagh Bann	16	3.3
South West	51	10.4
Shannon	183	37.3
North East	0	0
West	81	16.5

3.4 Station Type

An association was found between gauged waterbody/catchment type and station type (χ^2 (4) = 11.227, p = 0.024); a higher proportion of lake (82.4%) and tidal (100%) catchments have recorder stations installed than is the case in river catchments (54.7%). Findings indicate that station type is associated with geographical/administrative location (χ^2 (7) = 24.346, p = 0.001), with a significantly lower proportion of recorder stations currently employed in the Shannon RBD (41.8%) (Table 6). Accordingly, a significantly lower level of concurrent river flow and river level data are currently available for small catchments within the Shannon RBD (χ^2 (21) = 65.058, p <0.001) (29.9% in Shannon RBD vs. 51.9% among other RBDs). No significant mean differences were found between station type and continuous flow or precipitation records (e.g. 30-year mean annual precipitation, 50th and 95th percentile flows) among currently active stations; within the entire dataset (including inactive stations), findings indicate that 30-year mean annual precipitation was significantly higher in small catchments with recorder stations (t (704) = 2.912, p = 0.004 (1291 mm *vs* 1176 mm) thus reflecting the higher proportion of recorder stations historically employed in western areas. No association was found between station type (recorder or gauge only) and the year of (currently active) station activation; since 1975 (first year during which a station was inactivated), 85 recorder stations and 405 gauge only stations have been deactivated (χ^2 (32) = 75.585, p <0.001).

Table 6. *Station type associated with all actively monitored small catchments (n = 173)*

	NW	SE	E	Neagh Bann	SW	Shannon	NE	W
Recorder	12	17	16	10	7	28	2	12
Gauge Only	3	11	2	1	7	39	0	7

3.5 Catchment Area

Historically, analyses indicate that the mean catchment area associated with differing station type (Recorder Station Mean: 10.98km^2; Gauge Only Station Mean: 11.92km^2) was not significantly different (p = 0.163). While a greater mean difference currently exists among active stations (Recorder Station Mean: 11.77km^2; Gauge Only Station Mean: 14.06km^2), this is still not statistically significant at the 95% level (p = 0.082). Similarly, no difference was evident between the data availability (flow or level) and catchment size. In terms of catchment size and geographical location, a significant difference previously existed between monitored catchment size and River Basin District (F(7) = 1304.85, p = 0.009) with a significantly higher number of catchments monitored in the Western RBD, and a significantly lower number monitored in the South Western RBD. This inequity was not found within the currently active network (p = 0.206), thus indicating that while a lower number of catchments are now monitored, actively monitored catchments are more spatially representative.

Network amendments (station inactivations) have not significantly affected the mean catchment size associated with gauged waterbody types (Table 7). While river catchments are typically larger than other catchment types, this is not statistically significant at the 95% level (p = 0.056). Larger catchments were associated with an increased 50th percentile for measured flow (R_{sp} = 0.49, p <0.001), 95th percentile for measured (low) flow (R_{sp} = 0.425, p <0.001) and dry weather flows (R_{sp} = 0.382, p <0.001). No significant difference was found between mean annual precipitation and catchment size (p = 0.827). Similarly, no marked trend was found between mean catchment area and activation/initiation of the monitoring station, however a non-parametric correlation was found between catchment area and inactivation year (R_{sp} = 0.095, p = 0.036) i.e. station activation has tended to occur more recently within larger catchments.

Table 7. *Catchment type and mean catchment area associated with all monitored small catchments* (n = 744)

Catchment Type	Active Mean Area (km^2)	Total Mean Area (km^2)
River	13.5	12.1
Lake	8.9	8.5
Tidal	8.1	8.7
Well	1.4	1.4
Spring	7.3	6.9

3.6 Network Management

A significant pattern exists in terms of catchment type and hydrometric station management (χ^2 (20) = 70.592, p <0.001); local authorities currently manage 79.3% (n = 124) of the active small catchment hydrometric network, comprising 83.8% (n = 124) and 82.4% (n = 14) of monitored rivers and lakes, respectively (Table 8). Moreover, 98.6% of gauge only stations (n = 69) within the small catchment network are managed by local authorities (χ^2 (5) = 25.505, p <0.001), with higher levels of data availability thus associated with stations and catchments not operated/managed by local authorities. Within the entire database, a significant mean difference was found between mean catchment area and management agency thus reflecting organisational objectives; stations managed by the Marine Institute and Electricity Supply Board are traditionally larger than those operated by other agencies (F(5) = 2.847, p = 0.015). Within the active small catchment hydrometric network, no association exists between management agency and mean catchment size (p = 0.165).

Table 8. *Catchment type and management agency associated with actively monitored small catchments (n = 174)*

	River	Lake	Tidal	Well	Spring
Local Authority	124	14	-	1	4
NIRA	7	-	-	-	-
OPW	16	2	3	-	-
Marine Institute	-	-	1	-	-
ESB	1	-	-	-	-
Other	-	1	-	-	-

4. CONCLUSIONS

- The Register of Hydrometric Stations currently comprises 744 stations located in catchments <30km^2 (Mean Catchment Size = 11.65km^2) of which 76.6% are currently inactive, equating to an active small catchment hydrometric network of 174 stations,

- The small catchment hydrometric network increased significantly in the mid-1970s as a direct result of the nationwide drought experienced during 1976 leading to increased data requirements,
- Network size has decreased significantly since the mid-1990s, with the current network predominantly associated with river (85%) and lake (10%) catchments,
- There is a lack of available continuous flow data associated with the current network (e.g. low flow data (95^{th} %) is available for 45% of active stations),
- Within the active network, approximately 60% of stations are classified as recorder stations, with the remainder being 'gauge-only' stations; the majority of 'gauge-only' stations (98.5%) and small catchment monitoring (79.3%) is managed by Local Authorities,
- A disproportionately high small catchment network density is associated with the Shannon River Basin District, while low monitoring levels are associated with the North Western, South Western and Neagh Bann RBDs,
- Results suggest that while network amendments (resulting in a large inactive network) have led to higher levels of geographical and hydrological representivity within the network and increased levels of data availability associated with individual active stations, network density has declined significantly and is inadequate within several regions.

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6. REFERENCES

Chen L., Wang J., Fu B., Qiu Y. (2001). Land-use change in a small catchment of northern Loess Plateau, China. *Ag. Eco. Environ.* **86**(2): pp 163-172

Chiverton A., Hannaford J., Holman I., Corstanje R., Prudhomme C., Bloomfield J., Hess TM. (2015). Which catchment characteristics control the temporal dependence structure of daily river flows? *Hydrological Processes*.**29**(6): pp1353–1369

Environmental Protection Agency (EPA). 2011. Review of the EPA Hydrometric Network. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland.

Faulkner D., Kjeldsen T., Packman J., Stewart L. (2012). Estimating flood peaks and hydrographs for small catchments: Phase 1. Environment Agency, Horizon House, Deanery Road, Bristol BS1 5AH.

Gebre F., Nicholson O. (2012). Flood estimation in small and urbanised catchments in Ireland. Proceedings of the Irish National Hydrology Seminar, pp 88-100.

Kalantari Z., Lyon SW., Folkeson L., French HF., Stoltes J., Jansson PE., Sassner M. (2014). Quantifying the hydrological impact of simulated changes in land use on peak discharge in a small catchment. *Sci. Tot. Environ*. **466-67**: pp 741-754

Kannan N., White SM., Worrall F., Whelan MJ. (2007). Hydrological modelling of a small catchment using SWAT-2000 – Ensuring correct flow partitioning for contaminant modelling. *Jour. Hydrology*. **334**(1-2): pp 64-72

MacCárthaigh M. (2002). Parameters of low flow and data on low flows in selected Irish rivers. Proceedings of the National Hydrology Seminar 2002, pp 64–71.

Mishra AK., Coulibaly P. (2009). Developments in hydrometric design: A review. *Rev. Geophysics*. **47**(2)

Murphy C., Harrigan S., Hall J., Wilby RL. (2013). HydroDetect - The Identification and Assessment of Climate Change Indicators for an Irish Reference Network of River Flow Stations. Environmental Protection Agency, Johnstown Castle Estate, Co. Wexford, Ireland.

Office of Public Works (OPW). (2012). Flood Studies Update Programme, Work Package 4.2: Flood estimation in small and urbanised catchments. Draft Final Report. Hydrology & Flood Response Section, Engineering Services, Office of Public Works.

Pierret MC., Stille P., Prunier J., Viville D., Chabaux F. (2014). Chemical and U-Sr isotopic variations of stream and source waters at a small catchment scale (the Strengbach case; Vosges mountains; France). *Hyd. Earth Sys. Sciences Disc*. **11**(3): pp 3541-3598

Stokstad E. (1999). Scarcity of rain, stream gages threaten forecasts. *Science*. **285**(5431): pp 1199–1200

Sun F., Lu Y., Fu B., Ma Z., Yao X. (2013). Spatial explicit soil moisture analysis: pattern and its stability at small catchment scale in the Loess hilly region of China. *Hydro. Process*. **28**(13): pp 4091-4109